Detailed Project Report

For

'Technology Innovation Hub On Quantum Technologies'

Submitted by

IISER Pune

Under

National Mission on Interdisciplinary Cyber Physical Systems

सत्यमेव जयते

INTERDISCIPLINARY CYBER-PHYSICAL SYSTEMS
DEPARTMENT OF SCIENCE & TECHNOLOGY
MINISTRY OF SCIENCE & TECHNOLOGY
GOVERNMENT OF INDIA

OCTOBER 2020

EXECUTIVE SUMMARY

Quantum theory was developed during the early part of the 20th century to explain the behaviour of matter and light at the microscopic levels, and was subsequently extended to understand several emergent phenomena of aggregate matter. However, it is also well appreciated that most of technologies existing then, and even today, do not harness the inherent potential of quantum systems. Quantum properties such as coherent superposition, entanglement, nonlocal correlations, and unpredictable state collapses, if exploited cleverly, could open up hitherto unforeseen technologies far beyond the scope of those established by harnessing classical theory. Some of the examples of possible devices using such inherent quantum phenomena are quantum computers and sensors whose noise levels go well below that of classical devices, ultraprecise atomic clocks for navigation, accurate accelerometers, gravity sensors, inertial sensors, and also topological and opto-electronic materials with exotic properties. These systems and devices exploiting quantum phenomena open up a plethora of possibilities for national defence and socio-economic development with far reaching consequences in improving the quality of life in general and specifically in healthcare, agriculture, natural resources utilization and clean transportation, just to name a few.

The specific outcomes of quantum technologies are in the areas of quantum computing, secure communications and navigation, quantum sensing, quantum metrology, and futuristic quantum devices. There are many national and international programmes around the world with billions of dollars of investment to boost quantum technologies for delivering socio-economic impact. Some of the examples of such program are the UK quantum technology program (with over 270 million GBP), The European Quantum flagship program (over 1 billion Euros over 10 years), the Russian Quantum technology program at the Russian Quantum Centre, The quantum technology program in Japan, the Chinese quantum technology program with a spending of over 1 billion USD, and the Korean initiative on quantum computing. With such a large scale efforts underway around the world, it is imperative that India should recognize and work towards harnessing quantum technologies right from these early stages.

The establishment of such a Quantum Technologies (QT) development hub at IISER Pune will be a boost to develop quantum technologies. The main focus will be commercialization, generation of intellectual property and highly skilled manpower in QT. This hub will work and deliver on three main areas of quantum technologies : (A) Quantum Information and Metrology, (B) Quantum Communication, and (C) Quantum Materials and Devices. In addition, this hub will interface and collaborate with some of the major quantum technology initiatives around the world mentioned above.

Proposed activities

(a) Research and technology development: Focused research in experimental, commercialization as well as theoretical aspects in three themes: Quantum Information and Metrology, Quantum Communication, and Quantum Materials and Devices.

(b) Industrial collaborations: Collaborations will be set up with the government and non-governmental entities in order to translate academic research towards product development.

(c) Education & Human Resource Development: The hub will engage in teaching Quantum Technology related courses at the graduate and the undergraduate levels. A modern curriculum will be designed and implemented that caters to the future human resource requirements.

(d) Training: Seminars, conferences, and workshops will be organized regularly for the benefit of interested scientists, doctoral and postdoctoral researchers, and industry participants. Training and orientation programs will be conducted for college teachers so as to indirectly reach out to a wider student population.

Integration

Translation of research output from the laboratory to functional technological products and services is an important goal of any research program. The recent boom in global research investments in quantum technology programs shows our trust in their potential to generate crucial technologies in not too distant future. However, not every research effort needs to follow this goal - interesting and ambitious scientific explorations carry immense value in motivating further ideas. Such a long term vision is absolutely critical in evolving fields like quantum technologies, where solutions to the gaps in technologies will almost certainly come from unexpected and unexplored ideas. The hub aims to strike a healthy balance between the two approaches.

The primary focus of this research hub is to maximize the translation of research ideas into technologies. In this direction, the hub will engage with industries from the early stages since the industry footprint in the area of quantum technology within the country is virtually non-existent. This early engagement will not only help in directed research and development, but also help in addressing problems of immediate relevance in a holistic manner. This would enable bringing all the themes of the hub under one roof for enabling a solution. IISER Pune has a large pool of young students at various levels. These students will also be engaged in the research, development and translation of research ideas into products.

Grand Goals

1. Development of > 20 qubit state of the art tolerant quantum computers and simulators for applications in defence, healthcare and financial sectors
2. Building long distance quantum communication channels
3. Commercialization of quantum effect enhanced sensors and atomic clocks with unprecedented accuracy and stability
4. Capacity building in quantum technology development and human resources for self-reliance

Deliverables

The Hub will demonstrate and deliver several products for operational testing by the partner industries. In particular, in the initial stages, the Hub is planning to deliver a 20 qubit fault tolerant quantum computer that can be deployed for small scale problems and more importantly it will serve as a stepping stone to begin work on creating bigger quantum computers in India. This will be made available in the public domain through a web interface. As of now, India does not have such a quantum computer hardware and this will be the first of its kind. Another set of deliverable will be quantum communications over optical fiber over 5 kms, a feat not yet achieved in India. This will provide a first step towards secure communications over optical fibers for high speed and high bandwidth communications and synchronization of quantum clocks. Precise measurements of magnetic fields have many civil and defense applications. Some of these can be made portable by incorporating them in integrated chips. The hub will attempt to deliver quantum technology based sensitive and portable magnetometers for civil and defense applications. The Hub also plans to deliver a gravimeter (device for measuring local gravitational force, typically on the surface of the earth) that is widely used in prospecting underground natural resources and mapping seismic zones. Another related but distinct deliverable would be an inertial sensor, a device to measure inertial rotations and hence measure acceleration and other dynamical characteristics of an object. These inertial sensors have direct applications in defense and deep space navigation and in day-to-day consumer systems. While these would constitute some of the flagship deliverables at the level of a prototype, the Hub will also strengthen efforts towards making other quantum technology based products available to industries.

Description of the Hub

The technology Hub will be established and operated through a not-for-profit Section-8 company (Indian Companies act 2013). This company will be hosted by the Indian Institute of Science Education and Research, Pune.

The Government of India, through the Ministry of Education (MoE), has established seven Indian Institutes of Science Education and Research (IISER). The IISERs are unique among the Indian research institutes, with a mandate for teaching and education that are fully integrated with cutting-edge scientific research programs. Each IISER is an autonomous institution awarding its own Masters and Doctoral degrees.

Located in a vibrant city that houses several such eminent partner research institutes, IISER Pune is a research-intensive teaching institute. Bringing the young and the trained minds together, we work on some of the most challenging and ambitious questions in science. Since inception in 2006 IISER Pune has published over 2000 research papers in renowned scientific journals, representing the work not just by the faculty and the graduate researchers but also its undergraduate members. IISER Pune is a member of the Association of Indian Universities and is ranked 23 in the overall category in the NIRF 2019 India Rankings.

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CERTIFICATE

Name of the TIH: I-HUB Quantum Technology Foundation

Technology Vertical: Quantum Technology

1. This is to certify that the Detailed Project Report (DPR) on the Technology Vertical **Quantum Technologies** is prepared and submitted to Mission Office, NM-ICPS, DST is as part of implementation of Technology Innovation Hub (TIH) at **Indian Institute of Science Education and Research, Dr. Homi Bhabha Road, Pune 411008** under National Mission on Interdisciplinary Cyber-Physical System (NM-ICPS).

2. This is to certify that this DPR has been checked for plagiarism and the contents are original and not copied/taken from any one or from any other sources. If some content was taken from certain sources, it is duly acknowledged and referenced accordingly.

3. The DPR will be implemented as per the Terms, Reference and Clauses stated in Tripartite Agreement signed on 26Th March 2021 between Mission Office, DST **Indian Institute of Science Education and Research, Dr. Homi Bhabha Road, Pune 411008** and **I-HUB Quantum Technology Foundation**.

Date: 20th September 2021
Place: Pune

U. D. Rapol

Umakant D. Rapol

Name and Signature of Project Director

भारतीय विज्ञान शिक्षा एवं अनुसंधान संस्थान पुणे
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Endorsement from the Head of the Institution

1. Certified that the Institute welcomes participation of Umakant D. Rapol as the Project Director for the Technology Innovation Hub (TIH) and that in the unforeseen event of discontinuance by the Project Director, the Director of Indian Institute of Science Education and Research Pune will identify and place a suitable faculty as Project Director for fruitful completion of the TIH activities.

2. Certified that the Host Institute shall provide basic facilities, faculty support and such other administrative facilities as per Terms and Conditions of the award of TIH, will be extended to TIH.

3. As per Tri-partite Agreement, the Host Institute (HI) shall play its role and fulfill its responsibilities for the success of TIH.

Date: 21/9/21
Place: IISER, Pune

Prof. Jayant Udgaonkar
Director
Indian Institute of Science Education and Research Pune

प्रो. जयंत बी. उदगांवकर/ Prof. Jayant B. Udgaonkar
निदेशक / Director
भारतीय विज्ञान शिक्षा एवं अनुसंधान संस्थान
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TABLE OF CONTENTS

CHAPTER 1

1 CONTEXT AND BACKGROUND

1.1 INTRODUCTION

The interplay of quantum superposition and entanglement at a microscopic level leads to enormous possibilities in engineering devices and systems for the benefit of society and humankind. The three main pillars of the technologies that exploit the characteristic features of quantum physics are Quantum information processing and Quantum metrology, Quantum communications, and Quantum materials & Devices.

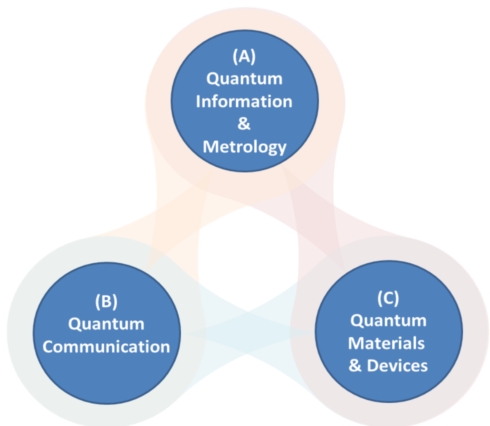

Figure 1.1: The three themes to be executed by the QT-TIH

Quantum computation/information processing has been one of the most coveted applications of the experimental and theoretical developments in quantum mechanics. Its promise to tackle a plethora of problems ranging from creating ultra-secure networks via quantum cryptography and quantum key distribution (QKD) to aiding synthesis of potentially life changing drugs via quantum computation/simulation attracts massive funding from government research budget/industry in developed countries. One of the most fundamental challenges in realizing such devices is to carry out useful computations at a time scale faster than the decoherence time of the underlying qubit architecture on a large number of qubits.

Quantum communications deals with transfer of information over channels that preserve quantum nature of the information unlike their classical counterparts. This involves transmitting photons on which the quantum information from internal states of stationary qubits is imprinted. Quantum communication is an essential requirement for secure communications and distributed quantum computing. Quantum materials are those where a number of attributes like the spin, strong electron correlations, and electronic (and magnonic) topology combine in unique and interesting ways. The quest here is to try and come up with new materials, where strong coupling between the electronic, magnetic, orbital, lattice, and topological degrees of freedom give rise to interesting multifunctional properties, which can form the bedrock for the new and improved devices.

1.2 MAJOR APPLICATION AREAS

1. Defence and Communication
2. Natural Resource mapping
3. Healthcare

1.3 MAJOR SCEINTIFIC AND TECHNOLOGICAL CHALLENGES

The Technology innovation hub at IISER Pune will lead country wide efforts in the above three verticals for paving a way to build technical infrastructure in the country through development of highly trained manpower, intellectual property and technical knowledgebase.

1.3.1 QUANTUM INFORMATION AND METROLOGY

Here the focus will be on experimental realization of a 20-qubit fault tolerant ion-trap and superconducting qubits based quantum computer, demonstration of a 50 qubit spin-register based on Nuclear Magnetic Resonance for quantum simulations, experimental multi-qubit quantum computing with defect-center based registers such as Nitrogen vacancy centers in diamond, theoretical research into the trapped-ion crystal with Rydberg excitations, Quantum Thermodynamics, as well as strongly correlated & open quantum systems. Several methodologies such as advanced quantum control techniques, adopting machine learning methodologies, novel protocols for decoherence suppression will also be developed.

1.3.1.1 CONSTRUCTION AND REALIZATION OF A 20 QUBIT FAULT TOLERANT ION TRAP QUANTUM COMPUTER

There are a variety of platforms that are being researched upon by many leading research groups across most of the developed world to build a quantum computer. These platforms are based upon solid state qubits, photonic and pure atomic qubits (either ions or atoms). One of the most mature platforms is that of an ion trap qubit system (*Phys. Rev. Lett.***74**, 4091 (1995)). This platform has been in the forefront of quantum computation architectures due to the existence of inherently long coherence times combined with the developments in ultra-stable laser systems and advanced control electronics that are used to address the ion qubits. With regards to practical applicability, there have been many blueprints to realize a scalable architecture for this system (eg. *Sci. Adv. 2017;***3***: e1601540*) and commercial giants like Honeywell (spectrum.ieee.org) have chosen this approach to realize a quantum computer. In addition to the use of this platform for quantum information processing, certain ions can also be used for building precision atomic clocks (Yb^+, Ca^+, In^+, Al^+ etc.) that can provide precise timing reference for applications ranging from precise navigation (GPS) to time tagging of precious information carrying photons in cryptographic systems. These clocks are also being used for understanding certain problems dealing with the foundations of physics.

Despite many advantages, an ion trap system has hurdles to cross before it can be used as a scalable quantum computer. Two of the major ones are a) the non-availability of simple techniques to realize a large number of ions (~100s) in a commonly addressable vibrational state and b) the build-up of decoherence when the number of qubits are increased. There has been considerable research done in this direction such as using Rydberg states to provide long distance coupling circumventing the use of vibrational modes (*Phys. Rev. Lett.***119**, 220501 (2017)) and also the concept of using segmented micro-fabricated electrode structures. The biggest concern in micro-fabricated traps that trap the ions near the electrode surfaces is the heating of the ion chains that destroys the coherence of phonon modes in the system which acts as the quantum bus. There have been considerable investigations of the nature of the heating induced due to surface irregularities and patch potentials. At the TIH, we would like to initially focus on building a 20 qubit ion trap quantum processor in a 3-D linear trap. In parallel, we would explore architectures for surface traps wherein the design will be optimized to reduce the heating of the phonon modes while achieving a tradeoff between with the number of achievable logical qubits.

By building an ion trap at IISER-Pune, we want to study these issues and realize qubit manipulation protocols that circumvent these. These will also serve as a standard test-bed consisting of a multi-qubit system for quantum information theory researchers in the country to implement and benchmark their protocols.

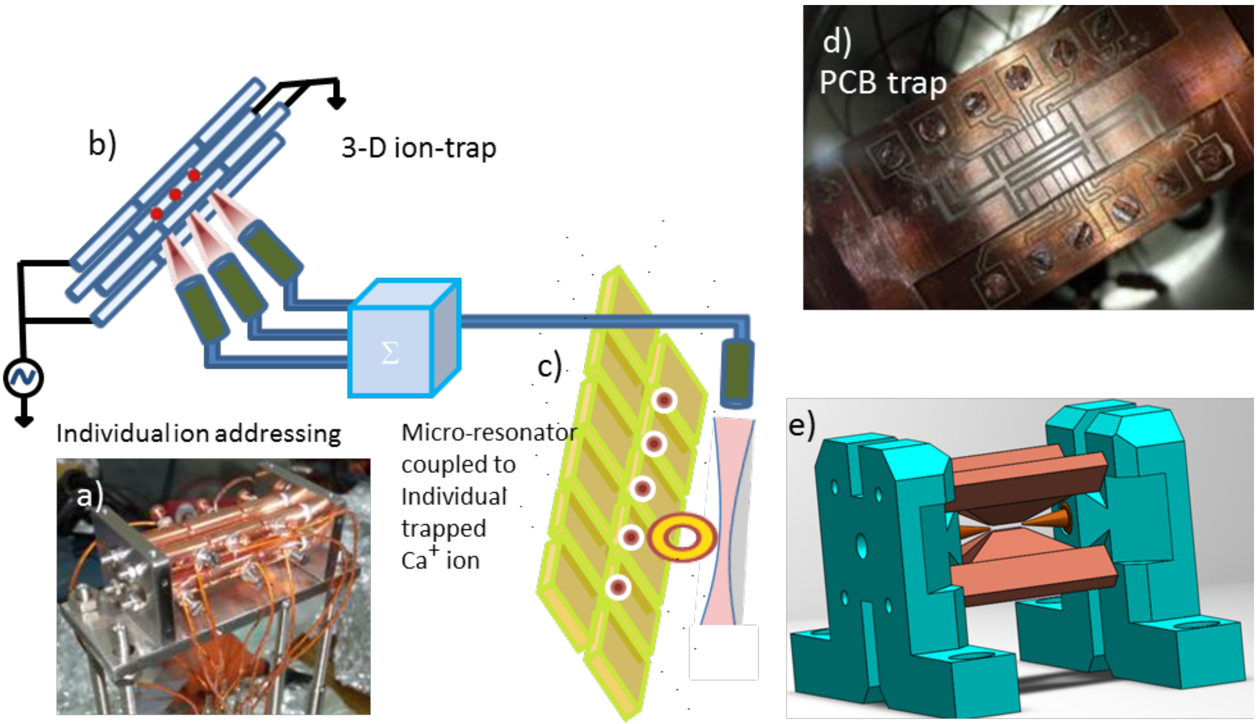

Figure 1.2: Images of a 3-D linear ion trap : a) A picture of a 3-D ion trap. a) Addressing of individual ion qubits. c) Possible photon coupling scheme from ions on a surface trap. The schematic shows a possible way of communication between two traps for distant communication d) A PCB surface trap for trapping ions. d) New 3-D ion trap being under design. The 3-D and the PCB traps were made under joint collaboration between IISER Pune and IISc Bangalore.

There has been no known demonstration of site resolved laser cooled ion crystal-chains in India. Demonstration of laser cooled clouds of Ca^+ ions on a printed circuit board (PCB) based surface trap and a segmented four rod trap has been done in collaboration with Prof. Vasant Natarajan's lab at IISc-Bangalore. Based on the experience gained during this experiment, the setup based on the four-rod trap will be optimized to avoid problems like RF induced heating. After the initial demonstration of ion strings in a classical four electrode trap, the team would start working on developing surface traps for trapping larger ion strings and having a architecture of segmented electrodes for shuttling ions. The problems related to heating and loss of coherence times will be addressed by optimizing the geometry. The next goal would be integration of chip traps with integrated waveguides and optics for compact ion-trap computing devices.

Ion Crystals in a classic 3-d trap can also be used for a special class of quantum computers called as the quantum simulators which are constructed for a specific purpose. In particular, they are useful for analyzing the properties of novel quantum matter and also for quantum simulations of molecular structure. The key ingredient in quantum simulators would be to engineer inter-particle interaction that is mediated by phonons. The desired inter-particle interactions can be attained via proper manipulations of phonon modes in the ion crystal.

1.3.1.2 Experimental demonstration of a 50 qubit spin-register based on Nuclear Magnetic Resonance for quantum simulations

Quantum registers are at the core of quantum information technologies such as quantum computers, quantum simulators, quantum communication devices, as well as quantum metrology. Accordingly, the development of quantum registers and their control forms a crucial step towards the physical realization of quantum information technology. A quantum register consists of a connected set of controllable and measurable quantum bits.

In NMR, the qubit connections are realized by spin-spin interactions, specifically either dipolar coupling or J-coupling or both. Depending on the architecture and topology, a varying degree of controllability can be achieved - from global control involving collective qubit-transformations to local control involving individual-qubit operations. Local control allows the construction of universal gates and implementing a general quantum circuit. In liquid state NMR quantum registers, the local control is achieved via either isotopic shifts or chemical shifts of Larmor frequencies. Accordingly, most of the quantum information protocols by NMR are so far carried out in such systems. With only about 12 completely addressable NMR qubits having been demonstrated so far, the challenge is to scale-up the register size. In solid-state NMR, one can realize quantum correlated clusters of 100+ qubits, but they allow only global control. Nevertheless, such systems find important applications developing decoherence-suppression schemes, quantum control schemes, many-body quantum simulators, and a variety of such quantum information tasks. Symmetry-restricted spin-systems with certain special topology offer a middle-ground allow partially controllable quantum registers with 30+ qubits, while retaining all the advantages of high-resolution liquid-state NMR.

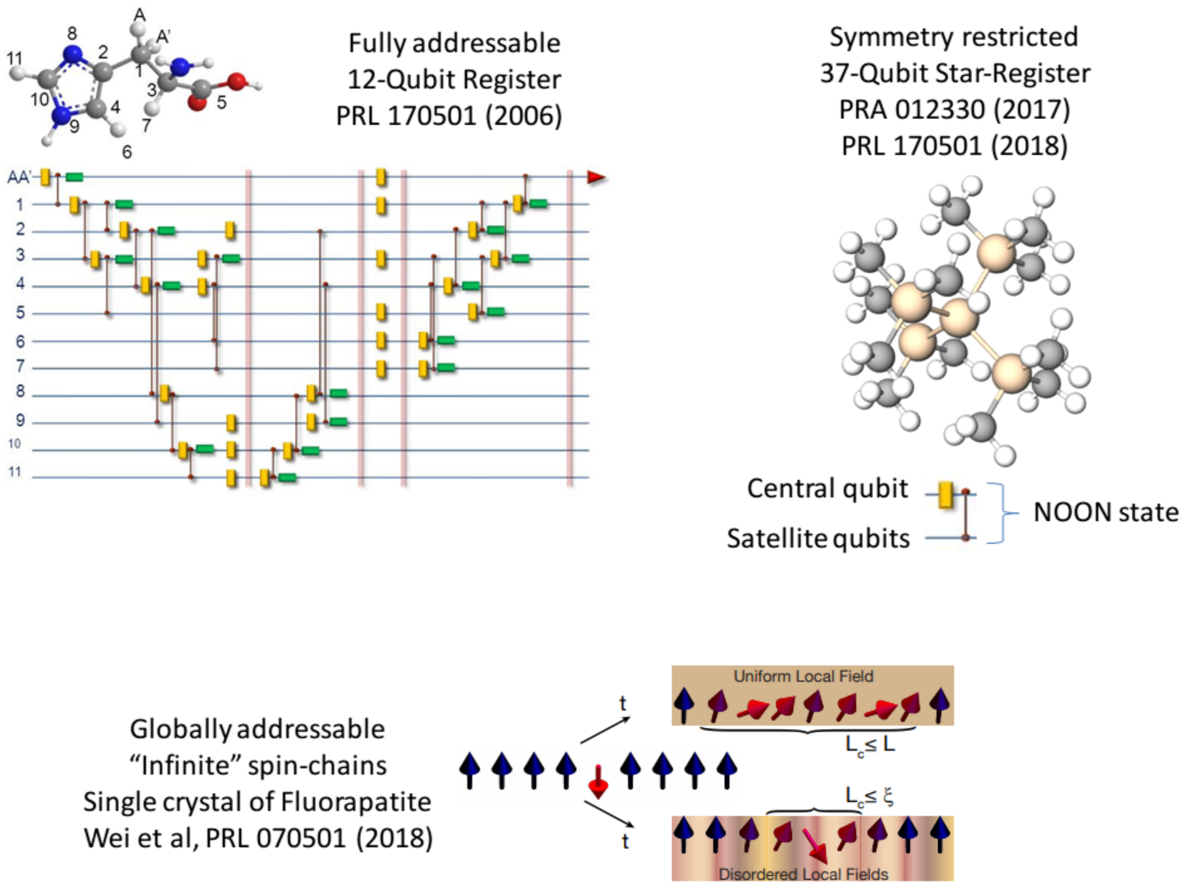

Figure 1.3: Types of NMR registers

The main context of this project would be to realize quantum registers with 50+ qubits using special-topology spin systems and utilize it to develop advanced methodologies for quantum control and decoherence suppression. The outcome of this development should be relevant not only to NMR but also to other quantum technologies based on quantum control.

Desktop NMR Quantum Computer for Education and Research

Recently, desktop NMR spectrometers are increasingly popular for spectroscopic and imaging applications [1] as well as for potential quantum computing applications [2]. These are mostly based on permanent magnets, typically in a composite Halbach design, capable of producing magnetic fields from 0.1 to 3 Tesla [3]. They include low-power broadband excitation transmitters [4] and analogue or FPGA-based [5] receivers. Here we propose to develop a low-cost, low-field, desktop, NMR system optimized for quantum computing applications with up to five qubits (see Figure 1.3A).

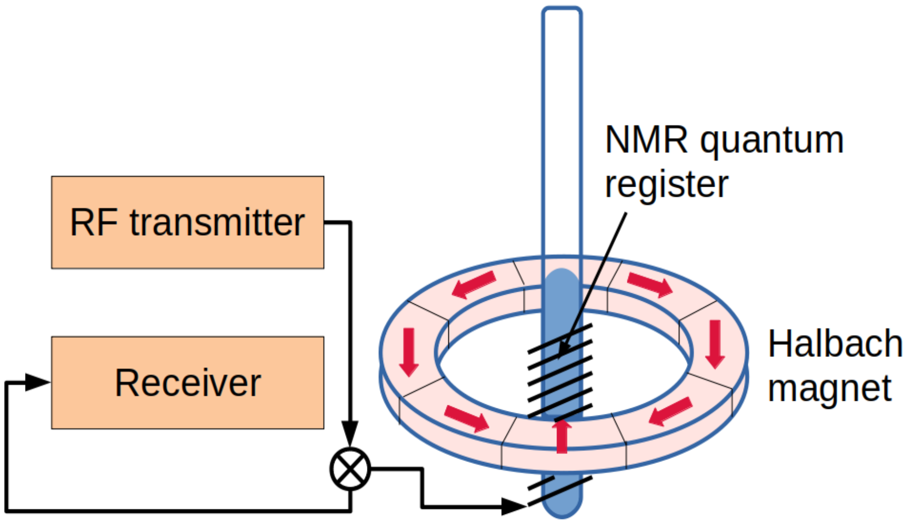

Figure 1.3A Table top NMR quantum computer for education and research

The main challenges would be sensitivity and resolution. The sensitivity issue can be overcome by choosing an isotopically abundant nuclear spin-register at suitably high concentrations. The resolution issue can be overcome by choosing a heteronuclear register. Previously, fully heteronuclear NMR quantum registers of up to five qubits have been reported [6]. We envisage the desktop NMR quantum computer system to be affordable for colleges to be included in the laboratory component.

References:

1. Blümich, Bernhard. "Beyond compact NMR." Microporous and Mesoporous Materials 269 (2018): 3-6.

2. Maguire, Yael, E. Boyden, and Neil Gershenfeld. "Toward a table-top quantum computer." IBM Systems Journal 39.3.4 (2000): 823-839.

3. Moresi, Giorgio, and Richard Magin. "Miniature permanent magnet for table-top NMR." Concepts in Magnetic Resonance Part B: Magnetic Resonance Engineering: An Educational Journal 19.1 (2003): 35-43.

4. Michal, Carl A. "A low-cost multi-channel software-defined radio-based NMR spectrometer and ultra-affordable digital pulse programmer." Concepts in Magnetic Resonance Part B: Magnetic Resonance Engineering 48.3 (2018): e21401.

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1.3.1.3 Superconducting Qubits

While several quantum technologies (e.g. trapped ions, spins in silicon, diamond NV centers etc.) are being pursued, superconducting quantum circuits operating at mill kelvin temperatures have emerged as a leading candidate for a scalable quantum processor architecture. This architecture is also the most pursued approach in the world with major efforts in the United States, Europe, China, and Japan, including significant industrial efforts by companies like IBM, Google and Intel to name a few. The early work on observing quantum effects in superconducting circuits took place in the 80s in the US and Europe but the first evidence of quantum coherence was obtained by a Japanese group in 1999. Since the year 2000, due to significant improvements in circuit design, choice of materials, careful fabrication procedures, microwave engineering, and robust filtering and shielding, the coherence times of superconducting qubits have improved by nearly 6 orders of magnitude More than 10 types of new qubits were invented by just choosing the right combination of the basic building blocks: inductors, capacitors and Josephson which points to the remarkable flexibility in constructing qubits using superconducting circuits. Out of all the qubit types, the transmon qubit and its variants (3D transmon, Xmon, Gatemon) have become the qubit design of choice to implement larger scale quantum processors. Further, significant improvement in the measurement of qubits was achieved with the development of ultra-low noise Josephson parametric amplifiers

There are two main areas of focus in the international arena as of today. The first is to demonstrate quantum error correction (QEC) where a single logical qubit composed of several physical qubits can be actively protected by repeated measurements and feedback. This is a crucial step before large scale robust processors can be implemented. The other area of focus is to demonstrate "quantum supremacy" where a quantum algorithm running on a quantum processor will outperform any classical computation for that problem. In 2019, the Google team demonstrated quantum supremacy in a 53-qubit superconducting quantum processor.

1.3.1.4 VACANCY CENTERS BASED METROLOGY

The quest to harness the power of quantum mechanical effects at the nano scale is driving a new generation of quantum devices capable of novel functionalities and enhanced performance that cannot be realized with devices purely based on the principles of classical physics. Over the past decade, the study and application of quantum phenomena in diamond spin qubits has shown promise for new technological prospects of processing quantum information in sensing, imaging, and metrology. By leveraging advanced quantum control of nitrogen-vacancy (NV) centers in diamond, quantum sensors with enhanced precision and accuracy capable of operation at the nano scale have been realized. High sensitivity NV-diamond magnetometers have also been developed which led to the study of magnetic phenomena in condensed matter nano systems at both ambient and cryogenic conditions. Here, we propose to use wide-field fluorescence microscopy platform for the development of novel quantum sensing and metrology applications with NV centers. In a wide-field quantum microscopy platform, optical pumping, fluorescence measurements and microwave manipulation are carried out on ensembles of NV centers to further enhance the sensitivity of the magnetometer by a factor of $\sqrt{N}$, where N is the number of NV defect spins.

1.3.1.5 QUANTUM METROLOGY USING TRAPPED ION OPTICAL CLOCK

The advancements in the field of quantum information processing (QIP), quantum metrology and exploring fundamental science demands long-distance (geographically separated) transfer of the "**phase & frequency stabilized**" optical photons. Thus, phase or polarization of electro-magnetic modes of the specially engineered photons needs to be preserved while transferring them through long optical fibers, to make them useful for any quantum enhanced measurements. Requisite technologies for this are very different from that of the commonly used standard optical communication through a fiber as in that case photons are disseminated at random frequency & phase due to instability of the fiber length. **Phase noise cancellation**, that is generally induced due to dynamicity of the optical path length of a communicating fiber was demonstrated by Long-Sheng Ma et. al. [Ref. Opt. Lett. 19, 1777 (1994).]. So far, **bi-directional transfer technique through a single optical fiber** to get the phase and frequency stabilized photons have been demonstrated over thousands of kilometers within the laboratory as well as between two geographically separated laboratories, as shown in Fig. 1.4. In some of the developed countries, transfer of the phase & frequency stabilized optical photons over long distances have been undertaken as one of the major challenges in the last one decade. Currently, these projects are not only limited to a country but also extended across various continents using specific telecom fibers for disseminating uniquely defined photons between two lands separated by sea. To best of our knowledge, internationally the phase noise cancelled long distance photon transfer projects are as follows,

ii) **European union:** The European network for optical frequency transfer (OFTEN Project) under EURAMET. Several laboratories in different EU countries are participating in this program. [Ref. https://www.euramet.org; https://www.ptb.de/emrp/often_home.html]

iii) **USA:** Univ. Boulder-NIST Boulder link [Ref. P. A. M. Williams, et. al., J. Opt. Soc. Am. B 25, 1284 (2008).]

iv) **Italy:** INRIM-LENS link [Ref. D. Calonico, et. al., Appl. Phys. B, 117, 979 (2014).]

v) **France:** LPL-Reims link [Ref. O. Lopez, et. al., Opt. Express 20, 23518 (2012).]

vi) **Germany:** MPQ-PTB link [Ref. S. Droste, Phys. Rev. Lett. 111, 110801 (2013).]

vii) **Netherlands:**Vrije Univ -- Univ. Groningen link [Ref. T. J. Pinkert et. al., Appl. Optics 54, 728 (2015).]

viii) **Japan:** NICT-Univ. Tokyo link [Ref. M. Fujieda, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 57, 168 (2010).

ix) **Italy:** Submarine link between Univ. of Malta and UnivScily [Ref. C. Clivati et. al., Optica 5, 839 (2018).]

x) **China:** Desert Urban fiber-link & others [Ref. Y Kang et al., Acta Phys. Sin. 68 060602 (2019).]

All these above-mentioned projects use telecom fibers available through the local service providers, which are leased for these specific projects. The available fibers are not stable in their lengths, due to dynamicity in the environmental parameters, unless otherwise phase noise cancellation via bi-directional communication technique are implemented to them. Few of the labs those are actively involved in development of the described technology are, NIST USA, NRC Canada, PTB Germany, NPL UK, NICT Japan, KRISS Korea, NMI China, INRIM Italy, Vrije Univ. and Univ of Groningen Netherlands, PIIM and SYRTE France and so on. These labs develop the peripheral technologies and demonstrate phase noise cancellation technique using fiber spool within the lab as well as over two physically separated places at a manageable short distance before scaling that up to very long distance. **Following this, here we propose to develop a quantum-link between IUCAA and IISER-Pune** (separated by about 5 km), as shown in Fig. 1.4**, which will act like a test bed before it is scaled up in pan-India and intercontinental distances.**

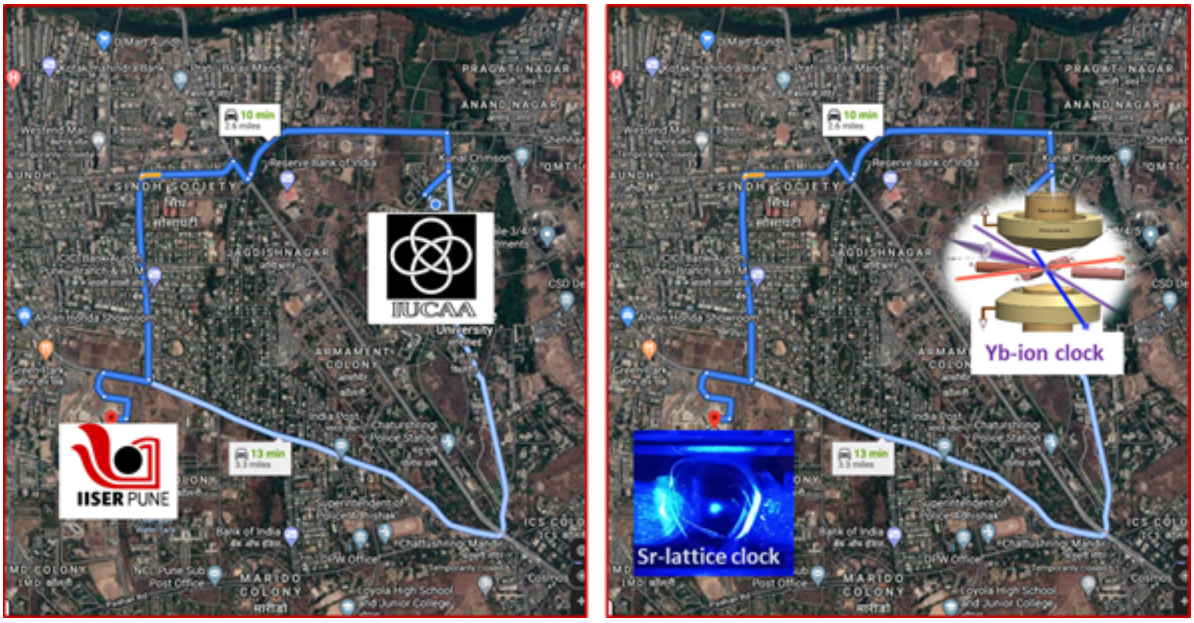

Figure 1.4: (Right) Location of IUCAA and IISER in Pune and schematic path(s) of the optical fibers that shall connect two institutes. Since both are educational institutes, these lease line may be easily available through NIC-NKN. (Left) Respective quantum clocks being built at IISER-Pune and IUCAA

A clock laser for Yb^+ ion clock is currently being built at IUCAA from the DST-QUEST program (project Q1). An Yb^+ ion trap will also be built. The two clocks (Yb+ and Sr) from IUCAA and IISER will be connected through this fiber link.

1.3.1.6 QUANTUM METROLOGY USING OPTICAL LATTICE SR OPTICAL CLOCK

Alkaline earth like element such as Mg, Ca, Sr and Yb are promising candidates for optical clock due to (a) Availability $^3P_0$ meta-stable states (b) Absence of magnetic dipole interaction in the ground state, $^1S_0$ and in meta-stable state, $^3P_0$ (c) Connectivity the meta-stable state to the ground state by narrow linewidth transition. (d) Presence of favorable laser cooling transitions. Among all the above mentioned elements, Sr is further most favorable because of availability of the lasers. The lasers required for the Sr fall in red region which are easily available through laser diode.

The optical lattice Sr optical clock, is the best clock reported till now which has precision of 10^{-18} (Nature **506**, 71–75 (2014)). The clock transition of the Sr is on the doubly forbidden singlet to triplet transition connecting $5S^2$ ($^1S_0$) → 5S5P ($^3P_0$) at a wavelength of 698 nm transition. This transition has a natural linewidth of 1 mHz for fermionic isotope ^{87}Sr. The relevant energy level is shown below. The high precision of the optical lattice Sr optical clock (or any other atomic lattice clock such as Yb) is due to large number of atoms (typically 10^4) for interrogation, which reduces quantum projection noise significantly as compared to single ion based optical clock.

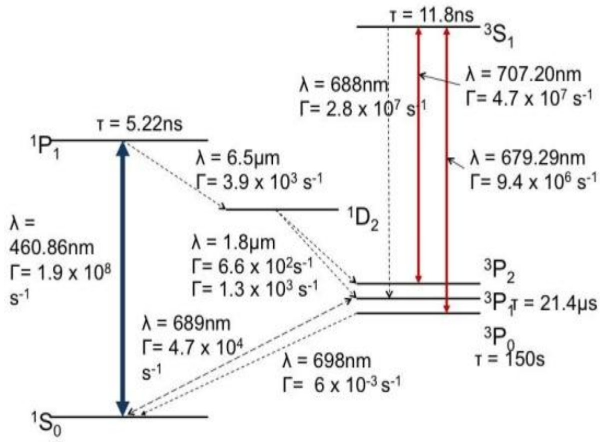

Figure 1.5: Relevant low lying energy levels of Sr atom. The clock transition is at 698 nm.

The disadvantages of the various broadening and shift mechanisms (such as Doppler, collisional broadening and the photon recoil shift) of the clock transition is suppressed by putting atoms in a **deep optical lattice.** The optical lattice can cause the broadening through light-shift. The laser is selected in such a way that it compensates for the light shifts, i.e., the light shift of the ground and the excited states are the same in both magnitude and direction. The wavelength selected in such a way is called the magic wavelength. The magic wavelength for the Sr clock transition is 813.428 nm. The knowledge of building Ultracold Strontium atom setup exits in IISER Pune where earlier through funding from DST-SERB and IISER Pune. And currently this setup is being augmented with state of the art laser systems to be able to perform distributed quantum information processing mentioned later.

1.3.1.7 Instrumentation development for Quantum computing, Metrology and quantum communications

For using any of the atomic or ionic systems for quantum computing and metrology platforms, many of these systems need a variety of lasers operating at different wavelengths (780, 399, 461, 397, 689, 698, 813, 866, 854, 729, 467, 935, 1064 nms etc.) the requirement for linewidths from these lasers ranges from few 10's of KHz for cooling atoms to less than 1 Hz in case of lasers that are needed to interrogate atomic clock transitions and qubit manipulation. In addition, in most of these cases the laser frequencies are stabilized to an absolute reference such as an atomic transition frequency. In some cases where the absolute reference frequency is not available in real time for monitoring the frequency, ultra-stable and high/ultra-high finesse optical resonators are used for frequency stabilization of these lasers. Most often, the laser sources are semiconductor lasers, while in some cases optical fiber based active media is used to generate the desired wavelengths. In some cases, in the absence of the availability of either semiconductor or fiber lasers at the desired wavelength, available lasers at half the frequency are doubled in frequency using frequency doublers or through optical sum frequency generation. The complexity involved in the construction of all of these lasers is mostly related to stable mechanical design, electronic current and temperature stabilization and active feedback with specifically engineered control loops. The hub will carry out activities of design and construction of mechanical systems, electronic systems, analysis and fabrication of components going into these laser systems.

For many experiments, often parameters like optical power, optical signals, magnetic and electric fields, and many other parameters need to be sensed and controlled. Most of these systems need to be imported often. In this program, many such requirements will be identified and the engineering would be done.

Quantum computing, quantum metrology and quantum simulations are carried out on a physical quantum layer that is made of material qubits (for e.g. atoms, ions, superconducting circuits, quantum dots, Vacancy centers etc.) constituting the 'quantum chip' or Q-Chip. Q-Chip needs to be integrated with classical computers for translation of user problems in computation, measurement and simulations is a layered approach. All the layers sitting above the Q-Chip are classical layers that operate on traditional classical electronic principles by way of microcontrollers, math processors and classical memory to store the classical operations. The immediate layer above the Q-Chip is usually an architecture comprising of high speed RF and Microwave electronics, engineered optical pulses sequence for initialization and readout of the states of QUBITS in the Q-Chip.

User problems are translated into quantum circuit problems incorporating all the error correction overheads and finally a pulse sequence is generated for driving the qubits during initialization, gate operations and for reading the final states of the qubits through standard tomographic techniques.

The control of Q-Chip heavily relies on high speed real time implementation of digital pulse sequences operating on Microwaves, RF, Optical pulses and for controlling

The following systems will be built for the above applications:

a. **Data acquisition and control systems**
b. **Field programmable Gate Array (FPGA) based re-programmable real time systems**
c. **Counting electronics**
d. **Optical component**
e. **Electronic detection systems**
f. **Optomechanical components**

As part of training activities, many subsystems such as interferometers, spectroscopy systems, and small modular training benches will be designed and standard kits would be developed for disseminating across various colleges and universities.

This instrumentation will have a direct bearing on the some Mega science projects in India such as LIGO India.

1.3.1.8 THEORETICAL RESEARCH INTO THE TRAPPED-ION CRYSTAL WITH RYDBERG EXCITATIONS, QUANTUM THERMODYNAMICS, AS WELL AS STRONGLY CORRELATED & OPEN QUANTUM SYSTEMS

a. Trapped ion-crystal with Rydberg excitations

Trapped cold ions are among the state of the art platforms for implementing quantum information protocols and developing special purpose quantum simulators. In the most recent experiments, entanglement of qubits has been achieved via quantum control of the collective vibrational motion of the ions. An advantage of this system, over other quantum simulators, is its expected scalability. Recent developments in exciting Rydberg atoms in an ion crystal have opened up further means to realize tunable interactions in these quantum simulators. Strong, long ranged, Rydberg interactions with its tunable anisotropy can help realize fast quantum gates while the ion crystals provide an additional layer of flexibility for realizing quantum simulations of lattice systems in different dimensions. Investigation of these systems through analytical and numerical tool-sets will likely provide useful inputs to guide research in the cold atom experiments.

b. Dynamics and thermodynamics of quantum many body systems

Out-of-equilibrium open quantum systems help us to model quantum machines with their working fluid made out of interacting localized qubits and can serve as building blocks for realizing potential quantum devices such as quantum diodes, quantum rectifiers, quantum sensors, and quantum thermal machines.

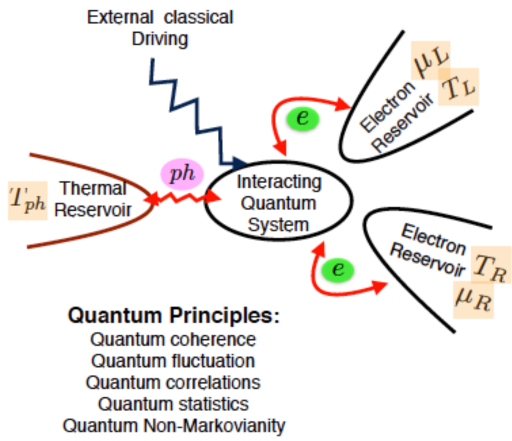

Figure 2.6 Schematic of open quantum systems

Interest in efficient utilization of the quantum mechanical effects in devices has resulted in the rapid growth in the field of quantum thermodynamics. The interaction of open quantum systems with the environment is depicted in Fig. 1.6. Development of theoretical and computational techniques here will aid in design and modeling of quantum machines of interest to the TIH.

c. Machine learning for the quantum problems

Quantum versions of machine learning algorithms are increasingly drawing interest due to the potential speed-ups they offer. For instance, the quantum support vector machine offers exponential speedup over its classical counterpart. Underlying such machine learning algorithms is the quantum linear systems solver, the HHL algorithm. HHL algorithm has indeed been experimentally demonstrated for smaller qubit (4 to 8 qubit) systems. Any machine learning technique which can be reduced to a matrix inversion can benefit from the application of HHL algorithms. It is of interest to identify specific classification problems that can be mapped to such a matrix inversion. In the absence of an accessible quantum computer these can be simulated in an emulator to analyze efficiency in specific tasks.

Classical machine learning is also of extensive interest - in practical experimentally relevant questions of state tomography, optimal control etc. in NMR and trapped ion systems. Identifying the right algorithms and strategies for specific experimental setups requires extensive analysis, and testing.

d. Quantum chaos, many-body effects and quantum computing

When many particles interact such as the qubits in a quantum computer it is almost impossible to shield the many-body effects, which could range from thermalization to a variety of localizing effects. A system of qubits provides a practical setting to study borders of quantum chaos as applicable to realistic quantum computers. Analysis and simulation of dynamics under unitary gate circuits with topology motivated by NMR systems can help understand the manifestations of quantum chaos in such systems of relevance to quantum computation.

e. Strongly correlated systems - hybrid quantum Hall systems

Quantum Hall (QH) effects occurring in high mobility 2DEGs subjected to high magnetic fields and low temperatures were among the first examples of topological insulators. The hallmark of the effect being robust, quantized, dissipation-less edge channels that carry the current around a 2D bulk region that is insulating due to an interplay of the applied magnetic field, disorder and electronic interactions. Though the complexity of the context may give an impression of fine tuning and fragility, the effect produces some of the most reliable examples of universal quantization in macroscopic many particle systems. Currently many experimental groups within India - in particular at TIFR, IISc and SINP (in addition to leading research institutes in the US, Israel, Germany, Italy and upcoming labs in Switzerland) - can produce refined measurements in such systems either using graphene or in GaAs/AlGaAs heterostructures. Though most explorations in QH systems are of academic interest, many of the fundamental themes and notions in current research in quantum many body systems - including topological insulators, topological order in electronic and spin systems, and quantized transport - have emerged through insights from research in QH systems.

We hope to make theoretical and computational progress in the analysis of QH phases and their interfaces with other quantum systems (motivated by experimental realizations in QH-superconductor interfaces at IISc/TIFR and QH-QH interfaces at SINP). The challenging part of modeling and analysis of these systems is tackling the problem of strong interparticle interactions. Tools developed to tackle strongly correlated systems here, especially using the numerical scheme called DMRG/MPS formalism, can directly be employed in the study of more general interacting and open quantum systems of interest in TIH.

1.3.2 QUANTUM COMMUNICATIONS

This theme involves the creation of India's first optical fiber-based quantum-link -- a phase-stabilized optical-link fiber (quantum channel) between IUCAA and IISER-Pune. This will be the first of its kind in India and will show a step forward towards quantum-communication. It also involves research into chiral and hybrid atomic-photonic and mesophotonics systems that have the potential of interfacing optoelectronic devices with communication devices. This vertical synergizes well with the ongoing project at IISER-Pune on 'A novel Atom Plasmon based platform for distributed and scalable quantum computer' under the QUEST program initiated by DST under theme-3 vertical. Project no Q-110 and Q001 will have direct synergies with the hub.

1.3.2.1 QUANTUM NETWORKS FOR SECURE COMMUNICATION

The fundamental tenet of a quantum network is based on deterministic generation of single photons with a high rate. The main applications for a high-quality single-photon source are quantum key distribution, quantum repeaters and quantum information science. Currently quantum random number generators are in high demand in the market due to potential applications in data security, secure key generation for financial transactions and defense communication, etc. The hub proposes (at IIT Tirupati) the development of a cold atom based hybrid quantum network that enables communication between two diverse quantum nodes using single photons communicating across the telecom band. Is to develop two single photon quantum nodes based on two diverse cold atom physics based platforms - one of them utilizing a non-linear interaction cold atoms to generate single photons while a trapped ion based cavity qed platform produces single photons on demand.

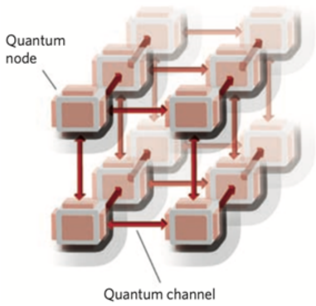

Figure 1.7: Schematic of a quantum network (adapted from *Nature* **453**, 1023 (2008)).

Although the quantum nodes of such identical quantum networks communicate (quantum state transfer) with each other via single photons, there is still a major debate over which platform is the best since each has its own merits and demerits. The development of hybrid quantum networks has thus been a new pathway that aims to combine the best of both worlds: easy storage and rapid readout of qubits. Linear ion traps [Fig. 1.8] provide significant isolation of quantum particles from the environment and ensure stable operation. On the other hand, magneto-optical traps using Rb (rubidium) atoms form the workhorse of many quantum matter and quantum optics experiments globally [*Phys. Rev. A.* **64**, 023402 (2001)]. Cavity QED [Fig. 1.8] has been a fundamental domain to understand light-matter interaction at the quantum level ever since the seminal paper by Edward Purcell in 1952 where he showed through calculations that the rate of emission of an entity can be altered depending on the environment in which it is working [*Proc. of the Am. Phy. Soc.* Abstract **B10**, April 25-27 (1946) &*Phys. Rev.***69**, 681 (1946)]. Combining cold trapped ions to an optical cavity was a natural extension to Purcell's work to understand the physics of quantum systems. Jaynes and Cummings [Proc. of the IEEE **51**, 89 (1963)] worked out the first analytical solution of the Hamiltonian connecting a two-level atom to an optical cavity field and showed the existence of vacuum Rabi oscillations of the composite atom-cavity system. These developments paved the way for generation of single photon emission using diverse platforms thereby establishing the basic infrastructure to set-up hybrid quantum networks.

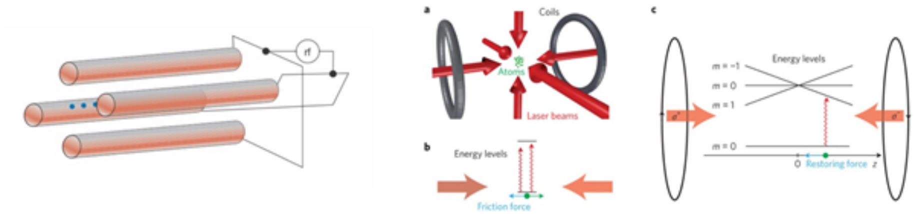

Figure 1.8: [Left] A simple schematic of a linear Paul trap. [Right] A simple schematic of a magneto-optical trap showing the 3-dimensional trapping and cooling of neutral atoms.

Single photon generation from atomic systems was initiated as early as 2006 with the work on gallium nitride by Kako et al. [*Nat. Mat.* volume **5**, pages 887–892 (2006)]. Single photon generation from an atom-cavity has been first demonstrated McKeever et al. [*Science*, Vol. **303**, Issue 5666, pp. 1992-1994 (2004)] and in the ion-cavity system [Fig. 1.9] by Keller et al. [*Nature*, volume **431**, pages 1075–1078(2004)]. Kimble in his seminal paper developed the concept of a quantum network with quantum nodes as either generators or repeaters or simply as storage nodes of quantum information. Keeping this vision in mind, several groups have taken different approaches to exhibit scalable quantum networks. Some have even extended the idea to development of hybrid quantum networks, which is eventually the final goal of the current proposal. With the recent works by N. Maring et al. [*Nature*, **551**, 485-488, (2017)] and H. M. Meyer et al. [*Phys. Rev. Lett.*, **114**, 123001 (2015)], it has become increasingly clear that long distance communication at the telecom band is no longer a distant dream. The current technological hurdles of converting single photons at different wavelengths to the telecom wavelength band have been overcome using QFCDs (quantum frequency conversion devices), a technical name for a periodically-poled lithium niobate ($LiNbO_3$) crystal that enables frequency conversion into the telecom band with a reasonable efficiency [*Optica*, Vol. **5**, Issue 5, pp. 507-513 (2018), *Nat. Comm*. volume **5**, Article number: 3376 (2014), *Opt. Exp.* Vol. **21**, Issue 17, pp. 19473-19487 (2013)]. The current project wishes to exploit this new technology and develop a cold atom-ion hybrid quantum network.

Central to the idea of developing a quantum network is the deterministic generation of single photons with high fidelity. Single photon sources are in huge demand globally due to the following key applications:

- Quantum key distribution – multiple photons in a pulse is not desirable for QKD
- Quantum metrology – low noise light source ensures sensitive optical measurements
- Quantum computing with photons – use photons as “flying” qubits
- True random number generation - encryption keys, gambling, modeling complex systems

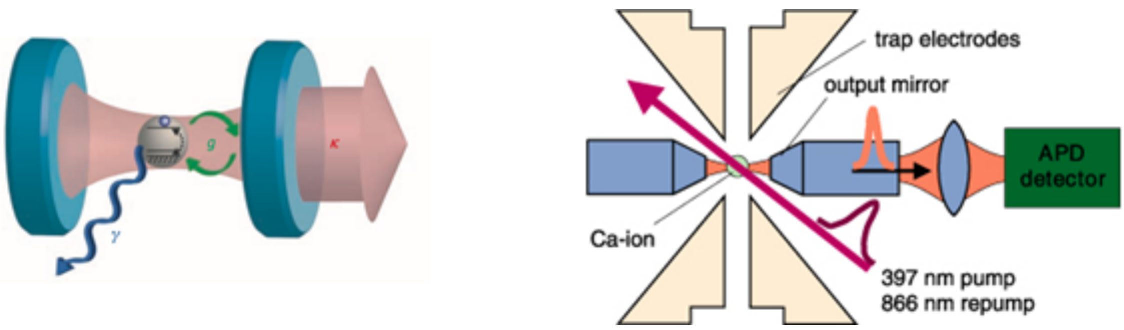

Figure 1.9: [Left] A simple schematic of an atom–cavity system depicting the three governing rates (g, κ, γ) in cavity QED [Adapted from *Nature*, **453**, 1023–1030, (2008)]. [Right] A simple schematic of an ion-cavity system for single photon generation.

There has been no known demonstration of site resolved laser cooled ion crystals in India. Demonstration of laser cooled ion clouds on Ca^+ ions on a printed circuit board (PCB) based surface trap and a segmented four rod trap has been done in collaboration in collaboration between IISER-Pune and IISc at IISc-Bangalore. At the Raman Research Institute, Bengaluru, cold Rb (rubidium) ions were produced from laser cooled and trapped Rb atoms, and their interactions were probed through lifetime studies. A few fundamental results linking the sympathetic cooling of ions using elastic collisions [*Nat. Comms.*, volume **3**, Article number: 1126 (2012), *Phys. Rev. Lett.,***118**, 113401 (2017)] and then through resonant charge exchange [*Phys. Rev. A***97**, 041401(R) (2018)] mechanisms were demonstrated. Apart from these works, the PI was associated with the development of a portable cold atom clock using $^{40}Ca^+$ ions at the University of Sussex, UK.

The country's first cavity QED experiment was also developed at the Raman Research Institute, Bengaluru. Here they demonstrated all-optical switching at sub millisecond timescales using room-temperature atomic vapor in a commercial vapor cell [*Phys. Rev. A,***91**, 043824 (2015)]. They also demonstrated strong coupling of trapped laser cooled atoms to a cavity field through a measurement of the vacuum Rabi splitting and then used this result to deduce the temperature of the cold atom cloud trapped inside the optical cavity [*Phys. Rev. A,***87**, 033832 (2013)]. A few other important results, most notably the demonstration of a lasing with atom laser [*Sci. Rep.*volume**7**, Article number: 11432 (2017)] and all-optical switching in a cold atom-cavity system [*Appl. Phys. Lett.*, **110**, 121107 (2017)] were also demonstrated by the same group. On the other hand, strong coupling of single atoms/ions with an optical cavity has not yet been pursued for quantum communications.

1.3.2.2 SYNERGETIC PROGRAM FROM DST-QUEST ON ATOM+PLASMON BASED DISTRIBUTED QUANTUM INFORMATION PROCESSOR

The atomic physics and quantum optics lab in IISER Pune is currently executing a project (Project no: QUEST- Q110) on a Novel Atom + Plasmon based quantum information processing platform scalable and distributed quantum information processing. This program will use coupling of single atoms to plasmonic nano structures.

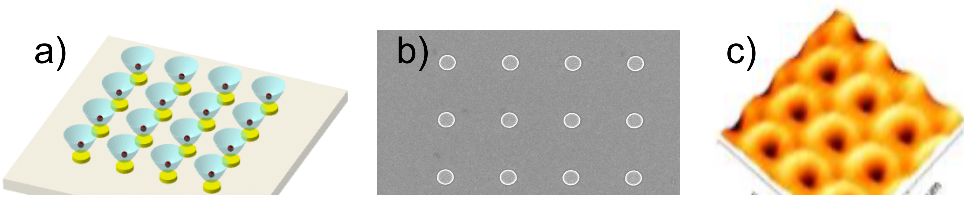

Figure 1.10: a) schematic of near field optical trapping potentials near silver nano structures. b) SEM micrograph of fabricated nanostructures. c) NSOM image of the near field optical potential (Umakant Rapol & coworkers, IISER Pune)

This program aims at building a complimentary platform for the atom – C-QED platform for transferring quantum information from an internal atomic state to a photon – 'flying qubit'

1.3.3 Quantum Materials and Devices

We are moving towards disruptive technologies that use quantum mechanical phenomena such as quantum many-body interactions among electrons, orbitals, spins, and crystal lattice. Manifestation and interplay between strong interaction, quantum fluctuation, entanglement, topology, and reduced dimensionality often lead to exotic and emergent quantum phenomena in materials such as two-dimensional materials and heterostructures; topological insulators and topological semimetals; and quantum spin systems. Such quantum phenomena in materials must be exploited in the future quantum devices in optoelectronics, spintronics, Mottronics, spin-caloritronics, and valleytronics. Quantum materials can also be the platform for the contemporary and future societal demands for disruptive information processing in the form of quantum computers, and dissipation less and secured data processing. Exploitation of such exotic quantum phenomena into electronic devices and operando control of spin, charge, orbital, lattice and topology will require concerted and collaborative quantum materials research and development efforts.

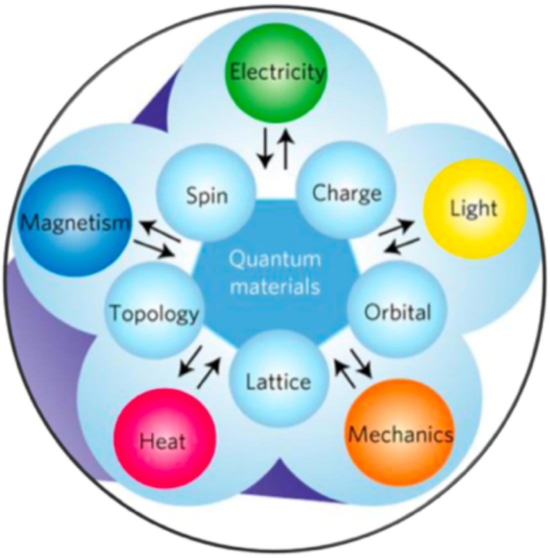

Figure 1.11: Five degrees of freedom of quantum materials, charge, spin, orbital, lattice and topology, that could be manipulated by various external perturbations. The strong coupling between the degrees of freedom leads to collective and emergent phenomena in quantum materials, which must be utilized in futuristic and disruptive technologies in the next generation spin-based electronics, quantum computing, and information processing. The figure is adopted from Nature Phys. 13, 1056 (2017).

Here, we propose concerted and complementary experimental and theoretical research and application efforts in the cutting-edge topics and challenges in quantum materials. Our efforts will include research and technology development in a wide array of areas as is elucidated in the following subsections:

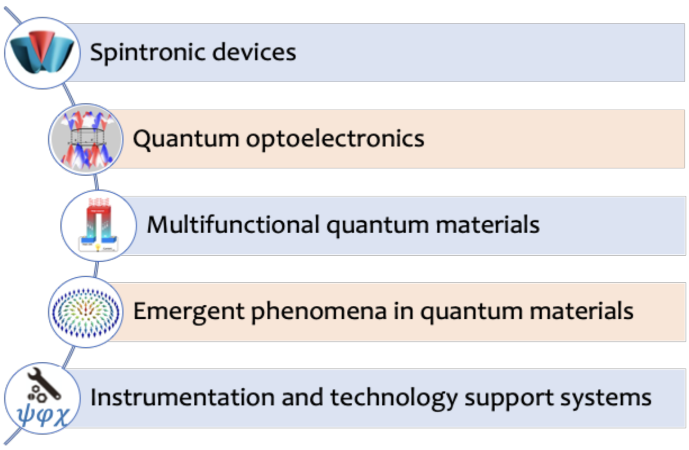

Figure 1.12: Landscape of Quantum Materials and Devices (Mukul Kabir, IISER Pune)

1.3.3.1 Spintronic Devices

Electronics – the manipulation and control of electron current – has revolutionized modern technology. What started off in the first half of the twentieth century as a purely scientific pursuit in solid state physics, has had an unprecedented influence on the way we lead our everyday lives. Though the progression from rudimentary vacuum tubes to the first prototype of a semiconductor based transistor took close to five decades, the progress from that point onwards has been spectacular and has made devices smarter, faster and smaller at a very rapid rate.

An interesting benchmark of this phenomenal rate of growth has been the so-called Moore's law, which stated that the number of transistors on a microprocessor chip would double approximately every two years. This in turn implied that the performance of processors would enhance at the same rate. However, this growth has now plateaued, and issues such as excessive heat generation and other detrimental quantum effects are seriously hindering further progress. It is now evident that new paradigms in device physics and technology would be required to make the next generation of electronic devices.

Amongst the probable candidates which could form this next generation of devices, Spintronic devices offer great promise, and have been the focus of extensive research for the past two decades. Here Spintronics pertains to the manipulation of the spin degree of freedom in conjunction with the electronic charge, in solid state devices. The viability of Spintronics as a potential game-changer was demonstrated by the Nobel prize winning work by Fert and Gruenberg, who demonstrated quantum mechanical magnetoresistance in alternating layers of ferromagnetic and non-magnetic metallic layers. This technology has progressed rapidly and is now extensively used in devices like magnetic Hard Disk Drives (HDDs), Magnetic Random Access Memories (MRAMs) and a variety of sensors.

In spite of the growth in this field, a number of technical challenges remain. For instance, though magnetic oxides have a number of exotic properties which could find utility in futuristic spintronic devices, their integration into devices remains an area of concern. To overcome this and other technological roadblocks, a number of radical device approaches are currently being carried out within the realm of Spintronics. This includes the possibility of incorporating Organic elements in Spintronic devices, and coupling functional magnetic oxides with carbon nanotubes in the quest for new nano-spintronic devices. Another interesting avenue of current research is the coupling of Spin, charge and thermal or optical degrees of freedom. A novel addition to this area of research has been the advent of Valleytronics, which pertains to the manipulation of charge carriers into conduction band 'valleys'. Our proposal focuses on the exploration of device functionalities that arise as a consequence of all the above mentioned phenomena.

The Spin Seebeck Effect SSE - a novel offshoot of Spintronics- has emerged in the past few years, and involves a complex the interplay of Spin, Charge and Heat currents in magnetic materials. The novelty of this effect is that one is able to generate and manipulate a flow of spin angular momentum by the application of a thermal gradient. More importantly, this happens in the absence of a charge current, and thus is independent of the normal scattering processes which plague electronic devices. Besides offering a possible route for heat dissipation in nano-electronic systems, these are now being looked into as potentially transformative spin-electronic devices in their own right. A number of potential applications, ranging from waste heat recovery systems, to purely spin driven diodes and transistors and logic gates are now being envisaged using this phenomena. Though initial measurements of the SSE concentrated on ferro or ferri magnetic systems, more recent investigations have bought the nature of magnonic currents in antiferromagnets (AFM) to the fore. Here, the spin current is either generated within the AFM itself at higher magnetic fields, or is pumped into the AFM from a source of spin current.

A novel approach herein pertains to the use of carbon nanotubes (CNT) in which multifunctional 3d transition metal oxides (TMOs) are synthetically encapsulated within the core cavity of the CNT. Electronic correlations in 1D lead to a number of fascinating phenomena, including Tomanaga-Luttigner liquid, Wigner crystal and concepts such as spin-charge separation. Pristine CNT with correlated electronic states in suspended form can be a clean quantum system for experimental exploration of emergent excitations in 1D. Encapsulation of strongly correlated 3d-TMOs within CNT, such as proposed here, can lead to hitherto unexplored 1D-magnets that couple exotic electronic states of CNT with that of the nano-scale TMO and provide some practical solutions for spintronic applications. The 2D quantum magnets in this proposal are derived from 4d & 5d based layered magnetic oxides with strong spin orbit coupling (SOC). These systems in bulk contain in plane magnetic honeycomb with antiferromagnetic correlations, which are known test-beds for exploring exotic Quantum Spin Liquid states (QSL), fractionalized excitations and strain mediated topological phases/10-12/. Often, such non-trivial QSL states are masked by out-of-plane AFM correlations, embedded in the intrinsic 3-dimensional lattice corresponding to bulk. Experimental realization of Graphene like 2D sheets of 4d-& 5d based TMOs, such as that proposed here, can provide a realistic experimental platform, to explore theoretical predictions pertaining to QSL. We investigate both 1D & 2D quantum magnets with an eye on fundamental physics and propose fabrication of nano –spintronic devices based on the same.

The **1D** systems proposed here are carbon nanotubes (**CNT**) in which multifunctional *3d* transition metal oxides (TMOs) are *synthetically encapsulated* within the core cavity of the CNT. Electronic correlations in 1D leads to a number of fascinating phenomenon, including Tomanaga-Luttigner liquid, Wigner crystal and concepts such as spin-charge separation. Pristine CNT with correlated electronic states in **suspended** form can be a ***clean quantum system*** for ***experimental*** exploration of emergent excitations in 1D. Encapsulation of strongly correlated 3d-TMOs within CNT, such as proposed here, can lead to hitherto unexplored 1D-magnets that couple exotic electronic states of CNT with that of the nano-scale TMO and provide some practical solutions for spintronic applications. Here the oxide-encapsulate are TMOs which possess specific functionalities relevant to spintronic applications. This includes systems such as *Half Metallic Ferromagnets* (CrO_2& Fe_3O_4), *Magnetoelectrics* (Cr_2O_3), Canted AFM or *Weak Ferromagnets & piezomagnets* (α-Fe_2O_3). All these TMOs have T_C or T_N above the room temperature and are therefore promising candidates for practical spintronic applications. It is important to mention that fabrication of actual *nano –spintronics* devices based on these **multi-functional** oxides still remains a challenge. For instance, oxides are often metastable in nature and the essential processing during device fabrication is detrimental to their specific functionalities. These are the limiting factors due to which ***oxide-based electronics*** is difficult to materialize. However, many such practical problems can be overcome by encapsulation of oxides inside carbon nanotubes. The CNT not only preserves the oxide-encapsulate but also can weather the device patterning process, due to unprecedented electrical, thermal and mechanical properties, intrinsic to CNT. These novel hybrids, referred to as Oxides@CNT, also bring into fore ***interface effects***, which exist between two highly functional materials, the graphitic shells of the CNT and the nano-scale TMO. Temperature variation of Raman in Oxides@CNT will be an important characterization tool.

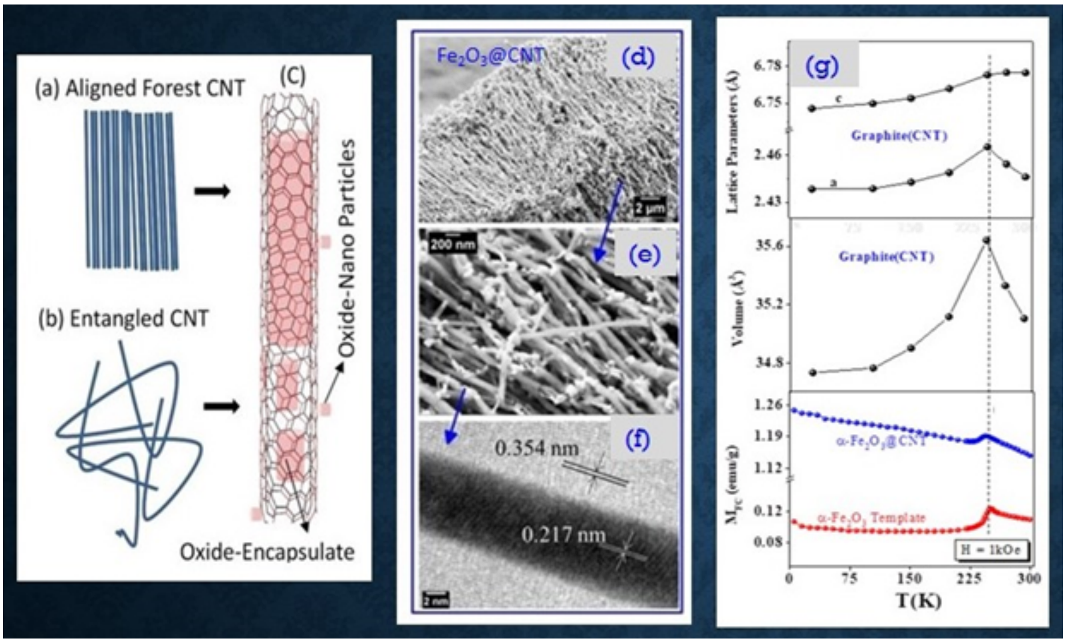

Figure 1.13: Panels (a)-(c) schematically depict self-organized carpets of carbon nanotubes that can be formed in **(a)** aligned forest **(b)** entangled geometry. Panel **(c)** Shows that CNT in both cases contains oxide-encapsulate within its core-cavity. Panels **(d)-(f)** SEM & TEM images of a typical aligned-forest samples of Fe2O3@CNT synthesized in Co-PI-s lab. TEM image in the panel **(f)** shows well –formed graphitic shells of CNT, filled with oxide encapsulate α-Fe_2O_3. Top and middle images in panel **(g)** shows temperature variation of lattice parameters, derived from synchrotron X-ray diffraction. The sample is α-Fe_2O_3@CNT and the lattice parameters are derived from two phase model of Rietveld profile refinement of the XRD data. These data show significant strain effects in the lattice parameters of (oxide-filled) CNT, in the vicinity of magnetic transition, intrinsic to α-Fe_2O_3. The Magnetization vs. Temperature shows Morin transition for sample α-Fe_2O_3@CNT (blue dots) and bare- α-Fe_2O_3 (red dots). These data depict novel interface-effects that enhance the functional properties of the oxide encapsulate.

The efficient generation, detection and manipulation of spin information through charge current and a refined control of their physics is crucial for functionalizing electronic spins for applications in information processing. The two-dimensional heterostructures are an excellent test bed to explore physics arising from the interfacial spin-orbit coupling. Versatility of the physics here arises from the gate tunability of electronic properties, spin-orbit coupling induced interplay of spin and pseudospin/valley degrees of freedom, and enhancement of spin-orbit coupling from asymmetries of the layers. Apart from having a clean interface, such 2D Van der Waals heterostructures possess many advantages to manipulate properties in the present context. (a) Interfacial charge transfer, orbital hybridization, dielectric screening, interfacial dipole moment and built-in electric field can modify the electronic and magnetic properties of the heterostructure systems. (b) The spin-orbit coupling and exchange anisotropy can be manipulated by proximity effect as well as with asymmetrically placed surface ad atoms (c) Induced stain due to lattice mismatch can also affect the properties. Here we plan to investigate various types of 2D magnetic heterostructures of Transition Metal Dichalcogenides (TMDCs) and topological insulators using theoretical and experimental approaches.

Another focus area would be the relatively less explored layered 2D magnetic materials based on Halides and Chalcogenides, which show an electrical behavior ranging from that of a good insulator to a good metal See Fig. 1). Though known since a long time ago [*L. J. de Jongh Magnetic Properties of Layered Transition*

Metal Compounds, Springer Netherlands (1990), L. J. de Jongh et al. Experiments on simple magnetic model systems Adv. Phys. 23, 1 (1974)], their synthesis in pure and single crystalline form, and the exploration of their magnetic and magneto-transport properties started only very recently [*Mak et al. Nature Reviews physics, 1, 646 (2019)*]. They exhibit a layered structure where the chemical bonds within a layer are much stronger than the inter-layer bonds, allowing exfoliation of atomically flat 2D magnetic layers. Further, when the magnetic ions in the 2D sheets are arranged on some special lattices -- triangular, honeycomb or Kagome -- a plethora of very interesting magnetic phases, including, the quantum spin liquids and topological magnetic skyrmions, both of which have attracted enormous attention in recent years, are expected to emerge [*Burch et al. Nature, 563, 47 (2018)*].

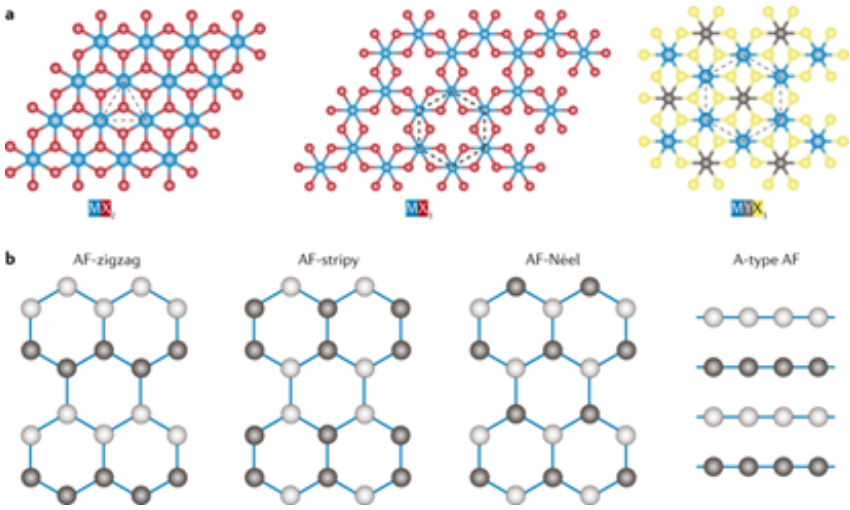

Figure 1.14: Fig. 1(a) A monolayer of MX_2, MX_3 and MYX_3 where M is typically a 3d transition metal ion, X belongs to the halide or chalcogen group, and Y can be either Si or Ge or P. The M atoms form either a triangular lattice structure (MX2) or a honeycomb lattice (MX_3 or MYX_3). (b) Various types of antiferromagnetic (AF) ordering in the layered magnetic materials. Light grey balls represent spin-up and dark grey balls represent spin-down. Taken from Ref. *Mak et al. Nature Reviews physics, 1, 646 (2019)*

In the past two years or so several intriguing cases of 2D magnetism has been reported in single atomic layers. For example, Lee et al. studied magnetic ordering in atomically thin $FePS_3$ [*Lee et al. Nano Lett. (2016)*]. In the same year, Wang et al. used Raman spectroscopy to study magnetic ordering in atomically thin 2D crystals of $FePS_3$ [*X. Wang et al. 2D Mater. 3, 31009 (2016)*]. Though Raman spectroscopy is a powerful technique, it does not provide a direct measurement of magnetic order parameter down to the

monolayer or 2D limit. This problem can however be mitigated using the magneto-optical Kerr effect (MOKE) that has proven successful down to the monolayer limit [*Huang et al. nature 546, 270 (2017), Gong et al. Nature 546, 265 (2017)*]. Gong et al. studied the layer dependence of T_c in $CrGeT_3$ (or $Cr_2Ge_2Te_6$ as is commonly referred to as) as a function of layer number [*Gong et al. Nature 546, 265 (2017)*], and Bionilla et al. demonstrated the occurrence of robust room-temperature ferromagnetism in

VSe$_2$ monolayers [*Bionilla et al. Nat. Nanotechnol. 13, 289 (2018)*]. Around the same time O'Hara et al. showed occurrence of room-temperature ferromagnetism in MnSe$_2$ in the monolayer limit [*O'Hara et al. Nano lett. 18, 3125 (2018)*].

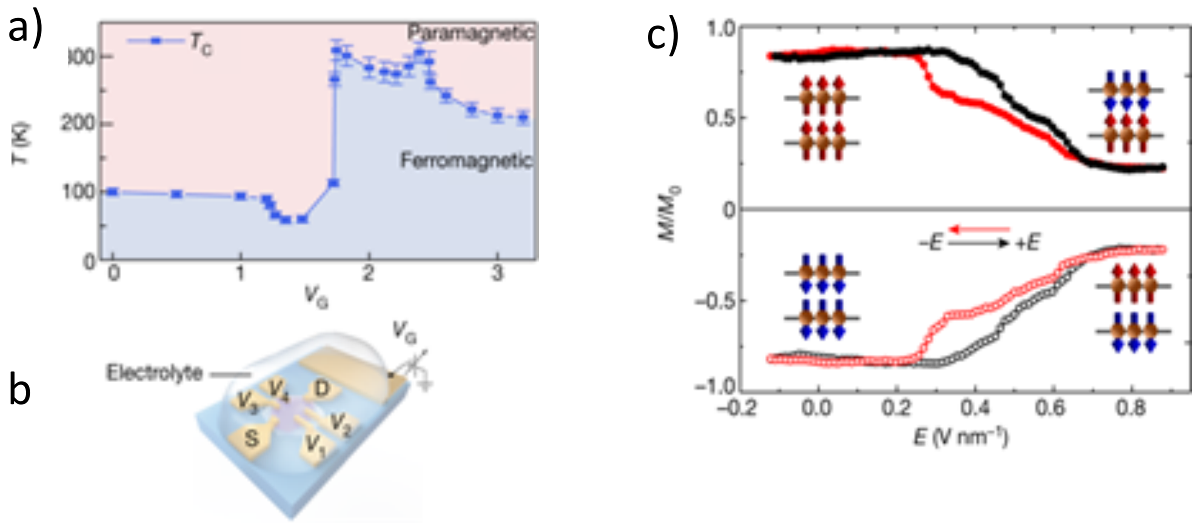

Figure 1.15 (a) Dependence of Tc of a monolayer Fe$_3$TeGe$_2$ sample as a function of GATE voltage. b) shows a schematic of the device., and (c) Electric field switching of magnetization in bilayer CrI$_3$; Taken from Refs. *Jiang et al. Nature Materials, 17, 406 (2018), and Nature 563, 94 (2018).*

Recent progress has also revealed the role of electrostatic gating and electric field in controlling the magnetization. Bulk Fe$_3$GeTe$_2$ samples has a T_c of ~180 K which suppresses further as sample thickness decreases, becoming as small as ~20 K in the monolayer limit [*Deng et al. Nature 563, 94 (2018)*]. However, by electrostatic doping T_c can be enhanced to as high as ~320 K, which is significantly higher than the bulk T_c (see Fig. 2a). Such a gate-tunable ferromagnetism at room-temperature can be potentially useful for fabricating gate voltage-controlled spintronics devices in the 2D limit.

In addition to the halides and the chalcogenides, we also envisage the investigation of **2D** quantum magnets derived from ***4d & 5d*** based layered magnetic oxides with strong spin orbit coupling (SOC). These systems in bulk contain in-plane *magnetic honeycomb* with *antiferromagnetic* correlations, which are known test-beds for exploring exotic Quantum Spin Liquid states (QSL), fractionalized excitations and strain mediated topological phases/10-12/. Often, such non-trivial QSL states are masked by out-of plane AFM correlations, embedded in the intrinsic 3-dimensional lattice corresponding to bulk. Experimental realization of ***Graphene–like 2D*** sheets of 4d-& 5d based TMOs, such as that proposed here, can provide a realistic experimental platform, to explore theoretical predictions pertaining to QSL. We investigate both 1D & 2D quantum magnets with an eye on fundamental physics and propose fabrication of ***nano–spintronic*** devices based on the same.

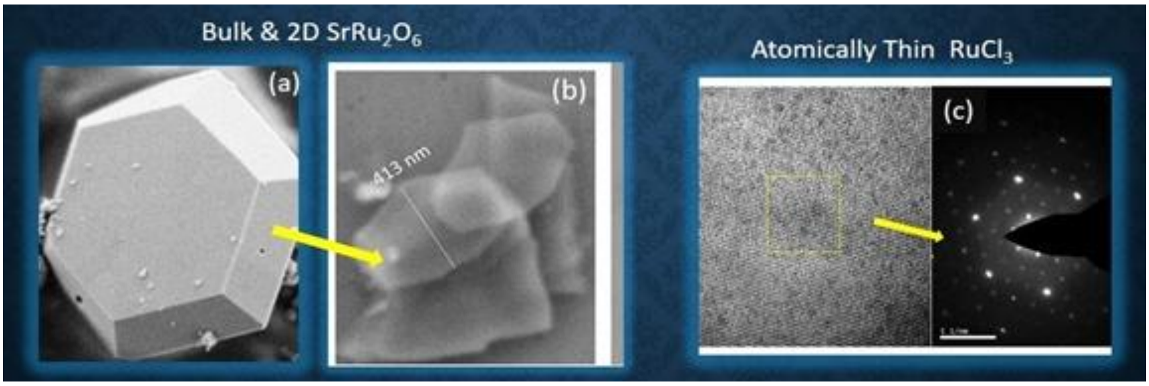

Figure 1.16: a) SEM image of Crystallite of $SrRu2O_6$, which is synthesized using hydrothermal route. (b) SEM image of the exfoliated 2D nano-sheets of the same using the scalable technique of liquid exfoliation. (c) shows high resolution TEM image of a typical 2D-sheet of Kitaev QSL candidate $RuCl_3$. The crystalline nature of the nano–sheets of $RuCl_3$ (synthesized using liquid exfoliation technique) and the inherent hexagonal lattice of RuCl3 is evident in **(c).** (Unpublished data from co-PI's laboratory)

1.3.3.2 Quantum Optoelectronics

Electrons in semiconductor nanostructures are in quantum states and interact very differently with light, compared with the electrons in larger structures. This opens up opportunities to source, detect and control light, which can be utilized in futuristic and disruptive quantum technologies (*Nat. Photonics 8, 899; Nat. Rev. Mater. 1, 16055).* Due to the unprecedented strength of light-matter interaction, the two-dimensional van der Waals materials are a very attractive class of optoelectronic materials that have band gaps in the visible to near IR range. Topological photonics is another emerging field of interest that either utilizes light-matter interaction in materials with nontrivial electronic states or in topological metamaterials and photonic crystals. Due to the enormous flexibility and diversity of photonics systems, topological photonics is opening up new opportunities to realize exotic topological models and to probe and exploit topological effects in new ways (*Nat. Photonics 8, 821; Rev. Mod. Phys. 91, 015006),* and applications in dissipation less communication to topological quantum computing.

Light-matter interaction in semiconductor nanostructures. Two-dimensional materials fundamentally exhibit a rich variety of electronic phases such as metals, semimetals, semiconductors and insulators; and thus offer a range of optical responses (*Nat. Photonics 8, 899 (2014)).* Till date, a number of remarkable optical properties have been discovered in 2D materials such as ultrafast broadband optical response ranging from ultraviolet to radio-waves, strong and tunable light–matter interaction, and large optical nonlinearities. Additionally, electrical tunability of physical properties makes these materials suitable for functionalized photoelectric information devices. Moreover, since they are easy to integrate with the photonic structures such as fibers and chips *(Adv. Funct. Mater.19*, *3077 (2009); Nature 558*, *410 (2018)*; *Nat. Photonics 12*, *22 (2017))*, two-dimensional materials have attracted a lot of attention in device applications in diverse emerging fields of valleytronic, straintronics, and twistronics, quantum emitters and detectors (Science *329, 544 (2010); Nat. Rev. Mater. 1, 16055 (2016))*.

Tuning properties of 2D materials using strain is very interesting because various properties of these materials are greatly linked to its lattice structure. Moreover, the individual atomic sheet of 2D material can withstand strains close to their theoretical limit which is much larger compared to either their bulk counterparts or conventional electronic materials. Due to their 2D nature it is possible to apply large local strains easily by poking, bending, or folding. This gives us a continuous control over the properties of these materials as locally applied strain can alter the band structure of materials by changing the interatomic distance of the atoms. This degree of freedom creates enormous opportunities to use these materials as a test bed for the study of new fundamental physics and potential applications to quantum technologies.

It has been observed that application of local strain can change the band structure locally which has profound effect on the photo-generated charge carrier dynamics and mobility. In MoS_2 funneling of photogenerated excitons from flat regions of the strained region has been reported. The strained regions serve as traps with a local confinement potential for excitons. It has been proposed that by applying non-uniform strain on monolayer MoS_2 one can create a continuously varying bandgap profile which can generate a broad-spectrum solar energy funnel. Utilizing the phenomena of exciton funneling and electrically controlled valley polarization we are proposing fabrication of electrically tunable valley-Light Emitting Diodes (vLED). We plan to make arrays of nano-cone structures that can give circularly polarized light which can be controlled locally and electrically. This will bring the emerging field of valleytronics one step closer to realization. This structure will also help us to tune the mobility which is expected to enhance greatly due to the change in effective mass of the charge carriers caused by the strain and also due to the reduction of various scattering mechanisms.

The nanocone patterns will be generated with the help of block copolymer lithography and reactive ion etching. We can make devices with different structures from pillars to cones to control the maximum strain experienced by the monolayer TMDs. The finer control of the nanostructure will be possible by etching the substrate using inductively coupled reactive ion etching (ICP RIE). We will then transfer the TMD on these nanotextured substrates and finally make contact using optical and e-beam lithography. We will study electronic and optoelectronic properties of these nanodevices to understand the effect of strain on photo-generation and dynamics of charge carriers.

Strain induced lattice deformation in 2D materials will be probed using Raman spectroscopy. In general, Raman spectroscopy assesses the phonon modes and depending upon the strain it can soften or harden. This causes a shift in the frequencies of the peaks in Raman spectra which directly reflects the strain level. The same nanotextured substrate platform can be used for making quantum-emitter arrays

Turning to the semiconductor nanostructures, it is well established that the substrate materials and their top-layers texturing play a crucial role in determining the on-demand properties of photonics and electronics devices. Substrates patterned with nano-pillars have been used to produce arrays of quantum emitters (*Nature Communications 8, 15053 (2017))*. When monitoring the quantum-emitters using a hyperspectral imaging system, the collection intensity of photons decreases as a function of spatial distance, and therefore, it becomes very crucial to position the emitter with a highest level of positional-accuracy. Almost all work that has been carried out in literature focuses on cylindrical-shaped pillars which have flat surfaces on top, and therefore, the flakes of 2D materials do conform nicely with the surfaces of the pillars. A random conformation provides a random location of quantum emitters, which is a cause of a poor accuracy in their location. Here, we propose to use substrates that are nanotextured with cone-shaped nano-pillars, which would provide a smooth conforming of flakes on the pillar's top surface, and therefore, it would provide a pin-point location of the quantum emitters.

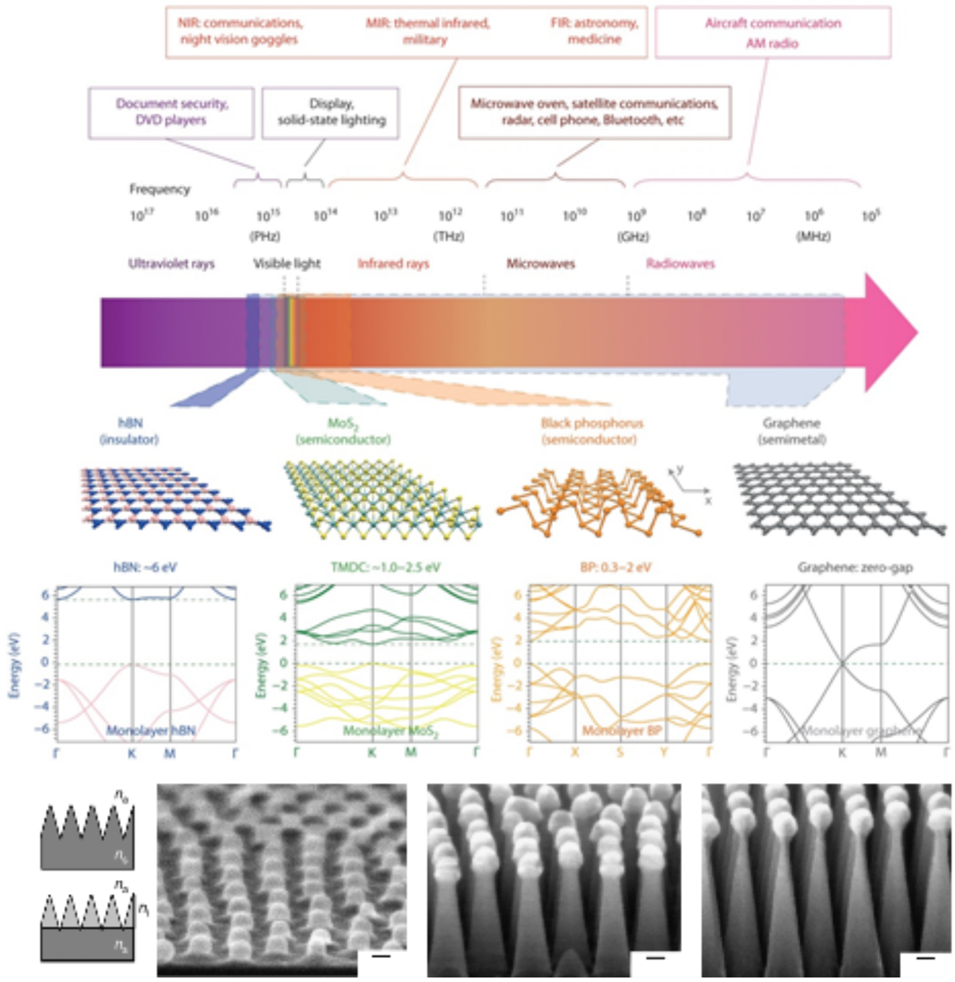

Figure 1.17: Electromagnetic spectrum of two-dimensional materials and the plausible applications that utilize the different spectral ranges. Lattice structures of various 2D materials and their corresponding electronic phases are shown (Adopted from Nat. Photonics **8**, 899 (2014)). In the bottom panel, silicone nano cones are created using block copolymer self-assembly and plasma etching for enhanced broadband solar cells. The figure is adopted from Nat. Commun.6, 5963 (2015).

Topological photonics: Light-matter interaction in the emerging class of topological materials and in artificial topological crystals have attracted enormous attention that paves the way to engineer novel quantum states of matter and exploit that to quantum devices. Different material platforms such as photonic crystals, metamaterials, coupled cavities and waveguide arrays have been used in implementing the topological phase of light (*Nat. Photonics 8, 821 (2014); Rev. Mod. Phys. 91, 015006 (2019))*. Tremendous successes have been already achieved including demonstration of protected edge states. Here, the ideas are drawn from the concept of topology in condensed matter physics that was crucial for understanding quantum Hall effect. At the interface of two different materials with different topological invariants the bulk-edge correspondence guarantees the existence of topological edge states with unidirectional propagation. In the optical context, Haldane and Raghu showed that topological band structures are ubiquitous property of waves inside a periodic medium regardless of the quantum or classical nature of the waves (*Phys. Rev. Lett. 100, 013904 (2008), Phys. Rev. B 25, 2185–2190 (1982))* The Bloch bands of photonic crystal designed with time-reversal symmetry-breaking produce non-zero Chern numbers. Since then, taking advantage of the flexibility and diversity of the systems, topological photonics is opening up new opportunities to realize, manipulate and exploit exotic topological models. In topological photonics, the absence of back-scattering opens up new technological applications such as it enables dissipation less transport in efficient optical communication. With topologically protected robust features these photonic systems can serve as on-chip devices for communications and data processing. For example, the quantum valley Hall effect in the terahertz regime was used to transport uncompressed video using a photonic crystal (*Nat. Photonics* 14, 446–451 (2020)). Going forward, it would be important to address the issues in the design of topological systems, tunability and practical applicability.

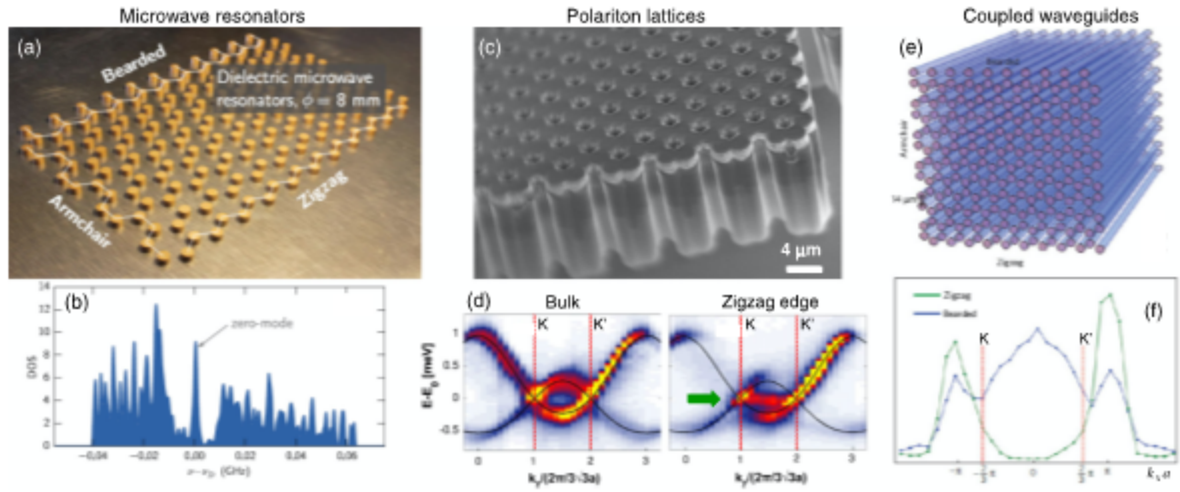

Figure 1.18: Panels (a-b) Microwave resonator with different edge structures and the measured density of states as a function of frequency (*New J. Phys.* **16**, 113023(2010)). Panels (c-d) Scanning electron microscope image of polariton micropillar on a honeycomb lattice, and the photoluminescence spectrum measured at the center of the lattice showing Dirac cone and flat-band edge states (*2D Mater.* **2**, 034012(2015)). Panels (e-f) Schematic of a lattice of coupled waveguides and the measured momentum space distribution of transmission through various edge types *(Nat. Mater.* **13**, 57(2014)). The figure is adopted from *Rev. Mod. Phys.* **91**, 015006 (2019)

ɔlex quantum networks. To this end, various research groups around the world are exploring (*Nature, 541, 473*) a variety of nanophotonics systems that can cater to this requirement. Specifically, the control of directionality of scattering and absorption of photons has emerged as a key control parameter for on-chip quantum photonic operations. Importantly, such platforms can facilitate an uncharted territory to study quantum many-body effects on a chip. (See *Haroche, S. & Raimond, J.-M. Exploring the Quantum: Atoms, Cavities, and Photons Oxford Univ. Press, 2006)* One of the promising ways to create interconnects on a quantum optical chip is to couple emitted photons to optical nanofibers and waveguides. Arno Rauschenbeutel and his group (*Science 346, 6 (2014); Nat. Commun. 5, 5713 (2014)*) have been studying this problem for a few years now, and have shown the photonic coupling efficiencies to be sensitive to parameters such as excitation polarizations. Interestingly the transverse component of the electric fields and its chiral properties have emerged as promising candidates to study spin-orbit coupling effects in photons. Zoller's group has extensively been involved in understanding interaction between quantum matter and light.*(Gardiner, C. & Zoller, P. The Quantum World of Ultra-cold Atoms and Light. Book II: The Physics of Quantum-optical Devices 1st edn. Imperial College Press, 2015)* Bliokh, K. Y. & Nori, F. (*Phys. Rev. A*

85, 061801 (2012)) have been extensively studying the role of surface plasmonpolaritons in facilitating the transverse spin at interfaces that have huge implications in quantum nanophotonic coupling, propagation and networking. Interfacing quantum systems with nanophotonic systems is a topic which is still in its infancy in India. Most of the work done until now has been theoretical in nature. There is a dearth of experimental exploration, especially in interfacing quantum systems with nanophotonic systems, and this proposal aims to fill in this gap.

This project requires nanopatterning and nanotexturing substrate, integration of 2D TMDs to fabricate the desired nanodevices. Nanopatterning will be done primarily using block copolymer lithography. Block copolymer based nanopatterning has been widely used to generate patterns of few tens of nanometre feature size over a large area substrates. BCP based self-assembly is a simple and scalable technique to generate very high density ($>10^{10}/cm^2$) nanostructure with feature size few tents of nanometer. To study the effect of strain we need to place the monolayer 2D materials atop of the nanotextured substrates. Effect of strain on the electronic and optoelectronic properties of 2D materials has also been studied by several groups *(Nano Lett.16, 5836 (2016); Nature 550, 487 (2017)*). While mobility limiting factors in 2D materials have been studied by various groups *(Nat. Nanotechnol.* 3, 206 (2008); *Nat. Commun*. 3, 734 (2012)), the effect of strain on mobility has not been studied in great details.

1.3.3.3 MULTIFUNCTIONAL QUANTUM MATERIALS

The notion of Quantum materials has now emerged as a unifying theme at the forefront of contemporary condensed matter physics. This area of research which typically spans across the areas of solid state chemistry, condensed matter, and device engineering, has been a fertile test bed for understanding the physics which drive a host of interesting electronic ground states, as well as a large number of potential applications which these quantum materials have to offer. The quest here is to try and come up with new materials, where strong coupling between the electronic, magnetic, orbital, and lattice degrees of freedom give rise to interesting multifunctional properties, which can form the bedrock for the new and improved devices. Notable amongst these that would be incorporated into the goals of this TIH are new and improved thermoelectrics, rare-earth free permanent magnets, and electrocaloric and magnetocaloric material systems.

Thermoelectricity – the phenomena by virtue of which heat energy can be converted to usable electrical energy – is a phenomena which has been investigated in right earnest for the last five decades or so. The quest here is to try and synthesize materials with large conversion efficiencies, that would enable thermoelectricity to become a commercially viable source of energy. In spite of the fact that viable large scale power generation using thermoelectric devices is still in its infancy; these devices have already found applications in several niche areas. For instance, radioisotope based thermoelectric power modules – where the heat released during a radioactive decay process is converted to usable electrical energy – has been used for many decades in space applications. There is considerable impetus in many parts of the world in trying to harness the utility of thermoelectric materials in a number of military applications, in areas ranging from portable power generators in conflict areas, to thermal clothing, and cooling modules for infra-red sensing equipment.

The utility of various materials as potential thermoelectrics is evaluated on the basis of the thermoelectric figure of merit ZT, where $Z = \sigma S^2/ \kappa$, and S is the Seebeck co-efficient, T is the temperature, and σ and κ are the electronic and thermal conductivities respectively (G.S. Nolas, 2001). A figure of merit ZT of the order of 1 is typically considered to be a benchmark in the scrutiny of potential thermoelectric candidates, and the best available thermoelectrics have a maximum ZT above 1 in specific temperature ranges. As is evident from the equations given above, an ideal thermoelectric should have a large thermal conductivity and Seebeck co-efficient (or thermopower), but a small electronic conductivity. However, in real world materials these parameters are often intimately coupled to each other, making the optimization of *ZT* a serious technological challenge. For instance, the requirement of a large electrical conductivity (σ) and low thermal conductivity (κ) in a single material is symptomatic of the inherent contradictions involved in developing a good thermoelectric, since these two quantities are coupled through the Weidemann-Franz law which states that $\kappa_e = L\sigma T$, where κ_e is the electronic contribution to the thermal conductivity, and *L* is the Lorentz number.

The quantum confinement of quasi-particles, which is vividly manifested under low-dimensionality, is crucial for obtaining novel properties unique to the low-dimensional systems. Some of the low-dimensional antiferromagnetic spin-1/2 compounds, for example, exhibit a very high thermal conductivity parallel to the spin chains or the magnetic 2D sheets [*Hess et al. Physics reports (2019)*]. In some cases this can be as large as the thermal conductivity of a good metal even near room-temperature [*Hess et al. Phys. Rev. B (2001)*]. This counter-intuitive property -- metal-like thermal conductivity along with poor electrical conductivity -- is rather unique to the low-dimensional quantum magnets and can be exploited for designing thermal coatings for controlling heat flow in microelectronic devices [*Hess et al. Physics reports (2019)*].

Closely related to this area is the development of new materials systems for thermal management solutions. Such thermal management platforms are critical in a number of defense applications, varying from enhancing the performance of imaging sensors to cooling solutions in hostile environmental conditions. Applications range from the cooling of Infra-red Focal Plane array detectors, to cooling control electronics of unmanned terrestrial or aerial vehicles in harsh environments. In this context, solid state refrigeration is an attractive alternative to traditional cooling systems. Recent research has made interesting finds with regard to discovering new materials for magneto-caloric applications near room temperature. The magneto-caloric effect is best observed near a simultaneous magnetic and structural transition leading to a magnetic field driven thermal output. The magnetic Heusler compounds, due to their simple crystal structures and abundances have turned out to be a class of materials where significant magneto-caloric effects can be realized. The key to this in magnetic Heusler compounds is the first order structural transition, often known as the martensitic phase transition as the large entropy changes associated with a first-order transition may lead to substantial cooling. A good number of experiments on Heusler compounds have been performed, the results of which are to be interpreted with suitable theoretical models.

Another, relatively underutilized technique is that which uses the electrocaloric (EC) effect- where an adiabatically removed electric field reduces the temperature of a dielectric material. Though the existence of the EC effect has been known for the past four decades, its magnitude was too small to be put to use. The efficiency of an EC candidate can be typically defined as the temperature change induced by an electric field (kV/cm). In early ECs like the Rochelle Salts, this ratio was of the order of 0.003 K/kV/cm. This figure has steadily increased over time, and in some oxides this ratio is almost an order of magnitude higher. These effects are also enhanced in the vicinity of ferroelectric (FE) phase transitions, and hence polar oxides are promising candidates. Moreover, the effective electric field density can be easily enhanced by reducing the refrigerant to micron size thin films. Recently, flexible ferroelectric polymer composites have also shown potential. A recent report by the US Department of Energy listed EC's as a promising Early Stage Technology option, and this research area is being increasingly pursued by a number of international laboratories. The primary quest in this area would be to enhance the efficiency of the EC material to greater than $0.05 K/kVcm^{-1}$. A number of avenues, like tuning the dielectric constant, creating frozen nanopolar domains in ferroelectrics, and creating nanoscale ferroelectric media could be used for enhancing the EC effect. However, research activity on EC's in general, and in these areas in particular has been sparse, a lacuna which we propose to address as part of this TIH.

An area of extreme technological relevance - especially in the Indian context- pertains to the development of 'rare-earth free' permanent magnets. Permanent magnets are crucial ingredients in a range of applications, and modern permanent magnets extensively rely on rare earth elements like Nd, Dy and Pr. However, with China controlling more than 95% of the production of rare earth elements, and placing stringent controls on its mining/exports, it has become imperative to look for alternatives. Though ferrite magnets are well known, and constitute an important component of the permanent magnet industry, their performance is typically inferior to the rare earth based ones. The performance of a permanent magnet depends on its so called 'figure of merit', which is a product of the coercively and the saturation magnetization (also called the 'energy product'). The performance of a permanent magnet depends on its so called 'figure of merit', which is a product of the coercively and the saturation magnetization (also called the 'energy product'). Though these ferrite magnets (typically Fe_2O_3 with a combination of SrO or BaO) are now commonly used for a number of applications, their magnetic 'energy product' is almost an order of magnitude lower than the rare earth magnets at this point. However they also do offer certain advantages, since they can withstand much higher temperatures, and are also lighter in weight.

Though ferrite based permanent magnets does not necessarily constitute a large area of research at present, the quest to increase the 'figure of merit' of these ferrite magnets is an important consideration. An enhancement in this figure would mean that they could emerge as viable alternatives at-least in some of the applications driven by Nd based permanent magnets. A number of strategies can be employed to try and increase this magnetic 'figure of merit'. This could include the synthesis of new ferrites, or the use of nanostructuring in known ferrite magnets to improve on its performance. Another route could be the synthesis of core shell structures using ferro-antiferromagnetic oxides, to increase the magnetic 'figure of merit'. Amongst the goals of this TIH would be the quest for new and improved magnets based on earth abundant materials to offer possible alternatives to the current rare earth based permanent magnets.

1.3.3.4 EMERGENT PHENOMENA IN QUANTUM MATERIALS

Emergent phenomena indicate the collective behaviour and functions that are realized only when a considerable number of elements get together and interact strongly *(Science 177, 393 (1972))*. In quantum many-body systems remarkable emergence appears due to strongly correlated electrons and the interplay between the many degrees of freedom of the electrons; namely lattice, charge, spin, orbital and topology *(Nat. Phys. 13, 1056 (2017))*. Consequently, emergent phenomena appear in the form of high-temperature superconductivity, topological superconductivity, Mott transition, magnetoelectric and magnetoresistive effects, quantum spin liquids, topological insulators and semimetals, etc. Next-generation quantum technologies must exploit these novel phenomena in novel devices for energy harvesting, dissipation less electronics, and fault-tolerant quantum computing and communication. While quantum emergent phenomena in materials have tremendous future in technological applications, one needs to circumvent many hurdles that could only be addressed by investigating the fundamental science to understand the appearance, origin, dependence and manipulation of these quantum states. We propose to initiate research in this direction, especially involving the following areas.

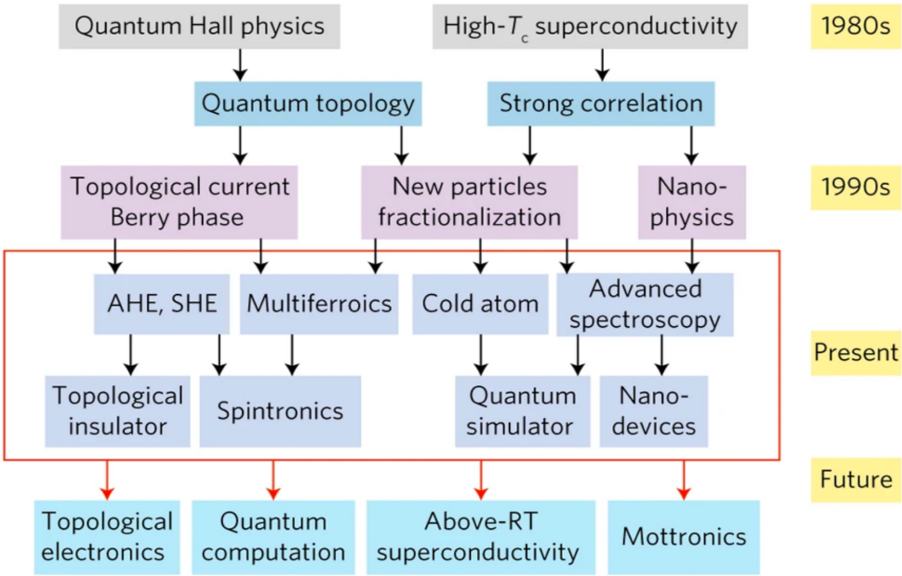

Figure 1.19: Emergent functions of quantum materials. The picture is adopted from Nature Physics 13, 1056 (2017)

TOPOLOGICAL MATERIALS AND ELECTRONICS.

While the broken symmetries characterize most of the quantum states of matter, the discovery of the quantum hall effect cannot be explained by such principles (*Nat. Phys.* **13**, 1045 (2017); *Nat. Phys.* **12** 1056 (2017)). In this regard, topology, the new degree of freedom for the electronic state, emerged as the fundamental concept that plays the central role in quantum hall effect, topological superconductivity, topological semimetals, and insulators (*Rev. Mod. Phys.* **82**, 3045 (2010); *J. Phys. Soc. Jpn.* **82**, 102001 (2013); *Rev. Mod. Phys.* **90**, 015001 (2018)). The concept of connection and curvature associated with the Berry phase provides a unified description of these topological phenomena. The idea of topology is merging with the other intrinsic electronic features at the microscopic level, such as spin-orbit interaction and strong correlation to create new concepts, and is paving ways for novel emergent phenomena. However, how these topological properties will be utilized in the next generation of quantum devices is yet to be seen. Some of the possible applications that have been envisioned are circuits with dissipationless currents, and high-security information processing and quantum computing. It is encouraging that during the last decade, topological phenomena have surfaced into the real worlds of experimental physics from the predictions in theoretical physics. The field offers new challenges to synthesize compounds with heavy elements, observe and understand new phenomena and lastly manipulate and control properties as desired for disruptive technologies. We propose to initiate research on these aspects.

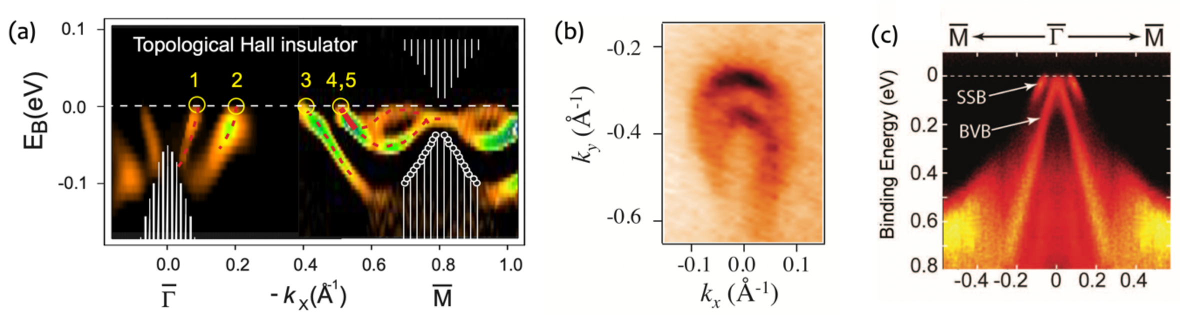

Figure 1.20: (a) Three-dimensional topological gapless surface state in bulk insulating BiSb, ARPES data (Nature 452, 970 (2008)). (b) Observation of topological Fermi arc surface states on the (001) surface of TaAs via ARPES Fermi surface map (Science 349, 613 (2015)). (c) Observation of Dirac fermion in Na_3Bi (Science 343, 864 (2014)).

Quantum spin liquid and quantum computing. In quantum magnets the unpaired electrons are arranged on a periodic lattice, and the spin of the electrons interact with those of their neighbors. At low temperatures, these spins usually organize in a regular pattern, and the resulting macroscopic magnetic ordering is characterized by spontaneously broken symmetry. Appearance of ferromagnetism, antiferromagnetism, and various spatially oscillating magnetic ordering are well understood within the realm of broken-symmetry. However, the question arises that if such a material exists, in which the electron spins interact but strong quantum fluctuation prevents any long-range magnetic order. From a pure theoretical point Anderson showed that such a quantum spin liquid phase is possible for which no symmetry breaking is needed *(Science 235 1196 (1987))*. In such a novel quantum phase of matter a variety of unusual features arise such as fractional excitation and long-range quantum entanglement. If proven to exist, quantum spin liquids would be a step toward realizing quantum computers.

Following the theoretical predictions, experimental physicists have longed to discover the quantum spin liquid phase in real materials *(Rep. Prog. Phys. 80, 016502 (2016); Phys.Today 69, 30 (2016))*, which has not been realized till date, despite tremendous efforts. The most important approach has been to use geometric frustration, such in organic salts and herbertsmithite *(Rev. Mod. Phys. 88, 041002 (2017); Nat. Phys. 4, 459 (2008))*, leading to degenerate spin configurations and consequently entangled quantum state arises. On the other hand, within Kitaev's picture the spins on a honeycomb lattice are assumed to interact in anisotropic fashion resulting in a quantum spin liquid phase with exotic magnetic excitations including Majorana fermions *(Ann. Phys. 321, 2 (2006))*. While many real materials in Li_2IrO_3, Na_2IrO_3, and $RuCl_3$ fulfil the requirements of Kitaev spin liquid, it is unfortunate that all these compounds magnetically order down to few Kelvin (*Nat. Rev. Phys. 1, 264 (2019)*). Thus, it is imperative to keep on searching for the elusive quantum spin liquid phase in new materials theoretically and experimentally. It would be interesting to seek possibilities in geometrically frustrated minerals.

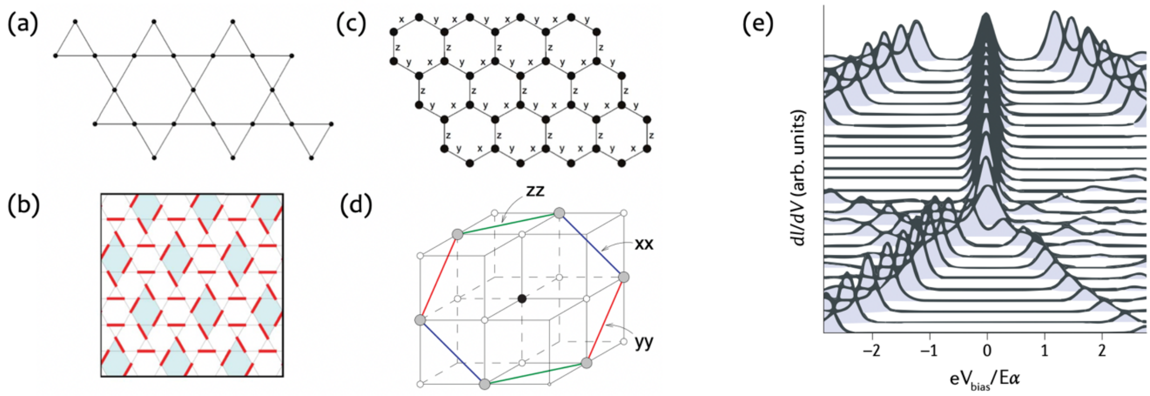

Figure 1.21: Panels (a-d) Various geometrically frustrated magnetic models for plausible realization of quantum spin liquid states. (a) Kagome lattice (b) valence bond state on Kagome lattice (c) Kitaev model on honeycomb model and (d) bond dependent Kitaev interaction in a sixfold coordinated lattice. The figure is adopted from Science 367, 263 (2020). (e) Signature of Majorana zero mode. The dependence of the differential tunneling conductance on the magnetic field. The characteristic zero-bias peak in tunneling conductance appears at a finite field, which is a signature of MZMs. The figure is adopted from Nat. Rev. Mater. 3, 52 (2018).

Topological superconductivity and Majorana fermion. Topological superconductivity may emerge in a hybrid system, where a conventional superconducting metal is combined with a strong spin-orbit coupled material *(Nat. Phys. 16, 718 (2020), Rep. Prog. Phys. 80, 076501 (2017)).* This distinct phase of matter is profoundly distinct from the conventional superconductors, which can foster states that are neither fermionic nor bosonic. Such non-Abelian states may find its application in fault-tolerant quantum computing *(Phys. Rev. B 61, 10267 (2000) ; Phys. Rev. Lett. 86, 268 (2001))*. The most exciting manifestation of topological superconductivity is Majorana zero modes, which are quasiparticle excitations that are their own antiparticles that can serve the basis of robust quantum information technology. Therefore, condensed matter physicists are fervently chasing the elusive existence of Majorana excitation. In this regard, while a variety of systems are proposed to host topological superconductivity, the two-dimensional platforms in superconductor/semiconductor hybrids are being investigated for the realization of Majorana modes *(Phys. Rev. Lett. 105, 077001 (2010))*. Thus, one of the main challenges and goals in this regard is to gain a deeper understanding of the interface between superconductors and semiconductors, which we propose to address here. The other distinct channel to generate topological superconductivity at the surface of topological insulators *(Phys. Rev. Lett. 100, 096407 (2008), Phys. Rev. Lett. 104, 057001 (2010)).*

Quantum devices. In this section, we propose to take up the challenge of bringing in topological phases in quantum devices made from quantum materials that are explored in the project by utilizing quantum transport theory based on the non-equilibrium Green's function (NEGF) formalism. The formalism allows one to seamlessly augment materials chemistry with an atomic description of current flow, which is of foremost importance to device engineers. This is because the NEGF computational framework includes the "electrodes", along with the channel geometry in the simulation, the electrodes –namely the source and the drain inject and maintain currents, while the gate maintains the modulating electric field required to necessitate the topological transition.

During the past one decade there has been an enormous interest and scientific development in the fields of emergent phenomena in condensed matter systems. A group of theoretical scientists lead by Kane and Mele laid out the requirements for a non-magnetic material to be a topological insulator and have quantum spin Hall effect *(Phys. Rev. Lett. 95, 146802 (2005); Phys. Rev. B 75, 121306 (2007))*. Following the theoretical predictions, the group of Hasan in Princeton first experimentally realized the topologically insulating phase through ARPES measurements *(Nature 452, 970 (2008)),* and also observed unconventional quantum spin textures *(Science 323, 919 (2008))*. The next breakthrough in the discovery of large-gap topological insulators came by the same group in Princeton *(Nat. Phys. 5, 398 (2009))* and by the group of Zhang in Stanford *(Nat. Phys. 5, 438 (2009))*. The groups of Cava at Princeton and Bansil at Northeastern played integral roles. In Weyl semimetals the low energy excitations are massless Weyl fermions that carry electrical charge. Theoretical prediction of Weyl semimetal phase by Vishwanath and Savrasov in pyrochloreiridates triggered the intensive research on Weyl fermion (*Phys. Rev. B* 83, 205101 (2011)). Such emergent quasiparticle in a low-energy condensed matter system was discovered by three groups independently in TaAs, Zahid Hasan in Princeton *(Science 349, 613 (2015)),* Hongming Weng at the Chinese Academy of Sciences *(Phys. Rev. X 5, 031013 (2015))* and Marin Soljačić at MIT *(Science 349, 622 (2015))*. Parallelly Dirac semimetals phase was discovered in Na_3Bi and Cd_3As_2 (*Science. 343, 864 (2014)*; *Science. 347, 294 (2015)).*

Possibility of a quantum spin liquid phase was first proposed by Anderson *(Science 367, 263 (2020))*. Many candidate materials have been investigated experimentally such as organic salts and herbertsmithite *(Rev. Mod. Phys. 88, 041002 (2016); Nat. Phys. 4, 459 (2008))*. In this regard 2D materials are also being studied following Kitaev's theoretical suggestion. Collaborating researchers from Oak Ridge National Laboratory, University of Cambridge, and the Max Planck Institute for the Physics of Complex Systems measured the first signatures of these fractional particles, known as Majorana fermions, in a two-dimensional material with honeycomb lattice *(Nat. Mater. 15, 733 (2016))*. The field of frustrated quantum spin systems and quantum spin liquids are currently poised with the arrival of promising candidate spin liquid (QSL) materials most convincingly identified via probes such as neutron scattering, however, an understanding of the microscopic origin of the putative QSL is at large. There is a vibrant frustrated magnetism community in India working on the experimental identification and theoretical understanding of quantum spin liquids, however, there is much scope for development of state-of-the-art quantum many-body numerical approaches, which can complement the existing efforts of experimentalists and theoreticians. There are only a few people at the moment who are working in this area in India such as Yogesh Singh from IISER Mohali, Surjeet Singh and Ashna Bajpai from IISER Pune.

Internationally, an intense attention has been given to the research in topological superconductivity to univocally detect the existence of Majorana fermion (Nat. Rev. Mater. 3, 52 (2018)). Some experimental evidences of Majorana zero mode has been detected in various platforms. Semiconductor nanowires with strong spin-orbit coupling and ferromagnetic chains proximated with a superconductor are prominent examples *(Nat. Rev. Mater. 3, 52 (2018); Rep. Prog. Phys. 80, 076501 (2017);Science* 336, 1003 (2012)). Another experimental platform that is being investigated is doped topological insulators *(Phys. Rev. Lett. 100, 096407 (2008), Phys. Rev. Lett. 104, 057001 (2010))*. However, such systems host disorder and are difficult to integrate into a device structure. Thus, researcher are moving to a new platform of VdW heterostructures made with two-dimensional ferromagnet and superconductor, where the interfaces are much cleaner and much tractable in device architecture *(Phys. Rev. Lett. 123, 167001 (2019); arXiv:1905.10648; arXiv:2002.02141)*.

1.3.3.5 INSTRUMENTATION AND TECHNOLOGY SUPPORT SYSTEMS

An important aspect of development in the area of quantum materials and devices pertains to the design, development and deployment of specialized instrumentation - both in the areas of materials preparation/fabrication, as well as in the domain of characterization. This would involve extensive efforts aimed at developing experimental and computational facilities, which are not available from commercial manufacturers. A significant amount of such specialized equipment is always imported, and we are yet to create a base for indigenous development of such facilities. Even when these facilities are created- say at the level of individual research labs- there have been no efforts made to commercialize these products, or make them available to the Indian community at large. We envisage a substantial instrumentation activity as part of this TIH, with the express aim of addressing this shortcoming. In addition to contributing to the development of the deliverables outlined in this TIH, this is expected to spur activity in the form of startups and spin offs, which would translate the knowhow developed in the hub into the marketplace. The developments as a part of this activity is expected to cover hardware development in the form of sophisticated test and measurement system, turnkey sample preparation and device fabrication facilities, sophisticated sample characterization apparatus, specialized computational modules, as well as educational kits targeted at the undergraduate and postgraduate levels. Wherever possible, the TIH would also aim to liaise with Indian manufacturers to develop local infrastructure and a critical knowledge/manufacturing base.

CHAPTER 2

2 PROBLEMS TO BE ADDRESSED

2.1 BACKGROUND AND SCOPE OF THE HUB

Excellence in quantum technologies and through targeted delivery of projected outcomes relies heavily on the identification of the problems that need to be addressed through the Technology innovation hub. The problems in the three verticals viz. are identified in such a manner so as to start giving output in terms of technology development and at the same time address some of the current scientific issues in the short term and paving way to long term research and development goals. The main issues that are addressed also include technologies that are developed in leading research groups around the world and technologies that are futuristic. In doing so, one of the major factors that has been taken into account is the development of skills through modular projects that can be executed in a distributed manner as well as hub centric problems. The thrust in doing this would be through the identification of front-end research themes pertaining to quantum technologies, generation of intellectual property (IP) through patents, translation of the generated knowledge into commercial products and through knowledge sharing and training amongst the next generation of researchers and entrepreneurs.

The list of various problems that are identified are given in the following chapter. The list will evolve dynamically during the progress of various projects in line with the global developments and learning in various technical areas.

2.2 GRAND PROBLEMS TO BE ADDRESSED BY THE HUB

1. Development >20 qubits fault tolerant Quantum computers and simulators for applications in defence, healthcare and financial sectors
2. Building long distance quantum communication channels
3. Commercialization of quantum effect enhanced sensors and atomic clocks with unprecedented accuracy and stability
4. Capacity building in quantum technology development and human resources for self-reliance

2.3 VERTICAL 1 - QUANTUM INFORMATION AND METROLOGY

2.3.1 CONSTRUCTION AND REALIZATION OF A 20 QUBIT ION TRAP QUANTUM COMPUTER

1. Development and construction of 3-D ion trap architectures for trapping strings at least 20 qubits and scaling up to 40 ion qubits
2. Coherent state manipulation of ion qubits
3. Demonstration of single qubit and 2-qubit gates
4. Creation of multi-Qubit entangled states
5. Demonstration of basic quantum algorithms on a 10 qubit quantum register
6. Design and construction of 2-D surface traps
7. Development of integrated photonic circuits for surface traps
8. Large ion chains on 2-D surface traps and fidelity analysis

2.3.2 EXPERIMENTAL DEMONSTRATION OF A 50 QUBIT SPIN-REGISTER BASED ON NUCLEAR MAGNETIC RESONANCE FOR QUANTUM SIMULATIONS

1. Identify the spin-systems that allow quantum registers with 50+ qubits with maximum controllability. This would require sampling a fairly large number of possible candidate molecules and studying their strengths and weaknesses.
2. Quantum control of 50+ qubits will be a major challenge. Depending on the specific topology, isotopic compositions, molecular structure, one has to develop novel quantum control schemes.
3. Decoherence or the loss of quantum memory - is a major problem in any quantum computer architecture. Preserving large quantum coherences for sufficiently long time to carry out a desired quantum circuit is going to be another major problem.

2.3.3 MULTI-QUBIT QUANTUM COMPUTING AND METROLOGY WITH DEFECT-CENTER BASED REGISTERS SUCH AS NITROGEN VACANCY CENTERS IN DIAMOND

1. Setting up advanced NV center / SiC center facility that allows precise and robust quantum control of the electronic qubit

2. Preparation of a hybrid quantum register based on defect centers requires detailed knowledge of interactions between the electron and nuclear spins of the centers and of the surrounding nuclear spins.

3. Controlling of nuclear spin qubits within the timescales of electron spin coherence times should be addressed to realize multiqubit gates on defect center quantum registers.

4. Development of dynamical decoupling techniques to improve coherence times of the electron spins of the defect centers.

5. Identify the diamond surface treatments that lead to improvement in the spin relaxation and spin coherence properties of the NV centers. This would involve detailed studies of the quantum properties of NV centers through tailored engineering of the surface in order to establish the link between surface chemistry and quantum coherence.

6. Performing quantum metrology in noisy environments will be a major challenge. The noise can originate due to random control errors and unwanted interactions with the environment, thereby limiting the achievable gains in sensitivity and precision.

7. Many of the quantum metrology protocols involve measurement of a desired physical quantity in the presence of unwanted qubit-bath interactions. Hence, accurate information about the unknown parameters of the environment such as the qubit-bath coupling strength and bath correlation time is required for implementing a sensing protocol that is best suited for the precise estimation of the physical quantity.

2.3.4 THEORETICAL RESEARCH INTO THE TRAPPED-ION CRYSTAL WITH RYDBERG EXCITATIONS, QUANTUM THERMODYNAMICS, AS WELL AS STRONGLY CORRELATED & OPEN QUANTUM SYSTEMS.

1. **Efficiency of quantum machines:** A particular rich setup that promises to realize efficient quantum thermal engines (microwave laser, photon amplifier) are the interacting quantum dot based mesoscopic circuits coupled to cavity photons which are now being experimentally engineered with high degree of tunability and scalability by international groups. Principles of quantum thermodynamics can be used to provide useful guidelines to the design of quantum devices, in particular for optimal utilization of the quantum nature of the many-body systems that form the quantum thermal machines such as amplifiers, quantum refrigerators, thermoelectric engines.
2. **Engineering phonon modes via Rydberg excitations in an ion crystal:** Selective, isolated excitations of few Rydberg ions can induce complex changes in the properties of ion crystals, especially the phonon modes in the system in important ways. Each Rydberg excitation can induce localized phonon modes with oscillations only among the ions neighboring the Rydberg ion. Understanding how to control this behaviour of the Rydberg ion systems can provide a route for quantum simulations for various spin-models.
3. **Computational approaches for out of equilibrium quantum dynamics:** Study of out-of-equilibrium interacting open quantum systems requires development of efficient and accurate

computational algorithms. Efficacy of algorithms can depend on the time scales of interest, strength of interactions, dimension of the systems, level of coarse graining and a complex set of other factors. In addition to direct modeling of systems of immediate experimental relevance, the algorithms will aid in theoretical understanding of the underlying physics.

4. **Quantum machine learning - identifying efficient practical strategies:** Quantum versions of standard machine learning techniques can in principle give significant speed up. Underlying such quantum algorithms is the quantum linear systems solver called the HHL algorithm, which at its core provides a quantum matrix inversion technique and has been experimentally demonstrated in few qubit (4 to 8 qubit) systems. We hope to make progress by identifying specific problems that can be reduced to such a matrix inversion and can thus take advantage of the HHL algorithm. One of the challenges is to represent HHL and related algorithms in terms of quantum gate operations. This part of the project aims to identify protocols that can be represented in gates which can then be executed in current quantum computers.
5. **Classical machine learning for quantum problems:** Classical machine learning can be and is being extensively used for quantum state tomography, prediction of dynamics of quantum correlations, optimal control, and state preparation. However employing this in a concrete experimental system will require extensive testing of different algorithms, and development of system specific strategies.
6. **Modeling of QH interfaces:** Experiments have made great strides in interfacing different quantum Hall systems diverse geometries, some of them with a significant level of gate tunability of geometries Many of these studies are motivated by predictions of edge bound localized anyonic states potentially useful for technological applications. These predictions rely on field theoretical calculations at the long wavelength or topological scaling limits. Backing this up with careful microscopic computational calculations will go a long way in reliably understanding the physics of these interfacial systems and identifying short wavelength features.

2.2.5 SUPERCONDUCTING QUANTUM CIRCUITS

1. **Broadband or multi-band quantum limited amplifiers:** These are some of the quietest microwave frequency amplifiers which are crucial for any superconducting quantum processor as they help in achieving high fidelity measurements. This makes them an invaluable tool for quantum error correction projects as well. These can be quickly commercialized and the engineering needed is not that complicated. Making them broadband and high dynamic range will required some initial research and can be soon turned into a marketable technology with a wide market both in industry and academia.
2. **Cryogenic microwave components and assemblies:** These include components like absorptive filters, reflective filters, attenuators, directional couplers, power splitters, multiplexers and circulators. Optimizing performance at cryogenic temperatures will require correct choice of materials to ensure both electrical and mechanical performance. Another approach is to combine these components to develop signal processing assemblies that can operate as plug and play systems in cryogenic environments
3. **Control and measurement electronics:** Quantum computing technology requires a significant amount of cutting edge high speed electronics for control and measurement. These can be developed by putting together of the shelf modules to develop custom assemblies and later even

designed at the chip level for custom applications. Development of FPGA IP cores can be a major activity which can add significant value to these modules.

4. **Small quantum processor chips:** Small scale superconducting quantum processors (5 to 10 qubits) could have a target market in academia and industry involved in quantum computing research. The challenge will be to produce a robust design which will perform to specs in many different kind of experimental setups. The clients are those who are interested in using the processors for their own research and testing but don't want to invest in nanofabrication facilities and chip design.
5. **Small-scale quantum processors in the cloud:** This can be developed as a service where small-scale quantum processors operating at host location can be accessed by clients via the cloud. Development of a robust superconducting architecture and control circuitry would be needed to achieve this. It is possible to do this in a phased manner with 5, 10 and 20 qubits in 3, 4 and 5 years respectively with industry partners playing a significant role in terms of expertise and funds

2.4 VERTICAL 2 - QUANTUM COMMUNICATIONS

2.4.1 QUANTUM METROLOGY USING OPTICAL LATTICE SR OPTICAL CLOCK

1. Development of the clock laser at 698 nm for Sr
2. Construction of ultra-cold Sr atom setup
3. Development of the optical lattice laser at 813 nm
4. Loading the Sr atom in Optical lattice
5. Exciting and measurement of the clock transition
6. Measurement of clock stability

2.4.2 QUANTUM METROLOGY / COMMUNICATION USING TRAPPED ION OPTICAL CLOCK

1. "Phase-stabilized" optical-link fiber (quantum channel) between IUCAA and IISER-Pune. This will be the first of its kind in India and will show a step forward towards quantum-communication.
2. Dissemination of the phase & frequency stabilized optical photons through this quantum channel.
3. Synergy with the development of a trapped ion based quantum clock at IUCAA (as part of the QUEST program).
4. (IISER-Pune is also developing an optical-lattice based quantum clock. The developed quantum channel will be used for interconnecting both quantum clocks.)
5. Capability building on various quantum-phenomena based measurements.

2.4.3 Quantum Networks for secure communication

1. Construction of an ion trapping set-up overlapping the mode of an optical cavity using the well-known linear Paul trap design.
2. Construction of a high finesse cavity synchronized with the linear trapping axis
3. Development of a high number density 2D+ magneto-optical trap
4. Coupling of single photons from Strontium atoms on optical fiber link to IUCAA
5. Synergy with development of Plasmons assisted Atom+Photon interface at IISER Pune (as part of the QUEST program)

2.4.4 Quantum sensing and metrology based on defects in diamond

1. Identify the diamond surface treatments that lead to improvement in the spin relaxation and spin coherence properties of the NV centers. This would involve detailed studies of the quantum properties of NV centers through tailored engineering of the surface in order to establish the link between surface chemistry and quantum coherence.
2. Performing quantum metrology in noisy environments will be a major challenge. The noise can originate due to random control errors and unwanted interactions with the environment, thereby limiting the achievable gains in sensitivity and precision.
3. Many of the quantum metrology protocols involves measurement of a desired physical quantity in the presence of unwanted qubit-bath interactions. Hence, accurate information about the unknown parameters of the environment such as the qubit-bath coupling strength and bath correlation time is required for implementing a sensing protocol that is best suited for the precise estimation of the physical quantity.

2.4.5 Instrumentation for quantum computing platforms

1. Development and commercialization of stable tunable lasers systems for a variety of atomic and ionic systems:
2. ECDL laser systems
3. Master Oscillator Power amplifier based lasers systems
4. Frequency doubling systems
5. Robust interference filter based tunable laser systems
6. Development of high stability optical cavities for laser line width narrowing and optical references
7. Development of analog and digital control systems for quantum machines

8. Development of Non Linear Optical Crystals
9. Development of coating techniques for high reflectivity optics
10. Development of FPGA modules for addressing and controlling quantum layers
11. Development of software for real time data acquisition, control and addressing of hardware for quantum cores
12. Development of capabilities for optical technologies
13. Development of artificial intelligence and machine learning for tuning complex control systems for quantum processors
14. Development of teaching aids and training kits for training and quantum optics, Light-matter interaction and quantum physics for undergraduate and post graduate students

2.5 VERTICAL 3 - QUANTUM MATERIALS AND DEVICES

2.5.1 SPINTRONIC DEVICES

1. Temperature dependent Spin Seebeck platforms based on quantum Antiferromagnets especially at high magnetic fields
2. Investigation of the Spin Seebeck Effect in devices based on strongly correlated electron systems to evaluate the nature and dynamics of these spin currents. Complemented with IR and THz spectroscopy.
3. Investigation of thermally induced spin currents in graphene like 2D magnetic oxides
4. Evaluating ferro-antiferro multilayers and multiferroic based devices for specific spintronic applications
5. Investigation of superfluid spin transport in quantum magnets and superconducting spintronic platforms
6. Evaluating nano-spintronic devices based on 1D and 2D carbon nanotube-transition metal oxide hybrids
7. Investigation of the intrinsic and extrinsic contributions to the Spin-Hall angle
8. Fabricating 'designer' magnonic crystals and evaluating their device possibilities including THz emitters
9. Use of first-principle based density functional theory approaches to investigate spin and valley polarization, anisotropy effects etc. in TMDCs heterostructured with 2D ferromagnets with FM/TMDC bilayer and FM/TMDC/FM and TMDC/FM/TMDC trilayer architectures

10. Exploration of topological insulators and topological crystalline insulators in heterostructures with the 2D ferromagnets and the resultant Quantum Anomalous Hall Effect phenomena
11. Single crystal growth and exfoliation of layered magnetic 2D systems, and electrically controllable spintronic devices based on these systems
12. Tso develop and control a spin qubit efficiently to generate useful instructions or gate operations on a large scale.

2.5.2 QUANTUM OPTOELECTRONICS

1) Improving the positional accuracy of quantum emitters. This is crucial since the collection intensity of photons decreases as a function of spatial distance.
2) Development of broad-band and high-speed photo detectors towards single-photon detection.
3) Development of a platform for 2D materials based quantum-emitters.
4) Investigation of valley selective electrical and optoelectrical properties through novel measurement techniques.
5) Manipulation and exploitation of light-matter interaction in designer van der Waals heterostructures.
6) Optical manipulation of magnetism in two-dimensional magnets for futuristic spintronic applications.
7) Development of chiral quantum optical devices to sort photons by their polarization and momentum states.
8) Key on-chip photonic ingredients to develop interconnects for quantum optical networks.

2.5.3 MULTIFUNCTIONAL QUANTUM MATERIALS

1) Investigating different oxides and other earth abundant materials, in the quest for new and improved permanent magnets
2) Exploring the role of nanostructuring and possible core-shell structures in improving the magnetic 'figure of merit'.
3) To explore different material classes in the quest for new and improved magnetocalorics and electrocalorics
4) Discovery of new high-performance thermoelectrics (figure-of merit >1.5), preferably comprising of earth abundant elements
5) Development of novel material synthesis and nanostructuring techniques for enhancing thermoelectric performance

2.5.4 Emergent phenomena in Quantum materials

1) Design, growth, and characterization of new topological quantum materials for topological electronics.

2) Realization of the quantum spin liquid state in real materials that will serve as the building blocks of quantum computation.

3) Develop systems to realize the elusive Majorana zero mode in topological superconductors which will be a step toward robust quantum information technology.

4) Finding new platforms for topological superconductivity.

5) Understanding the interplay of electronic and lattice degrees of freedom for explaining critical elasticity and the possibility to tune the strength of the electron-lattice interaction.

6) Development of quantum many-body numerical methods to study emergent phenomena in quantum materials.

7) Screening of promising materials to discover novel quantum materials using the state of the art first-principles quantum calculations, and integrate it with powerful machine learning techniques.

8) Development of new solid-state electrically tunable ultrawideband oscillators with frequency tunable in the range of 10 GHz to THz

9) Develop tools for novel phases of quantum matter such as quantum spin liquids that are candidates for potential use in future information technologies

10) Develop local capabilities to perform state of the art Matrix Product States calculations for strongly correlated electronic systems in FQHE. Application of FEAST algorithms to questions on FQH systems.

2.5.5 Instrumentation and Technology Support Systems

1) Development of low temperature apparatus for the measurement of the Spin Seebeck Effect, the Spin Hall Effect and the planar Hall Effect

2) Development of a low temperature ac susceptometer for linear and non-linear magnetic susceptibility

3) Development of apparatus to enable simultaneous local magnetic field and electric current imaging technique valid over a broad temperature range.

4) Development of apparatus for measurements of the thermal conductivity, Anomalous Hall effect (AHE) and magnetoresistance (MR) for ultrathin (2D limit) specimens

5) Development of (room temperature and above) vibrating sample magnetometer for characterizing permanent magnet candidates

6) Development of apparatus for measuring electrocaloric effect for near room temperature applications

7) Electronic test and measurement modules useful for the above mentioned tasks.

8) Development of advanced atomistic quantum transport simulators.

9) Development of real-time TDDFT (RT-TDDFT) based methods to study photo-excited dynamics in topological materials.

10) Development of sample growth facilities for the preparation of high quality quantum material specimens

11) Design of development of educational kits for outreach and undergraduate education

CHAPTER 3

3 AIMS AND OBJECTIVES

The project comprises three verticals: (A) Quantum information and metrology, (B) Quantum communication, and (C) Quantum material and devices. The summary of aims and objectives is depicted below and detailed point by point descriptions of vertical-specific aims and objectives are in the later pages.

3.1.1 GRAND PROBLEMS TO BE ADDRESSED BY TIH

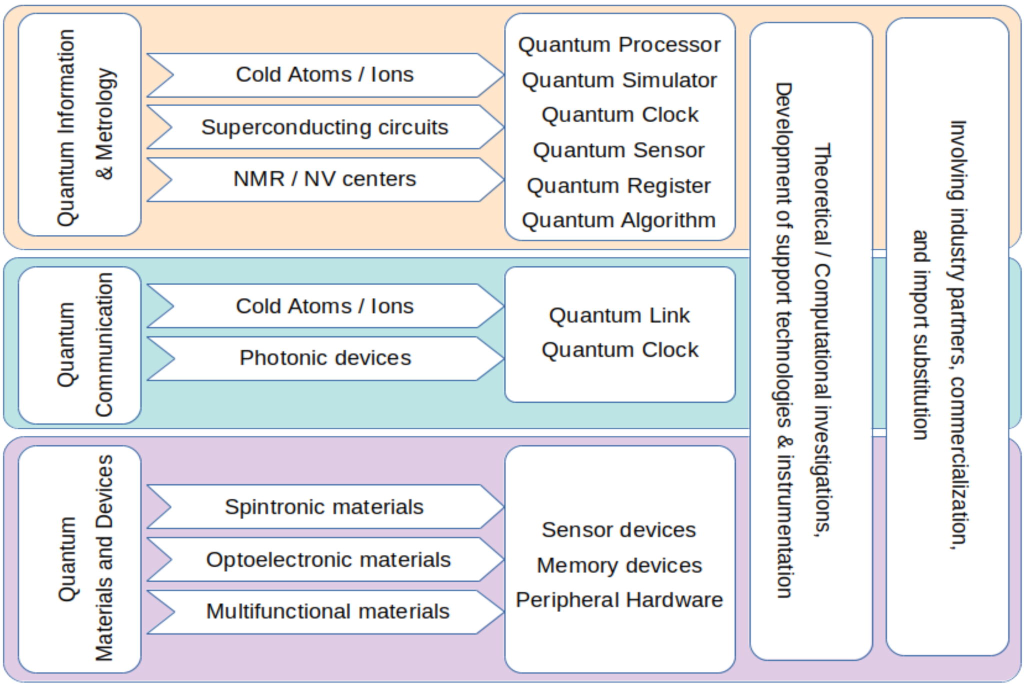

Figure 3.1 Broad Objectives of the TIH

1. Demonstration and development of > 50 qubit quantum computers and quantum simulators
2. Demonstration of detectors, light sources, quantum repeaters and quantum link over > 5 kms for secured quantum communications
3. Development of state of the art quantum sensors for photons, inertial sensors and unprecedented time keeping
4. Indigenization of key technology enablers (materials, devices, instrumentation and control systems, algorithms and software) for quantum technologies

3.1.2 VERTICAL A: QUANTUM INFORMATION AND METROLOGY

Aims:

Aim 1: Development of Quantum hardware such as a quantum register, quantum simulator, quantum computer, single-photon generators

Aim 2: Development of Quantum Algorithms and Processes

Aim 3: To develop robust quantum technology using superconducting quantum circuits and market them to the quantum computing community in academia and industry and develop custom peripheral control and measurement electronics for the quantum computing community

Aim 4: To develop custom peripheral control and measurement laser, electronics and optoelectronic components for the quantum computing community

Aim 5: Development of theoretical / computational tools for enabling

Aim 6: Involve industry partners from the beginning to quickly find strategies for commercialization.

Overall objectives:

5. Construction of a 5-20 bit Ion trap, superconducting circuits and diamond defect centers' based Quantum Computers and make at least one the systems available on a cloud for nationwide usage
6. Development of 50+ qubits based NMR quantum simulators and information processors
7. Construction of single photon generators from atomic and ionic platforms
8. Development of quantum simulators with long range interaction (Rydberg states)
9. Development and technology translation of high end critical instrumentation technology for enabling quantum technologies (for e.g. high precision, low noise, narrow linewidth laser systems, control systems and data acquisition systems, RF and Microwave electronics components and systems)
10. Development of metrological systems for quantum limited frequency, magnetic field, electric field, gravitational acceleration and inertial sensing.

Details of objectives:

a. Ion Trap Quantum Computer

- Design and construction of a 3D linear Paul trap and surface trap. This will be helpful in the following ways :
  - Testing of known protocols for qubit addressing, sideband cooling, multi-qubit entanglement, readout, qubit heating and decoherence characterization.
  - Establishment of laser locking to stable reference cavities. This also is congruent with development of the same for realizing optical clock based on ions.
  - Development of stable RF and DC electronics for trapping and shuttling ions.
  - This setup can also be used in parallel for simulating many body Hamiltonians and cold chemistry.
- Construction of surface traps

  These will be used to test the scalability schemes in ion trap computing.

  - Implementation of custom geometries can be realized that can shuttle ions between different loading, addressing and readout zones.

  - Fabrication protocols to minimize the effect of surface induced heating of the trapped ions.

  - The facilities developed can also be used to fabricate chip traps for cold atom systems

- Quantum Simulations of trapped-ion quantum computers

  - Develop Q-ASCS (Quantum-Application Specific Computers and Simulators) to study quantum matters that are not accessible via conventional methods. Technology for controlled engineering of Phonon modes in the ion crystal.

- Import substitution of the general and critical instruments.

  - The technology developed in pursuit of the end deliverables will have applications in quantum metrology and precision sensing both of which have commercial prospects.

- Development of ultra-stable laser systems
- Demonstration of laser-cooled ion crystals
- Design and construction of site-resolved addressing and readout optics
- Single qubit rotation and C-NOT gate demonstration on a two ion chain
- Realization of a 10 qubit ion trap quantum computer
- Demonstration of multi-qubit entanglement and quantum algorithms
- Quantum simulations with few qubits

b. Development of single photon generators from cold atom and ion-based platforms

- Design and construction of a linear Paul trap overlapping high finesse cavity
- Design and construction of a 2D+ MOT
- Development of laser systems for trapping and cooling Rb (Rubidium) atoms and 40Ca+ (Calcium) ions
- Generation and characterization of single photons from 2D+ MOT
- Generation and characterization of single photons from ion-cavity system
- Demonstration of heralded single photon generation from 2D+ MOT
- Demonstration of heralded single photon generation from ion-cavity system
- Dissemination of results

c. Instrumentation for Atom+ion based quantum technologies

- Design and construction of an atomic based microwave (MW) detector
- Design and construction of 1013 nm and 420 nm diode laser systems (Littrow configuration)
- Littmann-Metcalf external cavity configuration (780 nm)
- Development and design of optics and electronics for line-width reduction of laser systems
- Detection system for low light (noise free)
- Embedded systems hardware and software development for interface with Quantum core

d. Development of laser for Rydberg excitation of Yb atoms

- Design and construction of frequency doubled laser for 395 nm, 507 nm, 458 nm wavelength
- Design and construction of 497 nm and 423 nm diode laser systems
- Design and construction of 1140 nm and 948 nm Tapered amplifier laser systems
- Development and design of optics and electronics for line-width reduction of laser systems
- Development and design of optics and electronics for phase noise reduction of laser systems
- Observation of Rydberg blockade

- Design and construction of an Yb atom based microwave (MW) detector

e. Development of quantum technology compatible lasers system for Yb and Rb atoms

- Design and construction of 780 nm and 795 nm extended cavity laser (ECDL) in Littman and Littrow configurations.
- Design and construction of 420 nm, 480 nm, 960 nm and 1013 nm diode laser systems (Littrow configuration).
- Design and construction of 420 nm, 480 nm, 960 nm and 1013 laser diodes to injection lock for enhancing the laser power.
- Design and Construction of high power laser system using Tapered Amplifier (TA) for 960 nm and 1013 nm.
- Assembly of frequency doubling unit for generation of 480 nm laser using amplified 960 nm.
- Characterization of the high finesse ULE cavity for 420 nm, 480 nm, 780 nm and 1013nm and construction of vacuum chamber
- Development and design of optics and electronics for line-width reduction of laser systems.
- Development and design of optics and electronics for reduction of high-frequency phase noise of laser systems.
- Design and construction of detection system for low light (noise free)
- Assembly of 1156 nm extended cavity laser (ECDL) with 200-300mW power
- Assembly of frequency doubling unit for generation of 578 nm laser using 1156 nm ECDL.
- Assembly of the high finesse and ultra-low expansion (ULE) cavity mirror 1156 nm.
- Characterization of the high finesse ULE cavity for 1156 nm
- Linewidth narrowing 1156 nm ECDL
- Characterization of narrowed 578 nm laser
- Assembly of 649 nm extended cavity laser (ECDL) with 50-100 mW power
- Assembly of high finesse ULE cavity for 649 nm ECDL
- Linewidth narrowing 649 nm ECDL
- Assembly of 1130 nm extended cavity laser (ECDL) with 100mW power
- Assembly of Tampered Amplifier at 1130 nm with 2 W power
- Assembly of frequency doubling unit for generation of 565 nm laser using 1130 nm.
- Assembly of the high finesse and ultra-low expansion (ULE) cavity mirror for 1130 nm.
- Characterization of the high finesse ULE cavity for 1130 nm
- Linewidth narrowing of 1130 nm ECDL
- Characterization of narrowed 1130 nm laser
- Characterization of narrowed 565 nm laser

f. Quantum metrology using optical lattice Sr optical clock

- Assembly of 698 nm extended cavity laser (ECDL)
- Assembly of the high finesse and ultra-low expansion (ULE) cavity
- Characterization of the high finesse ULE cavity for 698 nm
- Linewidth narrowing 698 nm ECDL
- Characterization of narrowed 698 nm laser
- Assembly of 813 nm ECDL
- Assembly of Tampered Amplifier at 813 nm with 2 W power
- Loading the atoms in optical lattice at magic wavelength
- Characterization of the optical lattice
- Excitation and measurement of the clock transition

g. Trapped ion-crystal with Rydberg excitations

- Design scheme to engineer phonon modes to mimic various interparticle interactions
- Developing models for fast quantum gates
- Quantum simulators for exotic spin models to study quantum many body

h. Superconducting Quantum Circuits

- Setup state of the art cryogenic measurement setup for testing superconducting quantum chips and cryogenic microwave technology.
- Design and develop ultra-low noise microwave amplifiers as a product
- Design and develop control and measurement electronics for the quantum computing community
- Design and develop robust small scale quantum processor chips (5-10 qubits) as a product
- In collaboration with industry, design, construct and operate small scale quantum processors (5 – 20 qubits) and provide as a service via the cloud.

i. Nuclear Magnetic Resonance (NMR) Quantum Computing

- Realization of 50+ qubits restricted-symmetry NMR register with node-bus architecture
- Identifying, characterizing, and categorizing special-topology spin-systems and compiling a database of such large symmetry-restricted quantum registers.
- Development of advanced quantum control methods for efficient and robust implementation of quantum circuits
- Characterizing decoherence in such large quantum registers and developing general and powerful methodologies to suppress decoherence.
- Experimental demonstration of controlled quantum dynamics with 50+ quantum qubits
- Adapting machine learning techniques for applications in quantum information
- Experimental investigations into emerging fields such as quantum batteries, quantum thermal machines, and quantum chaos

j. Quantum Computing & Metrology using Defect Center based Quantum Registers

- Preparation of a 5-10 qubit quantum register based on single electron and nuclear spins of defect centers in diamond and silicon carbide.
- Realization of multiqubit quantum gates on quantum registers based on defect center spins.
- Realization of quantum algorithms, quantum error-correction, and quantum simulations on quantum registers based on defect center spins.
- Design of a diamond magnetometer combining wide-field microscopy and ensemble NV centers for the measurement of physical quantities such as magnetic field, temperature, pressure etc.
- Implantation and fabrication of color centers (NV, SiV etc.) in diamond and exploring various surface modification procedures to improve coherence times.
- Experimental studies on the optimization of gate fidelities and speeds in the presence of random control errors. Substantial improvements in gate fidelities and speeds would pave the way for the development of highly effective quantum sensors.
- To further advance and broaden the applicability, a combination of dynamical control and estimation theory tools will be employed for quantum sensing with NV qubits.
- Utilize the NV center platform for realizing novel quantum metrology protocols and quantum-enhanced magnetometry measurements.
- Experimental demonstration of quantum sensing using NV-diamond imaging chip.

k. Designing efficient quantum thermal machines

- Design and implement tools to investigate finite time and steady-state quantum thermal machines
- Develop working principles to realize most favorable limits for quantum engine operations via characterizing the power output and associated quantum and thermal fluctuations.
- Realizing efficient quantum thermal machines in suitable and promising experimental platforms namely in NMR setup, nitrogen-vacancy (NV) centers in diamond, and cold ion-trap setup

l. Algorithms for quantum dynamics and thermodynamics

- Development of optimal Matrix Product States (MPS) based techniques for open quantum systems in strong coupling limits
- Building local capabilities for high performance MPS approaches to many body quantum dynamics

m. Quantum machine learning algorithms and applications

- Development of novel quantum inspired algorithms for commonly encountered problems in a variety of applications
- Development of prototype for such algorithms
- Implementation of quantum algorithms in quantum computing systems in IISER Pune or through systems available in the public domain

3.1.3 VERTICAL B: QUANTUM COMMUNICATION

Aims:

Aim 1: Developing in-house test facility (lab scale) of the optical fiber phase noise cancellation using long fiber spool (> 100 km).

Aim 2: Establishment of the quantum-link between IUCAA and IISER-Pune (~5 Km).

Aim 3: Developing the quantum clocks.

Aim 4: Import substitution of the general and critical instruments.

Overall Objectives:

1. Atoms and ions based quantum communication devices
2. Quantum repeaters with atoms and ions
3. Generation of photons on demand

Details of Objectives:

- Quantum Communication Devices: Construction of an ion trapping set-up overlapping the mode of an optical cavity using the well-known linear Paul trap design. This will be helpful in the following ways:
    - Testing of known protocols for qubit addressing, sideband cooling, multi-qubit entanglement, readout, qubit heating and decoherence characterization.
    - Establishment of laser locking to stable reference cavities. This also is congruent with development of the same for realizing an optical clock based on ions.
    - Development of stable RF and DC electronics for trapping ions and minimizing ion micromotion.
    - This set-up can also be used simultaneously for simulating many/few body Hamiltonians and cold chemistry of ion-atom mixtures under the cavity mode.
- Construction of a high finesse cavity synchronized with the linear trapping axis
    - These will be used to test the scalability schemes in ion trap computing and single photon generation using strong coupling of ions to the cavity field.
    - Test and characterize single photons generated
    - The know-how gained shall be applicable in general to problems associated with frequency metrology developed can also be used to fabricate chip traps for cold atom systems.
- Development of a high number density 2D+ magneto-optical trap
    - Setting up the platform for single photon generation from the trapped atoms
    - Test and characterize single photons generated

    - Developing a scheme for heralded generation of single photons from the platform
- Import substitution of the general and critical instruments

3.1.4 Vertical C: Quantum Materials and Devices

Aims:

Aim 1: Development of Spintronic Materials and Devices

Aim 2: Development of Quantum Optoelectronics Materials and Devices

Aim 3: Development of multifunctional materials

Aim 4: Investigating Emergent phenomena in Quantum Materials

Aim 5: Development of instrumentation and Technology Support Systems

Overall Objectives:

1. Spintronic and Spin-caloritronic devices
2. Quantum optoelectronic devices
3. New multifunctional quantum materials
4. Instrumentation and Technology Support Systems

Details of Objectives :

Spintronic Devices

- Establishment of a high field ultralow temperature apparatus for spin caloritronic measurements
- A rigorous scrutiny of a number of quantum materials, including geometrically frustrated magnets for their utility in mediating thermally induced spin currents
- Fabrication of atomically-sharp high-quality 2D interface phases of complex transition metal oxides with different electronic and magnetic structures.

- Fabrication of Spin Caloritronic devices based on graphene like 2D sheets of quantum magnets
- Testing of multilayered ferro-antiferro devices for use as potential thermal spin switches
- Developing and fine-tuning device architectures for use as thermal spin diodes, spin transistors and spin field effect transistors.
- Development and commercialization of low temperature measurement systems for measuring the spin-Hall effect.
- Shortlisting new materials useful for wiring magnetic memories
- Growth and characterization of thin films of Weyl semimetals (WSM) as a potential spintronic quantum material
- Demonstration of spin-orbit torques in WSM/HM system
- Establish the switching dynamics of artificial magnetic nanoarchitectures with frustrated interactions.
- Development of a state-of -the-art ac- susceptometry apparatus for the measurement of linear & nonlinear susceptibility for quantum magnets.
- Magnetic Tunnel Junctions, magnetoresistive and spintronic devices based on micro-crystals of CrO2 with ultra-thin surface layer of Cr2O3
- Theoretical design of new spin-orbit coupled van der Waals heterostructure of quantum materials for efficient spin and charge conversion for experimental verification.
- Manipulating spin-orbit coupling at the 2D van der Waals interfaces using adatoms and asymmetric structures for efficient spin and charge conversion.
- Synthesis of high quality single crystals of layered magnetic van der Waal systems. Device prototypes based on these systems.
- Optimization spin-torque based qubit architecture by reducing the number of operations for the elementary gates such as CNOT, SWAP, Toffoli, and Fredkin gates and their implementation.
- Optimization of the quantum circuits for the reversible Boolean logic such as AND, OR, XOR, half adder and full adder and their implementation.

Quantum Optoelectronics Materials and Devices

- Improving the positional accuracy of quantum emitters with a highest level that is crucial since the collection intensity of photons decreases as a function of spatial distance.
- Development of broad-band and high-speed photo detectors towards single-photon detection.
- Development of a platform for 2D materials based quantum-emitters.
- Investigation of valley selective electrical and optoelectrical properties through novel measurement techniques.
- Manipulation and exploitation of light-matter interaction in designer van der Waals heterostructures.
- Optical manipulation of magnetism in two-dimensional magnets for futuristic spintronic applications.
- Development of chiral quantum optical devices to sort photons by their polarization and momentum states.
- Key on-chip photonic ingredients to develop interconnects for quantum optical networks.

Development of Multifunctional Quantum Materials

- Identification of new earth abundant based permanent magnets
- Use of new materials/finite size approaches to enhance the effective magnetic figure of merit to a maximum energy product of 7 - 10 Mega Gauss Oersted.
- To identify potential electrocalorics with the magnitude of the Electrocaloric effect of 0.05- 0.1 K/ kVcm-1
- To fabricate a prototypical electrocaloric cooling module using these solid state refrigerants
- Development of prototypical solid state EC cooling modules which provides a temperature drop of 5-10 degrees, at or around room temperatures
- Identification of new earth abundant thermoelectrics; and nano-structuring approaches to enable ZT in excess of 1
- Development of prototypical thermoelectric modules with an effective power density of the order of at least 2 W/cm2
- Development of polymer based ‘flexible’ thermoelectric modules with for near room temperature applications
- Establishment of measurement facilities to enable the evaluation of thermoelectric, electrocaloric and permanent-magnet candidates.

Emergent phenomena in Quantum Materials

- High quality crystal growth of quantum materials with strong electron-correlation, high spin-orbit coupling, and topology.
- Growth and characterization of thin films of Weyl semimetals
- Topological properties such as Dirac, Weyl, and multi-degenerate nodal point semi-metals, Berry phase/curvature and anomalous Hall effect will be investigated.
- Two-dimensional magnetic materials with magnetic ions (4d or 5d) on frustrated geometrical lattices, including, triangular and Kagome will be investigated using NMR, muSR, INS and other bulk techniques for possible spin liquid ground state. Further, impurity substitutions in the pristine materials will be carried out and their effect on the local spin structure and their dynamics will be probed by NMR. While this is of basic interest, such studies can help in tuning of the properties for applications.
- Investigating topological superconductivity in hybrid systems built with superconductors and semiconductors (for example CrI3 and NbSe2).
- Investigate the possibility of topological superconductivity in doped topological insulators.
- Development of quantum many-body numerical methods to study emergent phenomena in quantum materials.
- Acquire an identification tool for novel phases of quantum matter such as quantum spin liquids which fall outside Landau’s symmetry breaking paradigm.
- Attempt to address the fundamental question of how S = 1 magnon excitations in an ordered magnet dissociate into fractional S = 1/2 spinon excitation as one approaches the quantum spin liquid regime, i.e., addressing the possibility of fractionalization in dimensions greater than one.

- Establish the switching dynamics of artificial magnetic nanoarchitectures with frustrated interactions

Instrumentation and Technology Support Systems

- Design, development and fabrication of measurement apparatus for critical spintronic and spin-caloritronic measurements. This includes measurements of the spin Seebeck effect (at temperatures down to at least 0.3K, and magnetic fields up to at least 9 T), and measurement platforms for the Spin Hall Effect using a 4K CCR mated with an electromagnet.

- Design and development of a sensitive ac susceptometer for measurements of the linear and non-linear magnetic susceptibility of quantum magnets
- Design and development of a magneto-optical platform for imaging the local magnetic fields and electric current in 2D ultrathin specimens and singly crystalline quantum materials.

- Design and development of sensitive apparatus for the measurement of electronic and thermal properties of ultrathin specimens. This would include measurements of the thermal conductivity (using the 3ω method) and a combination of high field magnetoresistance and Hall effect measurements. The latter would operate at temperatures down to 2K and magnetic fields of at least 7 Tesla.

- Design and development of a room temperature (and beyond) vibrating sample magnetometer for routine characterization of permanent magnet candidates. This is envisaged to be an electromagnet based system, with applied magnetic fields of the order of 2-3 Tesla.

- Design and development of apparatus to measure the temperature dependent Electrocaloric effect. Emphasis would be on near room temperature operations.

- The development of a number of test and measurement apparatus is envisaged to contribute to the activities of the TIH participants, as well as the Indian scientific community at large. This would include instruments like power supplies, voltmeters, lock-in amplifiers, low noise preamplifiers, temperature controllers, etc.

- Development of quantum transport simulators and other analytical/numerical tools that can handle realistic topological device structures and also make predictive simulations by including the effects of disorder, DE phasing and other scattering agents. Incorporation of additional functionalities like methods to study photo-excited dynamics in topological materials.

- Development of advanced sample preparation facilities, preferably in collaboration with Indian manufacturers who are already in this area of operation. This would include costly import substitute items like vapor transport furnaces and Bridgeman crystal growth systems.

- Design and development of educational kits for the undergraduate and the postgraduate levels. These low cost kits can be made available to select colleges/universities across the country as a part of the TIH’s outreach and human resource development activities. The aim here would be to expose a large community of our students to exciting experiments/developments in the area of quantum technologies.

- Development of scanning tunneling microscope and atomic force microscope which can measure currents in the range of 1-10 pA and cantilever displacements in the range of 0.1 to 1 nm respectively. The servo control to facilitate the tip actuation with precision range of 10-1000 nm will be developed in-house

Theory Development and Support for Quantum Technology Innovations

Aims:

Aim 1: Investigating quantum machines from a quantum thermodynamics perspective

Aim 2: Realizing spin models using isolated excitations Rydberg ion chain

Aim 3: Simulating Transport Dynamics of Rydberg ions

Aim 4: Rydberg ion chain to simulate open quantum systems

Aim 5: MPS based approaches for out of equilibrium quantum dynamics

Aim 6: Path integral based computational approaches for out of equilibrium quantum dynamics

Aim 7: Employing quantum and classical machine learning

Aim 8: New semi-analytical approaches for QH systems

Aim 9: MPS based modeling of hybrid quantum Hall edges

Objectives:

- Developing computational methods to simulate out-of-equilibrium many-body open quantum systems using path integral approaches
- Develop working principles to realize most favorable limits for quantum engine operations via characterizing the power output and noise to signal ratio, a key indicator for devices.
- Realize efficient quantum thermal machines in suitable and promising experimental platforms namely in NMR setup, nitrogen-vacancy (NV) centers in diamond, and cold ion-trap setup.
- Develop MPS based approaches to probe quantum Hall systems
- Develop gate models for quantum machine learning algorithms
- Apply the gate models and demonstrate working of quantum machine learning algorithms on available quantum computers
- Map the parametric regimes in which NMR and ion-trap based quantum computers can perform useful operations
- Develop analytical schemes to explore coupled quantum Hall systems
- Develop a strategy for simulating interacting spin systems in Rydberg ion systems.
- Develop designs for fast quantum gates in ion crystal utilizing strong Rydberg-Rydberg interactions.
- Develop models for quantum transport phenomena and spin-boson coupling in Rydberg ion systems.

CHAPTER 4

4 STRATEGY

This QT-TIH will be based upon a Hub-Spoke model as shown in figure 4.1. The nodal center will the section-8 company established by IISER to implement the goals of the NM-ICPS under the quantum technology sub-area. This company will be the main implementing hub while the institutes or organizations which win competitive projects floated by the QT-TIH will be designated as spokes. These spokes could be from across the country. The following strategy is suggested to be implemented.

Figure 4.1: Implementation strategy: QT-TIH will be hub which will drive the program at various institutes.

For the QT-TIH to succeed and bear fruits in the long term to the overall impact on the nation's development this hub needs to put significant efforts on the three following aspects:

1. Human resource development
2. Technical infrastructure

3. Knowledge generation and incubation

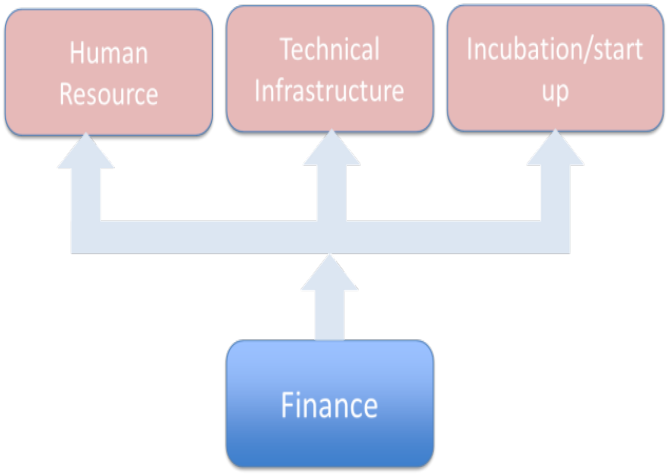

Figure 4.2: The three pillars of the development at the TIH: Human Resources, Technical infrastructure and innovation/incubation/Start-ups

Significant efforts need to be put in the development of human resources at various levels supported with all the necessary technical infrastructure that is needed towards translation of developed/invented technologies for making successful products. These products are expected to create a direct impact in trade and industry, thus indirectly leading to an impact among the people for a better quality of life. However, growth and development of the above mentioned activities need generous financial resources combined with an effective resource management.

4.1 HUMAN RESOURCE DEVELOPMENT

Human resource development is the most important and complex task that needs special attention in the execution of the program at the hub. Human resource development, as we understand, needs nurturing at all levels starting from School, high school, undergraduate, Postgraduate and Research (PhD) levels to inculcate the desire to innovate and to nurture the drive for invention and innovation. At the school and high school level, it is an issue at a much broader scale which is beyond the scope of this mandate of the hub. However, through the outreach programs of the various institutions involved in this TIH, school students would be motivated to pursue careers in technology development and scientific research/innovation. At the other remaining levels, it is important that, through this hub adequate training programs and infrastructure be provided. As shown in Figure 4.3, There are four major training/support blocks where different kinds of support mechanism is deemed to be necessary. Listed below are some details about these.

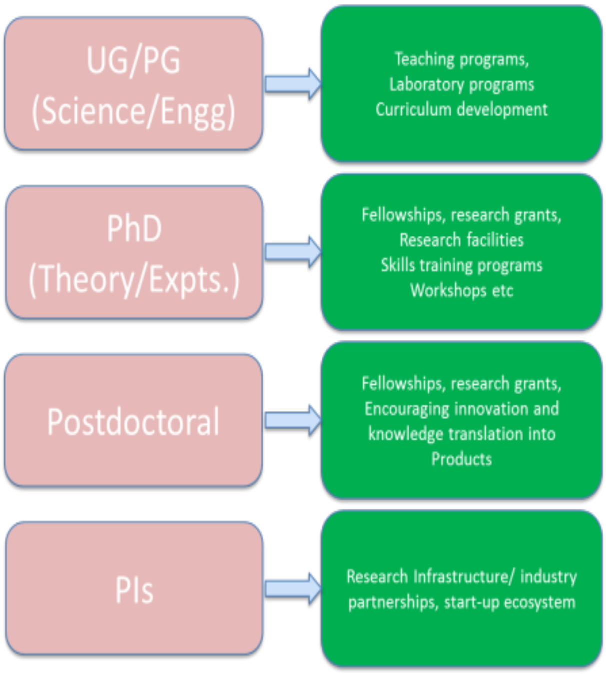

Figure 4.3: Different levels of Human resource development for nurturing skills and inculcating the spirit of innovation and technology translation

4.1.1 Undergraduate and Postgraduate level: This is a crucial stage in the career of young researchers when they make choices about their future research careers. These young minds are highly energetic and flexible towards their future scientific endeavors and the choices of career options. It is important that at this stage a significant fraction of the students are motivated and encouraged to pursue their careers either in experimental or theoretical Quantum technologies. However, it is desired that a majority of the students drift towards experimental and translational research while some of them are encouraged to pursue theoretical research and development. In order to be successful at achieving these goals, a variety of directions need be implemented. eg. Teaching programs will be strengthened at various spokes so that state-of-the-art undergraduate experiments are setup in their teaching laboratories. The curriculum will to be tailored in such a manner that, focus should be put on fundamentals of all those areas of physics which are important in finally training the students in the foundational aspects of optics, atomic physics, solid state physics, instrumentation science, experimental techniques in addition to the their ongoing programs in the core foundational subjects in physics (Electromagnetic theory, Quantum and Classical physics, Statistical physics). In addition, there will be a provision for having short term training programs and workshops in targeted areas.

4.1.2 Research Level (PhD) Doing a PhD in experimental research is a challenging and time consuming process. The average age of students during which they join a PhD program is a prime time in their lifetime. In the presence of competing job opportunities and the financial need of youngsters at this age, it becomes challenging to attract students towards PhD programs. Thus, it is very important that special efforts are taken to attract this pool of human resources towards the career of quantum technologies research. For young people getting attracted into a research process keeping the motivation levels high throughout the duration of the PhD is extremely important. There are a few proposed methodologies that can work to address the above issues.

4.1.3 Research Fellowships:

There will be special provision for targeted JRF hiring from Physics and Engineering streams to have a dual benefits a) meeting the goals of the hub and b) generate a pool of talented researchers in quantum technologies. In order to attract a large pool of students for pursuing PhD, a generous funding scheme equivalent to the Prime Ministers Research Fellowship will be initiated. Students will be provided with generous contingency grants towards the expenses of basic needs of research.

4.1.4 National and International travel funds: Research fellows should be provided with sufficient funding for National travel (2 times per year) and once every two years for international travel for collaborations, student exchange and participation in conferences. There should be at the maximum two short international visits and one extended visit for a period of a maximum of 3 months. This would allow for getting international training and research experience.

4.1.5 Skills training workshops: At the national level, it is aimed to have topical training workshops to be held at various spoke institutes, where these researchers can get advanced classroom as well as hands on skills-training from national experts. Special provision for at least 10 such workshops for 50 participants each over a period of five (5) years is envisaged in this program.

4.1.6 Postdoctoral Fellows (PDFs) Researchers at this level are important and invaluable assets to the overall success of the program. These researchers normally work at a layer below a principal investigator (PI). PDFs are people who will be directly involved in the day to day functioning of the research labs including direct supervision of PhD students and project assistants. Post-doctoral work is normally an additional step in the careers of researchers which develops the abilities of a person to conduct independent research and teachers and move onto potentially becoming full-edged researchers, teachers and entrepreneurs. A suitable mechanism will be developed for nurturing this pool of human resource and provide potential job opportunities. A majority of this pool will be encouraged to pursue industrial research, development and incubating small startup companies. The key to success of the program, i.e. of the people involved, highly relies on attracting, retaining, training and providing job and career opportunities. Special financial provisions will be made to attract, retain, train and setting up of startup ecosystem in this program. It is proposed that special fellowships (1.5 times of the existing PDF salaries), Special research grants for pursuing independent problems in the attached labs, special grants for incubating startups etc. will be incorporated. It is projected that at least 50 such PDFs be supported through under this TIH.

4.1.7 Investigators level

Identifying talented collaborators, attracting and retaining new investigators, research scientists, junior project leaders, and faculty at the hub and spoke institutes will be the main agenda of the program. Thrust should be on seeking young post-doctoral fellows from national and international level to augment and strengthen the human resource pool in the research areas of the program. To achieve these goals of the program, following will be implemented:

1. Identify specific project directions in line with the aims and objectives of the hub and call for proposals in those areas
2. Extreme due diligence in evaluating proposals
3. Generous funding to achieve those goals of the program
4. Have a provision for generous national and international travel

4.1.8 Technical and administrative posts

The success of the HUB depends crucially on having a critical mass of technical and administrative staff.

1. Technical staff: This staff will comprise of Engineers and technicians who will form the backbone of development and translation activities
2. Administrative staff: This staff is important for managing finances, technical seminars and workshops, handling procurement processes, handling staff management etc.

4.2 TECHNICAL INFRASTRUCTURE

Technical infrastructure is the again a crucial requirement for the success of the program. In order to execute the various research/development projects in the area of Quantum technology, state-of-the-art facilities are an essential feature. Most of the equipment for setting up the facilities for design, construction, testing and validation are niche equipment which are manufactured by a select few developers and manufacturers from around the world. The nature of equipment can be classified into following broad categories:

a. Project specific dedicated equipment
b. Locally shared equipment
c. Common shared facilities

a. **Project specific dedicated equipment:** Many projects that will be run under this program will be dedicated towards achieving a specific objective with a specific physical system i.e. building a quantum clock with Sr or Yb., likewise with many other projects. In this scenario the requirement of equipment for the projects are very specific and these equipment cannot be shared with other experiments. Some of this equipment, although they may be of general use, they are fixed to the experiment and specifically programmed to certain kind of task. Hence, there will be a need of many such equipment that will be dedicated.
b. **Locally shared equipment:** In a given physical location of the execution of research activities a number of different class of projects from different verticals will be executed. For e.g. at the HUB, there will be activities from the three verticals viz. Quantum Computation and metrology, Quantum Metrology and Quantum materials & devices. All these activities will certainly need common infrastructure for e.g. characterization, micro and nano-fabrication, mechanical engineering, electronics engineering and software development. These will need setting up of common facilities.

c. **Common shared facilities:** In addition to the locally shared facilities there will some facilities like mechanical engineering, electronics engineering and software development that will be setup at the HUB which will serve the entire TIH and its associated spokes and even others if resources are available.

4.3 INCUBATION AND STARTUP

4.3.1 Incubation

One of the main goals of NM-ICPS is job creation and development of indigenous products and services under the broad umbrella of Interdisciplinary cyber physics systems. The Quantum technology focus of this Hub will be to drive inventions, innovation and nurturing start-ups to make marketable products. These products will be used by various government and non-government stake holders.

The main focus of the activities driven by the hub will be to innovate and develop technologies that use the subtleties of quantum mechanics and its inherent features like entanglement and superposition. These features of quantum mechanics will be used to develop platforms for quantum computing, quantum information processing, secure communications, development of novel materials and devices. In addition, plenty of classical devices and software will also be given emphasis due to their enabling nature for quantum technologies. In calling for proposals and in designing specific projects, the key question that would be addressed is about innovation. Innovation would be the driver for exceling in overall quality of life and meeting the national goals of economic and technical superiority and making the country self-reliant and fulfilling the mission of 'Atma-Nirbhar Bharat'.

4.3.2 Startup ecosystem development

As part of the innovation hub, the concepts that have been proven in the lab will be taken to the next level in the final of commercialization. For achieving this, it is imperative that an ecosystem is developed at the hub from the very beginning of its incorporation. This would need the following key elements collaborating with the researchers:

a. Mentors
b. Small and medium scale industries
c. Large industrial organizations
d. Advisors
e. Investors

People from various industries from the vicinity of Pune and across the country will be pooled in from the beginning to start establishing an ecosystem. This would be done by carrying out frequent workshops and brainstorming sessions through industry consortia like the CII, Maharatta chamber of commerce, NCL innovation hub and local heavy industries and SMEs.

4.3.3 Industry collaborations

From the beginning of all activities, every effort would be made to involve industrial partners. However, since quantum technologies as an area, has just started germinating around the world, and in particular in the local context, there are hardly any industries that have focused efforts going on developing devices and systems that harness the power of quantum physics. In such a scenario, a strategy will be formulated wherein industry partners will be sought for initially classical technologies that will enable quantum technologies. Such technology areas would be identified and partnerships would be established for transfer of technology and commercialization. For the most advanced projects when they start showing positive outcomes, using the startup ecosystem, several industries would be pursued to partner and commercialize the technologies.

4.3.4 Placement of generated manpower

There will be plenty of highly skilled and trained manpower in the form of PhDs, post graduates and senior researchers will be generated during the course of execution of the objectives of the hub. In addition to that several industrial collaborations and partnerships would be established during the course. A solid startup ecosystem and innovation culture would also be established during the course. In such a scenario, the manpower that would be generated, would be of great value for industries. There would also be several startups that would actually be entering into a manufacturing and commercialization phase which would need immense trained and skilled manpower in the area of quantum technology.

4.3.5 National collaborations

Apart from the various spoke institutes that would be involved in this innovation hub, there will be many other institutes who are already working on adjacent technologies. We envisage that several of the PIs from these institutes, will be directly or indirectly collaborating with the PIs from the Hub. There are many PIs from other quantum initiatives who are currently working on programs similar to the ones that will be carried out in this hub. We will have frequent collaborative meetings in the form of workshops and conferences that will bring all these PIs together and share the knowledge and exchange ideas for their mutual benefit.

Indicative list of possible collaborating Institutes and Spokes

Sr. no.	Institute
1	IISER, Mohali
2	IIT-Madras, Chennai
3	IIT, Roorkee
4	IIT, Guwahati
5	IIT, Delhi
6	IIT, Mumbai
7	IIT, Tirupati
8	IISER, Tirupati
9	IISc, Bengaluru
10	Bennett University
11	IUCAA, Pune
12	IIT Goa
13	IISER Bhopal
14	SN Bose NCBS, Kolkata
15	IIT Kanpur
16	NISER, Bhubaneshwar
17	HRI, Prayagraj
18	JNCASR, Bengaluru
19	IIT, Patna

20	IISER, Thiruvananthapuram
21	IISER, Kolkata
22	IIT, Jodhpur
23	PRL, Ahmedabad
24	IMSc, Chennai
25	JIIT, Noida
26	IISER, Behrampur
27	IIT Ropar
28	Bangalore University, Bengaluru
29	GGSI University, New Delhi
30	IIT, Kharagpur
31	University of Calcutta, Kolkata
32	NIT, Patna
33	SINP, Kolkata

Indicative list of potential national collaborators including *(This list is only indicative and TIH grants will be released based upon a competitive bidding process as per the Governing Board's recommendations)***:**

	Name of Team Member	Area of Expertise	Roles / Responsibilities
1	Souradeep Tarun IISER Pune	Cosmology, Gravitational waves Physics and Astronomy (LIGO-India)	Theme A
2	Umakant Rapol IISER Pune	Ultra cold atoms, Ion trapping, Interaction of Plasmons and atoms	Themes A,B
3	Sunil Nair IISER Pune	Strongly correlated electron systems, Spin-Caloritronics	Theme C

4	T S Mahesh IISER Pune	NMR spectroscopy, quantum information, optimal control and artificial intelligence	Theme A
5	G V Pavan Kumar IISER Pune	Nanophotonics, Soft-matter physics and Light Scattering	Theme B
6	Rejish Nath IISER Pune	Quantum Optics, Atom Optics, Condensed Matter Physics	Theme A
7	M S Santhanam IISER Pune	Quantum Chaos and Nonlinear Dynamics, Quantum information, Complex networks	Theme A
8	Surjeet Singh IISER Pune	Magnetism and superconductivity, single-crystal growth	Theme C
9	Mukul Kabir IISER Pune	Electronic structure theory, 2D Materials, strongly correlated system, Magnetism, Superconductivity,	Theme C
10	Ashna Bajpai IISER Pune	Experimental Condensed Matter Physics, Nanomagnets & Spintronics, Carbon nanotubes, 2D-Material	Theme C
11	Atikur Rahman IISER Pune	Quantum transport in nanoelectronic devices, applications of quasi-1D and 2D materials	Theme C
12	Bijay Kumar Agarwalla IISER Pune	Charge and energy transport, Fluctuation relations, Quantum thermodynamics, Engineered light-matter quantum systems, Multidimensional spectroscopy	Theme A
13	G J Sreejith IISER Pune	Theoretical condensed matter physics, computational methods, strongly correlated systems	Themes A, C
14	Subhadeep IUCAA Pune	Atomic Clocks, Quantum Communication	Theme B
15	Vasant Natarajan,	Laser cooling, precision measurements	Theme A, B

	IISc		
16	R. Vijay Raghavan	Superconducting qubits	Theme A
17	Phani Kumar Peddibhotla IISER Bhopal	Scanning probe microscopy, Quantum sensing, Nanomechanics, Optics, Nitrogen-vacancy centers in diamond	Theme A
18	Rama Koteswara Rao Kamineni Bennett University, Noida	Nitrogen-Vacancy centers in diamond, Nuclear Magnetic Resonance	Theme A
19	Tanusri Saha Dasgupta SNBNCBS, Kolkata	Theoretical and computational condensed matter, Density functional theory, Strongly correlated systems	Theme C
20	Aftab Alam IIT Bombay	Topological materials, materials modeling	Theme C
21	Bhaskaran Muralidharan IIT Bombay	Quantum transport, topological materials, Non-equilibrium Green's function formalism	Theme C
22	Varadharajan Srinivasan IISER Bhopal	Functional materials, excited state dynamics, time-dependent DFT	Theme C
23	Yasir Iqbal IIT Madras	Theoretical condensed matter, quantum many-body theory, frustrated magnets, spin-liquids	Theme C
24	Subhradip Ghosh IIT Guwahati	Density functional theory, materials modeling	Theme C
25	Sudipta Datta IISER Tirupati	Magnetic materials, condensed matter theory, energy materials	Theme C
26	Dhanvir Singh Rana IISER Bhopal	Ultrafast Spectroscopy of Quantum Materials	Theme C
27	Surajit Saha	Raman Scattering, Multiferroics, 2D materials	Theme C

	IISER Bhopal		
28	Ashwin Tulapurkar IIT Bombay	Spintronics, Spin Transfer Torque, spin current, spin-Hall effect,	Theme C
29	P. K. Muduli IIT Delhi	Spin Transfer Torque, THz emitters, Weyl metals	Theme C
30	Avinash Mahajan IIT Bombay	Nuclear Magnetic Resonance, Quantum Materials	Theme C
31	Satyajit Banerjee IIT Kanpur	Magnetooptics, Quantum materials, 2D systems	Theme C
32	Santosh Kumar IIT Goa	Solid-state Quantum Photonics, Strain, Localized Exciton, Single-photon Emitters, Nanoelectronics	Theme C
33	Arijit Sharma, IIT Tirupati	Experimental Atomic Physics and Quantum Optics, Precision Laser Spectroscopy, Laser Cooling, Ion Trapping, Cavity QED, Cold and Ultracold Atoms, Ions and Molecules, Fundamental Physics Searches and Metrology, Quantum communication and sensing, Low temperature plasma spectroscopy	Theme A,B
34	Bodhaditya Santra, IIT Delhi	Cold atom Quantum technology	Theme A, B
35	Dr. Ajay Wasan, IIT Roorkee	Atomic spectroscopy, precision spectroscopy (experimental), quantum optics, EIT (theoretical and experimental), quantum computation and quantum information, (experimental and theoretical)	Theme A,B
36	Brajesh Kumar Kaushik IIT Roorkee	Optoelectronics, Spintronics	Theme C

37	Ashok Mohapatra NISER, Bhubaneshwar	Quantum optics, Quantum metrology, Physics with Rydberg atoms	Theme A, B
38	Kanhaiya Pandey IIT Guwahati	Quantum Computation, Rydberg atoms, Quantum Metrology	Theme A, B
39	Yogesh Singh IISER Mohali	Quantum materials	Theme C
40	Goutam Sheet IISER Mohali	Quantum materials	Theme C
41	Kanishka Biswas JNCASR	Quantum Materials	Theme C
42	Arvind IISER, Mohali	Quantum Information	Theme A
42	Ujjwal Sen HRI Prayagraj	Quantum Information	Theme A
43	Aditi Sen De HRI Prayagraj	Quantum Information	Theme A
44	Arun Kumar Pati HRI Prayagraj	Quantum Information	Theme A
45	Vibhor Singh IISC, Bengaluru	Superconducting Qubits, Quantum Materials	Theme A,C
46	Apoorva Patel IISC, Bengaluru	Quantum Information and computing	Theme A, B, C
47	Suddhasatwa Mohapatra, IIT Mumbai	Quantum Information and computing	Theme A, C
48	Sai Vinjanampati IIT Mumbai	Quantum Information	Theme A, B

49	Kasturi Saha IIT Mumbai	NV centers based quantum information and metrology	Theme A, B
50	Madhu Thalakulam IISER Thiruvananthapuram	Spin qubits, quantum dots based Quantum information and metrology	Theme A, C
51	Anil Shaji IISER Thiruvananthapuram	Quantum information	Theme A, B
52	Arul Lakshminarayan IIT Madras	Quantum information	Theme A, B
53	Prabha Mandayam IIT Madras	Quantum information	Theme A, B
54	Kavita Dorai IISER Mohali	NMR based Quantum information	Theme A, B, C
55	C M Chandrasekhar IMSc, Chennai	Quantum information	Theme A
56	Arindam Ghosh, IISc Bengaluru	Quantum Materials	Theme C
57	P. S. Anilkumar, IISc Bengaluru	Quantum Materials	Theme C
58	Anjan Barman, SNBNCBS, Kolkata	Spintronics	Theme C
59	Ajay Thakur, IIT Patna	Quantum Materials	Theme C
60	Karthik Senapati, NISER Bhubaneshwar	Spintronics	Theme C
61	Saptarshi Choudhury, RRI Bengaluru	Quantum Information and metrology	Theme A, B
62	Urbasi Sinha, RRI Bengaluru	Quantum Information and communications	Theme A, B
63	Sadiq Rangawala, RRI Bengaluru	Quantum Information and metrology	Theme A, B

64	Sankar De, SINP, Kolkata	Quantum Information	Theme A, B
65	Sanjeev Kumar, IISER Mohali	Quantum materials	Theme C
66	Brajesh Kumar Koushik. IIT Roorkee	Spintronics	Theme C
67	Sachin Srivastava	Photonics	Theme B

Theme-wise*: Theme A - Quantum Computing and quantum metrology, Theme B - Quantum communications, Theme C - Quantum materials and devices

4.3.6 Industry and PSU collaborations

The HUB will actively seek partnerships and collaborations in all the three themes. There is a large group of private and sector companies and Government organizations that would be benefited by the developmental activities of the HUB. Each of the companies listed below are involved in various sectors of national importance for e.g. Defence, Aerospace, Space science, solutions for healthcare and finance, metrology and high performance computing and information technology. The Hub would collaborate with these organizations and provide technology and steer them into commercializing quantum technologies and deploy them into practical applications. There would be joint workshops, conferences and technical sessions to keep them abreast with quantum technologies.

Sl. No	Organization	Relevant Theme
1	Tata Advanced Systems	Theme A, C
2	Larson and Toubro Defense	Theme A, C
3	Kalyani Group	Theme A, C
4	Mahindra and Mahindra	Theme A, C
5	Reliance Defense	Theme A, C
6	ONGC	Theme A, C
7	Indian Space Research Organization (ISRO)	Theme A,B, C
8	Defense Research and Development Organization	Theme A,B, C

9	IBM, India	Theme A,B
10	Tata Consultancy Services	Theme A,B
11	CDAC	Theme A,B
12	Siemens, India	Theme A,B, C
13	Amazon Web Services	Theme A,B
14	Defense Institute of Advanced Technologies	Theme A,B, C
15	CSIR, NPL	Theme A,B, C

Theme-wise*: Theme A - Quantum Computing and quantum metrology, Theme B - Quantum communications, Theme C - Quantum materials and devices

4.3.7 International collaborations

The hub currently has many international collaborations from institutes in Europe, Japan and other parts of the world. We will have periodic meetings in the form of conferences, meetings, brainstorming and workshops to exchange ideas. This hub will initiate memorandum of understanding with many other quantum initiatives in different countries such as the UK Quantum technology initiative, Russian Quantum Initiative, Japanese Quantum Initiative etc. We envisage setting up virtual centers for collaboration and knowledge exchange between the hub and several foreign universities and institutes. Table below shows the list of current collaborations.

Following is the list of international collaborations (theme wise*):

International Partners			
1	Jens Mueller Goethe University, Frankfurt	Novel quantum phases in correlated electron systems	Theme C
2	Kai Bongs, University of Birmingham, United Kingdom	Quantum Metrology and sensors with Atoms, Atom interferometers, Leads one of the four Quantum technology Hubs in UK	Theme A
3	Biplab Sanyal	Condensed matter theory, functional materials, magnetization dynamics	Theme C

	Uppsala University, Sweden		
4	Abhay Shukla IMPMC, Sorbonne University	Electronic properties, vibrational states and applications of 2D materials and devices	Theme C
5	Ruediger Klingeler Heidelberg University	Multiferroics, Quantum materials, Quantum magnets & quantum nanomagnets	Theme C
6	Masashi Tokunaga ISSP, University of Tokyo	Multiferroics, magnetocaloric effects, high magnetic fields	Theme C
7	Dieter Suter TU Dortmund, Germany	High resolution laser spectroscopy, Nuclear Magnetic Resonance, Electron Spin Resonance	Theme A
8	Giacomo Prando, University of Pavia, Italy	Muon Spin Spectroscopy in 2D materials	Theme C
9	Yeshpal Singh, University of Birmingham	Quantum Metrology, Quantum sensors, Atom interferometers	Theme A
10	Giles Hammond, University of Glasgow	Quantum Metrology, Gravitational wave detectors	Theme A
11	Sara Diegoli	Photonics, Quantum Metrology	Theme A, B

Theme-wise*: Theme A -- Quantum Computing and quantum metrology, Theme B -- Quantum communications, Theme C -- Quantum materials and devices

CHAPTER 5

5 BENEFICIARIES

Quantum technologies are expected bring about revolutionary changes in many areas that can potentially affect the way we carry on our lives. This can range from exponential speedup in computing for certain classes of problem, designing novel materials, drug discovery, to many types of optimization problems, metrology and possibly several others. Since many of these domains of application can potentially have significant commercial impact, it is expected that apart from research laboratories and academic institutions, many large and small industries would also be major stakeholders in pursuit of this technology. For instance, many industries across the board can benefit from novel materials with desired properties and financial institutions can benefit from faster computing.

At present, quantum technology infrastructure such as quantum computers with limited capabilities are available for solving a niche set of problems. Already, several companies such as Google, IBM, Microsoft, D-Wave, and Rigetti provide cloud based quantum computing services. However, as quantum computing infrastructure becomes widely available, many problems could be ported in to quantum computers to obtain solutions.

Similarly, quantum materials is an area that is continuously under active development, whereas quantum metrology is fast emerging as an area that might have direct impact in terms of products in the markets for niche purposes. For instance, in the last one decade, quantum dot bio-imaging products have hit the market and are now routinely used. Quantum key distribution protocols have also reached markets with at least a few companies such as Toshiba and ID-Quantique providing quantum key based services to the clients.

Anticipating much of these developments, the list of potential beneficiaries is enumerated below:

5.1 LIST OF TARGET BENEFICIARIES

- BARC and other units of the Department of Atomic Energy
- Defense Research and Development Organization
- Department of Space
- Micro, Small and Medium Industries
- Many public sector industries such as ONGC, IOC, BP, SAIL etc.
- Large private sector industries in areas of automobiles, steel, petro-products and other consumer goods.

- Centre for Development of Advanced Computing
- Digital India Program
- Start-up India Program
- Skill India Program
- Universities and Higher Education institutions
- National research laboratories of CSIR, DST and other apex bodies.
- Technology based Start-ups
- Fund Managers and Stock markets
- Finance and banking sector
- Many ministries of the Government of India
- Indian Railways and IRCTC
- Training and R&D programs of mega science initiatives such as LIGO-India

The TIH will attempt to understand the needs of at least some of these industries and will be in a position to target its prototypes and products for immediate deployment in field trials or in the markets.

The TIH would also provide consultation services to help modify the industrial or standard set of processes that can benefit from deployment of quantum technology based solutions. This is expected to enhance the pool of industries who might not, at first sight, be aware of or take interest in the emerging quantum technologies. This would be a continuous effort and will target industries that will benefit from quantum technologies.

CHAPTER 6

6 LEGAL FRAMEWORK

Over a short period of time the usage of Quantum technologies is going to spread across various horizontals in the country. That will eventually give rise to a number of issues related to usage of quantum technologies and related legal aspects, especially concerning the intellectual property, standards and classification of technical data from strategic and domestic civil use. Therefore, there is need to think about the security classification and regulatory framework around quantum technology, as it will increasingly impact on the operations of the stake holders, lives of individuals and underpin customer service, innovation, quality and business operations.

Strengths of Legal Framework

(1) India has established legal systems which has basic framework to address IPR, Patents and Copyrights.

(2) Cyber Laws also are framed and/or operating at very broader level.

(3) Required legal expertise, international exposure and the legal ramifications are well understood by the industry, government and other stakeholders.

Weakness of Legal Framework

(1) There is no active participation of India in standards development, particularly, ISO, ITU, W3C, DIN, SAC and IEEE-SA.

(2) India should have dedicated institutes/organizations, a group of experts who are continuously keeping track of process and participation. One such group will be established at QT-TIH to look into these matters

(3) Bureau of Indian Standards is the nodal agency for standards, there should be a core group within BIS to look into aspects related to Quantum technology.

CHAPTER 7

7 ENVIRONMENTAL IMPACT

QT-TIH will be involved in generating knowledge through experimental, theoretical and computational research similar to any reputed academic research laboratory. The hub will utilize existing immovable infrastructure established at IISER Pune where building infrastructure is available. Land acquisitions and population displacements are not involved. All the spokes that will be implementing the program will be at their respective existing academic and research institutions where building infrastructure already exists.

1) Environmental clearances are not involved as it is based on green technologies
2) Forestry clearances are not required as there is no clearance of forest land or acquisitions are involved
3) Wildlife clearances are not required as the project is being implemented within the existing IISER campus and there is no direct or indirect impact on wildlife.
4) Use and disposal of chemicals associated with some of the themes in this area would be based on the standard operating procedures in the respective research institutions, in accordance with local governmental guidelines.

CHAPTER 8

8 TECHNOLOGY

The major quantum technology verticals that the Hub is concentrate on in developing the crucial technology components for futuristic as well as current quantum technologies are as follows:

1. Quantum Information and metrology
2. Quantum Communications
3. Quantum materials

The specifics of the technical approaches are as follows:

Quantum Information and metrology

Quantum computing, information processing, sensing and metrology will be the subparts under this vertical. Focus would be on building an > 10 qubit ion trap based quantum computing device which will be scaled to larger number of qubits, Transmons based Superconducting qubits and small quantum processors, 50 qubit based spin register based on nuclear spins, Nitrogen vacancy defect-center based qubit registers, and all the necessary aspects of theoretical understanding of these systems. The goal of this vertical would be to deliver an integrated device which can also be made available on the cloud for access to multiple users across the country in addition to continuous development of the device for practical quantum information processing and for metrology.

Construction and realization of a 10 qubit ion trap quantum computer

At the TIH, we would like to initially focus on building a 10 qubit ion trap quantum processor in a 3-D linear trap. In parallel, we would explore architectures for surface traps wherein the design will be optimized to reduce the heating of the phonon modes while achieving a tradeoff between with the number of achievable logical qubits.

By building an ion trap at the HUB, we want to study these issues and realize qubit manipulation protocols that circumvent decoherence and scaling issues. These will also serve as a standard test-bed consisting of a multi-qubit system for development of software layers and Software Development Kits (SDKs) for control quantum cores.

After the initial demonstration of ion strings in a classical four electrode trap, the team would start working on developing surface traps for trapping larger ion strings and having architecture of segmented electrodes for shuttling ions. The problems related to heating and loss of coherence times will be addressed by optimizing the geometry.

Ion Crystals in a classic 3-d trap can also be used for a special class of quantum computers called as the quantum simulators which are constructed for a specific purpose. In particular, they are useful for analyzing the properties of novel quantum matter and also for quantum simulations of molecular structure. The key ingredient in quantum simulators would be to engineer inter-particle interaction that is mediated by phonons. The desired inter-particle interactions can be attained via proper manipulations of phonon modes in the ion crystal.

Demonstration of a 50 qubit spin-register based on Nuclear Magnetic Resonance

An NMR quantum register will be realized by qubit connections through spin-spin interactions, specifically either dipolar coupling or J-coupling or both. Local control allows the construction of universal gates and implementing a general quantum circuit. In liquid state NMR quantum registers, the local control is achieved via either isotopic shifts or chemical shifts of Larmor frequencies. In solid-state NMR, one can realize quantum correlated clusters of 100+ qubits, but they allow only global control. Nevertheless, such systems find important applications developing decoherence-suppression schemes, quantum control schemes, many-body quantum simulators, and a variety of such quantum information tasks. Symmetry-restricted spin-systems with certain special topology offer a middle-ground allow partially controllable quantum registers with 30+ qubits, while retaining all the advantages of high-resolution liquid-state NMR.

The main goal of in this hub would be to realize quantum registers with 50+ qubits using special-topology spin systems and utilize it to develop advanced methodologies for quantum control and decoherence suppression. The outcome of this development should be relevant not only to NMR but also to other quantum technologies based on quantum control.

Superconducting Qubits

While several quantum technologies (e.g. trapped ions, spins in silicon, diamond NV centers etc.) are being pursued, superconducting quantum circuits operating at mill kelvin temperatures have emerged as a leading candidate for a scalable quantum processor architecture. This architecture is also the most pursued approach in the world with major efforts in the United States, Europe, China, and Japan, including significant industrial efforts by companies like IBM, Google and Intel to name a few. The early work on observing quantum effects in superconducting circuits took place in the 80s in the US and Europe but the first evidence of quantum coherence was obtained by a Japanese group in 1999. Since the year 2000, due to significant improvements in circuit design, choice of materials, careful fabrication procedures, microwave engineering, and robust filtering and shielding, the coherence times of superconducting qubits have improved by nearly 6 orders of magnitude More than 10 types of new qubits were invented by just choosing the right combination of the basic building blocks: inductors, capacitors and Josephson which points to the remarkable flexibility in constructing qubits using superconducting circuits. Out of all the qubit types, the transmon qubit and its variants (3D transmon, Xmon, Gatemon) have become the qubit design of choice to implement larger scale quantum processors. Further, significant improvement in the measurement of qubits was achieved with the development of ultra-low noise Josephson parametric amplifiers

There are two main areas of focus in the international arena as of today. The first is to demonstrate quantum error correction (QEC) where a single logical qubit composed of several physical qubits can be actively protected by repeated measurements and feedback. This is a crucial step before large scale robust processors can be implemented. The other area of focus is to demonstrate "quantum supremacy" where a quantum algorithm running on a quantum processor will outperform any classical computation for that problem. In 2019, the Google team demonstrated quantum supremacy in a 53-qubit superconducting quantum processor.

1. Broadband or multi-band quantum limited amplifiers: These are some of the quietest microwave frequency amplifiers which are crucial for any superconducting quantum processor as they help in achieving high fidelity measurements. This makes them an invaluable tool for quantum error correction projects as well. These can be quickly commercialized and the engineering needed is not that complicated.

Making them broadband and high dynamic range will require some initial research and can be soon turned into a marketable technology with a wide market both in industry and academia.

2. Cryogenic microwave components and assemblies: These include components like absorptive filters, reflective filters, attenuators, directional couplers, power splitters, multiplexers and circulators. Optimizing performance at cryogenic temperatures will require correct choice of materials to ensure both electrical and mechanical performance. Another approach is to combine these components to develop signal processing assemblies that can operate as plug and play systems in cryogenic environments

3. Control and measurement electronics: Quantum computing technology requires a significant amount of cutting edge high speed electronics for control and measurement. These can be developed by putting together of the shelf modules to develop custom assemblies and later even designed at the chip level for custom applications. Development of FPGA IP cores can be a major activity which can add significant value to these modules.

4. Small quantum processor chips: Small scale superconducting quantum processors (5 to 10 qubits) could have a target market in academia and industry involved in quantum computing research. The challenge will be to produce a robust design which will perform to specs in many different kind of experimental setups. The clients are those who are interested in using the processors for their own research and testing but don't want to invest in nanofabrication facilities and chip design.

5. Small-scale quantum processors in the cloud: This can be developed as a service where small-scale quantum processors operating at host location can be accessed by clients via the cloud. Development of a robust superconducting architecture and control circuitry would be needed to achieve this. It is possible to do this in a phased manner with 5, 10 and 20 qubits in 3, 4 and 5 years respectively with industry partners playing a significant role in terms of expertise and funds

VACANCY CENTERS BASED METROLOGY

We propose to use wide-field fluorescence microscopy platform for the development of novel quantum sensing and metrology applications with NV centers. In a wide-field quantum microscopy platform, optical pumping, fluorescence measurements and microwave manipulation are carried out on ensembles of NV centers to further enhance the sensitivity of the magnetometer by a factor of $\sqrt{N}$, where N is the number of NV defect spins.

QUANTUM METROLOGY USING TRAPPED ION OPTICAL CLOCK

Here we propose to develop a quantum-link between IUCAA and IISER-Pune (separated by about 5 km, distance between IUCAA and IISER Pune) which will act like a test bed before it is scaled up in pan-India and intercontinental distances.

A clock laser for Yb^+ ion clock is currently being built at IUCAA from the DST-QUEST program. The two clocks (Yb^+ and Sr) from IUCAA and IISER will be connected through this fiber link. Ultracold Sr atoms in 1-D optical lattices at the HUB and an electrodynamically trapped Yb+ ion at IUCAA (Spoke institute) will be used for developing ultrahigh precision optical quantum clocks. These clocks will be phase synchronized and communication applications. All the necessary auxiliary systems will be developed and commercialized. These auxiliary systems would be ultrastable laser systems, frequency synthesizers, control systems etc. This technology will be augmented with the atomic systems for development of portable atomic clocks.

INSTRUMENTATION DEVELOPMENT FOR QUANTUM COMPUTING, METROLOGY AND QUANTUM COMMUNICATIONS

Laser systems and control systems, data acquisitions systems, ultrahigh precision mechanical engineering are essential and integral to the quantum engineering and quantum devices. A variety of lasers operating at different wavelengths (780, 399, 461, 397, 689, 698, 813, 866, 854, 729, 467, 935, 1064 nms etc.) the requirement for linewidths from these lasers ranges from few 10's of KHz for cooling atoms to less than 1 Hz in case of lasers that are needed to interrogate atomic clock transitions and qubit manipulation. In addition, in most of these cases the laser frequencies are stabilized to an absolute reference such as an atomic transition frequency. In some cases where the absolute reference frequency is not available in real time for monitoring the frequency, ultra-stable and high/ultra-high finesse optical resonators are used for frequency stabilization of these lasers. Most often, the laser sources are semiconductor lasers, while in some cases optical fiber based active media is used to generate the desired wavelengths or some nonlinear optical media. The absence of the availability of either semiconductor or fiber lasers at the desired wavelength, available lasers at half the frequency are doubled in frequency using frequency doublers or through optical sum frequency generation. The complexity involved in the construction of all of these lasers is mostly related to stable mechanical design, electronic current and temperature stabilization and active feedback with specifically engineered control loops. The hub will carry out activities of design and construction of mechanical systems, electronic systems, analysis and fabrication of components going into these laser systems.

For many experiments, often parameters like optical power, optical signals, magnetic and electric fields, and many other parameters need to be sensed and controlled. Most of these systems need to be imported often. In this program, many such requirements will be identified and the engineering would be done.

Quantum computing, quantum metrology and quantum simulations are carried out on a physical quantum layer that is made of material qubits (for e.g. atoms, ions, superconducting circuits, quantum dots, Vacancy centers etc.) constituting the 'quantum chip' or Q-Chip. Q-Chip needs to be integrated with classical computers for translation of user problems in computation, measurement and simulations in a layered approach. All the layers sitting above the Q-Chip are classical layers that operate on traditional classical electronic principles by way of microcontrollers, digital signal processors, math processors and classical memory to store the classical operations and to translate quantum information to classical information. The immediate layer above the Q-Chip is usually an architecture comprising of high speed RF and Microwave electronics, engineered optical pulses sequence for initialization and readout of the states of QUBITS in the Q-Chip. Photon detection and counting systems are also at the also form a front end for the Q-Chip in some cases

User problems are translated into quantum circuit problems incorporating all the error correction overheads and finally a pulse sequence is generated for driving the qubits during initialization, gate operations and for reading the final states of the qubits through standard tomographic techniques.

The control of Q-Chip heavily relies on high speed real time implementation of digital pulse sequences operating on Microwaves, RF, Optical pulses and for controlling

The following systems will be built for the above applications:

a. Data acquisition and control systems
b. Field programmable Gate Array (FPGA) based re-programmable real time systems
c. Counting electronics
d. Optical component
e. Electronic detection systems
f. Optomechanical components

As part of training activities, many subsystems such as interferometers, spectroscopy systems, and small modular training benches will be designed and standard kits would be developed for disseminating across various colleges and universities.

This instrumentation will also have a direct bearing on some of the Mega science projects in India such as LIGO India.

QUANTUM COMMUNICATIONS

This theme involves the creation of India's first optical fiber-based quantum-link -- a phase-stabilized optical-link fiber (quantum channel) between IUCAA and IISER-Pune. This will be the first of its kind in India and will show a step forward towards quantum-communication. It also involves research into chiral and hybrid atomic-photonic and mesophotonics systems that have the potential of interfacing optoelectronic devices with communication devices.

QUANTUM NETWORKS FOR SECURE COMMUNICATION

Quantum networks rely on a deterministic generation of single photons at a high production rate. The main applications for a high-quality single-photon source are quantum key distribution, quantum repeaters and quantum information science. Currently quantum random number generators are in high demand in the market due to potential applications in data security, secure key generation for financial transactions and defense communication, etc. The hub proposes (IIT Tirupati one of the spoke institutes) the development of a cold atom based hybrid quantum network that enables communication between two diverse quantum nodes using single photons communicating across the telecom band. Is to develop two single photon quantum nodes based on two diverse cold atom physics based platforms - one of them utilizing a non-linear interaction cold atoms to generate single photons while a trapped ion based cavity qed platform produces single photons on demand. At the HUB, with the ongoing program at IISER Pune through the QUEST funded program (Q110), single atoms would be strongly coupled to plasmonic nanostructures to generate and transport photons coherently from one quantum system to the other. This would enable coupling of distant atomic qubits and build quantum repeaters.

QUANTUM MATERIALS

Activities in this vertical would span across the areas of Spintronics, Quantum Optoelectronics, Multifunctional Quantum Materials, Emergent phenomena in Quantum Materials, as well as the development of instrumentation and technology support systems to enable these activities. The goal of this vertical would be to provide a platform for translational research in quantum materials, and to enable the design and development of device prototypes across different technology readiness levels. In collaboration with academic and industrial partners, this vertical would aim to contribute to research in frontier areas in quantum materials, as well as be a technology incubator which feeds the fledging Indian capacity in the areas of sensors, actuators, and other multifunctional devices.

SPINTRONIC DEVICES

Spintronics pertains to the manipulation of the spin degree of freedom in conjunction with the electronic charge in solid state devices, and remains the most viable alternative to the existing electronic platforms. The TIH would aim to contribute significantly to the national capacities in this area by fostering an inter-institutional and translational research approach aimed at delivering (nano)spintronic device prototypes ranging from spin-diodes, spin-transistors, spin transfer-torque devices as well as rudimentary spin-logic gates. A key focus would be the development of devices based on the coupling of Spin, charge and thermal or optical degrees of freedom, which could find applications in areas ranging from defense and aerospace to biomedical instruments.

QUANTUM OPTOELECTRONIC DEVICES

Quantum optoelectronic devices which source, detect, and control light is expected to play a key role in futuristic and potentially disruptive quantum technology platforms. Activities at the TIH would be focused on the development of designer semiconductor nanostructures which aim to translate these phenomena into functional device prototypes. A key aspect here would be the use of strain-engineering to tailor photo-generation as well as the dynamics of charge carriers in these systems. These strain-engineered systems are expected to be functional over a number of spectral ranges, and material systems would be optimized for specific applications like solid state lighting, displays and infrared thermometry.

MULTIFUNCTIONAL QUANTUM MATERIALS

New quantum materials, where strong coupling between the electronic, magnetic, orbital, and lattice degrees of freedom give rise to interesting multifunctional properties, promise to form the bedrock for the new and improved devices. Notable amongst these that would be incorporated into the goals of this TIH are : (i) new and improved thermoelectrics for thermal scavenging solutions, with an effective figure of merit in excess of 1 at room temperatures, (ii) rare-earth free room temperature permanent magnets with an energy product of at least 7 mega-Gauss-Oersted, and (iii) New electrocaloric material systems for solid state cooling applications with prototypical devices which provide a temperature drop of 5-10 degrees at or around room temperatures.

EMERGENT PHENOMENA IN QUANTUM MATERIALS

The area of emergent phenomena is quantum materials is one that is of great fundamental interest and is the cynosure of a host of research programs across the world. Though they constitute the lower rungs of the technology readiness landscape, they are still extremely important owing to their exceptional promise, as well as the increasingly short laboratory-to-market turnaround times. The TIH would aim to raise the Indian footprint in this niche area of research, and to ensure that local capacities – both in the form of facilities, as well as trained manpower- are at hand to make good use of future advancements in this area. The focus of the TIH in the context of emergent phenomena would include (i) the role of topology in the context of electronic materials, (ii) identifying spin-liquid systems with utility in the area of quantum computing, and (iii) the phenomena of topological superconductivity with an eye on identifying the elusive Majorana excitation.

INSTRUMENTATION AND TECHNOLOGY SUPPORT

Research in the area of quantum materials is driven by continuing progress in new and improved material systems as well as increasingly sophistical instrumentation tools. In spite of the reasonably large Indian presence in this and allied areas, indigenous development of such facilities is lacking and a significant part of such equipment continues to be imported. The TIH would aim to address this shortcoming and pursue hardware development in the form of sophisticated test and measurement systems, turnkey sample preparation and device fabrication facilities, sophisticated sample characterization apparatus, and specialized computational modules. Efforts would be made to commercialize these products for the Indian and global market.

CHAPTER 9

9 MANAGEMENT

The mission of the proposed Hub is a successful delivery of products and services to key stakeholders ranging from government organizations to general public. Although the very nature of quantum technology is extremely niche with the technology being in its nascent stages, it promises to be revolutionize the quality of life through outcomes that of are direct benefits to Healthcare, security, food security, transportation etc. While the basic essentials of these technology exist within the country it is extremely important to channelize this knowledge into giving successful technical outputs. In order to achieve these goals, the management of the hub is very crucial to ensure that there is due diligence, sufficient freedom, careful monitoring and providing vision to all the participants while taking all the key stake holders into confidence.

The proposed management structure of the hub is shown in Figure 8.1

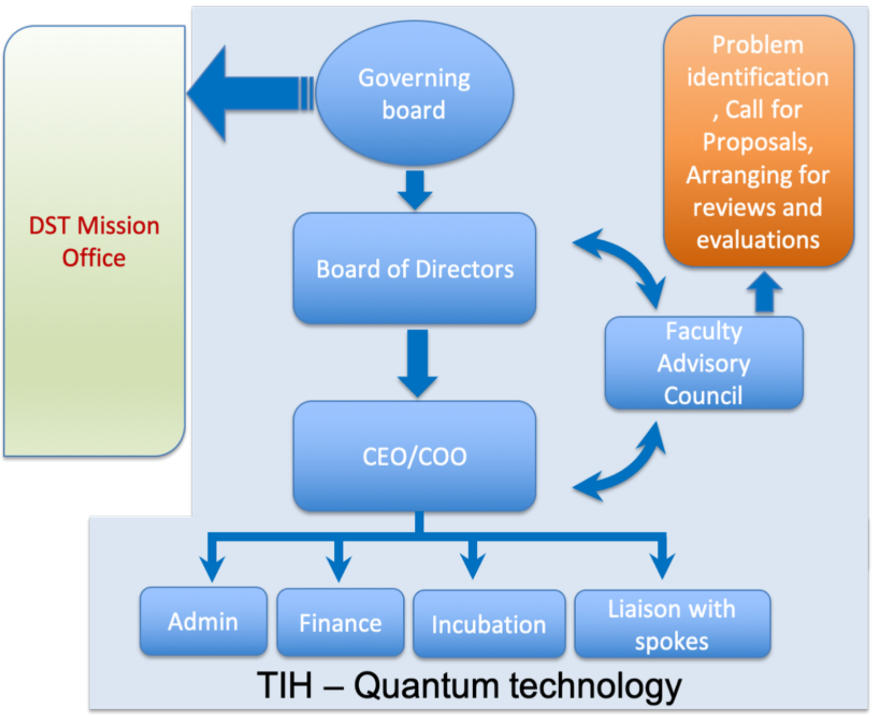

Fig. 8.1: QT-TIH Management structure

The hub will be incorporated as a Section-8 (not-for-profit) company regulated by Indian companies act (2013 and amendments thereof). The main purpose of this company in the current context would be to promote Scientific Research and Education. While any proceeds would be used back to promote the objectives of the company without any dividend to anybody. While the initial funding for carrying out the activities of this hub (Company) will be done by the Mission, the long term sustenance of the hub will be carved out through various means such as establishment of Startups, licensing of technologies, providing services in terms of pedagogical training, and seeking industry partnerships in research and development programs.

The proposed management structure has four following important layers.

1. The Governing Board
2. The Board of Directors
3. The office of the Chief Operating Officer
4. The Faculty Advisory Council
5. The administration and support staff

9.1 GOVERNING BOARD

The Governing Board (GB) will be the apex decision making body of the QT-TIH. It will be empowered to take key decisions for the successful implementation of the objectives of the hub in a seamless manner. The GB will be comprised of:

a. The Chairman (Director IISER-Pune)
b. Academic representative (>2)
c. Industry representative (>3)
d. Mission Director (or representative), Mission Office DST
e. Chief Executive Officer

The GB will be the apex decision making for the QT-TIH after due ratification from the Mission Governing Board (MGB) of the NM-ICPS at DST. It would be empowered to take key decisions within the ambit of the allowances of the MGB.

1. The Governing Board shall be the apex body for overall supervision, control, direction and needed mid-course correction in the implementation of QT-TIH.
2. In consultations with the board of directors and the faculty advisory council the GB will set specific targets and deliverables for IIQT.
3. Whenever necessary, the GB will seek advice from external members for review and monitoring
4. The GB will be empowered to appoint Standing Committees and sub-committees, like Expert Committee, Scientific Advisory Committee, from time to time, and assign them tasks for efficient implementation of goals of the hub.

9.2 BOARD OF DIRECTORS

1. The Board Of Directors (BOD) will supervise and monitor the activities of the hub
2. BOD will take advice from the Faculty Advisory Council (FAC) on the technical matters related to research and development
3. The BOD in discussions with the CEO and the FAC will prepare executive action for matters related to operations of the spokes and prepare detailed reports through the CEO to be presented to the GB

9.3 FACULTY ADVISORY COUNCIL

1. The Faculty Advisory Council (FAC) will be the first responders on any scientific matters related to the hub
2. On the directives of the GB, the FAC will draw up scientific plans for the hub
3. The FAC will get the progress reports from the various spokes through the CEO and do preliminary screening and present the reports for review to the CEO to be further taken up by the GB
4. The FAC will liaise with the Spokes through the CEO in organizing technical and scientific meetings with the spokes and the PIs of the activities at the Hub
5. The FAC will monitor international trends in the areas of quantum technology and give timely advice to the BOD which will finally be taken up by the GB for any necessary policy decisions

9.4 CHIEF OPERATING OFFICER

1. The Chief operating officer (CEO) will manage the day to day operations of the hub
2. The CEO will liaise with the FAC, BOD and FAC for all policy related matters and scientific matters
3. The CEO will oversee the administration, Finance and communications with the spokes
4. The CEO will prepare reports, recommendations and other matters to be presented in the GB

CHAPTER 10

10 FINANCE

The funding for the hub will come from the public funds from Department of Science and technology through the National Mission on Interdisciplinary Cyber Physical Systems (NM-ICPS).

10.1 COST ESTIMATES

The cost estimates are arrived at through deliberation of all the collaborators, scientists, administrators from various collaborating institutes, the administration of IISER-Pune and from recent experiences of all the collaborators.

10.2 HUB COST ANALYSIS (AMOUNT IN CRORES)

Sr. No	Main objectives	Budget heads	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	Total
1	Technology development	Recurring	2	3.5	2.00	1.25	1.25	10
		Non-Recurring	0	72	28.10	3	3	106.1
		Sub total	2	75.5	30.1	4.25	4.25	116.1
2	HRD and skill development	Recurring	3	3	3.00	3	3	15
		Non-Recurring	0	1	0.50	0.5	0.5	2.5
		Sub total	3	4	3.5	3.5	3.5	17.5
3	Innovation, Entrepreneurship , and Start-up ecosystem	Recurring	1	3	1.75	1	1	7.75
		Non-Recurring	0	7	5.00	2.7	2.7	17.4
		Sub total	1	10	6.75	3.7	3.7	25.15
4	International Collaborations	Recurring	0.25	0.5	0.50	0.25	0.25	1.75
		Non-Recurring	0	0	0.00	0	0	0
		Sub total	0.25	0.5	0.5	0.25	0.25	1.75
5	Hub management unit	Recurring	1.5	1.5	1.50	1.5	1.5	7.5
		Non-Recurring	0	0.5	0.50	0.5	0.5	2
		Sub total	1.5	2	2	2	2	9.5
	Total	Recurring	7.75	11.5	8.75	7	7	42
		Non-Recurring	0	80.5	34.1	6.7	6.7	128
		Grand Total	**7.75**	**92**	**42.85**	**13.7**	**13.7**	**170**

CHAPTER 11

11 TIME FRAME

The outcome of the hub will crucially depend upon well charted and detailed roadmap to all the identified problems. The various milestones are identified based on their Technology Readiness Levels (TRL). The roadmaps of various activities are presented below

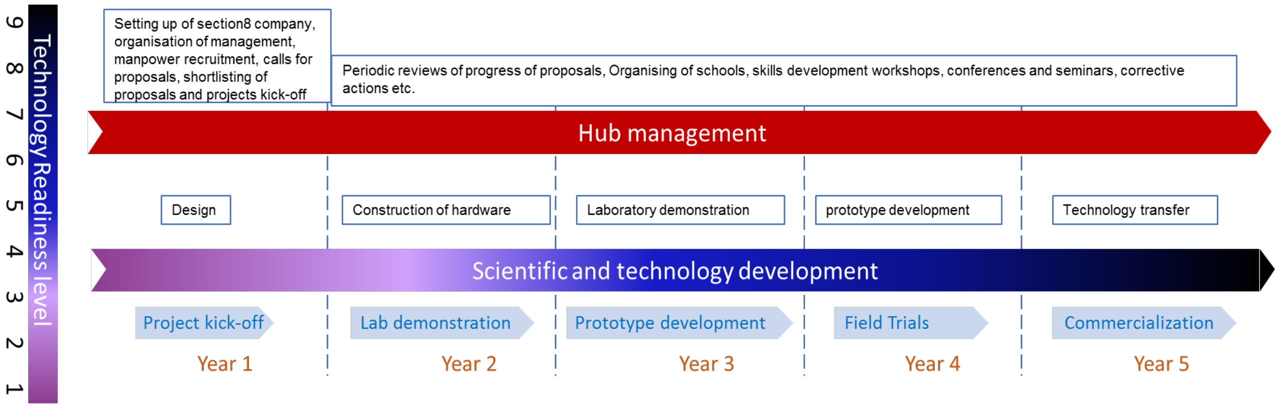

Figure 11.1: Roadmap for the QT-TIH

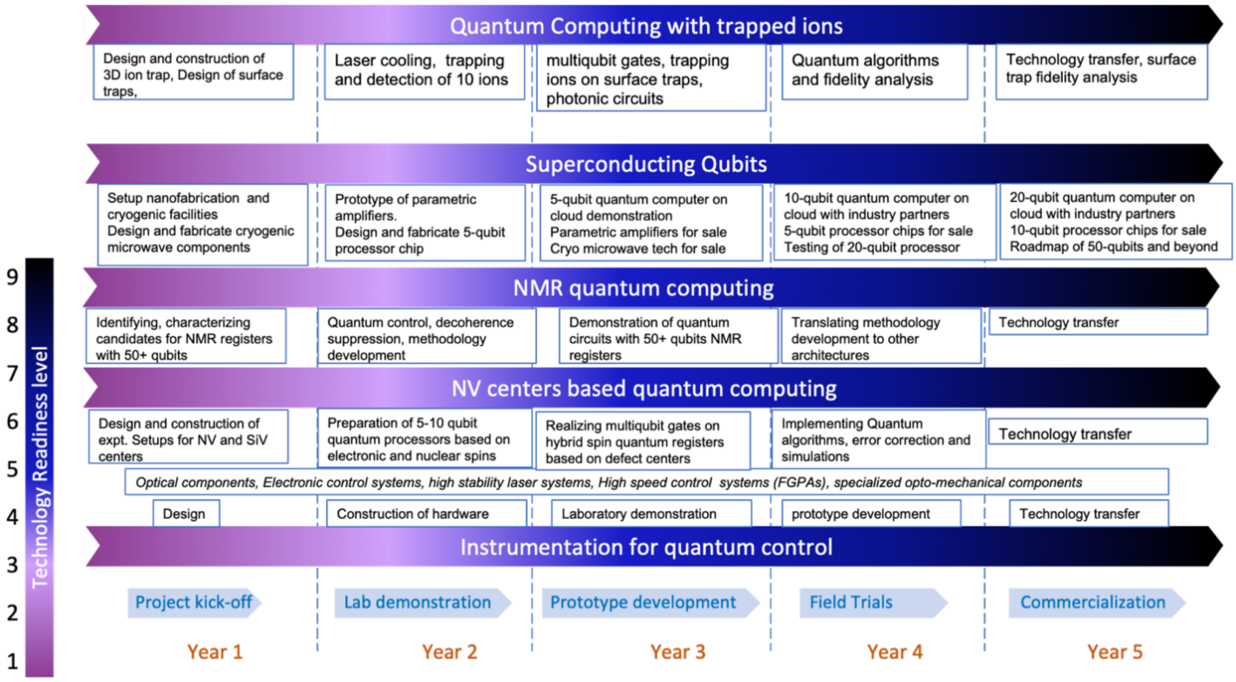

Figure 11.2: Roadmap for the Quantum computing

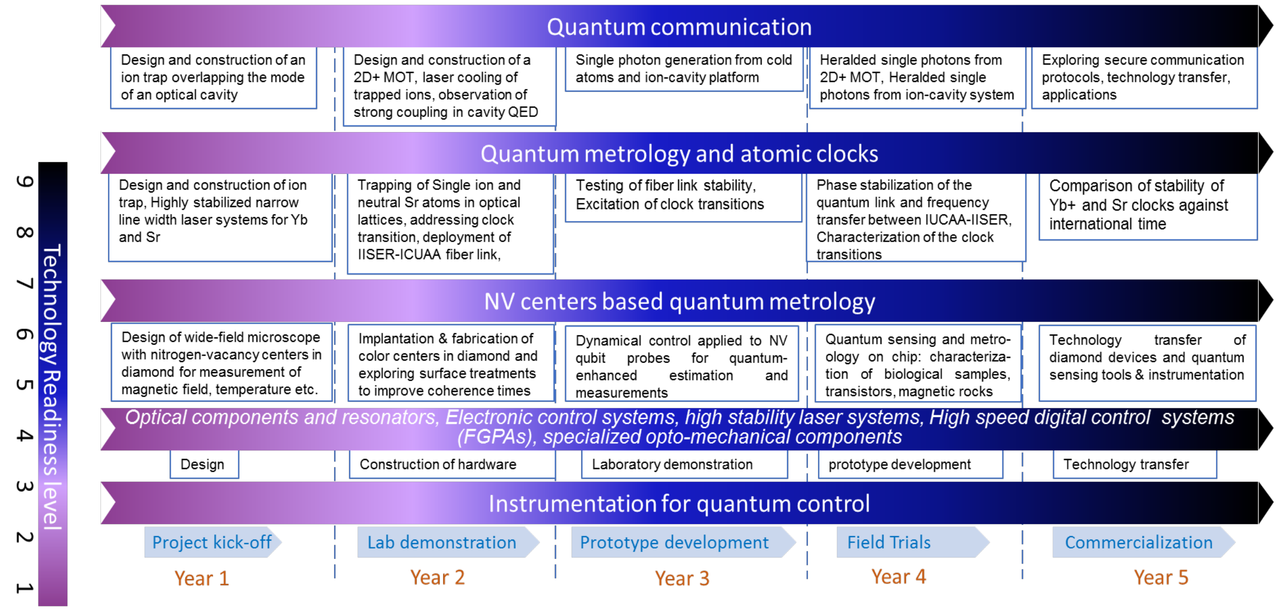

Figure 11.3: Roadmap -- Quantum Communication

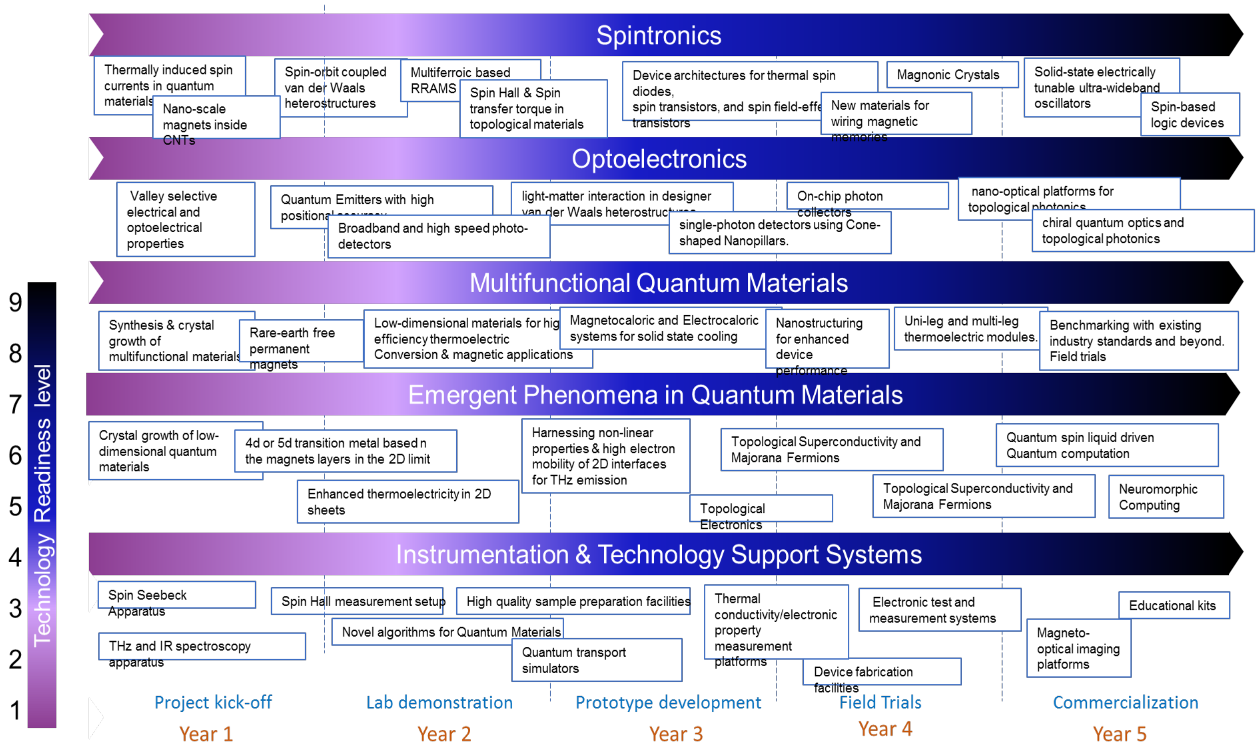

Figure 11.4: Roadmap -- Quantum Materials and Devices

CHAPTER 12

12 COST BENEFIT ANALYSIS

The use of traditional Cost-Benefit-Analysis methods to evaluate Research and Development activities is fraught with problems. This is primarily due to the fact that the results of research programs are often intangible – especially in shorter time frames. This is especially true of an area like quantum technology. For instance, many of the benefits arising from this kind of research maybe realized many years down the line, and sometimes, even in areas far away from where it was initially envisaged. It is due to this reason that there are no proven and universally accepted approaches to perform cost-benefit-analysis in futuristic research programs.

However, now significant amount of public money is being spent on such activities, with the express aim of accelerating the technological development of the country, coupled with the economic and social development of its citizens. Hence it is imperative that a reasonable measure of the costs accrued and benefits delivered to the society at large is analyzed. In the implementation of this TIH, we plan to accomplish this by broadly dividing the spectrum of activities into three major areas:

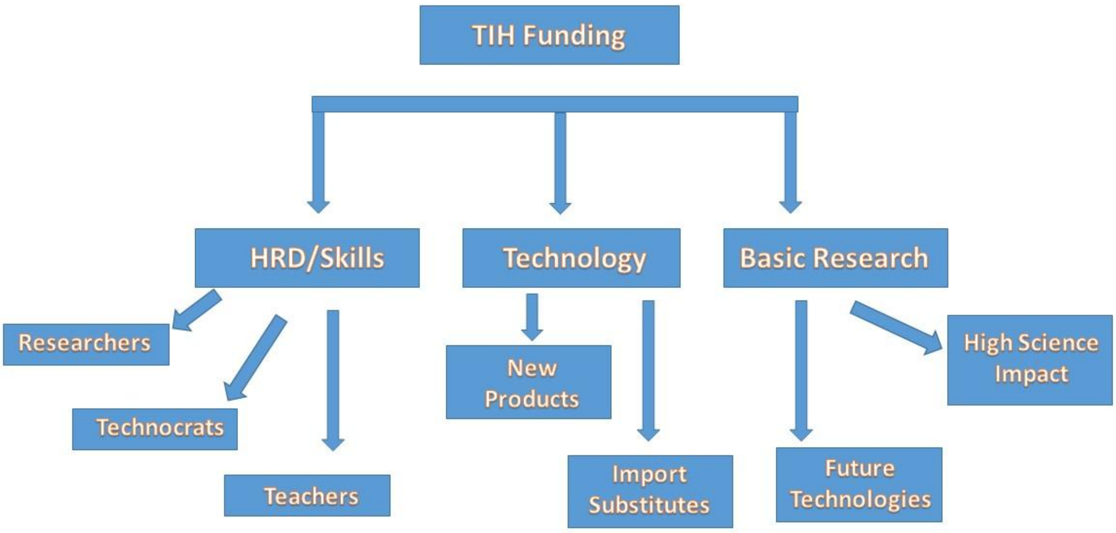

Figure 12.1: Flow of benefits of TIH funding

1) HRD and Skill Development: All activities under this head can be broadly quantified. For instance, the number of research students, and industry partners who benefit from the existence of this hub would be continuously monitored, and would be benchmarked against the goals of the National Mission on Interdisciplinary Cyber Physical Systems.

2) Product Development and Translational Research: A major focus of the TIH would be to perform translational Research, with the aim of developing critical technology for the Indian Industry and other

Government Organizations. This can be quantified to some extent, by monitoring the number of end products which can be made available by the TIH, as well as a number of start-ups etc. However it has to be borne in mind that in some cases, the gestation periods for product development and deployment can be large. Marketability, and other economic variables would also be beyond the control of the TIH.

3) Fundamental Research in Quantum Technologies: A certain fraction of the resources of the TIH would be dedicated to perform research in topical problems. The areas and projects would be carefully chosen in line with the goals of the national mission, and these progress in these projects would be continuously monitored. The benefits here would be in form of Knowledge (and not necessarily, Product) outputs, and also in increasing the Indian footprint in this niche area of research.

CHAPTER 13

13 RISK ANALYSIS

Research and Development is by definition a high risk-high reward activity. This is especially so in areas such as quantum technologies, which are very futuristic in nature. The risks are manifold, and vary from failure to deliver in select scientific and technological goals, to the uncertain economic viability of the developed products and processes. That being said, the risk of not investing in such areas is even higher, since it puts the country on a permanent technological disadvantage. This would make us completely dependent of externally sourced products and technology, which is inconsistent with the aim of making India self-reliant and a significant scientific and technological power. It has to be borne in mind that investment in science and technology is an investment for our future, and imperative if we have to meet our national security and economic goals.

A few steps can be taken to partially mitigate the risks associated with the implementation of such research programs. This includes a period and systematic review of the various sub-units of the TIH, and a continuous feedback to the involved researchers regarding the progress expected from them in reasonable time frames. The management of the TIH, comprising of the Governing Board, Board of Directors, and the Faculty Advisory Council would be empowered to carry out such review activities, so that risks involved with the sub-optimal implementation of individual research projects can be minimized.

CHAPTER 14

14 OUTCOMES

14.1 TARGETS

S No	Target Area	Targets					
		1stYr	2ndYr	3rdYr	4thYr	5thYr	Total
1	**Technology Development**						
(a)	No of Technologies (IP, Licensing, Patents etc.)	2	3	5	10	12	32
(b)	Technology Products	1	2	7	8	12	30
(c)	Publications, IPR and other Intellectual activities	5	10	20	25	40	100
(d)	Increase in CPS Research Base	10	20	25	25	30	110

S No	Target Area	Targets					
		1stYr	2ndYr	3rdYr	4thYr	5thYr	Total
2.	**Entrepreneurship Development**						
(a)	Technology Business Incubator (TBI)			1			1
(b)	Start-ups & Spin-off companies	2	5	10	15	20	52
(c)	GCC - Grand Challenges & Competitions		1				1
(d)	Promotion and Acceleration of Young and Aspiring technology entrepreneurs (PRAYAS)			1			1

(e)	CPS-Entrepreneur In Residence (EIR)	3	7	7	7	7	31
(f)	Dedicated Innovation Accelerator (DIAL)				1		1
(g)	CPS-Seed Support System (CPS- SSS)			1			1
(h)	Job Creation	500	1400	2000	4000	5300	13200

S No	**Target Area**	**Targets**					
		1st Yr	**2nd Yr**	**3rd Yr**	**4th Yr**	**5th Yr**	**Total**
3.	**Human Resource Development**						
(a)	Graduate Fellowships	60	70	70	70	70	340
(b)	Post Graduate Fellowships	15	15	10	10	12	62
(c)	Doctoral Fellowships	5	5	5	5	5	25
(d)	Faculty Fellowships	1	2	1	1	1	6
(e)	Chair Professors	2	1	1	1	1	6
(f)	Skill Development	30	100	100	200	200	630

S No	**Target Area**	**Targets**					
		1st Yr	**2nd Yr**	**3rd Yr**	**4th Yr**	**5th Yr**	**Total**
4.	**International Collaboration**						
(a)	International Collaboration		1				1

14.2 SCIENCE AND TECHNOLOGY OUTCOMES

14.2.1 VERTICAL 1: QUANTUM INFORMATION AND METROLOGY

Sl. No	Description	Unit of Measurement	Baseline (present)	Target
A	Ion Trap Quantum Computer	Number of qubits	N/A	20
A1	Development of ultra-stable laser systems	linewidth and drift (**Hz and < 1 MHz/Hr**)	N/A	<10, < 1
A3	Demonstration of laser-cooled ion crystals	No of Ions in the Coulomb Crystal	N/A	> 20
A4	Design and construction of site-resolved addressing and readout optics (Electro-optic deflection and/or electrical transport and/or SLM based addressing, and/or photonic waveguides)	Functionality, diffraction limited addressability of neighboring Ion	None	Yes
A5	Single qubit rotation and C-NOT gate demonstration on a two ion chain	Fidelity	N/A	> 98%
A6	Realization of a 20 qubit ion trap quantum computer	Fidelity	NA	>99 %
A7	Demonstration of multi-qubit entanglement and quantum algorithms	Fidelity	NA	>99 %
A8	Quantum simulations with few qubits	Fidelity	NA	>95
B	Single photon generators from cold atom and ion-based platforms	Efficiency (**%**), Bandwidth (**nm or MHz**), Brightness (**kHz** or **MHz**), Entanglement Fidelity (**%**)	NA	> 25, ≤ 10, > 50, > 95%
B1	Design and construction of a linear Paul trap overlapping high finesse cavity	Finesse (**Number**)	NA	>60000

B2	Design and construction of a 2D+ MOT	Density (**Atoms/cc**), number	NA	$\geq 10^7$, $\geq 10^9$
B3	Development of laser systems for trapping and cooling Rb (Rubidium) atoms and 40Ca+ (Calcium) ions	Linewidth (**kHz**), Drift rate (**MHz/Hour**)	NA	< 10, < 1
B4	Generation and characterization of single photons from 2D+ MOT	Efficiency (**%**), Bandwidth (**nm**), Brightness (**kHz**), Entanglement Fidelity (**%**)	NA	> 25, ≤ 10, > 50, > 95%
B5	Generation and characterization of single photons from ion-cavity system	Efficiency (**%**), Bandwidth (**nm**), Brightness (**kHz**), Entanglement Fidelity (**%**)	NA	> 85, ≤ 10, > 50, > 95%
B6	Demonstration of heralded single photon generation from 2D+ MOT	Efficiency (**%**), Bandwidth (**nm**), Brightness (**kHz**), Entanglement Fidelity (**%**)	NA	> 25, ≤ 10, > 50, > 95%
	Demonstration of heralded single photon generation from ion-cavity system	Efficiency (**%**), Bandwidth (**nm**), Brightness (**kHz**), Entanglement Fidelity (**%**)	NA	> 85, ≤ 10, > 50, > 95%
C	**Instrumentation for Atoms and ions based quantum technologies**			
C1	Design and construction of an atomic based microwave (MW) detector			
C4	Development and design of optics and electronics			

	for line-width reduction of laser systems			
C5	Detection system for low light (noise free)			
C6	Embedded systems hardware and software development for interfacing with Quantum core			
C7	Development of tunable solid state laser systems for cooling lasers (103 nm, 420 nm, 780 nm, 397 nm, 370 nm, 866 nm, 854 nm) for the Laser cooling of Ca+ ions	Unlocked Frequency stability, line width and power: **MHz/Hr, KHz, mW**	NA	<100, <100, >10
C8	Development of ultra-stable cavity for 729 nm qubit transition for driving the Ca+ clock transition	Unlocked Frequency stability, line width and power: **MHz/Hr, KHz, mW**	Import substitute	<100, <100, >100
C9	Development of Indigenous ultranarrow linewidth optical cavity for linewidth narrowing of clock and qubit transitions	Frequency stability and linewidth: **MHz/Hr, Hz**	Import substitute	1 , 1000
C10	Development of FPGA based control and acquisition systems	No of digital outputs, pulse widths and speed of pulses: **No, micro seconds, MHz**	Import substitute	>32, <0.2, 1
C11	Development of Indigenous laser systems for trapping Sr atoms (460 nm, 689 nm, 698 nm, 407 nm)	Unlocked Frequency stability, line width and power: **MHz/Hr, KHz, mW**	Import substitute	<100, <100, >10
C12	Development of programmable Frequency synthesizers for driving AOMS, local oscillators	Frequency range: **MHz**	NA	0.001 -- 10000

	for laser frequency shifters, homodyne and heterodyne detection and PLLs			
C13	Development of temperature controllers for laser systems and optical frequency references	Cooling/heating power (**W**) and stability (**mK/Hr**)	NA	100 and 5
C14	Development of time stamping and real-time photon counting and correlator systems	Count rates and timing resolution: **Pulses/s** and **ns**	NA	10^7 and 0.1
C15	Development current controllers for driving laser systems	Current range and Current noise: **mA, micro A**	NA	0-500 mA, 0.1
D	**Development of lasers for Rydberg excitation of Yb atoms**			
D1	Design and construction of frequency doubled laser for 395 nm, 507 nm, 458 nm wavelength	Unlocked Frequency stability, line width and power: **MHz/Hr, KHz, mW**	NA	<100, <100, >100
D2	Design and construction of 497 nm and 423 nm diode laser systems	Unlocked Frequency stability, line width and power: **MHz/Hr, KHz, mW**	NA	<100, <100, >10
D3	Design and construction of 1140 nm and 948 nm Tapered amplifier laser systems	Unlocked Frequency stability, line width and power: **MHz/Hr, KHz, mW**	NA	<100, <100, >10
D4	Development and design of optics and electronics for line-width reduction of laser systems	NA	None	Yes
D5	Development and design of optics and electronics	NA	None	Yes

	for phase noise reduction of laser systems			
D6	Observation of Rydberg blockade	NA	None	Yes
D7	Design and construction of an Yb atom based microwave (MW) detector	NA	None	Yes
E	**Nuclear Magnetic Resonance (NMR) Quantum Computing**			
E1	Realization of Large NMR Quantum registers	Qubits (control type)	12 (universal) 37 (restricted)	15(universal) 50+(restricted)
E2	Development of control methods for high-fidelity quantum gates	Fidelity (with/without noise)	0.999 (ideal) < 0.8 (with noise)	0.999 (ideal) > 0.95 (with noise)
E3	Methodologies for decoherence suppression and their demonstration in NMR spin-systems	Coherence time of 10+ qubit entanglement	Approx. 10 ms	> 100 ms
E4	Adapting machine learning techniques for applications in quantum information	Experimental demonstration	Measurement	Measurement and Control
E5	Experimental investigations into emerging fields such as quantum batteries, quantum thermal machines, and quantum chaos	Qubits	1-3 qubits	10+ qubits
F	**Superconducting quantum circuits**			
	Broadband parametric amplifiers	Bandwidth(MHz)	600	1000
F1		1 dB compression (dBm)	-110	-90
F2	Quantum processor chips	No. of qubits	3	10

F3	Quantum processor on cloud	No. of qubits	NA	20
F4	Cryogenic microwave technology	No. of products	0	8
F5	Control electronics technology	No. of qubits controlled	0	10
G	**Trapped ion-crystal with Rydberg excitations**			
G1	Design scheme to engineer phonon modes to mimic various interparticle interactions	NA	None	Yes, will aim to achieve
G2	Developing models for fast quantum gates	NA	None	Yes, will aim to achieve
G3	Quantum simulators for exotic spin models to study quantum many body phases	NA	None	Yes, will aim to achieve
H	**Designing efficient quantum thermal machines**			
H1	Design and implement tools to investigate finite time and steady-state quantum thermal machines	NA	None	Yes, will aim to achieve
H2	Develop working principles to realize most favorable limits for quantum engine operations via characterizing the power output and associated quantum and thermal fluctuations.	NA	None	Yes, will aim to achieve
H3	Realizing efficient quantum thermal machines in suitable and promising experimental platforms namely in NMR setup, nitrogen-vacancy (NV)	NA	None	Yes, will aim to achieve

	centers in diamond, and cold ion-trap setup			
I	**Algorithms for quantum dynamics and thermodynamics**			
I1	Development of optimal Matrix Product States (MPS) based techniques for open quantum systems in strong coupling limits	NA	None	Yes, will aim to achieve
I2	Building local capabilities for high performance MPS approaches to many body quantum dynamics	NA	None	Yes, will aim to achieve
J	**Quantum machine learning algorithms and applications**			
J1	Development of novel quantum inspired algorithms for commonly encountered problems in a variety of applications	NA	None	Yes, will aim to achieve
J2	Development of prototype for such algorithms	NA	None	Yes, will aim to achieve
J3	Implementation of quantum algorithms in quantum computing systems in IISER Pune or through systems available in the public domain	NA	None	Yes, will aim to achieve
K	**Defect-Center based Registers (NV centers and other defect centers)**			
K1	Quantum Register size	Qubits	1-2 (national) 10 (international)	12 qubits
K2	Implementation of quantum algorithms and	Qubits	2-3 qubits (international)	4-6 qubits

	error correction on NV registers			
K3	NVC sensors with high sensitivity to detect magnetization of electron and nuclear spins of nano-scale volumes	Sensitivity		
K3	Paramagnetic defect centers in silicon carbide based register	Qubits	Coherent control at single spin level	A quantum register of a few qubits
K4	Experimental investigations into emerging fields such as quantum heat engines	Type of heat engines	Two-stroke, Continuous	Four-stroke
K5	Adapting dynamically controlled quantum thermometry techniques for improved quantum Fisher information	Current status	Theoretical proposal	Experimental demonstration
K6	Quantum sensing on a NV-diamond chip	Current status	CMOS-integrated quantum sensing (International)	CMOS-integrated quantum sensing (National)
K7	Magnetic sensing with defect centers in various materials	Material	Diamond (National) Diamond, SiC (International)	Diamond, SiC (National)

14.2.2 VERTICAL 2: QUANTUM COMMUNICATION

Sl. No	Description	Unit of Measurement	Baseline (present)	Target
A	**Creation of optical fiber-based quantum-link between IUCAA and IISER Pune**			
A1	Dissemination of the phase and frequency stabilized optical photons through this quantum channel	stability	NA	10^{-15}@1s
A2	Developing a trapped ion-based quantum clock at IUCAA	fractional accuracy	NA	10^{-18}

A3	Indigenous development of instruments such as optical sub-systems, low-noise control electronics (digital as well as analog hardware) as required for these experiments	Import substitution	None	Yes
A4	Capability building on various quantum-phenomena based measurements	Capacity building	None	Yes, will aim to achieve
A5	Magneto-optic trapping of Sr Atoms	Temperature, no of atoms	Micro kelvins, number	10, 100000
A6	Transfer of Sr atoms to1-D optical lattice	Transfer Efficiency (%)	None	>50
B	**Chiral and Hybrid Mesophotonics Systems**			
B1	Experimental realization of chiral quantum optical matter such as chiral single photon sources on a microchip that can be readily interfaced with optoelectronic devices	NA	None	Yes, will aim to achieve
B2	Experimental realization of hybrid nano-optical platforms to study topological photonics including orbital angular momentum of light	NA	None	Yes, will aim to achieve

1.

14.2.3 VERTICAL 3: QUANTUM MATERIALS AND DEVICES

Sl. No	Description	Unit of Measurement	Baseline (present)	Target
A	**Spintronic Devices**			
A1	Spin Caloritronic devices based on graphene-like 2D sheets of quantum magnets	Layer Thickness, Lateral device size	NA	2-5 monolayers, 1 μ meter^2
A2	Testing of multilayered ferro-antiferro and multiferroic devices	Switching ratio (r)	NA	$r > 2$

	for use as potential thermal spin switches			
A3	Fabrication of atomically-sharp high-quality 2D interface phases of complex transition metal oxides with different electronic and magnetic structures	Interface roughness		<0.2 nm
A4	Using non-linear properties and high electron mobility of 2D interface phases to create strong sources of THz radiation	Emission frequency **(THz)**	NA	1-2
A5	Developing and fine-tuning device architectures for use as thermal spin diodes, spin transistors, and spin field-effect transistors	Spin-charge Rectification ratio (γ)	NA	$\gamma > 0.1$
A6	Growth and characterization of thin films of Weyl semimetals (WSM) as a potential spintronic quantum material	Material systems in thin film form	NA	Will be achieved
A7	Magnetic Tunnel Junctions, magnetoresistive and spintronic devices based on micro-crystals of CrO2 with ultra-thin surface layer of Cr2O3	Tunneling Magnetoresistance Ratio		>15% at 300K
A8	Broadband Spin torque based nano-oscillators	Emission Frequency		10 GHz to 2 THz
A9	Carbon Nanotube- Transition metal oxide hybrids for spintronic applications	nanotube diameter, length		30-60 nm, 1-20 μ meter
B	**Quantum Optoelectronics**			
B1	Development of nanotextured substrates with precise shape and size	nm	>200	20
B2	Synthesis of large area monolayer 2D material using chemical vapor deposition	um	30	>500
B3	Controlled transfer of the 2D materials on the textured substrates and fabrication of the	NA	None	Yes, will aim to achieve

	nanodevices with the help of lithography and preliminary characterization			
B4	Investigation of valley selective electrical and optoelectrical properties	NA	None	Yes, will aim to achieve
B5	Development of a platform for 2D materials based quantum-emitters	NA	None	Yes, will aim to achieve
C	**Multifunctional Quantum Materials**			
C1	Earth abundant material based permanent magnets	Magnetic Energy Product	None	5 M Gauss-Oe
C2	Potential electrocaloric materials	Magnitude of Electrocaloric Effect	None	0.05- 0.1 K/ kVcm-1
C3	Prototypical solid state EC cooling modules	Temperature drop across module	None	5 – 10 Degrees
C4	New (and nanostructured) thermoelectric materials	Thermoelectric figure of Merit (ZT)	0.4-0.9	> 1.25
C5	Thermoelectric model prototypes	Power Density	None	0.2 W/ cm^2
D	**Emergent phenomena in Quantum materials**			
D1	High-quality single crystals of 2D magnetic materials comprising 3d, 4d and 5d transition metal ions	New material platforms		
D2	Development of exfoliation techniques to obtain bilayer and monolayer samples	layer thickness, lateral size		1-5 monolayers, 1 µm 2
D3	Development of advanced atomistic quantum transport simulator for realistic topological device structures,	No Benchmarking exists	NA	NA
D4	Realization of the quantum spin liquid state to serve as the building blocks of quantum computation.	No Benchmarking exists	NA	NA

D5	Topological superconductivity and Majorana fermions	No Benchmarking exists	NA	NA
E	**Instrumentation and Technology Support Systems**			
E1	Establishment of a high field, ultralow temperature apparatus for spin caloritronic measurements	Temperature, Magnetic fields	National - None	≤ 0.3 K,
E2	Development and commercialization of low temperature measurement systems for measuring the spin-Hall effect.	Base Temperature, Max magnetic field	NA	5 K, 5 kG
E3	Development of a state-of -the-art ac- susceptometry apparatus for the measurement of linear & nonlinear susceptibility of quantum magnets.	Minimum Temperature, Number of measured harmonics, Sensitivity	NA	4.2K, >5, > 10^{-6} emu
E4	Apparatus for the measurement of electronic and thermal properties of ultrathin specimens.	Thermal Conductivity (3 ω), Anomalous Hall, Magnetoresistance, Planar Hall Effect	None	T down to 2K, H > 7 Tesla
E5	Vibrating sample magnetometer for routine characterization of permanent magnet candidates.	Temperature range, Sensitivity, Max field	Import substitute	300 - 800 K, 10^{-4} emu, 30 kG
E6	Temperature dependent Electrocaloric effect apparatus	Temperature range	None	80K to 400K
E7	Development of simultaneous local magnetic field and electric current imaging techniques	Temperature range	None	5K to 325 K
E9	Development of scanning tunneling and atomic force microscopes	Current Sensitivity, Cantilever displacement, nano-actuation precision	Import substitute	1-10 Pico-amps, 0.1-1 nm, 10nm – 10 μ m

2.

CHAPTER 15

15 EVALUATION

The parameters against which the performance of the Technology Innovation Hub at IISER Pune on Quantum Technologies must be evaluated is set out in the tables given below. This process takes into account the level of sustained activities, specific outcomes and benefits accrued directly and indirectly from these activities. Furthermore, evaluation is also mechanism to document the implementation and progress and share with stake-holders. A broad list of indicators have been identified by NM-ICPS and we use them here as the basis for QT-TIH evaluation as well.

15.1 INDICATORS

Indicator	Purpose & Description
Input indicators	Input indicators are quantified and time-bound statements of the resources financed by the Mission, and are usually monitored by routine accounting and management records. They are mainly used by managers closest to implementation, and are consulted frequently (daily or weekly). They are often left out of discussions of project monitoring, though they are part of essential management information. An accounting system is needed to track expenditures and provide data on costs for analysis of the cost effectiveness and efficiency of project processes and the production of outputs.
Process indicators	Process indicators monitor the activities completed during implementation, and are often specified as milestones or completion of sub-contracted tasks, as set out in time-scaled work schedules. One of the best process indicators is often to closely monitor the project's procurement processes. Every output depends on the procurement of goods, works or services and the process has well defined steps that can be used to monitor progress by each package of activities
Output indicators	Output indicators monitor the production of goods and delivery of services by the Mission. They are often evaluated and reported with the use of performance measures based on cost or operational ratios. The indicators for inputs, activities and outputs, and the systems used for data collection, recording and reporting are sometimes collectively referred to as the project physical and financial monitoring system, or management information system (MIS). The core of an M&E system and an essential part of good management practice, it can also be referred to as 'implementation monitoring'.
Outcome indicators	Outcome indicators are specific to a Mission's purpose and the logical chain of cause and effect that underlies its design. Often achievement of outcomes will depend at least in part on the actions of beneficiaries in responding to project outputs, and indicators will depend on data collected from
Impact indicators	Impact indicators usually refer to medium or long-term developmental change to which the project is expected to contribute.

15.2 Research and technology development

Component	Inputs	Outputs	Outcomes
Knowledge generation and discovery	Funds Review	New Knowledge	° Generation of intellectual property ° Papers in high quality peer reviewed journals ° New vistas and application areas ° Development of research skills on non-trivial problems
Development of products / prototypes using existing knowledge base	Funds Review Evaluation	Proofs of Concept and Prototypes	° Generation of intellectual property ° New quantum technology based product or prototype development ° Skilled research staff with product development experience ° Interaction with industry partners
Technology development and delivery in identified sectors	Funds Review Evaluation	New technologies/ products/ solutions	° Development of new technologies suitable for commercialization ° Generation of intellectual property / patents ° Closer interaction between industry & academia ° Prototyping / Translational research ° More quantum technologies based industries
Directed research	Problem definition Funds Evaluation	Solutions to specific problems	° Use of quantum technologies to solve specific problems of interest to industry/government/ministries ° Development of institutionalized capacity in government for research

15.3 R&D Infrastructure development

Component	Inputs	Outputs	Outcomes
Infrastructure for research	Funds Monitoring	Institutional infrastructure	° Creation of requisite infrastructure at the Hub institution, namely, IISER Pune. ° Facilitating and sharing research facility with spokes and other groups.
Common research facility at the spokes	Funds Manageme nt Monitoring	National/Reg ional facilities Institutional infrastructure	° Creation of major research infrastructure at spoke institutions ° Providing research facilities to research fraternity in other universities and institutions

15.4 Innovations and Entrepreneurship development

Component	Inputs	Outputs	Outcomes
Hackathons	Funds Evaluation	Novel ideas/ concepts/ and may be prototypes	° Ideas for start-ups and new ventures ° New quantum technology applications ° More awareness among students
Start-ups based on quantum technologies	Funds Evaluation	New entrepreneurs	° More student led initiatives and start-ups ° More technologies from lab to market ° Employment generation ° Create value of quantum technology products in the market
Quantum Technology based Business Incubator	Funds Evaluation	Technology-based enterprises	° Commercialization of developed technologies ° Kick start quantum tech based business operations in India ° Employment generation ° More visibility for quantum tech companies ° Help industries assimilate the advantages of quantum technologies
Quantum Technology awareness programs	Funds Evaluation	Industry is more aware of quantum technologies	° Seminars/workshops/meetings targeted at industries. ° Increase in the adoption of quantum technologies into products ° More quantum tech trained workers in work force across industries ° Joint discussions with industry to understand their needs

15.5 Human Resources Development

Component	Inputs	Outputs	Outcomes
Scientist cadre with 2 to 5 year positions	Salaries	Work force behind maintain quantum infrastructure	° Provide backbone to continuing quest for quantum technologies ° Manage quantum research infrastructure ° Manage and work with UG/PG and doctoral students

Undergraduate and postgraduate students	Funds Selection Review	More undergrads into QT areas	° Best talent gets into quantum tech related fields ° More innovators and entrepreneurs in these areas ° Talent pool from which research students are enrolled at various institutions
Doctoral students	Funds Review	Trained professionals in specialized areas	Pool of trained professionals available for academic institutions and industry.
Post-Doctoral Fellowships	Funds Review	Advanced training beyond doctoral studies	° Pool of trained professionals available for academic institutions and industry.
Women scientists with career gap	Funds Review	Re-engagement of trained people	° Diversity and gender parity in workforce ° Tapping into dormant potential
Quantum technology awareness in colleges and universities with special emphasis on north eastern states	Funds Monitoring Review	Increase in research activity in quantum technologies	° Wider engagement with academics at colleges and universities ° Training for teachers in quantum technologies. Indirectly improves student pool entering this field ° Expose more students to a research and developments in quantum technologies ° Closer integration of technology based initiatives with the north eastern states
Training schools and teaching laboratories	Funds organizatio n	Trained personnel	° Training for taking up theoretical and experimental research in quantum tech
Summer school-cum-internships for students (with special provision for women students)	Funds	More students exposed to quantum technologies	° Creating opportunities for all students and also achieving gender parity in R&D in the field
Skill development program for Technicians and Engineers	Funds Organizatio n	Produce a Quantum aware skilled workforce	° Training and re-skilling for engineers and technicians in quantum tech areas ° Wider base for R&D in quantum technologies
Conferences with industry participation	Funds Organizatio n	Exchange of ideas and learn about recent development s	° Facilitate seamless exchange of ideas ° Produce new collaborations and industry connects through dissemination of information

CHAPTER 16

16 CONCLUSIONS

The Quantum Technologies - Technology Innovation Hub (QT-TIH) at IISER Pune will represent the first of its kind initiative that will not only nucleate quantum technologies related research under one broad umbrella, but will also take the next step of translating research into products and services. India has a large pool of scientists working in areas related to quantum technologies and the QT-TIH will effectively synergise their research efforts. The activities of the QT-TIH will be operated through a Section 8 company and will be physically established at the Indian Institute of Science Education and Research, Pune. In the long term, QT-TIH effort will go a long way in keeping India ahead of the technology curve in this field.

In summary, QT-TIH will undertake research and development work in quantum technologies with a strong focus on applications. Some of these technologies are expected to hit the markets in the future. The gamut of problems to be addressed are divided under three broad heads, namely, (a) quantum information and metrology, (b) quantum communications, and (c) quantum materials and devices. These problems represent a broad range of issues of current research interest in quantum technologies and its applications. Apart from core technology development and focus on applications for the market, QT-TIH will create a large pool of trained human resources, especially students, who will support and take part these activities in both the academia and industry. As this technology matures and becomes relatively easy to access, India will also have a sufficient trained human resources for this purpose. Another component of the QT-TIH is outreach to all the stakeholders, prominent among them being the industry, academic people in all the institutions, students, and the general public. The outreach part has programmes that have been planned to reach every stakeholder of quantum technologies. As industry take interest in this programme, it will lead to more tech based employment generation, technology based companies and a sustained user base for tech products based on quantum technologies.

It is hoped that QT-TIH, established at IISER Pune, will make a significant positive impact in the emerging area of quantum technologies and will catalyse its growth in India in the years to come.

CHAPTER 17

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