TAKSHASHILA INSTITUTION

# *Building India's Quantum Ecosystem*

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TAKSHASHILA DISCUSSION DOCUMENT 2022 – 01

V1.0, 3 February 2022

## *Executive Summary*

Advancements in quantum information science have enabled technological applications that can address and solve problems that seemed intractable just a few years ago. This discussion document explores the current state of the global quantum ecosystem and how different states are positioned in the race towards quantum supremacy. The primary focus of the document is to underline why India needs a nationally coordinated quantum policy and what strategies it can adopt to build a robust domestic quantum ecosystem. The main aspects covered in this document are:

1. The key applications (civilian and military) of quantum information science, along with specific use cases of extant quantum technologies.
2. The quantum value chain and the different focus areas involved in building quantum systems.
3. Aims, objectives, and policy measures of different quantum programmes around the world to better understand the global quantum landscape, especially the geopolitical contest between established technological powerhouses.
4. Ethical considerations when formulating policies related to the usage of quantum technologies.
5. An overview of India's existing quantum ecosystem, and proposed policy recommendations to build a better quantum industry within the country.

# I. Introduction

## *Quantum: An Emerging Technology Fast Assuming Critical Commercial and Geopolitical Significance*

Advancements in quantum information science from the early 2010s has opened the doors for a variety new applications, products, and services based on the theoretical principles of quantum physics. The resulting quantum technology combines the fields of engineering and physics to create real-world applications leveraging quantum mechanics principles like entanglement and superposition. Quantum information science was deemed a technology that was decades away from being commercially exploitable. Breakthroughs in scientific methods, however, coupled with massive private and public investments into developing quantum technologies have yielded extremely promising results.[1]

Quantum technologies have become a key area of consideration for states, given their economic and strategic benefits.[2] Technologically advanced states have started their own quantum tech programs, but have also signed agreements with others to jointly develop quantum tech applications. Offering both economic and geopolitical incentives for states, there has been extensive support both from governments and the private sector in the development of quantum technology.

Technology giants like Google, Microsoft, and IBM have thrown their hats in the ring for achieving what is known as 'quantum supremacy'. Quantum supremacy is the definitive effort of demonstrating that a quantum computer can solve a problem that no 'classical' supercomputer can in any comparable amount of time.[3] These efforts have already resulted in the creation and development of modern-day quantum computers that can achieve computing power, over5000 times that of an existing supercomputer. Other than technology companies, states like China have also managed significant quantum achievements. This is due to the fact that modern-day quantum technology offers solutions for a wide range of existing issues.

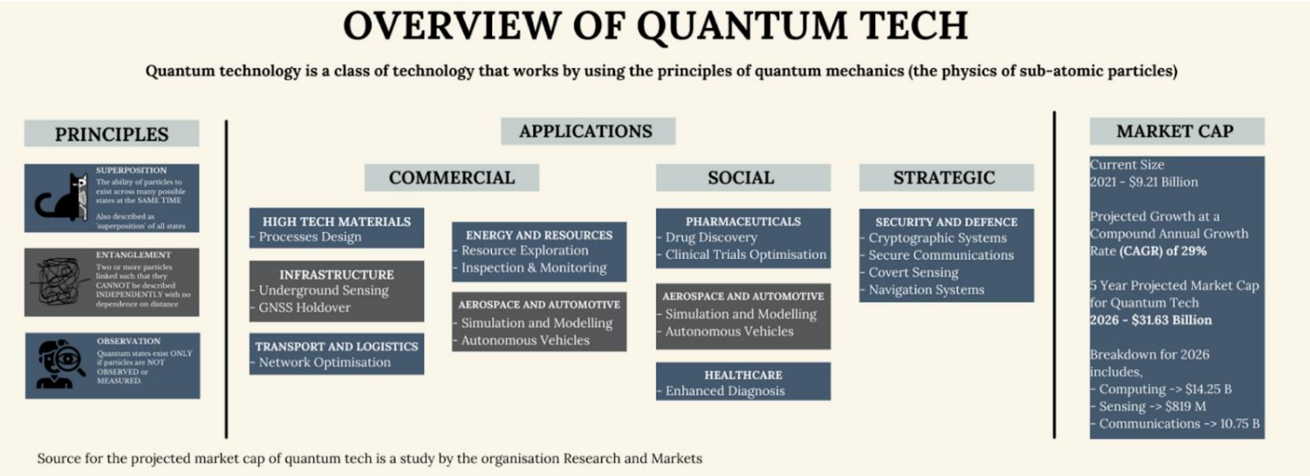


Figure 1: An overview of Quantum Technologies

## The Primary Applications of Quantum Tech

Quantum tech applications can be divided into three broad areas of interest, namely: sensing and metrology, communications, and computing. Below we explore each of these in-depth.

### Quantum Sensing and Metrology

This field includes the use of quantum technology in specialised sensors that are ultra-sensitive and used for precise and accurate measurements, for example, gravitational sensing in the fields of mining and civil engineering.[4] They are also useful in acceleration sensing in navigation systems that are resistant to GPS hacking. Other uses include sensing magnetic fields during the inspection of electronic circuits. An interesting instance of research that uses quantum sensing/metrology is in the United Kingdom's National Quantum Technologies Program's (NQTP) SPLICE Project which deals with the development of cameras equipped with quantum sensors that are used in the leakage of greenhouse gasses into the atmosphere.[5]

### Quantum Communication

Quantum comms is a rapidly evolving sub-field of quantum technology with crucial applications in telecommunications and cyber security. It is the bedrock of modern-day cryptography. This is because of its ability to process certain types of logical problems and having the capacity to easily break normal cryptographic encryption codes configured across networks. Countering this has led to the development of secure communications using quantum-safe technology such as Quantum Random Number Generators

(QRNGs) and Quantum Key Distribution (QKD) systems.[6] The QRNGs generate random numbers with high levels of unpredictability and QKDs involve the sharing of encryption keys in the form of quantum particles which are 'unhackable' given their entangled nature.[7] This helps in the creation of 'Quantum Resistant Cryptographic Algorithms' that remain secure even against advanced computers.

Certain limitations still exist in the field, such as high susceptibility to background noise and signal strength losses over long distances. There is also the issue of the use of amplifiers due to the technology's 'no cloning' property, a phenomenon specific to quantum technology, which states that it is impossible to create an identical copy of a quantum state. This has resulted in the use of 'nodes' for re-encoding messages across the network but it has also created vulnerabilities. The development of 'quantum repeaters' or the use of quantum satellites for safe and long-distance communications is underway which can effectively revolutionise communication networks.

**Quantum Computing**

Last, and certainly not least, quantum computing is the most talked-about, and commercially lucrative application of quantum technology. This field involves the use of quantum bits or 'qubits' which can handle any value between 0 and 1 at any point of time moving away from digital bits of 0s and 1s. Qubits / quantum bits are the basic units of information storage in a quantum computer capable of adopting multiple states (hence any value between 0 and 1) based on the principle of superposition. The use of qubits helps in the processes of optimisation, search, and solving problems at an extremely quick pace due to their quantum superposition state.[8] The computing power of these systems dwarfs of the power of supercomputers and helps in decoding issues that might take a classical or supercomputer thousands or millions of years to decipher.

While the physics associated with these qubits has been worked out in theory, the engineering required to implement these in real-life situations remains a challenge. Various methods have been tried by both governments and large corporations, each with their own advantages and shortcomings. For example, they have been created using superconductors (zero resistance offered) by companies like Google and IBM. But the superconductors maintain their quantum states for a very short period of time and there is a requirement of maintaining an absolute zero temperature environment for these superconductors to function as qubits.[9] There are also 'trapped ion' systems where the qubits are ions (electrically charged particles) that are cooled and "trapped" with the help of lasers to maintain their superposition.[10] Other technologies used to create qubits and quantum computers include 'photonic' quantum devices where photons are used as information carriers instead of electrons and 'silicon spin' quantum devices where the spin of single electrons is controlled in Silicon.[11]

Currently, quantum computers have been developed by both private companies (Google, Microsoft) and research labs that have been funded by the government (the case of China). However, there is the issue of these quantum computers still having a high error rate. There is still the need for implementing quantum error correction systems that can improve the efficiency of these quantum computers.

## How to Harness these Applications?

With improved research and increased investments, there are bound to be more areas of utilisation that will emerge. India, as a technologically advanced state, must recognise the multitude of economic and strategic benefits that quantum technologies have to offer and build a robust quantum ecosystem for harnessing them. This can only be achieved through a comprehensive national policy on quantum technologies that deal with areas like financial support, trade and technology transfers, multilateral cooperation, and playing the field to India's strengths.

# II. The Quantum Value Chain

## *Components Needed to Build a Functional Ecosystem*

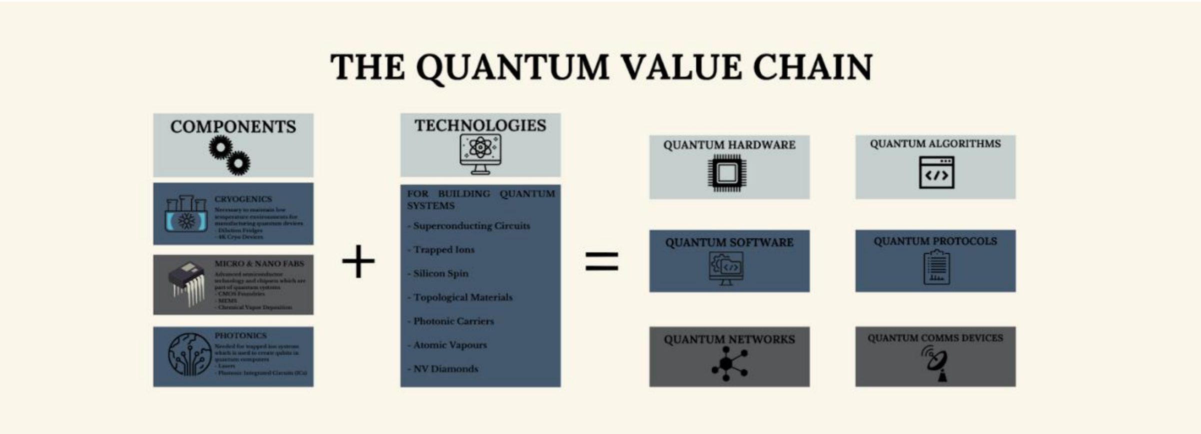


Figure 2: The Quantum Value Chain

Building a robust quantum ecosystem for a country requires advanced research and extensive infrastructure development, along with deep capital investment across the entire value chain.

The quantum value chain comprises materials, hardware components and communication system devices that are used to build and operate quantum systems. In addition to the necessary physical components, the quantum ecosystem also requires certain software algorithms and protocols on top of which the quantum systems function. While focusing on the entirety of the value chain can help improve the quantum ecosystem in the country, there are certain crucial areas of focus within the quantum value chain that can strengthen the ecosystem drastically and develop proficiency in manufacturing and commercialising specific quantum tech components.

Starting from the bottom-up, there are certain components that are vital in building the hardware used in quantum technology systems. These include cryogenics (to maintain near absolute zero temperatures to conduct quantum mechanical experiments), micro and nano fabrication tools (for manufacturing advanced semiconductor devices) and photonics (for lasers and other integrated circuits).

Quantum hardware, software, networks, and communication devices form the backbone of the quantum systems and quantum information science and technology. Components like cryogenics and nanofabs help in the manufacture and development of specific hardware or software that can be used in quantum systems. These devices can be used as per the requirements of the quantum systems with each having its own set of applications.

The technology and software used to build quantum computers (superconducting qubits, trapped ions, silicon spin, photonics) and other devices vary depending on the hardware used and specific applications. The trapped ion system technology is also used in spectrometry which in turn helps in the development of accurate atomic clocks. Other technologies like nitrogen-vacancy (NV) centres in diamonds is used in photoluminescence applications especially in the development of masers (devices producing electromagnetic radiations using light as a stimulus). These technologies act as the bridge between the basic components and finished products that go into the development of quantum systems.

# III. Current Quantum Policies

## *Transnational Comparative Analysis of Quantum Strategies*

This section provides a snapshot and a comparative overview of the various policy objectives and strategic measures being adopted by countries and supranational entities around the world in support of quantum technology R&D. It then delves into the military and security aspects associated with the geopolitics of exploiting quantum technologies, and positions a broad "China vs. The West" narrative that characterises this debate in global policy circles.

### Strategic Aims and Objectives: Economic and Security Considerations

The primary strategic aims for governments to invest in quantum tech are twofold: economic and security related. With hundreds of billions in value creation forecast for quantum technologies (especially quantum computing), governments are keenly aware of the economic imperative to nurture this emerging technology for their businesses, industries, and broader commercial and social spill over effects.[12] Secondly, the possibility that a quantum computer that is not so advanced can also break any existing public encryption key means that governments are in a race to secure their own data and information, while also wishing to be in an offensive position to gain the technology for advantage over their rivals. So, while not a totally zero-sum game, sovereignty or relative autonomy in quantum technology for countries will mean gaining comparative strategic advantages in multiple spheres.

Unlike some emerging technologies (like Artificial Intelligence, Blockchain and IoT that are solely based on software modelling and infrastructure), quantum requires a huge amount of initial investment, physical infrastructure, and human capital in the form of scientists and advanced researchers to build large hardware devices that have quantum capabilities. Accordingly, we see that only around 25 countries around the world have ongoing quantum programmes and initiatives, with large variances between the top and bottom tiers in terms of investments, programmes, and technology readiness.[13] For these same reasons, governments tend to focus efforts on a two-fold strategy: bringing together academic and industry players to spur R&D, while also creating an ecosystem where the outputs of the research can be commercialised and seeded for general application purposes.

## Policy Measures and Implementation: Dedicating Investment, Promoting R&D, and Spurring Collaboration

The policy measures to implement this strategy are generally along four basic lines:

- Creating academia-industry bridging collaboration hubs/centres of excellence to nail down the underlying science;
- Instituting 'challenge prizes' which solve targeted use cases via a consortia approach;
- Dedicated funding for projects of national interest or importance; and
- Providing or facilitating investments in product/service innovation via start-ups and scale-ups often via deep-tech accelerator and incubator programmes.

The operationalisation of these strategies is either a cross-government holistic policy, or broken into the component quantum technologies that are handled by specific government departments and agencies in charge of science & tech, defence, or telecommunications.[14] The Canadian Institute for Advanced Research (CIFAR), in its report on global quantum technology policies, has identified three main approaches to government quantum R&D programmes:

- Coordinated national quantum strategies published, or in development (e.g., USA, China, UK, Russia)
- No distinct national strategy, but government spending occurring (e.g., Australia, Scandinavia, Italy, UAE)
- No significant initiatives, but are part of international partnerships (e.g., Belgium, Poland, Turkey)

While all countries with quantum aspirations will support the three primary areas of quantum tech (sensing, communication, and computing) at some level, emphasis on any one of the three areas is dependent on that country's mid to long-term geostrategic objectives and their existing domestic strengths. For example, China is emphasising quantum communications (quantum key distribution (QKD), cryptography, and satellites), while the UK's national mission is to build a fault-tolerant quantum computer in the next 5-10 years.

## Global Quantum Technology Landscape: An Elite, Lopsided, and Top-Heavy Club of Countries and Companies

While a number of countries harbour quantum ambitions, there are only a handful of countries and entities that possess the means and capability to any significant or meaningful extent.[15] At the top of the list, both in terms of spending and impact, are the US and China, which are locked in a race to claim quantum superiority. The US government, via the National Quantum Initiative Act of 2018, has spent $1.2 billion on five research centres specialising in quantum information systems.[16] To bolster this, US tech giants like Microsoft, Google, IBM have also spent hundreds of millions of dollars to both conduct scientific research and commercialise quantum tech. China, for its part, specifically listed quantum tech as a national priority in its 13th five-year plan (2016-2020) and dedicated $10 billion in 2017 to build a national lab for quantum information science, with a focus on quantum communications.[17] Meanwhile, Chinese tech entities such as Alibaba, Tencent, and Baidu have also invested heavily in quantum labs, research centres, and computing institutes.

Countries within the EU, and the UK, have been funding quantum initiatives for decades, and are now ramping up spending as this technology reaches commercial and defence application readiness.[18] Germany and France are the leaders in the EU and the UK has recently published its national strategy for the next decade. India, Netherlands, South Korea, Russia, and Canada are in the next tier of quantum technology advancement and are increasing their outlays on this technology via direct support for research and indirect means such as innovation collaborations with businesses and industry partners. A number of smaller countries (e.g., Israel, UAE, Japan, Singapore) are also pursuing quantum programmes, but largely in collaboration with other nations as a means to defray costs and piggyback on existing innovations. The necessity for a robust quantum policy in India can be explained by digging deeper into the main geopolitical, military and security currents in the quantum landscape.

# IV. Military and Security Angles

## *Offensive as well as Defensive Advantages*

Other than the diverse commercial applications of quantum technology, there is also a high probability of these systems playing a major role from military and security standpoints. There is immense potential for quantum technology, but this has not yet matured into credible quantum military applications. Therefore, it is essential to understand where quantum can actually give an edge to security forces in this domain.

Firstly, in terms of building secure communication networks, there is the possibility of using quantum computers as offensive tools to break high-level encryption codes, helping gain access to existing military systems.[19] Hence, quantum technologies remain on the military's radar, especially to develop defensive solutions such as new encryption mechanisms using QKDs to secure their systems against these types of attacks. Next, there is also the possibility of quantum satellites being used for surveillance and gaining unauthorised access to crucial defence systems. These quantum satellites, enabled with quantum cryptographic systems (using QKDs) with offensive capability, can break any modern-day security system. Quantum technologies are forcing governments and militaries to rethink developing security systems that can remain secure regardless of any technology being used to subvert them.[20]

In addition, the applications of quantum-based sensors in the military domain have grown in the last decade, for example in the detection of submarines and in airborne stealth systems.[21] To this end, the optimisation of drone movements and unmanned aerial vehicles all now use quantum sensing and metrology. However, the most important application of these sensors is in devices like gyroscopes and systems like RADAR for precision guidance and geopositioning.[22]

The working principles behind these devices are simple: instead of using conventional microwaves, the devices use two groups of entangled photons (signal and idler photons). The signal photons are sent out towards the object of interest, while the idler photons are measured in isolation, free from interference and noise. When the signal photons are reflected, true entanglement between the signal and idler photons is lost but a small amount of correlation survives, creating a signature or pattern that describes the existence or the absence of the target object (such as the enemy vehicle) — regardless of the noise within the environment.

With quantum technologies playing a vital role in modernising defence technology, building a robust quantum ecosystem becomes critical for advanced industrial countries looking to gain a comparative strategic advantage vis-à-vis their geopolitical opponents - a phenomenon we explore in further detail below.

# V. The Geopolitical Climate

## *China vs. The West?*

### China's Rise

In 2016, President Xi Jinping established a national strategy for China to become technologically self-reliant, with a view to surpassing the United States as the global leader in emerging and critical technologies. At the heart of this was quantum innovation and research. Apart from allocating funds for a long-term quantum mega project, President Xi also announced the establishment of a National Laboratory for Quantum Information Sciences.[23]

An announcement made by a group of Chinese scientists in late 2021 buttressed the country's growth in the field. They declared the creation of a quantum communication network in space using their quantum satellite to secure the national power grid against blackouts and other long-distance attacks.[24] This is a massive leap forward in building secure communication networks using quantum information science. It also underlines the strides made by China in the field and the significant advantage it has gained over its competitors in the recent past.

In 2008, renowned quantum physicist Pan Jianwei returned to China in the hope of facilitating quantum research in the country. Hailed as the 'Father of Quantum Physics' in China, Jianwei founded a lab at the University of Science and Technology of China (USTC) dedicated to achieving quantum breakthroughs. This ushered in a quantum revolution in the country with extensive research projects on quantum science, especially communications, taking shape. This focus on quantum communications resulted in advanced telecommunications and cryptography systems being developed by the scientific community within the country.

The Beijing-Shanghai communication line, which was opened in 2017, was a result of this decade-long quantum research. It was hailed as the world's longest unhackable communication line.[25] Though not a fully realised quantum connection, the line is divided into multiple nodes (based on the distance travelled by each photon before succumbing to noise) which provides a high level of security. China also launched the world's first quantum satellite in 2016 that was pushed to a higher orbit for a wider coverage to develop the quantum internet (a network entirely made up of quantum devices sharing information through qubits within an environment as per the laws of quantum mechanics). The satellite program was started in the hope of securing communications between military outposts, embassies, government bodies, and financial institutions. These advancements have effectively made China the global leader in quantum communications.[26]

In terms of quantum computing and its applications, China was behind the United States in both investments and technological superiority until this year. The revealing of Zuchongzhi 2, a Chinese-made quantum computer consisting of 66 superconducting qubits easily surpasses the speed and computing power of Google's quantum computer, Sycamore (made of 53 qubits). There was also a major improvement to their photonic quantum computer, raising the number of qubits from 76 to 113. Owning two of the fastest computers in the world, China now is the only country to achieve a quantum advantage in both photonic and superconducting quantum computing.[27]

With China pulling ahead in the quantum race, there is also the possibility of the Chinese government exploiting and weaponising critical quantum technologies for military purposes. This would mean that the Chinese military might develop capabilities to neutralise many offensive and defensive military technologies of its rivals. Chinese scientists have claimed to have developed Quantum Radar which is supposedly capable of determining the type of airplane and the weapons a rival airplane is carrying. If true, this would render any existing stealth technology moot.[28] The Chinese National Academy of Science has reported the development of a quantum submarine detector using extremely sensitive sensors called SQUIDs (Superconducting Quantum Interference Devices). This has the ability to detect a submarine from a long-distance creating limitations for all opposing forces. If these technologies are functional as the Chinese government claims, the possibility of China gaining a military quantum advantage is imminent.[29]

However, there are certain systemic challenges that China still faces before becoming a quantum superpower. China may own the world's fastest quantum computers, but there have not been any universally accepted real-world applications of these systems until now.[30] The current quantum computers have also reported considerably high error rates meaning that the error-correction systems in use still need to raise their efficiency.[31] There is also the issue of maintaining a low-temperature environment (often close to absolute zero) for conducting credible quantum research. Chinese companies are still in the process of developing cooling machines specifically for this.[32] China also faces sanctions and embargoes on critical semiconductor equipment, placed by the United States, which is needed for breakthroughs in quantum technology.[33] With the country still developing production and assembly lines for leading-edge semiconductor manufacturing, this can, at least in the short-term, cripple China's vision of dominating the quantum industry.

China has definitely made incredible progress in building its quantum ecosystem. With quantum research driven by the state and concentrated in a few university research labs, the funding provided by the Chinese government consistently remains on the high. This has resulted in critical breakthroughs in the domain. However, as described, inherent challenges remain for China to navigate before officially winning the quantum race.

## 'The West' Pushes Back

With China making large strides in this emerging technology, November 2021, saw a slew of agreements between the United States and its Western allies, namely the UK, Australia, and Canada, that addressed quantum tech in some form or another. The Australian government signed perhaps the most comprehensive quantum technology cooperation agreement with the US and comes at a time when the global quantum ecosystem is rapidly evolving with increased participation from different states.[34] The emerging picture, although it is still early days, is of a coordinated front amongst like-minded Western powers.

An official statement from the Australian and American government spokespersons underlined the importance of science and technology in the information age along with the need for collaborative and transnational efforts in the pursuit of scientific discovery and societal benefit. The statement also mentioned how quantum technology, as a critical and emerging technology, can help in enabling the development of faster computers, secure communication networks, and more accurate sensors. Similarly, the United States and United Kingdom also recently issued (Nov 4th, 2021) a Joint Statement to enhance cooperation and deepen ties on quantum information science and technology, building on the inaugural U.S. – U.K. Science and Technology Agreement signed in 2017-18.[35] In parallel, the United States' Director of the White House Office of Science & Technology Policy and Canada's Minister of Innovation, Science and Industry also issued a joint statement on science, technology, and innovations (ST&I), which includes collaborative initiatives on quantum technology.[36]

These agreements explore the prospects of new scientific and practical applications of quantum technology, along with the translation of credible research in the field into potential military/security applications that would be of mutual benefit. They are built on the realisation of the field's benefits in a new quantum-enabled world. But these treaties and agreements also implicitly recognise China's ambitions in this space and therefore emphasise the need for joint research and development in the field of quantum security, for example by prioritising critical tech transfers between the countries.

There is also a coordinated focus in the various agreements between these advanced Western countries on building a quantum technology market with the help of the private sector and other industry bodies. Practically, this means diversifying the supply chain, which is still in its infancy, so that it does not concentrate in the hands of a few entities, a key consideration when viewed through the lens of national security issues that utilise quantum technology.

Other practicalities of the agreement include decisions between governments to hold periodic quantum policy dialogues that involve senior government officials who are experts in the field to flesh out emergent issues, coordinate subsequent agendas and eventually help in the identification of practical civilian and military initiatives that can be taken forward by respective governments.

As China races ahead with multiple quantum technology developments, the United States and its Western allies will look at enhanced multilateral cooperation to counter their rival's growth and stem China's influence in the domain. This could take several forms including: cross-border collaboration to fast-track significant research in the field and building a workforce for the future; technology transfer agreements for the exchange of skills and development and the protection of intellectual property rights; and building safe and secure research environments along with developing and setting technical standards that foster interoperability, innovation, and transparency.

# *VI. An Ethical Framework for Quantum Technology*

## *Proactive Efforts on Transparency, Accountability and Equity Measures Urgently Required*

As described above, the advent of the $2^{nd}$ quantum revolution has spurred several countries and supranational bodies to develop national strategies, strategic initiatives, and international partnerships. Like any other emerging deep technology, quantum too portends many possibilities of progress, but also entangled within it are political, social, ethical, and legal implications. So, while the pure computing power of a quantum machine may be able to help tackle Alzheimer's Disease or aid in reducing the effects of climate change, it could also spell the end of privacy and exacerbate inequality, especially if a small number of states and corporations dominate the field. The need, therefore, is to have transparent and accountable global bodies which can set standards and work in the spirit of cooperation to harness and push the frontiers of this powerful new technology.[37]

Also, as with other emerging technologies, there is a need for the creation of ethical frameworks to address any unintended consequences from the use of quantum technologies. Instead of retrospective regulations and policies that might hinder the growth of the sector, it is imperative that any biases, exclusions, and unethical practices with respect to quantum technologies be addressed *a priori.*

There is also the question of whether different emerging technologies compound ethical issues when used together. Hence, developing a rules-based order for the governance of these emerging technologies (like quantum and artificial intelligence (AI) is necessary before they become too unmoored to regulate. With different states undertaking credible research in the field of quantum technology, there is a call for the middle powers to play a pivotal role in the facilitation of norms and guidelines of the quantum field.[38]

The potential regulations of the quantum field should ensure sustainable growth of the specific technology while simultaneously addressing issues like technological inequality.

The rules, norms, and guidelines should be broad while ensuring the participation and input of governments, transnational corporations, technical experts like programmers, and multi-stakeholder organisations. Generally, the standardisation process by the stakeholders is dominated by a few states and industry alliances which lobby for influence at international forums. This calls for an inclusive process (with the help of civil society organisations and academic stakeholders) and a networked approach for developing quantum technology regulations and norms.[39]

There also arises the concept of 'Quantum Divide' which is the gap created between those who can benefit from quantum technologies and those who cannot. Closing this divide is necessary for the development of other related technologies. The ethical framework to be created should ensure that there is equitable distribution of quantum technology.[40]Instead of inaccessibility to quantum tech being a disadvantage, this should provide a platform for bilateral and multilateral cooperation resulting in technological transfers between the technologically advanced states and other states.

The process of utilising quantum technology should be on the basis of maximising benefits and minimising harms of the technology in use. This includes not just the goals but also the means to achieve them. Negative effects must be taken into account when dealing with quantum and developing related norms. An important caveat to be addressed with ethical frameworks is that there should not be a failure to achieve consensus between the great technological powers. Evolving quantum principles and guidelines should not be split among two regimes - authoritarian and democratic technology governance models - each with their own principles.

Finally, getting the right balance in regulation between innovation and misuse of quantum technologies is pivotal for the growth of the sector. Self-regulation by private entities will not work in complex technologies like quantum. AI is an example of where self-regulation has failed.[41] Accountability is also hard to determine in technologies like quantum where causes and effects are not easily determinable. Hence, government intervention is needed when dealing with the ethics of emerging technologies. But realistically, no single government or state can unilaterally develop ethical frameworks.

The first step towards building an ethical framework on quantum technology is to create a separate organisation dealing with quantum tech standards similar to the International Telecommunications Union (ITU) that deals with telecommunication standards. This organisation, led by a democratic discourse between like-minded countries is the need of the hour. Specifically, with quantum technology, the approach to be followed when formulating an ethical framework or guideline must give precedence to the utilitarian, social development aspect of the technology, rather than the strategic aspect.

# *VII. The Current Quantum Situation in India*

## *Big Budget Sanctioned, But Underdeveloped Ecosystem Needs a Quantum Leap to Achieve Even Basic Utility*

While India was relatively late in getting on the quantum train, the government has recently recognised the importance of harnessing this technology via a five-year, Rs 8000 crore National Mission on Quantum Technologies & Applications in the 2020 Budget.[42] In a Lok Sabha question that was answered by the Minister of Science and Technology in 2019, the government expressed its desire to develop a detailed project report on a potential National Mission related to Quantum Technologies. The primary aims were to promote research and development, strengthen international research cooperation and nurture start-ups in the field. Even before the official announcement of the mission, the Department of Science and Technology (DST) started a research programme, Quantum Enabled Science and Technology (QuEST) to groom young scientists in the field of quantum research.[43] This programme was allocated a sum of Rs 186 crore over three years with a total of 51 researchers selected to undertake both experimental and theoretical research in the field of quantum technology.

The DST has also managed to initiate a new directed research programme on 'Quantum Information Science and Technology (QuST)' aimed at the development and demonstration of quantum information systems at various technical institutes across the country like TIFR, IISc and IISERs.[44] Under the programme, a Centre of Excellence in Quantum Technology at IISc and the Raman Research Institute has been established. This has also resulted in the introduction of targeted PhD programs in quantum sciences at different educational institutions to increase the availability of scientists and credible researchers in the field.

As cited above, in the Budget for the fiscal year 2020-21, the government officially announced the National Mission for Quantum Technologies and Applications (NM-QTA) with a total outlay of Rs. 8000 crores over five years.[45] The aims of the mission are:[46]

- Engineer, industrialise and maintain a competitive advantage as a global supplier of quantum devices, components, systems, and expertise while continuing to play a leading role in the development of quantum technologies.
- Continue fundamental research in the specific fields of science and technology to support the capabilities of quantum technologies.
- Nurture the development of world-class industrial quantum technology workforce and startups.

With these broad aims in mind, the mission also outlined the necessary actions that needed to be taken in order to achieve those said aims. The main targets of the mission include:[47]

- Developing quantum processors, communication devices, memory devices, accelerators, and simulators.
- Developing quantum clocks, sensors, and imaging devices along with designing advanced materials for civil and military applications.
- Enhancing the research base and strengthening cross-border collaborative research in the field of quantum technologies.

The objectives of the project were enhanced in the next year (2021) and a response by the Minister of State for Science and Technology to a question asked in Lok Sabha elucidates this.[48] A goal of building a 50-qubit quantum processor along with the development of new algorithms for quantum simulators was created. Along with this, a satellite-based quantum key distribution (QKD) link with a range of about 1000 km, superconducting single photon detectors, high temperature photonic memory, high sensitivity atomic based magnetometers and quantum technologies based on novel quantum materials were all envisioned as part of the five-year mission.

In September 2021, MeitY also launched the 'Quantum Computer Simulator (QSim) Toolkit'. This was to provide a quantum development environment to academics, industry professionals, students, and the overall scientific community in India.[49] Apart from the specific aims and objectives, there was a mention made in response of a project report from the NM-QTA that contains the detailed specifics of projects and a timeframe for the implementation of the mission. The guidelines on ethical practices to be followed while conducting research under NM-QTA were also purportedly incorporated in the project report. However, the report has not yet been published or released for public consumption.

While there have been movements with regard to NM-QTA, there are some caveats for the mission to be considered a success. A Lok Sabha question posed in July 2021 asked whether the NM-QTA was being implemented in a public-private partnership with key private sector partners. It also asked whether any individuals (academics, scientists) or corporates involved in quantum research had been engaged as consultants for the mission.[50]

The reply that was provided by the Minister of State for Science and Technology mentioned that no private sector partners had been identified yet as the mission had not even received approval and no one from outside the government had been roped in for consultations. The Minister also announced that no funds were allocated, disbursed or utilised under NM-QTA during the Financial Year 2020-21. This would imply that though the mission was introduced in 2020, no credible advancements have been made by the government. Even with the Rs. 8000 crore outlay, it is concerning that funds are yet to be allocated and disbursed for specific quantum projects across the country.

A serious overhaul of the existing strategy is needed if India plans to harness the positives of quantum technology. With incredible strides and massive investments being pumped into the global quantum industry, India cannot afford to miss the bus. With the country already behind other technological powers in the quantum field, the government has to focus on certain critical areas to get the quantum programme up and running. Fast tracking projects, efficient allocation of resources, private sector partnerships and roping in credible scientific advisors are the needs of the hour for building a robust quantum ecosystem in India.

# VIII. Recommendations for Building India's Quantum Ecosystem

## A Fourfold Path to Quantum Enlightenment

The Indian government has taken the first step by acknowledging the importance of quantum technology through their plan of kickstarting a quantum programme in the country. However, without an effective overarching strategy, without ensuring proper allocation of resources, and without concentrating efforts in key strategic areas, India will lose any leverage it may have in the global quantum playing field.

The recommendations made in this document on the type of actors that can get involved in building India's quantum ecosystem. Importance to all those who can contribute in developing and growing quantum technology must be the government's top priority.

### Establishing Research Centres Within Universities

For a critical and emerging technology like quantum, the focus on research and development is imperative. Cutting-edge research in technical fields is heavily concentrated in higher education institutes and university laboratories. The same can be said for quantum technologies too.

Priority must be given to these educational institutions in terms of both funding and government support (e.g., importing scientific equipment, international research collaborations). A large share of the government's outlay must be given to encourage the development of new applications and algorithms used in quantum systems. Connecting academic institutions and industry must be encouraged and facilitated in order to translate research into real-world applications.

An increased focus on academia is needed for the returns that these research centres offer through critical intellectual property (IP) development. Gaining IP rights in technologies like quantum can help India gain an upper hand both economically (licensing fees) and strategically (patent rights) across multiple industries where this technology can be applied.

Secondly, the enormous, and relatively low-cost talent pool that educational and research institutes offer can help immensely in strengthening the domestic workforce. The number of skilled professionals in the realm of quantum science and technology within India is currently small, with just a few hundred researchers, industry professionals, academicians, and entrepreneurs in the field. Focusing on academia and research can help in building the quantum ecosystem both intellectually and physically.

## Coordinating Efforts Across Union and State Governments

It should come as no surprise that the involvement of various pertinent Indian state administrations is essential for forging the domestic quantum industry, even if the Union government is the lead player involved in formulating the overall policies for quantum technology within the country. This is especially the case in the manufacturing and fabrication process of basic quantum devices using advanced semiconductor technology. With state governments playing an integral role in setting up fabs in the near future, quantum technology can benefit with coordination across domestic manufacturing facilities and units.

The lion's share of investments for basic research and development (at least in the initial phase) rests with the union government. It must be ensured that the resources (both financial and non-financial) available to the government for the national mission be allocated efficiently so that the best outcomes can be achieved. This can be done through the establishment of 'Quantum Innovation Hubs' along the lines of UK's policy.[51] These hubs, setup with the help of government resources, can serve as centres of collaborative innovation between academia and the private sector.

Other than investments, it is the government's responsibility to establish a conducive fiscal and legal environment to foster innovation. This will attract potential international collaborators to conduct their research in the country while involving Indian talent. Sufficient funds along with investment-friendly laws (trade policies to remove barriers and lowering imports for manufacturing equipment) by the government can also credibly help in the establishment and improvement of India's quantum industry.

## Harnessing the Power and Promise of Corporations and Start-ups

There is a heightened need to engage with the private sector for developing and growing the domestic quantum ecosystem. While university labs are largely involved on the research side, quantum tech corporations and start-ups are vital in converting and commercialising this research into applications and products that can be of use. With big-tech companies like Google, IBM and Microsoft leading the way in quantum computing, there is also now the emergence of smaller players to serve the burgeoning market. There is therefore a need for the government and industry bodies to facilitate collaboration between big technology corporations and fledgling start-ups.

The industrial and commercial capabilities of these global companies are top-notch and tie-ups and potential technology transfer agreements with them can help in both business process optimisation and securing more funding into quantum tech projects. With multinational tech corporations, there is also the added advantage of technology integration across their geographic markets.

The advantage of collaborating with start-ups anywhere is the pace and dedication at which they work. With just a few products absorbing their focus, the agility of these start-ups to develop and market their product is well documented. It is therefore in India's interest that start-ups indulging in quantum technology research are nurtured.

The government must also ensure allocation of funds to provide targeted microeconomic support (like subsidies and tariff cuts) to both established companies and scaling start-ups. Similar to the semiconductor package[52], production linked incentive (PLI) schemes could be provided for quantum technology companies. Upfront capital expenditure support, tax deductions, and interest-free loans could also be introduced through a scheme similar to the SPECS and designed specifically for companies engaged in quantum research.[53]

## Facilitating International Cooperation

Lastly, the quantum value chain remains highly complicated, and this makes it difficult for even the most technologically advanced countries to attain a high degree of self-sufficiency in the field. This is where plurilateral cooperation comes into the picture. In the field of quantum technology, bilateral and multilateral agreements are imperative for growth. The government needs to assess and form technology alliances with like-minded countries for better transfer, trade, and improvements in quantum technology.

The US-Australia/Canada/UK and other quantum technology agreements should serve as a base for India to pursue a collaborative effort on projects related to quantum technologies. The first step could be for the Indian government to engage with its allies in key groupings like the Quad, BRICS, and SAARC.

Similar to the Quad Semiconductor Supply Chain Initiative, which looked at diversification and collaboration in the semiconductor domain, the quantum field needs a multilateral approach to build an equitable and transparent global quantum technology ecosystem. With incredible research already made in the domain by some states in the West, India can work with these countries to translate this research into credible applications. That should be a primary focus of India's quantum programme as it would mean that India can benefit from giant leaps made in the quantum domain by countries like the United States and Australia. It would also help in building India's ecosystem through external technical advice or mentoring, and establishment of state-of-the-art facilities for joint research and development of quantum technologies.

# IX. Conclusion

## *Quantum Tech has Emerged: How Will India Respond?*

Quantum information science and technology has become one of the most sought-after emerging and critical technologies in the 21st century. Despite its many commercial and societal positives, modern day quantum technology also poses a significant risk to present-day encryption and country's' critical cyber infrastructure, and thereby, putting India's national security at stake. Confidential information (e.g., military intelligence) can be easily decrypted using quantum computers and their applications.

Considering these economic opportunities and potential risks, India needs to ramp up its efforts to reach parity with others already active in the global quantum landscape. Several states across the globe have charted their own quantum programmes, with many achieving critical breakthroughs. India, on the other hand, has just entered the quantum race. As countries increase their financial and intellectual resources towards harnessing quantum tech, India must ensure it does not lag far behind.

The NM-QTA that was announced in 2020 urgently needs to formulate a multi-stakeholder approach involving the government, academia and private sector actors involved in quantum research. Both short-term and long-term goals in terms of projects must be set within the scope of an overarching strategy. Efficient allocation of resources to all stakeholders must remain a top priority given India's poor track record in this area. Finally, multilateral cooperation in quantum technology remains a necessity, not a choice, for India. Ensuring these policy recommendations for building a robust quantum ecosystem are acted upon will help cement India's place in the global commercial landscape, while also protecting its strategic interests in the long-term.

# *References*

[1]Jeremy Kahn. "Two new quantum computing breakthroughs reveal the technology's commercial potential". Yahoo Finance. Published September 2021.
https://finance.yahoo.com/news/two-quantum-computing-breakthroughs-reveal-112909605.html

[2]Johnny Kung and Muriam Fancy. "A Quantum Revolution: Report on Global Policies for Quantum Technology". CIFAR Report. Published April 2021.
https://cifar.ca/wp-content/uploads/2021/05/QuantumReport-EN-May2021.pdf

[3]Corrine Reichert. "Amazon, IBM and Microsoft race to bring global access to quantum computing". CNET. Published April 2020.
https://www.cnet.com/tech/services-and-software/amazon-ibm-and-microsoft-race-to-bring-global-access-to-quantum-computing/

[4]Kai Bongs, Michael Holynski, Jamie Vovrosh, Philippe Bouyer, Gabriel Condon, Ernst Rasel, Christian Schubert, Wolfgang P. Schleich, and Albert Roura. "Taking atom interferometric quantum sensors from the laboratory to real-world applications." Nature Reviews Physics 1, no. 12 (2019): 731-739.
https://www.nature.com/articles/s42254-019-0117-4

[5]National Physical Laboratory. "Quantum-enabled gas imaging camera to dramatically cut methane leaks". Phys.org. Published November 2021.
https://phys.org/news/2021-11-quantum-enabled-gas-imaging-camera-methane.html

[6]Bang-Ying Tang, Bo Liu, Yong-Ping Zhai, Chun-Qing Wu, and Wan-Rong Yu. "High-speed and large-scale privacy amplification scheme for quantum key distribution." Scientific reports 9, no. 1 (2019): 1-8.
https://www.nature.com/articles/s41598-019-50290-1

[7]Xiongfeng Ma, Xiao Yuan, Zhu Cao, Bing Qi, and Zhen Zhang. "Quantum random number generation." npj Quantum Information 2, no. 1 (2016): 1-9.
https://www.nature.com/articles/npjqi201621

[8]Animesh Datta, Anil Shaji, and Carlton M. Caves. "Quantum discord and the power of one qubit." *Physical review letters* 100, no. 5 (2008): 050502.
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.100.050502

[9]Michel H. Devoret,, Andreas Wallraff, and John M. Martinis. "Superconducting qubits: A short review." *arXiv preprint cond-mat/0411174* (2004).
https://arxiv.org/abs/cond-mat/0411174

[10]Colin D. Bruzewicz, John Chiaverini, Robert McConnell, and Jeremy M. Sage. "Trapped-ion quantum computing: Progress and challenges." Applied Physics Reviews 6, no. 2 (2019): 021314.
https://aip.scitation.org/doi/abs/10.1063/1.5088164

[11]R. Maurand, X. Jehl, D. Kotekar-Patil, A. Corna, H. Bohuslavskyi, R. Laviéville, L. Hutin et al. "A CMOS silicon spin qubit." Nature communications 7, no. 1 (2016): 1-6.
https://www.nature.com/articles/ncomms13575?origin=ppub

[12]Jean-François Bobier, Matt Langione, Edward Tao, and Antoine Gourévitch. "What Happens When 'If' Turns to 'When' in Quantum Computing?" Boston Consulting Group. Published July 2021.
https://www.bcg.com/publications/2021/building-quantum-advantage

[13]Ibid.

[14]James Dargan. "15 Countries with National Quantum Initiatives." The Quantum Insider. Published April 2021.
https://thequantuminsider.com/2021/04/29/15-countries-with-national-quantum-initiatives/

[15]Ibid.

[16]Brandi Vincent. "Two Years into the Government's National Quantum Initiative." Nextgov. Published December 2020.
https://www.nextgov.com/emerging-tech/2020/12/two-years-governments-national-quantum-initiative/170949/

[17]CGTN. "China to include quantum technology in its 14th Five-Year Plan." The State Council of the People's Republic of China. Published October 2020. http://english.www.gov.cn/news/videos/202010/22/content_WS5f90e700c6d0f7257693e3fe.html

[18]Alice Pannier. "Strategic Calculation: High-Performance Computing and Quantum Computing in Europe's Quest for Technological Power." Institut français des relations internationals (IFRI). Published October 2021. https://www.ifri.org/sites/default/files/atoms/files/pannier_strategic_calculation_2021.pdf

[19]Michiel van Amerongen. "Quantum technologies in defence & security." NATO Review. Published June 2021. https://www.nato.int/docu/review/articles/2021/06/03/quantum-technologies-in-defence-security/index.html

[20]Krelina, Michal. "Quantum technology for military applications." EPJ Quantum Technology 8, no. 1 (2021): 24. https://link.springer.com/content/pdf/10.1140/epjqt/s40507-021-00113-y.pdf

[21]Brandi Vincent. "Army-Built Quantum Sensor Can Detect Wi-Fi, Bluetooth and Other Signals." Nextgov. Published February 2021. https://www.nextgov.com/emerging-tech/2021/02/army-built-quantum-sensor-can-detect-wi-fi-bluetooth-and-other-signals/171964/

[22]Johannes Fink. "Detection with Quantum Radar." Aerospace and Defense Technology. Published August 2020. https://www.aerodefensetech.com/component/content/article/adt/features/articles/37377

[23]Stephen Chen. "China building world's biggest quantum research facility." South China Morning Post. Published September 2017. https://www.scmp.com/news/china/society/article/2110563/china-building-worlds-biggest-quantum-research-facility

[24]Stephen Chen. "China uses quantum satellite to protect world's largest power grid against attacks." South China Morning Post. Published December 2021. https://www.scmp.com/news/china/science/article/3159234/china-uses-quantum-satellite-protect-worlds-largest-power-grid

[25]USTC. "The world's first integrated quantum communication network." Phys.org. Published January 2021. https://phys.org/news/2021-01-world-quantum-network.html

[26]Yuen Yiu. "Is China the Leader in Quantum Communications?" Inside Science. Published January 2018. https://www.insidescience.org/news/china-leader-quantum-communications

[27]Charles Q. Choi. "Two of the World's Biggest Quantum Computers Made in China." IEEE Spectrum. Published November 2021. https://spectrum.ieee.org/quantum-computing-china

[28]Matt Swayne. "Chinese Scientists Say Quantum Radar Could End Stealth Advantage." The Quantum Insider. Published September 2021. https://thequantuminsider.com/2021/09/04/chinese-scientists-say-quantum-radar-could-end-stealth-advantage/

[29]David Hambling. "China's quantum submarine detector could seal South China Sea." New Scientist. Published August 2017. https://www.newscientist.com/article/2144721-chinas-quantum-submarine-detector-could-seal-south-china-sea/

[30]Dan Garisto. "How Much Has Quantum Computing Actually Advanced?" IEEE Spectrum. Published December 2021. https://spectrum.ieee.org/quantum-computing-google-sycamore

[31]Ibid.

[32]The Editorial Team. "Refrigeration Breakthrough Takes Chinese Quantum Science Near Absolute Zero." Cryogenic Society of America. Published July 2021. https://cryogenicsociety.org/38186/news/refrigeration_breakthrough_takes_chinese_quantum_science_near_absolute_zero/

[33]Che Pan. "Semiconductor troubles cloud Beijing's efforts for self-sufficiency as US mulls tougher sanctions." South China Morning Post. Published December 2021. https://www.scmp.com/tech/tech-war/article/3159828/us-china-tech-war-semiconductor-troubles-cloud-beijings-efforts-self

[34]Department of Industry, Science, Energy and Resources. "Australia signs quantum technology cooperation agreement with United States." Government of Australia. Published November 2021. https://www.industry.gov.au/news/australia-signs-quantum-technology-cooperation-agreement-with-united-states

[35]White House Press Releases. "The United States and United Kingdom Issue Joint Statement to Enhance Cooperation on Quantum Information Science and Technology." Government of the United States of America. Published November 2021. https://www.whitehouse.gov/ostp/news-updates/2021/11/04/the-united-states-and-united-kingdom-issue-joint-statement-to-enhance-cooperation-on-quantum-information-science-and-technology/

[36]White House Press Releases. "Joint statement to Leaders from the United States' Director of the White House Office of Science & Technology Policy and Canada's Minister of Innovation, Science and Industry." Government of the United States of America. Published November 2021. https://www.whitehouse.gov/ostp/news-updates/2021/11/18/joint-statement-to-leaders-from-the-united-states-director-of-the-white-house-office-of-science-technology-policy-and-canadas-minister-of-innovation-science-and-industry-2/

[37]Bruce Levinson. "Why We Need to Establish a Regulatory Framework for Quantum Computing and Artificial Intelligence." CircleID. Published October 2021. https://circleid.com/posts/20211028-why-we-need-to-establish-regulatory-framework-for-quantum-computing-artificial_intelligence

[38]Perrier, Elija. "Ethical Quantum Computing: A Roadmap." *arXiv preprint arXiv:2102.00759* (2021).https://arxiv.org/pdf/2102.00759.pdf

[39]Ibid.

[40]Ibid.

[41]Cliff Saran. "Self-regulation of AI is not an option." Computer Weekly. Published November 2021.
https://www.computerweekly.com/blog/Cliff-Sarans-Enterprise-blog/Self-regulation-of-AI-is-not-an-option

[42]Department of Science and Technology. "Budget 2020 announces Rs 8000 cr National Mission on Quantum Technologies & Applications". Government of India. Published February 2020.
https://dst.gov.in/budget-2020-announces-rs-8000-cr-national-mission-quantum-technologies-applications

[43]Sweta Ganjoo. "India starts working on quantum computers, kicks-off Rs 80 crore project to build machines of future." India Today. Published January 2019.
https://www.indiatoday.in/technology/news/story/india-starts-working-on-quantum-computers-1428902-2019-01-11

[44]Department of Science and Technology. "R&D proposals are invited under Quantum Information Science and Technology (QuST)." Government of India Notification.
https://dst.gov.in/sites/default/files/QuST%20-%20CFP1.pdf

[45]Department of Science and Technology. "Budget 2020 announces Rs 8000 cr National Mission on Quantum Technologies & Applications." Government of India Notification.
https://dst.gov.in/budget-2020-announces-rs-8000-cr-national-mission-quantum-technologies-applications

[46]Lok Sabha Unstarred Question No 2621. Answered on 06/03/2020.
http://164.100.24.220/loksabhaquestions/annex/173/AU2621.pdf

[47]Ibid.

[48]Lok Sabha Unstarred Question No 1883. Answered on 30/07/2021.
http://164.100.24.220/loksabhaquestions/annex/176/AU1883.pdf

[49]Prasid Banerjee. "Govt launches QSim to aid quantum computing research in India." Mint. Published August 2017.
https://www.livemint.com/technology/tech-news/govt-launches-qsim-to-aid-quantum-computing-research-in-india-11630066951929.html

[50]Ibid.

[51]The Quantum Technologies Strategic Advisory Board. "National strategy for quantum technologies." Government of the United Kingdom. Published March 2015.
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/414788/Strategy_QuantumTechnology_T15-080_final.pdf

[52]Ministry of Electronics and Information Technology. "Semiconductors and Display Fab Ecosystem." Government of India. Published December 2021.
https://www.meity.gov.in/esdm/Semiconductors-and-Display-Fab-Ecosystem

[53]Ministry of Electronics and Information Technology. "Scheme for Promotion of Manufacturing of Electronic Components and Semiconductors." Government of India. Published April 2020.
https://www.meity.gov.in/esdm/SPECS