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Quantum technologies and National Defense: the role of military institutions in civil-military cooperation in Brazil

Tecnologías cuánticas y defensa nacional: el papel de las instituciones militares en la cooperación civil-militar en Brasil

Abstract: This study analyzes how Brazilian military institutions contribute to civil-military cooperation in the development of quantum technologies for national defense. Its main objective is to understand the role of the Brazilian Armed Forces in building this relationship within the defense sector. Specifically, it aims to 1) present how institutions develop models for applying quantum technologies; 2) analyze the operation of existing initiatives; and 3) propose recommendations to strengthen civil-military cooperation as a strategy for technological development. The study adopts a qualitative and exploratory, approach based on document analysis of the National Defense Strategy and National Defense Policy, a literature review, and institutional data collection from organizations such as the Instituto Militar de Engenharia (IME), the Escola de Comando e Estado-Maior do Exército (ECEME), the Rede Nacional de Pesquisa Quântica (Rede Rio Quântica), and the project Inteligência Artificial e Tecnologias Quânticas (IATQ). The study contextualizes the evolution of quantum technologies, examines their emerging military applications, and compares the strategies adopted by the United States and China. The findings indicate that military institutions are strategic actors in coordinating Brazil's quantum ecosystem.

Keywords: Quantum technologies; Civil-Military cooperation; National Defense; Defense innovation; Source triangulation.

Resumen: Esta investigación analiza cómo las instituciones militares brasileñas contribuyen a la cooperación civil-militar en el desarrollo de tecnologías cuánticas aplicadas a la defensa nacional. El objetivo general es comprender el papel de las Fuerzas Armadas en la construcción de esta relación en el sector de la defensa. Se busca 1) presentar cómo las instituciones desarrollan modelos de aplicación de las tecnologías cuánticas, 2) analizar el funcionamiento de las iniciativas existentes y 3) proponer recomendaciones para fortalecer la cooperación civil-militar como estrategia de desarrollo tecnológico. La metodología es cualitativa, de carácter exploratorio, y se basa en el análisis documental (de la Política Nacional de Defensa y la Estrategia Nacional de Defensa), la revisión bibliográfica y la recopilación de datos institucionales de actores como el Instituto Militar de Ingeniería (IME), la Escuela de Comando y Estado Mayor del Ejército (ECEME), la Red Nacional de Investigación Cuántica (Rede Rio Quântica) y el proyecto Inteligencia Artificial y Tecnologías Cuánticas (IATQ). El estudio contextualiza la evolución de las tecnologías cuánticas, analiza sus aplicaciones militares emergentes y compara las estrategias adoptadas por Estados Unidos y China. Los resultados indican que las instituciones militares son actores estratégicos en la articulación del ecosistema cuántico brasileño.

Palabras clave: Tecnologías cuánticas; Cooperación civil-militar; Defensa Nacional; Innovación en materia de defensa; Triangulación de fuentes.

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1 INTRODUCTION

Technological innovation has repeatedly reshaped relations among states throughout history. From gunpowder and nuclear energy to radar and artificial intelligence (AI), the incorporation of new technologies into military equipment has transformed both the conduct of warfare and the foundations of defense. Within this context, quantum technologies (QT) carry important implications for information sovereignty, cyber resilience, and state superiority.

QT draw on fundamental principles of quantum mechanics, including superposition, entanglement, and the uncertainty principle, all of which challenge classical understandings of physics (Smith III, 2020). These properties enable a new range of military applications, including high-precision sensors, navigation systems independent of the Global Positioning System (GPS), secure communication networks, and computers with exponentially greater processing power. Although many of these applications remain at early stages of development, the rapid pace of research and geopolitical competition for technological leadership suggest that the window of opportunity for strategic engagement is narrow.

In this technological environment, the defense sector serves as both a driver of and a major user of quantum solutions because of the sensitive information it manages (Brito; Ferreira; Chaves, 2023). The pursuit of decision situational, and cyber superiority has led the armed forces of countries such as the United States and China to invest in the military exploitation of these technologies through specialized research centers, strategic funding programs, and mechanisms designed to protect their industrial base.

In Brazil, although the quantum technology agenda remains at an early stage, strategic actors such as the Instituto Militar de Engenharia (IME), Comando de Defesa Cibernética (ComDCiber), Escola de Comando e Estado-Maior do Exército (ECEME), and the National Network of Quantum Research (also known as Rede Rio Quântica [RRQ], the first Brazilian quantum network). They all have become increasingly engaged in this field (Brasil, 2025d). Through research projects, training initiatives, and partnerships with universities, these institutions have sought to strengthen national capabilities in this area. However, challenges related to interoperability—the ability of different systems and organizations working together through efficient and integrated exchange of information (Mello, 2015)—still remain. Hence, civil-military cooperation is one of the key mechanisms to overcome these challenges.

Against this backdrop, this study addresses the following question: how do Brazilian military institutions contribute to the development of civil-military cooperation in QT for national defense? Its main objective is to analyze the role of military institutions in civil-military relations within the development of QT in Brazil's defense sector. To that end, the study pursues three specific objectives: (1) to describe how institutions have developed models for the use of QT in defense; (2) to examine the operation of existing defense initiatives; and (3) to propose recommendations for strengthening civil-military cooperation as a strategy for technological development in the sector.

This study adopts a qualitative, exploratory approach (Godoy, 1995; Gil, 2008). Its methodological design relies on source triangulation as a strategy for enhancing analytical robustness (Abdalla et al., 2018; Azevedo et al., 2013) and is structured around three pillars: document analysis, literature review, and institutional data collection.

The first pillar examines official national defense strategic planning documents selected for their normative relevance and their role in guiding public policy in the sector. The analysis includes the 2008, 2012, and 2020 editions of the National Defense Strategy (NDS) and the 2012 and 2020 editions of the National Defense Policy (NDP). Particular attention was given to references to strategic technologies, scientific capacity-building, and civil-military cooperation arrangements.

The second pillar consists of a review of the literature on defense innovation, civil-military relations, and QT. Searches were conducted in the Web of Science, Scopus, ScienceDirect, IEEE Xplore, CAPES Journal Portal, and Google Scholar databases. The selection criteria prioritized publications linking technological, institutional, and national security dimensions, with particular emphasis on empirical and comparative studies. The search strategy employed structured keywords in both English and Portuguese, including "Quantum Technologies," "National Defense," "Civil-military cooperation," "Defense innovation," and "Brazilian defense policy."

The third pillar involved collecting data from Brazilian military and scientific institutions directly engaged in QT, namely IME, ECEME, the RRQ, and the *Inteligência Artificial e Tecnologias Quânticas* (IATQ) project. Sources included institutional documents, project reports, and publicly accessible technical materials.

Triangulation was achieved through the convergence and comparison of these three pillars. Official documents provided the normative framework, the literature supplied the analytical foundation, and institutional data offered empirical evidence on ongoing initiatives. The international examples discussed throughout the article serve an illustrative analytical purpose, helping contextualize the strengths and limitations of the Brazilian model in light of more established experiences elsewhere rather than constituting in-depth case studies.

Although the Triple Helix model provides an important analytical lens for understanding these dynamics, civil-military cooperation in the field of QT extends beyond this framework. Other innovation pathways coexist, including linear models of technology transfer and initiatives led directly by the private sector. In the specific case of defense-related QT—classified as critical and sensitive technologies—a stronger degree of coordination among the state, military institutions, and academia can be observed, given the technical complexity, high costs, and strategic implications involved (Etzkowitz; Zhou, 2017).

The relevance of this study lies in the need to understand how national defense modernization can be advanced through coordination among academia, industry, and government. Building quantum capabilities requires a long-term vision, sustained investment, and synergy across different sectors of the state. By examining the role of military institutions at this interface, the study contributes to debates on the development of a native technoscientific defense base.

At the same time, an important gap remains in the specialized literature. Research on defense-related QT has focused predominantly on the strategies of major powers such as the United States and China, without considering the role of military institutions in developing countries in fostering national quantum innovation ecosystems (Krelina, 2021; Parker et al., 2022).

Likewise, the literature on civil-military cooperation in Brazil has concentrated on well-established sectors such as the nuclear, aerospace, and cyber domains, without systematically addressing QT as an emerging driver of this relationship (Hing, 2010; Moura, 2024). The intersection of these two agendas—the role of Brazilian military institutions in promoting civil-military cooperation in the quantum domain—remains largely unexplored in both national and international scholarship. This study addresses such gap by examining initiatives, institutional arrangements, and challenges that shape such cooperation in the Brazilian context.

2 QT AND THE DEFENSE SECTOR

By the end of the nineteenth century, classical physics was confronting theoretical problems that could not be resolved using existing conceptual tools. Phenomena such as blackbody radiation, the photoelectric effect, and atomic stability exposed important gaps in prevailing theories. In this context, Planck (1858–1947) proposed in 1900 that energy is not emitted continuously but rather in discrete packets known as quanta (Carson, 2000).

In 1905, Einstein (1879–1955) extended this idea by explaining the photoelectric effect, demonstrating the particle-like behavior of light, and contributing to the concept of the photon. In 1913, Bohr (1885–1962) incorporated quantization into his atomic model, proposing that electrons orbit the nucleus in discrete energy levels and that transitions between them explain atomic spectra (Kragh, 1999).

Between 1925 and 1928, quantum mechanics was formulated with the work of Heisenberg (1925), Schrödinger (1926), and Dirac (1928). Heisenberg developed matrix mechanics, Schrödinger formulated the wave equation that bears his name, and Dirac unified quantum mechanics with special relativity. These contributions established the formal foundations of the First Quantum Revolution, introducing concepts such as superposition, entanglement, and the uncertainty principle, the latter eliminating the notion of absolute predictability in the physical universe (Chibeni, 1992; Jammer, 1966).

The Second Quantum Revolution ushered in a new era centered on the manipulation of individual particle states, particularly entanglement, which became the foundation of contemporary advances in quantum computing, quantum cryptography, and ultra-precise metrology (Intonti, 2024). During the 1980s, Feynman (1918–1988) argued that only a system governed by quantum laws could efficiently simulate another quantum system, laying the groundwork for quantum computing and influencing the application of superposition and entanglement to computational tasks (Caldeira, 2018). At the same time, Bennett and Brassard proposed the BB84 protocol in 1984, establishing the foundations of quantum cryptography by demonstrating that quantum mechanics could enable fully secure communications, thereby consolidating one of the central fields of this new revolution (Rigolin; Rieznik, 2005).

The rise of QT in defense represents a quiet yet profound strategic transition whose implications extend far beyond the introduction of new equipment and reshape the informational, sensory, and decision-making foundations of the armed forces. Quantum computing, ultra-sensitive

sensors, and secure communications have emerged as sources of functional superiority, dramatically enhancing the precision, speed, and security of military systems (Krelina, 2021).

In the field of communications, quantum key distribution (QKD) offers unprecedented levels of security by enabling the detection of any interception attempt, shifting cryptography away from approaches based solely on computational complexity (Krelina, 2021). Protocols such as QKD ensure the immediate detection of eavesdropping attempts, providing a significant strategic advantage in sensitive operational environments (Neumann; van Heesch; de Graaf, 2023).

However, the incorporation of these technologies presents significant challenges. The vulnerability of orbital systems to directed-energy weapons and electromagnetic interference highlights the need for robust architectures and sophisticated defensive systems. Moreover, advances in quantum processors capable of breaking conventional encryption require investments in post-quantum cryptography and resilient security protocols. Thus, although many of these innovations remain experimental, their potential demands continuous monitoring and assessment (Krelina, 2023).

Within this technological race, the United States and China have emerged as global leaders. According to Julienne (2024), China has promoted the application of QKD with initiatives such as the Jing–Hu Trunk Line, considered the largest terrestrial quantum communication infrastructure in the world. Extending more than 2,000 kilometers of optical fiber between strategic cities such as Beijing and Shanghai, the network enables the secure distribution of cryptographic keys based on quantum-mechanical principles, including entanglement and the impossibility of measurement without disturbing the system. In practice, any attempt to intercept communications can be immediately detected, substantially increasing transmission security. Beyond its scale, the Jing–Hu Trunk Line is integrated with other Chinese initiatives, including the Micius quantum satellite, forming a hybrid terrestrial-space architecture designed to build a national infrastructure for secure communications. This achievement placed China at the forefront of quantum communications and indicated the strategic use of these technologies to ensure information sovereignty, protect sensitive data, and strengthen geopolitical influence in the cyber domain. Major private firms such as Alibaba have abandoned their quantum divisions, while the Chinese government has sought to centralize the sector with state-owned enterprises, including the recently established China Telecom Quantum Group. These developments are compounded by increasing international isolation resulting from geopolitical tensions and Western sanctions, which have restricted access to strategic inputs such as dilution refrigerators (Julienne, 2024).

The United States has pursued a robust strategy to develop its quantum industrial base. According to the United States (2021), through the National Quantum Initiative, the country has invested heavily in research and development (R&D), with funding exceeding US$700 million in 2021 alone. These efforts are carried out by civilian agencies such as the National Science Foundation (NSF), defense organizations such as the Defense Advanced Research Projects Agency (DARPA), and intelligence institutions including the National Security Agency (NSA).

In the private sector, the United States has fostered a network of more than 180 companies. Many participate in partnerships involving universities and national laboratories, including the Quantum Economic Development Consortium (QED-C), aimed at accelerating

technological maturation and translating scientific advances into defense applications (Parker et al., 2022). Unlike China, the United States relies heavily on private-sector leadership in technological implementation. In the Asian country, by contrast, private firms play a more limited role, with only a small number of prominent companies, such as QuantumCTek and Origin Quantum (Parker, 2024).

In 2024, the global quantum industry generated approximately US$1.5 billion in revenue from quantum computing and sensing technologies, with annual growth projected at roughly 25%. This expansion is supported by an ecosystem employing more than 200,000 professionals and backed by US$2.6 billion in private investment and US$44.5 billion in public funding (SRI International, 2024).

At the same time, China has consolidated a dominant position in quantum communications with its extensive QKD network and the Micius satellite, investing more than US$15 billion in public research in this field. In quantum sensing, the country remains broadly competitive with the United States, although it still trails in quantum computing, where the United States retains advantages in both hardware development and research quality (Omaar; Makaryan, 2024).

Technological supremacy has become a strategic imperative for preserving U.S. global influence, particularly amid intensifying competition with China. The close relationship between innovation and national defense requires coordinated action to secure supply chains, develop human capital, and accelerate the translation of basic research into practical applications (Schmidt, 2023).

Brazil has taken initial steps toward fostering research on QT with defense applications through initiatives involving both civilian and military institutions. Among the most significant milestones are the IATQ project, the Pró-Defesa V program, the RRQ, and the growing role of institutions such as IME, ComDCiber, and ECEME.

Funded by Pró-Defesa V (CAPES/Ministry of Defense), the IATQ project seeks to develop a research network focused on disruptive technologies—understood as those capable of generating significant shifts in existing technological paradigms and creating new strategic and operational capabilities (Girardi; França Junior; Galdino, 2024). Artificial intelligence and QT constitute the core pillars of this initiative. The project is organized around four dimensions: strategic studies and public policies applied to defense; science, technology, and innovation applied to defense; research, development, innovation, and evaluation; and capacity building.

IATQ brings together institutions including IME, the Instituto de Tecnologia Aeronáutica (ITA), ECEME, the Air Force University (UNIFA), the Escola Superior de Guerra (ESG), and the Escola Superior de Defesa (ESD), as well as the Universidade de São Paulo (USP), Universidade Federal de Pernambuco (UFPE), Universidade Federal do Rio de Janeiro (UFRJ), Universidade Federal do Amazonas (UFAM), Universidade Federal de Santa Catarina (UFSC), and Universidade de Brasília (UnB).

At the same time, the RRQ represents one of Latin America's leading quantum infrastructure initiatives by establishing a secure communication system based on QKD over optical fiber networks. Coordinated by Professor Antonio Zelaquett Khoury (IF/UFF), the network brings together institutions such as the Universidade Federal Fluminense (UFF), the Centro

Brasileiro de Pesquisa Física (CBPF), IME, and ITA, while also benefiting from the strategic oversight of ComDCiber.

The network Rede Hermes Quântica is a pioneering IME project aimed at establishing a metropolitan quantum communication network based on QKD. Beyond testing the technical feasibility of quantum cryptography in Brazil, the initiative seeks to assess its application to military command-and-control networks and other critical communications systems, thereby enhancing the resilience of the Brazilian defense system against cyber threats and emerging technologies (Brasil, 2024a).

IME concentrates its efforts on research and technological development, whereas ComDCiber and ECEME play coordinating roles by connecting stakeholders and integrating these technologies into strategic defense requirements. Longo and Moreira (2013) argue that Brazil's defense sector still operates within an innovation system under construction, in which military institutions often fill roles that, in more advanced countries, are typically performed by a well-established private industry. This characteristic is even more evident in the quantum field given the early stage of Brazil's quantum ecosystem.

The quantum race, already intensifying among the major powers, requires states to adopt proactive policies aimed at strengthening scientific ecosystems and integrating civilian and military capabilities. In Brazil, existing initiatives remain embryonic but point toward promising opportunities. Their success, however, depends on institutional coordination, sustained investment, and a long-term strategic vision (Abelém, 2026). In this context, deeper cooperation between civilian and military sectors emerges as a critical condition for facilitating knowledge transfer, accelerating technological maturation, and ensuring that quantum applications remain aligned with national defense objectives. The next section examines this issue by exploring the foundations, challenges, and opportunities of civil-military cooperation in the field of QT.

3 CIVIL-MILITARY COOPERATION AS A DEFENSE INNOVATION STRATEGY

Defense plays a fundamental role in a country's security and sovereignty. It encompasses a complex network of relationships among public and private institutions and firms. In this context, interaction between civilian and military sectors—commonly referred to as civil-military cooperation (CIMIC) or civil-military duality—has gained increasing prominence in Brazilian policy documents such as the NDP and the NDS. These documents emphasize that cooperation between the two sectors is essential for strengthening the Defense Industrial Base (DIB), enhancing technological autonomy, expanding national productive capacity, and improving industrial competitiveness (Brasil, 2020).

CIMIC may be understood as the structured interaction between civilian actors (including universities, research centers, and technology-based firms) and military institutions (such as the armed forces, military research institutes, and doctrine centers) for the development of shared capabilities. In the defense sector, this cooperation is driven both by demand for dual-use technologies and by the need to optimize resources while reducing dependence on foreign technologies (Hing, 2010).

Brazilian military institutions promote civil-military cooperation in quantum technology development via an interconnected set of institutional initiatives, strategic projects, and scientific partnerships that extend beyond formal cooperation mechanisms. This collaboration is not limited to institutional agreements; rather, it takes shape through the creation of tangible technological capabilities, the formation of research networks, and the development of scientific infrastructure aimed at strengthening national technological sovereignty. In this regard, IME has emerged as a key hub linking the defense sector to the civilian scientific community through partnerships with institutions such as Universidade Federal de São Carlos (UFSCar), USP, Centro Integrado de Manufatura e Tecnologia (CIMATEC), Instituto Federal do Amazonas (IFAM), UFPE, Centro Nacional de Pesquisa em Energia e Materiais (CNPEM), and universities associated with the RRQ (Brasil, 2024a).

This cooperation is reflected in projects such as Rede Rio Quântica (RRQ) and the Rede Hermes Quântica (RHQ). While the RRQ represents an initial effort to build institutional coordination and experimental capabilities, the RHQ introduces advanced technological challenges aimed to establish an infrastructure of quantum communications with strategic applications. Together, these initiatives help organize Brazil's scientific and technological environment while creating critical competencies for future advances in QT (Moreira; Carneiro; Galdino, 2025).

Within this context, the establishment of the Brazilian Army's QT Laboratory at IME represents a strategic milestone for the defense sector and one of the country's most significant investments in the field. The laboratory supports research on quantum communications and sensing technologies, with the goal of mastering the entire development cycle, from basic research to military applications. Projects such as the development of single-photon emitters intended for the future implementation of the RHQ illustrate how civil-military cooperation can generate tangible technological outcomes (Brasil, 2024a).

Moreover, civil-military cooperation is also strengthened through scientific production and knowledge exchange between civilian and military communities. Researchers affiliated with IME have contributed to strategic debates on QT, as evidenced by recent publications addressing the topic from the perspective of national sovereignty, including Oliveira, Azevedo and Moreira (2025), Costa, Azevedo and Moreira (2025), and Carneiro (2024). This dimension encompasses the construction of research agendas, the definition of strategic priorities, and the consolidation of an epistemic community focused on defense issues.

From a territorial and strategic perspective, efforts to expand these networks into sensitive regions such as the Amazon also deserve attention. Through integration with the Amazônia Conectada infrastructure program, plans for a metropolitan quantum network in Manaus, developed in partnership with local universities and funding agencies, demonstrate that civil-military cooperation is likewise organized around geopolitical and national integration objectives. Such initiatives extend the reach of QT beyond Brazil's principal research centers (Brasil, 2024c).

Based on these experiences, civil-military cooperation in the field of QT has already become an expanding reality in Brazil, supported by concrete projects, strategic investments, and increasing institutional coordination. It represents an active process of capability-building in

which military institutions play a significant role in coordinating, fostering, and applying scientific knowledge in support of national defense.

The NDP and the NDS have undergone several revisions over time. Although they represent different versions of the same policy framework, all emphasize the importance of civil-military integration. The dual nature of the sector refers to the functional interdependence that exists throughout the research, development, production, and application of defense-related technologies. This relationship enables the sharing of technical expertise, infrastructure, and innovation, generating mutual benefits for both the military establishment and the civilian productive sector (Brasil, 2008).

Effective management of CIMIC activities requires a supportive institutional environment characterized by incentive policies, sustained funding, and a shared strategic vision. In the case of QT, whose technical complexity and development costs are particularly high, CIMIC becomes not merely desirable but essential. Brazilian military institutions such as the Institute for Advanced Studies (IEAv), IME, and the Army Technological Center (CTEx) have played an important role in promoting civil-military cooperation in the field of emerging technologies. These organizations serve as bridges between civilian academic research and the strategic demands of the defense sector (Brasil, 2025c).

Several institutional arrangements have been employed to facilitate civil-military cooperation in Brazil. These include: (1) Technical Cooperation Agreements (TCAs) between universities and military commands; (2) thematic research networks, such as those organized under the National Strategy for Science, Technology and Innovation (ENCTI); and (3) projects associated with the Brazilian Navy and Air Force, including seminars on disruptive innovations and the Núcleo de Excelência em Ciências e Tecnologias Quânticas (Brasil, 2023c), with a particular focus on cryptography and secure communications.

One example is the project to develop quantum sensors for submarine detection. The initiative brings together civilian researchers and military engineers and is intended for use in tactical systems deployed on drones and naval vessels, including submarines, using entirely domestic technology (Brasil, 2016).

One of the most important projects currently underway at IME is the country's first quantum cryptography network. The RRQ is capable of transmitting quantum bits (qubits) through optical fiber and free-space laser links. A green laser beam visible across Guanabara Bay connects the Physics Institute of the Universidade Federal Fluminense (UFF) in Niterói to the CBPF in Urca as part of the RRQ. In addition to this free-space connection, the network links institutions such as the Universidade Federal do Rio de Janeiro (UFRJ), the Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), and IME through optical fiber infrastructure. Under testing since 2021, the project seeks to ensure secure data transmission through quantum cryptography (Lopes, 2024).

Another important initiative linking civilian and military sectors in defense innovation was the Defense Technologies Seminar organized by the Defense Products Secretariat (SEPROD) of the Ministry of Defense on May 12–13, 2021. The event brought together representatives from the armed forces, academia, industry, and research centers to discuss advances in quantum computing and communications. During the opening session, then Navy Commander Admiral Almir Garnier dos Santos emphasized the historical importance of technological innovation in

transforming military operational capabilities, underscoring the central role of science in defense strategy (Brasil, 2025c).

At the same event, the then director of IEAv, Air Force Colonel Fabio Almeida, presented a study on secure communication systems for the aerospace sector, which examined quantum communication technologies already tested or operational on aircraft and orbital platforms. The study identified at least ten successful international experiments using the exchange of atomic particles to establish secure communications among crewed vehicles, satellites, and ground stations. This initiative highlights the armed forces' institutional capacity to monitor, assess, and potentially absorb cutting-edge technologies, thereby strengthening the security of military communications while creating opportunities for partnerships with civilian institutions in the development of quantum applications tailored to national needs (Brasil, 2025a).

Beyond these initiatives, the ComDCiber has played an important role in coordinating Brazil's quantum technology ecosystem, particularly through the meeting *Encontro Nacional de Tecnologias Quânticas para a Defesa* [Nacional Meeting of Quantum Technologies for Defense]. The event brings together representatives from the armed forces, academia, industry, and government agencies to map existing capabilities, discuss strategic applications, and promote civil-military cooperation. In this context, ComDCiber acts as a coordinating body, fostering integration among stakeholders and directing attention to critical issues such as quantum-domain cybersecurity and secure communications development (Centro Brasileiro de Pesquisas Físicas, 2023).

Despite recent progress, CIMIC faces several important challenges: (i) the lack of political and budgetary continuity, as changes in government frequently lead to shifts in science and technology priorities that affect the stability of joint projects; (ii) cultural and institutional barriers, since differing organizational cultures in civilian and military institutions can hinder communication and collaborative project management; and (iii) a shortage of specialists in QT in both civilian and military sectors, requiring policies aimed at training and retaining qualified personnel (Rusinelli; Souza; Miano, 2024).

Brazilian defense policy has historically been characterized by discontinuity across governmental cycles, undermining long-term projects such as those involving QT (Silva; Souza, 2021). Without permanent mechanisms for funding and coordination, civil-military cooperation tends to rely on isolated initiatives, limiting the accumulation of capabilities over time.

If these challenges can be addressed, CIMIC may offer significant potential for building a strong, native, and competitive technological base in the defense sector. The combination of civilian scientific and technical expertise with the organizational and logistical capabilities of the armed forces can accelerate the development of critical technologies, including quantum sensors, quantum cryptographic systems, and ultra-secure communication networks (Moura, 2024).

From a comparative perspective, the United States and China have sustained their quantum technology efforts through long-term investment and strategic coordination (Parker et al., 2022; Julienne, 2024). Brazil, however, has yet to establish similar conditions. In this context, civil-military cooperation represents the country's primary pathway for advancing QT,

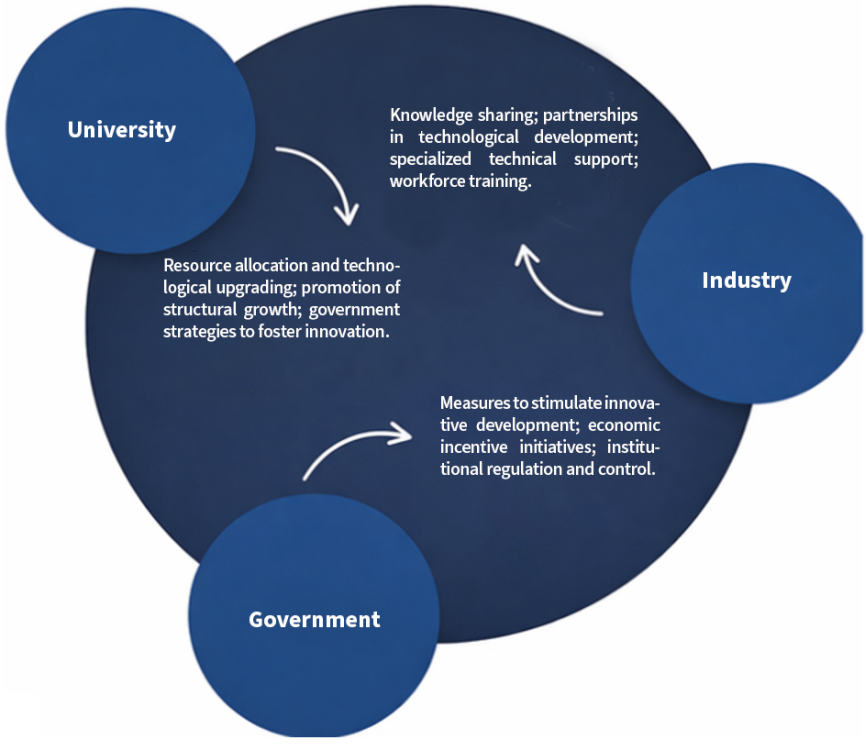
compensating for the absence of a robust private-sector ecosystem and an integrated national strategy for the field.

Strengthening cooperation between civilian and military sectors in research and technological development related to QT requires coordinated action. This effort depends on public policies that encourage collaboration among universities, research centers, industry, and defense institutions, as well as sustained investment in infrastructure, human capital development, and knowledge transfer. Integration among these sectors is essential for building a robust innovation environment capable of transforming scientific discoveries into strategic applications and advancing the development of QT in Brazil.

4 CONSIDERATIONS ON CIVIL-MILITARY COOPERATION IN QT

The development of new disruptive technologies and their adaptation to Brazilian military doctrine require alignment among the various institutions and organizations that make up society. Triple Helix Theory examines the interaction among universities, government, and the productive sector. Applying this framework to the analysis of disruptive technologies offers a useful perspective, as it recognizes that innovation in its purest form is no longer the exclusive outcome of a single institutional sphere (Etzkowitz, 2017). The theory argues that effective innovation depends on collaborative interaction among universities, industry, and the state, with aligned objectives across all actors (Figure 1).

Figure 1 –Triple helix



Source: The authors, based on Etzkowitz (2017).

Regarding the industrial sector, startups, deep-tech firms, and established companies can collaborate with university laboratories to accelerate innovation and internalize quantum capabilities. Such collaborations are essential for shortening the cycle between basic research and commercial application, enabling knowledge generated in academia to be rapidly tested, adapted, and transformed into high-value products and services. They also provide access to highly qualified talent, shared use of advanced scientific infrastructure, and participation in collaborative R&D projects. This strategic engagement further supports the creation of innovation ecosystems focused on QT, in which continuous interaction among research, application, and market actors becomes a source of national competitive advantage (Costa; Souza; Castro, 2020).

The practical application of the Triple Helix model in defense-related QT is reflected in the concrete collaboration among universities, military institutions, and the productive sector, spanning basic research through the implementation of strategic solutions. In Brazil, this dynamic can be observed in the activities of IME, which, in partnership with institutions such as UFSCar, USP, UFPE, and research centers such as CNPEM, develops projects in quantum communications and quantum sensing aligned with national defense requirements. Government programs such as Pró-Defesa, highlighting the state's role as both financier and coordinator (Brasil, 2024a), frequently support these initiatives.

Moreover, projects such as the RHQ and efforts to establish infrastructure in the Amazon region demonstrate how this cooperation translates into practical applications involving knowledge transfer, technological development, and testing in operational environments. In this sense, the Triple Helix extends beyond a theoretical framework and becomes an institutional arrangement capable of integrating scientific expertise, operational capabilities, and strategic interests, fostering innovation in sensitive areas and strengthening national technological sovereignty.

Within this context, the Triple Helix provides an appropriate framework for understanding and guiding innovation dynamics in QT. The formation of interinstitutional consortia, applied research networks, and shared innovation environments therefore represents concrete expressions of this collaboration, whose synergy is indispensable if Brazil is to achieve a leading position in the so-called Second Quantum Revolution.

Within the Triple Helix framework, universities play a central and multifaceted role, particularly in the field of QT. Beyond generating knowledge, they function as active agents of innovation, fostering strategic interactions with industry and government to advance the country's scientific and technological development. Universities are responsible for producing foundational knowledge in fields such as quantum mechanics, materials science, and information theory, thereby providing the scientific basis upon which technological innovations are built. They also contribute to the training of highly qualified human capital, preparing researchers, engineers, and technicians capable of working in both academia and industry and sustaining a robust and competitive innovation ecosystem (Sabato; Botana, 1975).

The growing interaction between universities and industry has generated applied research, prototype development, technology transfer, patent creation, and science-based startups,

particularly in quantum computing and communications. Universities also contribute directly to the state by participating in public policy formulation, providing technical expertise to government agencies, and leading strategic initiatives such as centers of excellence and interinstitutional research networks.

These institutions further support the internationalization of science by establishing global partnerships and participating in multilateral research networks, ensuring that the country remains connected to the most advanced frontiers of knowledge. Universities therefore occupy a strategic position within the innovation triad and are indispensable to strengthening national scientific and technological sovereignty (Rothwell, 1994).

The productive sector plays an important role within the Triple Helix dynamic, particularly in advancing QT, by transforming university-generated knowledge into scalable, applicable, and economically viable solutions. Established firms, startups, deep-tech companies, and high-technology industries serve as bridges between research and market application. This goes through investments in experimental development, technical validation, prototype design, advanced manufacturing, and commercialization.

The productive sector also contributes with direct investment in R&D, whether via internal innovation centers, partnerships with universities, or participation in public incentive programs. In addition, it plays a significant role in creating highly skilled jobs and providing practical training opportunities via internships, technological residency programs, and technical training initiatives (Schreiber, 2013).

In the field of QT, industry is essential for scaling prototypes developed in academic settings, testing them under real-world conditions, and carrying out the steps required for market deployment, including certification, standardization, and industrialization. Companies may also assume leadership roles in collaborative innovation projects by organizing industrial consortia or participating in networks involving universities and public research institutes such as IME. By absorbing emerging technologies and internalizing scientific and technological capabilities, the productive sector strengthens national competitiveness and technological autonomy, serving as a strategic driver of the Second Quantum Revolution (Brazilian Agency for Industrial Development, 2025).

Within the Triple Helix framework, government performs a strategic and coordinating role in the innovation process, particularly in the development of emerging technologies. Its involvement is essential for creating the institutional, economic, and regulatory conditions necessary for effective cooperation between universities and industry (Etzkowitz, 2017). First, government acts as a formulator of public policies and national strategies capable of guiding long-term scientific and technological development. Initiatives such as national quantum computing and communications programs illustrate this role by reducing technological uncertainty, directing investment, and establishing strategic priorities for the country (Dorff; Meyer, 2006).

The state also serves as a risk-financing actor, supporting research and development through funding agencies, grants, subsidized credit, scholarships, and tax incentives. This role is particularly important in frontier fields such as QT, where costs are high, returns uncertain, and private investment remains limited (Rodrigues; Libero, 2024). Another important function

is that of regulator and facilitator, involving the creation of legal and regulatory frameworks that support innovation, intellectual property protection, technology transfer, and legal certainty in public-private partnerships.

Government may also act as a qualified demander of innovation, particularly through public procurement in sectors such as defense, healthcare, telecommunications, and cybersecurity, thereby contributing to the validation and scaling of emerging technologies. This role is evident in initiatives such as the Ministry of Science, Technology and Innovation's (MCTI) QT program, which includes the development of a QT Laboratory at CBPF. The project aims to establish a facility dedicated to the fabrication, characterization, and operation of quantum bits and other superconducting devices (Brasil, 2025b).

Examples such as this illustrate the government's role in human capital development through support for educational programs, interdisciplinary graduate training, international exchanges, and access to advanced scientific infrastructure. Its integrated action alongside universities and industry is therefore indispensable for positioning the country competitively and sovereignly in the global race for leadership in QT. In this context, the articulation of the Triple Helix should not merely be encouraged but strategically and continuously structured to consolidate a national quantum innovation ecosystem (Brasil, 2023b).

The creation of public policies that encourage investment in frontier research, together with funding mechanisms specifically designed for quantum-based startups, is essential for transforming scientific knowledge into economically viable applications. Moreover, the active participation of the state as regulator, financier, and, in many cases, first customer—particularly in defense, telecommunications, and information security—can reduce technological uncertainty and attract private capital to high-risk projects (Brasil, 2024b).

In turn, human capital development should be treated as a national priority. This objective can be pursued through interdisciplinary graduate programs, international exchanges, and educational initiatives aimed at training specialists in quantum science and engineering.

The consolidation of a strong scientific base, combined with technological application capabilities and sustained state support, is what will enable Brazil not only to keep pace with, but also to influence the direction of quantum innovation on a global scale. In this sense, the Triple Helix is not merely an explanatory theory but a practical framework for designing technological development strategies that integrate capabilities and strengthen the country's scientific and economic sovereignty.

QT stem primarily from the so-called Second Quantum Revolution, characterized by the precise control and manipulation of individual quantum systems such as atoms, ions, photons, and quasiparticles. Unlike the First Quantum Revolution, which gave rise to technologies now widely disseminated—including semiconductors, lasers, and nuclear energy—the new revolution enables disruptive technological leaps. In other words, it introduces innovations that significantly transform existing capabilities, reshaping operational, strategic, and technological paradigms by replacing or surpassing previous technologies, particularly in areas considered critical to defense (Girardi; França Junior; Galdino, 2024). These transformations directly affect sensing, secure communications, navigation, and high-performance computing (LevelQuantum, 2023).

Although still at relatively early stages of technological readiness levels (TRLs), these technologies are widely recognized for presenting dual-use, with substantial overlap between

civilian and military applications. This convergence creates urgent demands for cooperation strategies linking both sectors (LevelQuantum, 2023).

Civil-military partnerships in the development of disruptive technologies can reduce technological asymmetries in the international arena. IME has developed a single-photon emitter for quantum communications designed to provide the foundation for ultra-secure quantum communication systems, strengthening the DIB and reducing external dependence. The project is based on cooperation among IME, UFSCar, and CNPEM, with contributions from UFSCar in nanostructure development and from the National Synchrotron Light Laboratory (Brasil, 2024a).

The development of the single-photon emitter at IME is directly linked to national quantum communication initiatives such as the RRQ. This type of device constitutes a fundamental component for implementing QKD protocols by enabling the controlled generation of quantum states of light. Although still experimental, these developments contribute to the validation and improvement of secure communication infrastructures based on quantum-mechanical principles in Brazil (Brasil, 2024a).

The institutions involved have enabled projects such as the single-photon emitter, one of IME's earliest initiatives in QT. Its objective was to develop a proof of concept for a metropolitan network based on quantum communications. Civil-military collaboration is essential to the project because it combines the technical expertise of universities and research centers with the operational requirements of the armed forces, following internationally adopted models such as NATO's initiatives to accelerate dual-use quantum solutions in partnership with startups (Otan/Nato, 2022). In the Brazilian context, the implementation of MCTI development plans alongside the participation of civilian researchers demonstrates how this synergy accelerates both technological development and validation in real defense environments (Carneiro, 2024).

IME is also involved in the Quantum Program, which encompasses three major initiatives. First is the Brazilian Army Center for Quantum Technology Development. The second is the DECEx Pro-Research project entitled Study of the Impact of Artificial Intelligence and QT on the Preparation and Employment of the Land Force. The third is the CAPES Pró-Defesa program entitled Artificial Intelligence and QT: Building and Integrating Research Agendas and Networks in Disruptive Technologies to Enhance and Expand National Security and Defense, conducted in collaboration with 42 additional institutions (Rodrigues; Libero, 2024).

Other institutions, such as ECEME, also carry out activities that bridge civilian and military sectors in order to develop critical thinking on QT. Its graduate program includes academic master's, PhD, and postdoc studies, with research lines focused on strategic studies and defense. While IME concentrates on the technical dimensions of QT, ECEME addresses the questions of why, when, and where these technologies should be employed. This role is vital for guiding investment decisions, doctrinal development, and institutional partnerships. Training strategic thinkers with technological literacy is one of the institution's principal objectives (Rodrigues; Libero, 2024).

The integration of military institutions makes it possible to align national defense interests with the country's scientific capabilities through collaboration with civilian institutions, fostering the development of dual-use technological solutions. Shared laboratory infrastructure, the exchange of scientific and technical knowledge, and the training of specialized personnel

improve the efficiency of implementing sensitive projects such as quantum communication networks. By institutionalizing this collaboration, Brazil advances toward greater technological autonomy, prepares for future cyber-threat scenarios, and strengthens its digital sovereignty in critical security domains (LevelQuantum, 2023).

ECEME has incorporated the Strategic Studies Cycle (SSC) as an important initiative for advancing military thinking on contemporary technological transformations (Brasil, 2025e). Through a series of courses and seminars, the SSC addresses topics such as quantum computing, quantum sensing, and secure communications not merely as scientific subjects but as key elements in the modernization of Brazilian military doctrine. The program is organized around thematic meetings that bring together military officers, civilian researchers, academics, and representatives of strategic institutions, including the Ministry of Defense, MCTI, IME, and the Amazon Protection System Management and Operational Center (CENISPAM) (Brasil, 2025b).

This multidisciplinary approach enables an integrated assessment of technological trends and their implications for armed forces capabilities. The studies adopt medium- and long-term perspectives, considering emerging technologies within the context of hybrid warfare (Fernandes, 2016), defense digital transformation, and the need for national sovereignty in sensitive areas. In addition, the SSC contributes directly to the development of military leaders capable of understanding and applying concepts derived from advanced science and technology while aligning them with the country's strategic requirements. In doing so, ECEME reinforces its role as a center of excellence in strategic thought, promoting a modern doctrine adapted to the challenges of the twenty-first century (Brasil, 2023a).

5 CONCLUSION

The findings indicate that QT have become a critical factor in national sovereignty and power projection in the twenty-first century. The analysis shows that Brazilian military institutions play an important role as catalysts of civil-military cooperation, acting simultaneously as users, coordinators, and developers of quantum technological capabilities.

The study found that IME has emerged as a center of technical excellence, developing pioneering projects such as the single-photon emitter and the RHQ, while establishing strategic partnerships with civilian universities and research centers. At the same time, ECEME has consolidated its position as a hub of strategic thought, incorporating the implications of QT into Brazilian military doctrine through educational programs and specialized study cycles.

The Triple Helix model helps explain the dynamics of quantum technology innovation in Brazil. The synergy among universities (producers of fundamental knowledge), industry (responsible for application and scalability), and government (provider of public policy and funding) proves essential for accelerating the development of national capabilities in an environment of intense international technological competition.

From a geopolitical perspective, the comparison between the strategies adopted by the United States and China revealed distinct approaches that nevertheless converge in their objectives regarding quantum technology development. While the United States relies on a diversified public-private innovation ecosystem, China has adopted a centralized model supported by large-scale state investment. Both approaches recognize that quantum leadership extends beyond scientific advancement and has become a decisive component of the contemporary international order.

For Brazil, the findings suggest that current quantum technology initiatives, although promising, require stronger institutional coordination, sustained investment, and a long-term strategic vision. The IATQ project, the RRQ, the initiatives associated with the ComDCiber (Centro Brasilieiro de Pesquisas Físicas, 2023), and the RHQ represent important milestones. However, their consolidation depends on strengthening civil-military cooperation through comprehensive public policies.

The study identified three priority challenges: (1) ensuring political and budgetary continuity for long-term projects; (2) overcoming cultural and institutional barriers between civilian and military sectors; and (3) developing scientific infrastructure capable of supporting emerging technological demands.

Accordingly, the study proposes several measures: institutionalizing permanent civil-military dialogue mechanisms; establishing multidisciplinary centers of excellence in QT; creating specialized training programs in partnership with universities; implementing public procurement policies for innovation that support the development of Brazil's DIB; and formulating a comprehensive national quantum technology strategy integrating defense, economic development, and science.

Civil-military cooperation contributes directly to the construction of Brazilian technological sovereignty. The ability to combine civilian scientific knowledge with military organizational capabilities will shape Brazil's position in the global hierarchy of power in the quantum era. In this regard, Brazilian military institutions strengthen the development of a technologically autonomous and competitive national defense environment by serving as agents of integration and innovation.

The quantum race is already underway and demands a proactive, coordinated, and forward-looking response from the Brazilian state, capable of transforming the country's scientific potential into effective strategic capabilities. The success of this process will depend on consolidating civil-military cooperation as a state policy, ensuring that Brazil plays an active role in shaping the future course of the global quantum revolution.

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