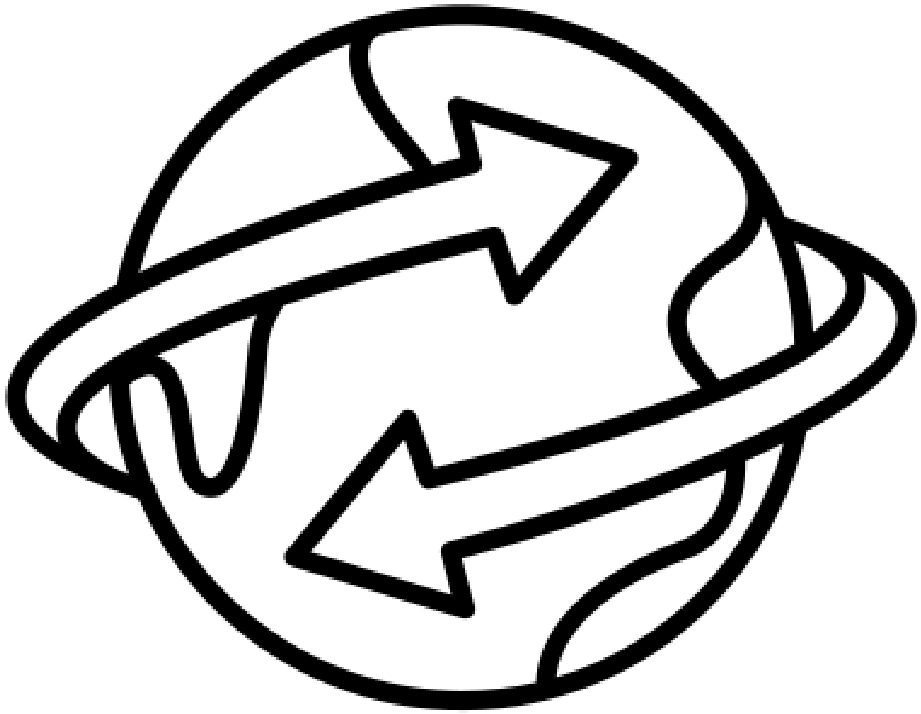
- Official Summary -



Critical Vulnerabilities in the Quantum Computing Supply Chain within the NATO Alliance

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This summary contains the following (parts of) chapters from the report:

“Critical Vulnerabilities in the Quantum Computing Supply Chain within the NATO Alliance”

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Conducted in the context of the NATO Transatlantic Quantum Community (TQC)

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1. Executive Summary

As part of the agenda of the Transatlantic Quantum Community (TQC), this report provides a comprehensive analysis of critical gaps and vulnerabilities in the quantum technologies ecosystem within the NATO Alliance. The study initially focused on quantum computing supply chains, employing a systematic methodology based on the SRI model for the Quantum Technologies Manufacturing Roadmap.

For this study we have developed ReQuEST, a Reusable Quantum Enabling Supply Chain tool that can be updated and potentially be used more broadly within the global quantum community. We have focused on quantum computing and have examined four key qubit modalities (Superconducting, Ion/Neutral Atoms, Photons, and Semiconducting Spin) alongside seven enabling technologies (Materials, Electronics, Lasers/Optics, Cryogenic/Vacuum systems, Controls, Transduction, and Software). The assessment utilized five key metrics to evaluate each component: supplier numbers within the Alliance, R&D leadership, scaling capability, IP position, and supply chain vulnerability.
The results of the systematic approach are captured in ReQuEST. In addition, a preliminary list is given of other relevant enabling conditions for the quantum technologies ecosystem as well as a comparison of the North American and European ecosystems, that may lead to additional vulnerabilities. Data collection involved industry reports, expert consultations, the internet and comprehensive reviews by leading experts in the field.

The analysis revealed several critical cross-cutting dependencies that pose significant risks to the quantum computing ecosystem within NATO. Most notably, the Alliance faces substantial challenges regarding semiconductor manufacturing supply chains (SMSC) and fabrication facilities (SMFF). There is a heavy reliance on non-NATO sources for rare earth elements, such as Erbium and Ytterbium, which are essential for various quantum components. The dependence on exotic materials, compounds and isotopes such as Niobium, Tantalum, Titanium, Lithium Niobate, Silicon-28 and Helium-3 presents another vulnerability, as these materials are often sourced from potentially unstable or non-allied regions.

In terms of technology-specific vulnerabilities, the study identified that over 90% of high purity material processing occurs outside NATO territories. The electronics sector shows considerable dependence on Asian fabrication facilities for advanced nodes, optical coatings and PICs, while the cryogenics field faces challenges with long lead times and a limited supplier base for critical components such as pulse tubes. The software domain experiences standardization issues and interoperability challenges across different platforms and systems.

Looking at the R&D position and possibility to scale the technology within the Alliance, it is noted that the position of NATO is mostly solid, with some fields in which non-NATO players are dominant, such as photodetection systems and Lithium Niobate processes. It should be noted that some qubit platforms are less mature, which means there are still several technical limitations and gaps in the supply chain, such as the need for environmentally stable laser systems, higher purity materials and more precise fabrication processes.

Key Recommendations

To address these vulnerabilities, the study recommends several strategic initiatives. Firstly, NATO should coordinate with existing semiconductor initiatives to address manufacturing risks that include needs for specialized chips (such as FPGAs and ASICs), electronics for lasers and control systems, and advance fabrication capabilities for ion traps, superconducting quantum chips, and, especially for semiconductor spin systems - the latter of which requires advanced fabrication capabilities. For the semiconductor spin systems it is recommended that Intel (US) and IMEC (EU) will be involved in this exercise given their interests and capabilities. *It is important to recognize that the semiconductor risk is spread through not only quantum specific fabrication capabilities but also the supporting supply chain hardware.* Separately, NATO should develop domestic capabilities for processing rare earth and exotic materials. This effort should focus on establishing secure supply chains for critical materials, even if only for minimal quantities needed for quantum applications.

Secondly, the Alliance should work to balance investment landscapes between North America and Europe, supporting European startups in scaling operations while maintaining stable base-level funding for the next decade. Interventions to impose barriers (tariffs, export controls) within the Alliance should be avoided. Thirdly, technical development efforts should focus on addressing non-NATO supply dependencies on components such as ion pumps, photodetectors and pulse tubes and on long lead times for critical components like dilution refrigerators.

For the model ReQuEST itself, it is recommended to update it regularly, and to implement improvements such as the division between the ion and neutral atom modalities and addition of qubits based on color centers and majoranas[1]. Lastly, it should be considered to expand the study to Quantum-HPC integration[2].

[1] *Color centers are point defects in crystals (e.g., nitrogen-vacancy centers in diamond) that trap electrons and can be used as qubits. Majorana-based qubits use non-Abelian quasiparticles—Majorana zero modes—in topological superconductors to encode quantum information; this approach is still in a nascent experimental stage.*

[2] *HPC–quantum computing integration refers to the coupling of high-performance classical computing systems with quantum processors, enabling hybrid workflows that leverage classical resources alongside quantum computation.*

2. Introduction

Goal

The objective of this study is to capture the critical gaps and vulnerabilities in the quantum technologies ecosystem within the NATO Alliance, with a focus on supply chains for the enabling technologies for quantum computers, quantum communication networks, and quantum sensors. The findings of the analysis are aimed to serve as an input to the work of the Transatlantic Quantum Community to allow for conclusions and potential follow-up actions to address identified gaps and vulnerabilities. This initial study focuses on quantum computing, follow-on studies are foreseen for quantum sensors and quantum networks.

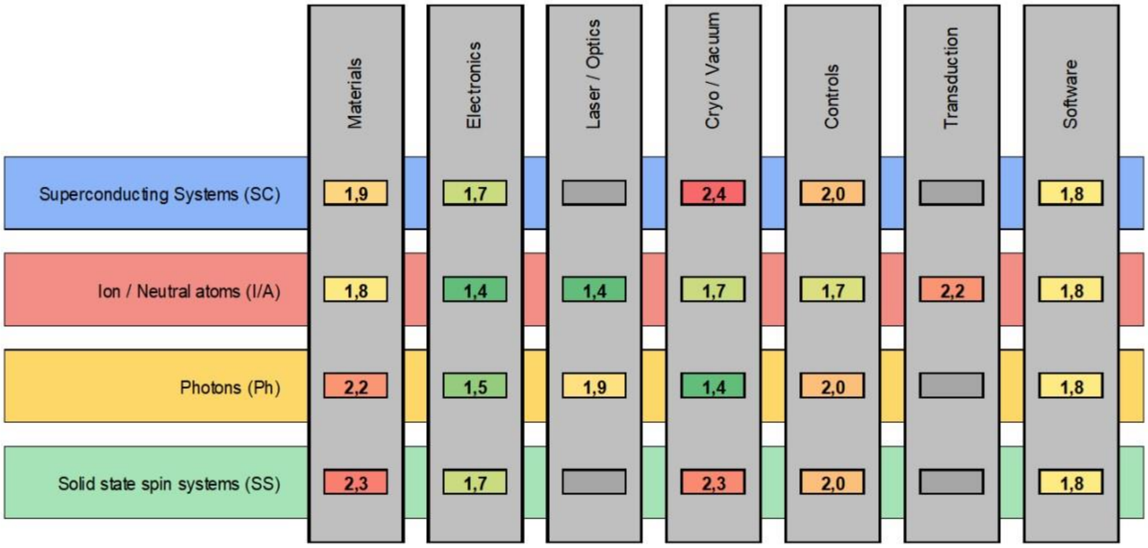
Approach

We have set up a Transatlantic team of CJW Quantum Consulting (Maryland) and Heijman Consultancy (Delft) to carry out the study, with the purpose to unlock as much knowledge and expertise from both North America and Europe as possible.
To contribute to the long-term development of the field and the NATO intelligence position, we have developed ReQuEST - a Reusable Quantum Enabling Supply Chain Tool, that can be updated and revised on a regular basis. This report contains the key findings of the model filled in for the field of quantum computing, complemented with qualitative assessments of other key enabling conditions and a comparison of the North American and European ecosystems. Based on the analysis the report identifies key vulnerabilities, pathways for solutions and concrete recommendations for follow-up.

3. Supply Chain Mapping for Quantum Computing

In this chapter, the results of the analysis are presented.

The primary objective of this analysis is to identify and clarify which parts of the quantum computing ecosystem are missing or underdeveloped within the Alliance. Consequently, this study focuses on critical dependencies—specifically, those components of the supply chain that require attention. Technologies or elements deemed to be "good enough" fall outside the scope, as they do not represent areas of concern or opportunity for improvement. Therefore, elements assessed as sufficiently developed or stable are not highlighted in the subsequent conclusions, allowing this study to maintain a targeted focus on areas in need of strategic improvement.



Final Matrix:
A score of 1.5 or less implies reasonably low risk, a score of 1.6-1.9 implies manageable risks, a score of 2.0 or greater suggests that attention needs to be paid. A black square implies that it is not applicable.

Enabling Conditions

In addition to the supply chain for the enabling technologies for the Quantum Computing modalities described in chapter 3, there are several facilities and conditions needed for the successful development and deployment of quantum computers within the Alliance. We have identified the following non-limitative list of important enabling conditions, with a qualitative assessment of the status within the NATO Alliance. In follow-on studies of the TQCthese aspects will be investigated more thoroughly, including the possibilities to address the vulnerabilities.

- Testbeds and Use Case Development
- Fabrication Facilities
- Talent Development
- Ethical and Regulatory Frameworks
- Investments
- Standardization and Interoperability
- Awareness and Readiness

Comparison of the North American and European Ecosystem

Based on the data we gathered on the supply chain of the enabling technologies for the various qubit modalities for quantum computing, there are some observations we can share about the balance and complementarity of the European side and the North American side of the NATO ecosystem. These are solely qualitative observations, that could require further analysis in possible follow-on studies when options for interventions are considered.

- Balanced supply chain with technical complementarity
- Vulnerabilities due to imbalance in investment landscape
- NA dominates in system integration

- Both ecosystems share dependencies on non-NATO allies

4. Vulnerabilities

The following key vulnerabilities are identified within the risk matrix. These are:

1. Semiconductor Manufacturing Supply Chain (SMSC) and Manufacturing Fabrication Facilities (SMFF): As NATO EU and NA have recognized over the past few years we have inadequate redundancy and capabilities in the semiconductor manufacturing space. This impacts the capability to scale and the suppliers supply chain for control systems for all qubit modalities. In addition, these capabilities are needed for ion trap fabrication and the fabrication of both superconducting and semiconductor spin quantum chips. The latter requires state-of-the-art fabrication capabilities. While there are some variations in control systems for various qubit modalities this remains a common risk. Additionally, electronics are also needed for laser systems and the control systems for cryogenics. This same risk also impacts the suppliers supply chain for electronics for the photonic qubit modality where the key facilities are IMEC and Global Foundries.

2. Dependency on rare earth elements: Rare earth elements such as Erbium (Er) and Ytterbium (Yb) relevant to photonic materials and neutral atoms.

3. Dependency on exotic materials: Exotic materials are found in electronics, and, on occasion, laser/optics and cryo/vacuum. Some of these transition metals are relevant to the fabrication of superconducting qubits along with Aluminum (Al); Alkali Metals and Alkaline Earths such as Strontium (Sr) and Rubidium (Rb) relevant to atom and ion trap quantum computing; and other materials essential to ion pumps and regenerators in cryostats and dilution refrigerators. In addition, some of these are compounds such as lithium niobate ($LiNbO_3$) and thin-film lithium niobate which are typically produced in Japan and China. Most of these exotic materials are sourced from the Global South or nonfriendly countries. In many cases, the high quality materials required are refined in China creating serious problems even when they are mined in a friendly country. Finally semiconductor spin qubits often require isotopically pure elements such as Silicon 28 (^{28}Si) or specific isotopes of Germanium, such as Germanium 70 (or more broadly Germanium depleted of Germanium 73), creating additional supply chain issues.

4. Dependency on ^{3}He: Helium 3 (^{3}He) is essential to dilution refrigerators and typically comes from the decay of Tritium (^{3}H), a radioactive isotope of Hydrogen (H), that typically comes from the nuclear weapons industry but also exists in some rare natural gas deposits.

5. Software Standardization: While there are significant efforts to allow cross platform compilation, the lack of standards, benchmarks, and other interoperability challenges prevent true comparisons.

6. Investment Landscape: As described above, the imbalance in the investment landscape including venture capital and internal investments by big tech creates an imbalance in both the startup scene and in the location of system integrators.

5. Conclusions and recommendations

This analysis has revealed several cross-cutting dependencies that pose significant risks to the quantum computing ecosystem within NATO.

Most notably, the Alliance faces substantial challenges regarding semiconductor manufacturing supply chains and fabrication facilities. We recommend that with regard to SMSC and SMFF that ongoing NATO efforts to address semiconductor manufacturing risks are addressed in a manner that also de-risks the quantum computing supply chain. To enable this, the NATO TQC could create a brief presentation or position paper on the essential needs that the quantum community requires. We recommend involving IMEC and Intel as European and NA actors in this dialogue.

In terms of technology-specific vulnerabilities, the study identified that more than 90% of high-purity material processing occurs outside NATO territories. Because the quantity of materials needed for ion and neutral atom quantum computing are relatively small, it could be possible to create a robust supply chain for these high-quality materials relatively cheaply.

Looking at the R&D position and possibility to scale the technology within the Alliance, it is noted that the position of NATO is mostly solid, with some fields in which non-NATO players are dominant, such as photodetection systems and Lithium Niobate processes.

The cryogenics field faces challenges with long lead times and a limited supplier base for critical components such as pulse tubes. One needs to work to shorten the lead time and also needs to guarantee that sufficient ^{3}He is available to support these systems. This is an issue that deserves an independent study.

There are also some key risks in the supply chain for components such as ion pumps, photodetectors, and pulse tubes. These probably can be de-risked through investments to create competitors for these products.

With regard to software, it is essential to create standards, benchmarks, and interoperability so that the one can achieve the full value of the software value chain. This includes being able to understand the strengths and weaknesses of various hardware platforms, different error correction schemes, different degrees of qubit connectivity, and other parameters. NATO could create a program that would encourage the development of standards and benchmarks.

Based on the identified vulnerabilities, recommendations are proposed including briefing documents to share within NATO to aid coordination on common problems, a few key studies, and a few targeted programs which are summarized briefly below:

Briefing Documents

- Key fabrication requirements for supporting superconducting systems
- Key fabrication requirements for supporting ion-trap systems
- Key fabrication requirements for supporting semiconductor spin systems
- List of critical materials needed for various quantum systems, whether rare earths, superconducting materials, or materials required for photonic systems and/or lasers and optics. **This excludes Helium-3, Silicon-28, and materials for atom and ion qubits.**
- List of critical components (such as pulse tubes, ion pumps, photodetectors) sourced from suppliers outside NATO within the quantum computing supply chain.

The goal of these briefing documents is to uplift NATO awareness and understanding with the goal of coordination with other ongoing NATO efforts to address semiconductor fabrication facilities and rareearth or other exotic materials within NATO. Each briefing should consist of a 2-page synopsis and a handful of slides.

Key Studies

- Develop an understanding of the key requirements needed to support the fabrication of semiconductor spin systems, including any specialized requirements for the successful integration of isotopically pure ^{28}Si into the process flow.
- Estimate the amount of ^{3}He that may ultimately be required and propose plausible pathways for obtaining the needed material.
- Estimate the amount of Silicon-28 that may be required and study the various approaches for producing the materials, including the pros and cons.
- Explore options for interventions to balance the investment landscape in NA with the EU specifically for the quantum technologies sector, as well as the possible interventions to avoid additional trade and export restrictions.

The goal of these studies is to provide either solutions or to inform NATO stakeholders on possible paths forward.

Targeted Programs

- Develop and fund a multinational effort aimed at software standardization and benchmarking to support the interoperability of quantum computing systems, and the evaluation of various hardware platforms, error correction schemes, and role of connectivity in an architecture.
- Explore and support a pilot program focused on producing the small quantity (less than 10 kg/year) qubit material needed to support neutral-atom and/or ion-trap quantum

computing, with a goal of understanding the feasibility and path toward technological independence. The proposers get to select the actual element.

- Continue to uplift an innovation program aimed at incentivizing new commercial activity to increase competitiveness within NATO for ion pumps, photodetectors, and pulse tubes.

These targeted programs are aimed at trying to address critical supply chain risks. The innovation program could involve NATO or NATO members innovation units contributing funding together with private or venture capital funds that would support innovation in these areas. A consideration could be to connect these programs to the NATO Innovation Fund.

Periodical update

Furthermore, we advise to update the ReQuEST model yearly to keep track of the dymanic quantum computing industry. This also allows for improvements in the model, such as the addition of colour centres and majoranas as qubit modalities, the separation of the ion trap and neutral atom qubit modalities and inclusion of the HPC-Quantum Computing Integration.