Quantum Technology Manufacturing Roadmap

Scaling Up Quantum

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Prepared for:

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Executive summary

Developments in quantum information science and technology (QIST) have the potential to dramatically affect multiple industries and radically shift the defense and intelligence capabilities of nations. Government, academic, and commercial entities are investing significant resources into QIST research and development (R&D), and rapid progress is being made in fields of quantum computing, sensing, and telecommunications. Realizing the full potential of QIST R&D will require the development of novel materials, devices, structures, and systems that can be manufactured at scale. As an emerging quantum industry takes shape, companies are developing internal roadmaps for specific quantum technologies, such as plans that anticipate slow but steady growth in the number of qubits available in the largest quantum computers. However, no industry-wide roadmap exists yet for quantum technology manufacturing.

To fill this gap, SRI International (SRI) and its team of industry, national laboratory, and academic partners has created a roadmap to support the development of technology critical to the scale-up of the quantum industry as a whole, including quantum computing, quantum sensing, and quantum telecommunications. This first-of-its-kind effort resulted in an initial quantum technology manufacturing roadmap (QTMR). The QTMR does not focus on scientific discovery. Rather, it focuses on a wide range of technologies and capabilities critical to QIST R&D and manufacturing, setting specific targets for technical performance for 2024 and 2028.

Creating the QTMR began with identifying the short-term (2024) and longer-term (2028) technology needs of quantum system developers. Quantum system developers included developers of quantum computing systems, quantum sensing systems, and quantum networking systems. A total of 43 broad needs were identified across six categories of quantum-relevant technologies:

- Materials and fabrication
- Electronics
- Lasers and optics
- Cryogenic and vacuum systems
- Control systems
- Testbeds

These 43 broad needs represent the prioritized list of most urgent needs from a longer list of needs identified by project participants. Within each of these 43 categories, system developers identified more detailed and specific technology and capability needs. There were between two and twelve needs identified by developers per technology category. Wherever possible, one or more technical performance targets were set for each need for 2024 and 2028, including such parameters as power, wavelength, and operating temperature.

Once the detailed needs were identified and described, technology providers reviewed each, providing extensive commentary on the prospect for meeting these needs over the 2024–2028 time horizon and insight into the challenges of meeting these needs. The result was a set of 43 individual technology roadmaps that together compose the overall QTMR.

Project discussion on the part of quantum system developers and their technology providers highlighted a range of issues affecting quantum technology manufacturing, including needs for basic research, the importance of refined manufacturing processes, business challenges, and policy issues. It is clear from these discussions that the quantum technology industry is still very nascent. There is not one universally used platform or approach, no standard configuration or set of components and materials. This lack of consensus in the industry is in part why 43 distinct needs were identified. The industry finds itself situated in a position in which many new industries find themselves: Suppliers are reluctant to invest in new technology until their customers—quantum system developers—are willing to commit to large sales volumes, but customers are reluctant to commit to significant purchases until they see the technology they need from suppliers and until the demand for their own products is clearer. A large share of the discussion across many of the 43 industry needs reflected this dilemma. These challenges typically resolve themselves as tipping points are reached, official and de facto standards are created, and dominant approaches emerge and refine the marketplace. The same will be true for QIST.

A challenge that applied to almost every identified need is the presence of tradeoffs. One major tradeoff for many identified needs is whether to choose an off-the-shelf component or software or pay a premium for a custom-built tool. Customized tools typically allow integrators more flexibility in the materials and configurations they employ, but the low purchase volume leads to high prices. This was especially true for control electronics, where tailoring them to meet one system integrator's unique needs and application makes them very costly.

Not surprisingly, many of the needs identified by project participants were not quantum per se, but technologies that are nevertheless central to quantum technology development. There were multiple non-quantum-technical needs related to software, including less complex software that can be used by technicians and open-source software. Additionally, several participants highlighted supply chain needs, such as greater domestic supply of components and higher quality materials.

In the context of roadmapping, QTMR is somewhat unique with respect to the maturity of the industry and scope of technologies assessed. A consequence of both these factors, views among industry participants regarding what is needed and what is achievable within a specific timeframe are more diverse. Accordingly, the roadmap presented herein is preliminary, though in most cases, is reflective of a consensus.

Future refinements should focus on developing roadmaps for individual quantum applications (i.e., communications and networking, computing, sensing) across which needs can vary considerably. The project team also recommends more extensive interaction between integrators and technology suppliers, including the latter in the process as early as possible. Finally, future iterations of the QTMR should seek more international involvement. Many countries have unique specializations, and including more experts will expand the comprehensiveness and usefulness of the roadmap.

Project background and approach

The emerging quantum industry

Research and development (R&D) in quantum information science and technology (QIST) is making rapid progress in the fields of computing, sensing, and telecommunications. Realizing the full potential of quantum technology will require the development of novel materials, devices, structures, and systems that can be manufactured at scale. An emerging quantum industry is taking shape, with early products entering the market and companies developing internal roadmaps for more complex systems, such as error-corrected quantum computers that may eventually outperform classical computers for some real-world applications.

Several roadmaps have been created to guide specific aspects of QIST development. One of the first quantum roadmaps developed was the trailblazing *A Quantum Information Science and Technology Roadmap*, published in 2004 by the Advanced Research and Development Activity (now part of Intelligence Advanced Research Projects Activity) (2004). This roadmap was focused on quantum cryptography and communications using quantum key distribution architectures, and it set specific goals and targets for 2007, 2010, and 2014. More recently, IEEE developed the International Roadmap for Devices and Systems focused on cryogenic electronics and quantum information processing (2022). Still, it is time for a quantum technology roadmap that sets new future targets and takes a broader look at needs across applications.

Roadmaps initiated by national laboratories and sponsored by the U.S. Department of Energy have focused on guiding scientific research, primarily by identifying milestones and scientific breakthroughs (Kleese van Dam, 2020). Other roadmaps, such as those developed by the National Aeronautics and Space Administration (NASA), have focused on specific applications like space-based quantum communication (National Aeronautics and Space Administration, 2020).

In contrast to these discovery-inspired efforts, SRI International (SRI) and its team of industry, national laboratory, and academic partners has created a roadmap to support the development of technology critical to scale-up of the quantum industry as a whole, including quantum computing, quantum sensing, and quantum telecommunications. This effort is the first of its kind that we know of and resulted in an initial quantum technology manufacturing roadmap (QTMR). The QTMR does not focus on scientific discovery. Rather, it identifies the technology and capability needs critical to QIST R&D and manufacturing between 2024 and 2028.

The roadmap focuses on a wide range of technologies and capabilities, setting specific targets for technical performance. It also addresses non-technology enablers that roadmap participants identified as essential for ongoing progress in technology development. For example, topics like data sharing and the need to develop a reliable domestic supply for specific technologies are included in the roadmap.

Roadmap approach

Figure 1 describes the overall approach the project team pursued to create the QTMR. The process began with identifying the short-term (2024) and longer-term (2028) technology needs of and challenges faced by quantum system developers. Quantum system developers included developers of quantum computing systems, quantum sensing systems, and quantum networking systems. In addition to identifying their short- and long-term technology needs, quantum system developers also described the challenges they faced as a result of current technology gaps.

These short- and long-term needs and challenges were shared with quantum technology suppliers, organized around six categories of quantum-relevant technologies:

- Materials and fabrication
- Electronics
- Lasers and optics
- Cryogenic and vacuum systems
- Control systems
- Testbeds

Within each of these categories, system developers identified several broad technology and capability needs. There were between two and twelve broad needs identified by developers per technology category, for a total of 43 broad needs. For each of these 43 need areas, system developers described more detailed and specific needs, including technical performance targets for both 2024 and 2028. In many cases, several detailed needs per broad need were highlighted with multiple associated desired performance benchmarks.

Technology providers reviewed the detailed needs identified by the system developers and provided extensive commentary on the prospect for meeting these needs over the 2024–2028 time horizon.

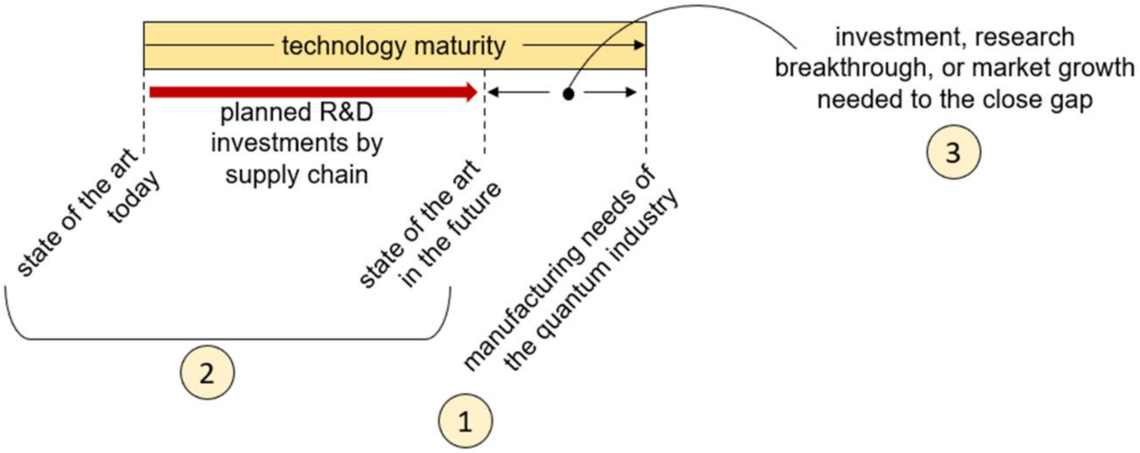


Figure 1: High-level roadmap approach

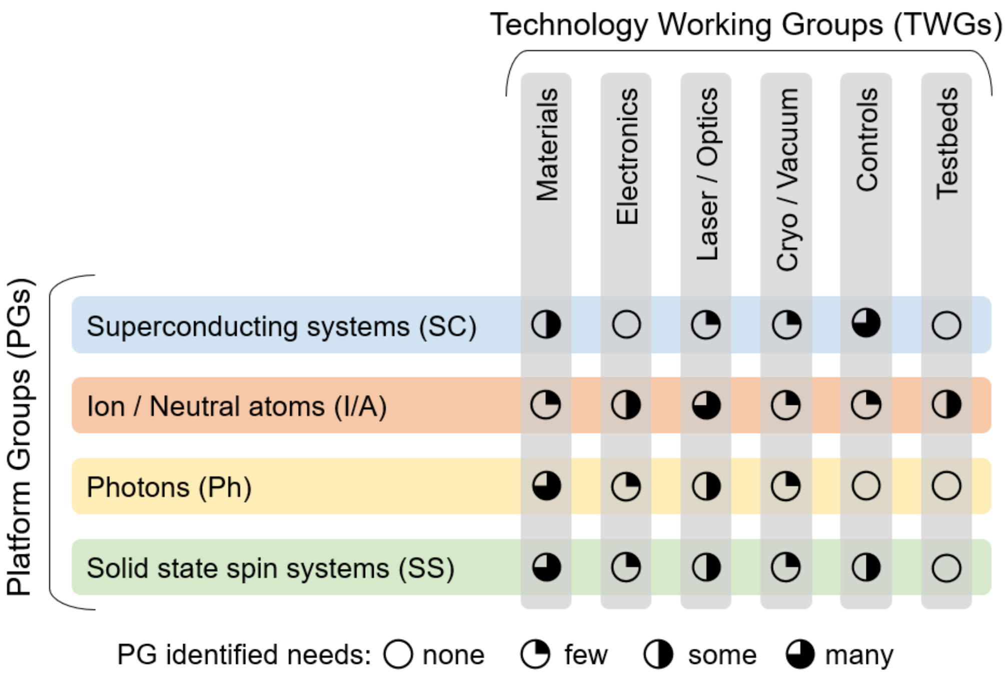
Figure 2 summarizes how project data collection was coordinated and how the final roadmap is organized. Participants in the development of the QTMR were recruited through outreach to Quantum Economic Development Consortium (QED-C) members, targeted outreach to specific organizations, and word-of-mouth. See the Acknowledgements section for the list of organizations that participated.

Quantum system developers were divided into four distinct platform groups, or PGs for short, based on the physical system underlying their technologies. This PG categorization was chosen over other schemes, such as dividing them by application or use, due to the expectation that this categorization would better reflect the structure and operation of supply chains. For example, ion trap-based quantum computers and neutral atom-based sensing platforms are more likely to share supply chain needs than are ion-trap-based quantum computers and superconducting qubit-based quantum computers.

Input on technology needs and challenges were collected for each PG separately. Each PG met four times to identify needs in the six technology areas, determine priorities, and develop quantifiable metrics for each need, to the extent possible. The process of soliciting quantum system developer needs generated an enormous amount of information on technology and capability needs. In Figure 2, the circles represent how needs identified for a particular PG were categorized by technology. Shaded portions of the circle are not intended to sum to 1 but instead are intended to serve as a point of comparison. For example, most needs identified by the superconducting systems PG were for controls, with smaller numbers of needs identified for materials, lasers and optics, and cryogenic and vacuum systems. The superconducting systems PG identified no needs for electronics and testbeds technologies. This information was consolidated across all PGs and then categorized into a set of common needs for each technology area.

Following the collection of data from the PGs, technology working groups (TWGs) were formed for each of the six technology areas. The final consolidated and categorized set of 43 detailed needs identified by the PGs were shared with individual TWGs, which comprised quantum suppliers and manufacturers. Each TWG met one to four times, depending on the number of needs in that technology area, to review the needs and provide insight into manufacturers' current plans to meet the needs and barriers to achievement.

The view of the short- and long-term needs, as described by PGs, together with the commentary of the TWGs, define the individual roadmaps for each of the 43 technologies and capabilities. The overall Quantum Technology Manufacturing Roadmap comprises these individual technology and capability roadmaps. The overall roadmap also highlights a set of themes that are common to many of the diverse sets of technologies and capabilities covered. These themes address the challenges associated with the emerging quantum technology supply chain and identify hurdles that will need to be overcome by suppliers and system developers alike. This report presents the 43 detailed technology and capability roadmaps and also presents the common challenges to developing a stronger quantum manufacturing technology ecosystem.



Technology Working Groups (TWGs)

Platform Groups (PGs)	Materials	Electronics	Laser / Optics	Cryo / Vacuum	Controls	Testbeds
Superconducting systems (SC)	◑	○	◔	◔	◕	○
Ion / Neutral atoms (I/A)	◔	◑	◕	◔	◔	◑
Photons (Ph)	◕	◔	◑	◔	○	○
Solid state spin systems (SS)	◕	◔	◑	◔	◑	○

PG identified needs: ○ none ◔ few ◑ some ◕ many

Figure 2: Overall framework for the Quantum Technology Manufacturing Roadmap

Limitations of the current work

The QTMR reflects the maturity of the industry and scope of technologies assessed. Many frequently roadmapped industries, such as semiconductors or telecommunications equipment, have market leaders that have been in place for long periods of time and technical paradigms have largely been determined. On the contrary, the quantum industry is an emerging one with considerable uncertainty present regarding what technical breakthroughs will be made, what approaches will prove the most effective, and what products will achieve widespread market acceptance. A consequence of this lower maturity level is that views among industry participants regarding what is needed and what is achievable within a specific timeframe are more diverse.

In addition to being less mature, the quantum industry is diverse, representing a remarkably broad range of applications, technical approaches, and underlying technologies. The quantum industry includes quantum computing, quantum sensing and metrology, and quantum telecommunications, and these individual domains, themselves, are diverse. For example, approaches being pursued to develop quantum computing include superconducting quantum computers, photonic quantum computers, neutral atom quantum computers, and trapped ion quantum computers, among others.

Given the modest level of maturity and significant technical diversity associated with the quantum industry, the roadmap presented herein is preliminary. It reviews 43 technologies and capabilities central to QIST development. Limitations of the approach notwithstanding, for most of these 43 technologies and capabilities, the roadmap provides consensus participant views of technical performance targets for the near-term and long-term. Participants reflected a representative cross-section of the industry, though it is possible that the consensus among project participants may not fully reflect all industry participants.

The process of creating this preliminary roadmap highlighted new and refined analysis paths that, though beyond the scope of this project, represent key areas for future work and creation of an updated roadmap. These are identified in the Future work section of this report.

Common themes and takeaways

When assessing the needs that arose across platform groups and technology areas, there were some common themes. Overall, the biggest takeaway was that the quantum technology industry is still very nascent. There is not one universally used platform or approach, no standard configuration or set of components and materials. This lack of consensus in the industry is in part why 43 different needs were identified, often with different specifications depending on the exact application or the materials used. For example, when participants were pushed to provide the linewidth needed for a laser, the number varied depending on if it was for a specific isotope, for use in an optical clock, or for Rydberg sensing.

Another commonality across platforms was non-quantum-technical and qualitative needs. For example, participants in the Superconducting Systems PG identified a need for greater knowledge sharing of configurations and specifications for both fabrication tools and cryogenic systems. There were multiple non-quantum-technical needs related to software, including less complex software that can be used by technicians and open-source software. Additionally, several participants highlighted supply chain needs, such as greater domestic supply of components and higher quality materials.

A challenge that applied to almost every identified need is the presence of tradeoffs. Integrators often pushed for dueling aspects, such as increases in both reliability and efficiency or improvements to size, weight, and power (SWaP) and lower costs. Of course, improvements in all of these areas would be highly beneficial for the industry; however, tradeoffs are a fundamental part of research, development, and engineering (RD&E) and many manufacturers were quick to point this out. Consequently, there is a need for integrators to prioritize which aspects are the most important for industry progress.

One major tradeoff for many identified needs is whether to choose an off-the-shelf component or software or pay a premium for a custom-built tool. Customized tools typically allow integrators more flexibility in the materials and configurations they employ, but the low purchase volume leads to high prices. This was especially true for control electronics, where tailoring them to meet one system integrator’s unique needs and application makes them very costly. Small production volumes and low market demand was a near universal barrier to achieving the identified needs. This emphasized the need for consolidation in the industry around set approaches and configurations and consensus around standards to enable higher production volumes and bring down costs.

Quantum technology manufacturing roadmaps

The technology and capability landscape

Figure 3 lists the number of needs identified in each technology category. Figure 4 through Figure 9 list the specific technology and capability needs identified by technology category. Most of the needs identified in these six tables are technology-related and have associated with them specific technical performance measures. Some of the needs, such as a more robust domestic supply of electronic components in Figure 5 and greater sharing of dilution fridge/cryostat specification data in Figure 7, are not technical in nature *per se*. Following Figure 4 through Figure 9, the 43 individual one-page roadmaps for each technology and capability are presented. The overall Quantum Technology Manufacturing Roadmap comprises these individual technology and capability roadmaps.

Technology Category	Technologies and Capabilities Assessed
Materials and fabrication	12
Electronics	5
Lasers and optics	12
Cryogenic and vacuum systems	4
Control systems	8
Testbeds	2
Total	**43**

Figure 3: Technology and capability needs by technology category

Technology & Capability Category	Technology & Capability Subcategories
Improved materials	1. Material platform requirements for optical switches, wave guides, photodetectors, and photon sources 2. Basic material research
Improved interconnections	3. Materials for qubit-to-qubit communication and interfacing 4. Heterogeneous integration of components and materials
Component functionality	5. Quantum memory and linear optical quantum operations
Fabrication data, tools, and facilities	6. Fabrication tool capabilities 7. Defined purity for substrates and chemicals used in quantum device manufacturing 8. Chip fabrication / integrated features / on-chip technology for ion and neutral atoms 9. Access to and quality of materials 10. Crystal growth tool availability 11. Improved defect placement
Packaging	12. Room temperature packaging

Figure 4: Materials and fabrication (12 technologies and capabilities)

Technology & Capability Category	Technology & Capability Subcategories
Noise management & shielding	1. Noise management/shielding 2. Noise management/shielding (AI assisted)
Control electronics	3. Scalable analog control electronics 4. Control electronics purpose-built for multi-qubit controls
Domestic supply of components	5. Domestic supply of components

Figure 5: Electronics (5 technologies and capabilities)

Technology & Capability Category	Technology & Capability Subcategories
Optical integration	1. On-chip light generation for visible and UV 2. Integrated photonics
High efficiency photodetectors	3. High Efficiency Photodetectors
Optical interconnection	4. Long-distance quantum interconnection
Components and sources	5. Non-telecom wavelength components (on-chip and qubit systems) 6. Non-telecom wavelength components (sensing focused) 7. Non-telecom wavelength components (high repetition rate devices) 8. Non-telecom wavelength components (communications) 9. Downscaled and ruggedized lasers for fieldable technology 10. Generation, sources, and integration of single photons 11. Compact, reliable, and fast photonic/optical components (isolators, modulators, fiber components, nonlinear optics, shutters) at UV to IR wavelengths 12. Compact, reliable, stable, high-power free space laser sources with specific wavelengths

Figure 6: Lasers and optics (12 technologies and capabilities)

Technology & Capability Category	Technology & Capability Subcategories
Cryogenic & vacuum systems	1. Cryogenic packaging 2. Greater knowledge sharing of dilution fridge/cryostat specification data 3. Ultra-high vacuum chambers and pump systems 4. Improved reliability and SWaP and reduced complexity of cryogenic, vacuum, and thermal management systems

Figure 7: Cryogenic and vacuum systems (4 technologies and capabilities)

Technology & Capability Category	Technology & Capability Subcategories
Improved control systems cost and usability	1. Scalable control systems, including scalable analog control electronics 2. Components that allow integration of spin systems into technologies 3. Technician usable systems
Fast device testing and validation	4. Cryogenic temperature fast device testing and validation
Tools for systems-level modeling and device parameters	5. Tools for system and device modeling
Low temperature operation (in-situ control electronics)	6. Low temperature operation (in-situ control electronics)
Efficient readout of solid-state spins	7. Advancements in Quantum Spin Readout and Microwave Control
FPGA feed forward hardware	8. FPGA feed forward hardware

Figure 8: Control systems (8 technologies and capabilities)

Technology & Capability Category	Technology & Capability Subcategories
Testbeds	1. Cloud accessible systems 2. Characterization hardware for specialized components

Figure 9: Testbeds (2 technologies and capabilities)

Some of the technology needs listed in Figures 4 through 9 overlap with one another. The overlap is inevitable with any quantum technology organization scheme and, accordingly, some of the needs described in these figures are relevant to more than one technology area. For example, the need for low-temperature operation for control systems is relevant for both control systems and cryo systems. For simplicity of presentation, each of the 43 detailed needs was placed in only one area—the area in which in which it was discussed the most by roadmap participants.

Technology and capability roadmaps

Individual quantum manufacturing technology roadmaps are presented in Figures 10 through 52. These 43 roadmaps are organized according to the technology categories and subcategories listed in Figures 4 through 9. Each of these 43 roadmaps describes the consensus needs of platform groups within each technology domain for 2024 and 2028, and the challenges they expect in addressing these needs. The header for each year, 2024 and 2028, is shaded to indicate the status of each need according to the following scale:

- Significant gap in expected capabilities: Light blue indicates there are significant gaps to addressing a technology need by a given year.

- Tech available but requires optimization: Medium blue indicates the technology is expected to be available on a limited scale but will need further refinement and optimization for use at scale by a given year.
- Tech expected to be deployed: Dark blue indicates the technology is expected to be available at scale by a given year.

These evaluations are based on the views of the technology working group participants (i.e., quantum suppliers and manufacturers). The project team sought a consensus of these views, as it did for those of the platform groups. While there was agreement in many areas, TWG views were less uniform overall. Accordingly, evaluations of the status of each need are very preliminary.

In addition to identifying technology needs, project discussion on the part of both platform group participants and members of the technology working groups highlighted a range of issues affecting quantum technology manufacturing, including needs for basic research, the importance of refined manufacturing processes, business challenges, and policy issues.

Materials and fabrication

Figures 10 through 21 present the roadmaps for the 12 Materials and Fabrication technology capabilities. Selected near-term materials needs are expected to be met, at least at lab scales. Transduction efficiency goals, for example, are considered realistic, though as with most of the technical goals discussed, the status will depend on specific applications. TWG participants reported that there are very good foundries for ion traps with short turn-around time, and that ½-inch diamond wafers are also a current capability.

Much of the challenge with materials development derives from the diversity of applications, materials properties sought, and candidate materials for those applications and properties. Depending on the application, materials are needed with specific optical, thermal, electrical, defect, and other properties. Without knowing specific specs for each application and how these specs are likely to evolve over time, technology developers find it challenging to make informed bets on what materials research to pursue. TWG participants indicated that consolidating spec information across applications in a common source would help guide the material research process.

Creating materials with desired defects will require significant research in several areas (see Figure 11). From a manufacturing perspective, introducing new materials into a process is a significant concern, as new materials require new processes that can lower yields when introduced. One way to address this is via line splits, but line splits bring their own challenges related to added complexity, production impact, quality control, coordination, and testing. In the long run, needed materials may be manufactured atom-by-atom to achieve completely custom materials, including materials with precise defect location, but that capability is well beyond the time horizon of the 2024–2028 roadmap.

Regarding ion and neutral atom development needs, PG participants identified clear needs and challenges related to fabrication, as indicated in Figure 17. In this area, there is considerable uncertainty regarding what is achievable in the 2024 to 2028 timeframe. TWG participants generally agreed with the chip fabrication challenges identified by the PGs but believe some progress is being made to provide the needed fab capabilities. On the other hand, they cautioned that these capabilities may not be low cost and may not be able to provide the quick turn-around times (i.e., one month or less) desired for iteration on prototypes. They may also not be fully scalable in the desired timeframe.

Diamond fabrication and diamond wafers represent another area around which there is uncertainty among TWG participants (see Figure 18). Notwithstanding their confidence about current ½-inch diamond wafer capability, they are less optimistic about future availability at larger wafer sizes and larger scales. This uncertainty exists more generally for the prospects of growing and processing other high-quality materials. Technology suppliers do not see commercial production growing and fear investing in new technology development, such as crystal growth technology, that gets superseded by new technology. Relatedly, they see little incentive to develop off-the-shelf (i.e., standardized) crystal growth equipment.

TWG participants believe some technologies may not lend themselves to mass production within the scope of the 2024–2028 time horizon of the roadmap. Vapor cells used for quantum memory, for example, are currently glass blown via a process that is as much artisan as it is technological. The prospects for R&D on vapor cell manufacturing over the next several years appear promising, but as with many of the technologies assessed in the roadmap, market demand will be a factor in providing incentives for R&D.

Going hand-in-hand with materials development is the development of fabrication tool capabilities. As Figure 15 indicates, in the long run, more quantum specific tools will be needed. Quantum industry demand is still small compared to that of other markets such as semiconductors, and tool makers are unsure when or whether quantum demand will be sufficient to incentive development of dedicated quantum tools within the timeline of the roadmap. Shared tools housed at a common facility can provide a useful option for research needs but are not expected to be suitable to scale manufacturing. Better design tools are also needed, especially in areas such as on-chip integration. Some of these tools exist, but they are not widely available for purchase and use by system developers.

Another area for which better tools are needed is in materials measurement, especially with respect to material purity. As Figure 16 indicates, there's a need for basic research (i.e., academic research) to understand precise purity requirements for chemicals and materials used in quantum technology. Regarding materials purity and materials properties more generally, project participants noted that materials handling and environmental conditions can have a significant effect on materials and degrade properties created in a pristine environment. As a complement to materials research itself, there is a need to improved processes for materials handling and preservation.

Higher temperature operation (above 10K) in the context of heterogeneous integration of materials is also a noted challenge. Growth in demand for some high-quality materials is currently driven by R&D rather than for production. Regarding room temperature packaging, the extended lifetimes desired by platform groups are considered achievable by TWG participants. Standardized packaging will help address this goal, as will magnetic shielding and vacuum packaging. In the longer term, new materials such as new epoxies and optimized light coupling will help. Temperature cycling parameters, including both the rate and profile of cool down and warm up, will affect packaging performance.

Both PG and TWG participants discussed the prospects of using machine learning (ML) for a variety of materials research applications. In principle, ML is a cross-cutting capability, though TWG participants expect it to be more useful in "front-end" uses associated with materials discovery and exploring materials properties than in characterization of existing materials.

■ Significant gap in expected capabilities

■ Tech available but requires optimization

■ Tech expected to be deployed

	Material platform requirements for switches, wave guides, photodetectors, and photon sources	
Materials & Fabrication	2024	2028
Need(s):	• Low voltage operation compatible with CMOS below 5 volts • High optical non-linearity with 30 pm/volt (e.g., lithium niobate type 0) • High electrooptic co-efficient • Low loss of .25 dB/cm • Spectral purity	• Low voltage operation compatible with CMOS below 2.5 volts • For switches: High optical non-linearity with ≥200 pm/volt • For photodetectors: Higher TC superconducting materials • For wave guides: Material platform for lower loss (<1dB/cm) • For sources: non-linear materials (maybe AIN or Ta_2O_5)
Challenge(s):	• Fab-compatibility necessary for scaling • Availability of elements • Consideration of varying frequency and bandgap requirements by application • Deterministic sources are currently at a low maturity	• Fab-compatibility necessary for scaling • Availability of elements

Figure 10: Roadmap for material platform requirements for switches, wave guides, photodetectors, and photon sources

◻ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

	Basic material research	
Materials & Fabrication	2024	2028
Need(s):	• Off-the-shelf tools to characterize quantum properties materials (e.g., ODMR)	• More light from high index materials (few percent / order of magnitude improvement) • Streamlined approach to materials discovery (including use of machine learning / data mining) • Funding / assistance to smaller labs • Software packages for rapid spin qubit search and characterization over large areas • Characterization of stress and defects over large areas (including software packages for characterizations)
Challenge(s):	• No identified challenges	• Exploring defects that aren't easily implanted (ML approaches are challenging) • Growing in situ with novel dopant sources • Access to more advanced doping techniques • Handling of toxic gases

Figure 11: Roadmap for basic materials research

░ Significant gap in expected capabilities

▓ Tech available but requires optimization

█ Tech expected to be deployed

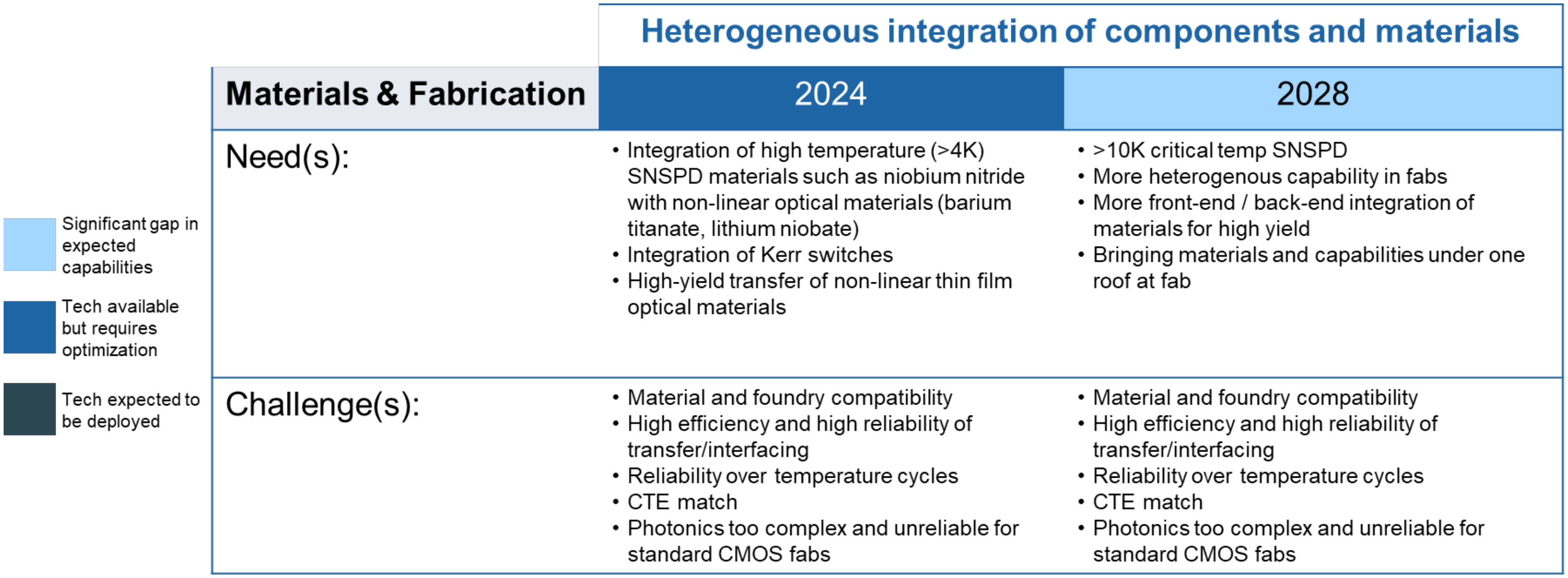
Materials for qubit-to-qubit communication and interfacing

Materials & Fabrication	2024	2028

Need(s):	• >50% transduction efficiency (efficiency for converting qubit's quantum state from regime to another, avg across transduction efforts)
	  • Efficiency target depends on transduction frequency
	  • Especially critical for optical-to-optical interfacing
		• >75% transduction efficiency (avg of transduction efforts)
		  • Efficiency target depends on transduction frequency
		  • Especially critical for x-to-y interfacing

Challenge(s):	• Achieving transduction efficiency (across all transitions: filtering of signals, managing parasitics that cloud signal, cross-talk/noise management) • Fab-compatible materials • Material availability • Expense	• Achieving transduction efficiency (across all transitions: filtering of signals, managing parasitics that cloud signal, cross-talk/noise management) • Fab-compatible materials • Material availability • Expense

Figure 12: Roadmap for materials for qubit-to-qubit communication and interfacing



- ▢ Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ■ Tech expected to be deployed

Heterogeneous integration of components and materials

Materials & Fabrication	2024	2028
Need(s):	• Integration of high temperature (>4K) SNSPD materials such as niobium nitride with non-linear optical materials (barium titanate, lithium niobate) • Integration of Kerr switches • High-yield transfer of non-linear thin film optical materials	• >10K critical temp SNSPD • More heterogenous capability in fabs • More front-end / back-end integration of materials for high yield • Bringing materials and capabilities under one roof at fab
Challenge(s):	• Material and foundry compatibility • High efficiency and high reliability of transfer/interfacing • Reliability over temperature cycles • CTE match • Photonics too complex and unreliable for standard CMOS fabs	• Material and foundry compatibility • High efficiency and high reliability of transfer/interfacing • Reliability over temperature cycles • CTE match • Photonics too complex and unreliable for standard CMOS fabs

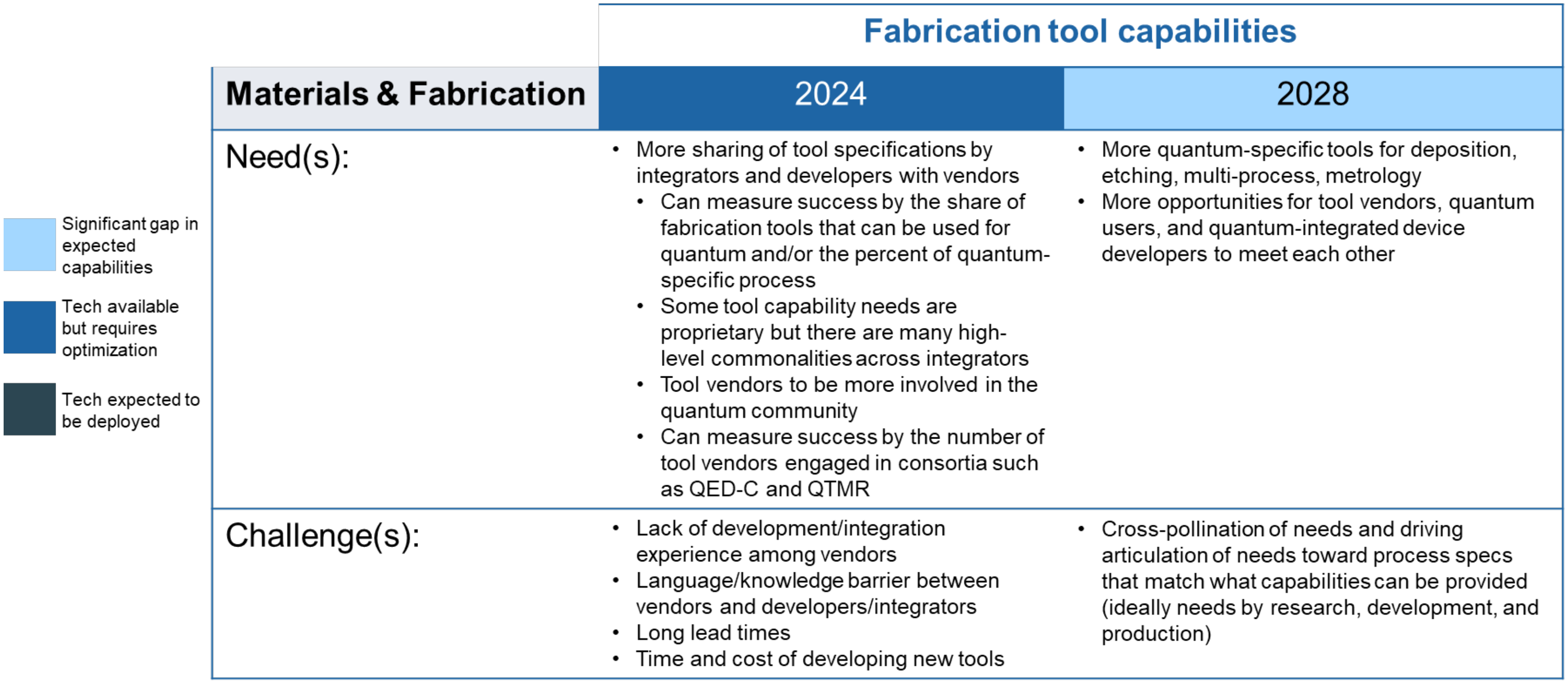
Figure 13: Roadmap for heterogeneous integration of components and materials

- ▢ Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

Quantum memory and linear optical quantum operations

Materials & Fabrication	2024	2028
Need(s):	• Standardized vapor cells (e.g., rubidium vapor cells) • Storage time / coherence time better than fiber (>3 μs) • Arbitrary access / access on demand vs. fixed delay	• Integrated telecom quantum memories and >125 μs storage time / coherence time (80% memory efficiency for >125 μs storage time / coherence time) • Stretch goal: 80% efficiency for >1ms
Challenge(s):	• Requires transduction for use in fiber communications applications • High expense • Low efficiency	• SWaP

Figure 14: Roadmap for quantum memory and linear optical quantum operations



Significant gap in expected capabilities

Tech available but requires optimization

Tech expected to be deployed

Fabrication tool capabilities

Materials & Fabrication	2024	2028

Need(s):	• More sharing of tool specifications by integrators and developers with vendors
	  • Can measure success by the share of fabrication tools that can be used for quantum and/or the percent of quantum-specific process
	  • Some tool capability needs are proprietary but there are many high-level commonalities across integrators
	  • Tool vendors to be more involved in the quantum community
	  • Can measure success by the number of tool vendors engaged in consortia such as QED-C and QTMR
		• More quantum-specific tools for deposition, etching, multi-process, metrology
		• More opportunities for tool vendors, quantum users, and quantum-integrated device developers to meet each other

Challenge(s):	• Lack of development/integration experience among vendors • Language/knowledge barrier between vendors and developers/integrators • Long lead times • Time and cost of developing new tools	• Cross-pollination of needs and driving articulation of needs toward process specs that match what capabilities can be provided (ideally needs by research, development, and production)

Figure 15: Roadmap for fabrication tool capabilities

- 🟦 Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

Defined purity for substrates and chemicals used in quantum device manufacturing

Materials & Fabrication	2024	2028
Need(s):	• Study conducted by academia or a national lab to understand required purity among various grades of commercially available chemicals and inform silicon and chemical suppliers • Should look at dopant concentrations and contamination thresholds and their impact on quantum performance	• Expanded availability for data regarding the starting levels of purity for silicon, sapphire, and other chemicals and reagents used in fabrication, which would increase standardization
Challenge(s):	• Though work in this area is being done, many in industry are not aware	• Lack of demand for this research

Figure 16: Roadmap for defined purity for substrates and chemicals used in quantum device manufacturing

- 🟦 Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

Chip fabrication / integrated features / on-chip technology for ion and neutral atoms

Materials & Fabrication	2024	2028
Need(s):	• Foundry-like service for ion traps - more options than what the goverment has developed (focused on research goals) • Simple traps where individuals can design the electrodes	• Government-sponsored foundry accessible by industry • Rapid turn around of prototypes (less than a month) • Affordable one-offs • PDK for quantum including neutral atoms and ions
Challenge(s):	• Very few providers of microfabricated sources traps • Many levels of approval required to access government developed systems • Production lab won't make one-offs • Lead times take years • Tech transfer is very difficult • Access to / availability of equipment to stand-up new process • Must modify process to fit existing equipment • Integrating light and delivery collection, other photonic components, and RF and microwave components	• Infrastructure; currently, no foundry does this – need FFRDCs support in the US • Nothing yet available to transfer directly to commercial foundry (still in R&D) • Funding

Figure 17: Roadmap for chip fabrication / integrated features / on-chip technology for ion and neutral atoms

▨	Significant gap in expected capabilities
🟦	Tech available but requires optimization
⬛	Tech expected to be deployed

	Access to and quality of materials	
Materials & Fabrication	2024	2028
Need(s):	• More options for academic research • Refining / improving materials • Identify optimum platform • Engineering materials tailored for specific applications • Materials research institute / facility for sensing materials • Matching design to need (e.g., Is SiC more mature in this area? Is synergy with GaN laser growth needed? What defects can be used for sensing in this material?) • Need to get to 1-inch round diamond wafers and then 2-inch to make research more efficient, effective, cost effective with sufficient quality / quantum grade	• Fabrication facilities • Dozens to hundreds of reactors • Larger area diamond / slice large diamond (1-2 inches) into wafers (wafer processing) • Larger area diamond growth • Slice large diamond (1-2 inches) into wafers (wafer processing) • Optimizing fabrication techniques for diamonds • Structuring diamond for efficient optics • Refine R&D and transition to production • Wafer scale growth that exhibits spin type defects • Boron nitride - highest quality materials come from mechanical exfoliation (scalable production with less quality degradation); identification and production of candidates for color centers (SiC, AlN, transition metal dichalcogenides)
Challenge(s):	• High quality materials for research are hard to access • Funding for research on materials, including diamond • Guidelines for need / design	• Understanding of defects in those materials • Growing high quality materials at manufacturing scale • High NA diamond machining • Limited disturbance to diamond (reducing disturbance of valuable properties) • Scalable approaches for positioning of defects in diamond in 1D and 2D arrays • Going from mm to cm • Thermal gradients lead to stresses in larger diamonds • Cost prohibitive access to diamonds of specific dimensions for research Increasing production and scaling of diamond

Figure 18: Roadmap for access to and quality of materials

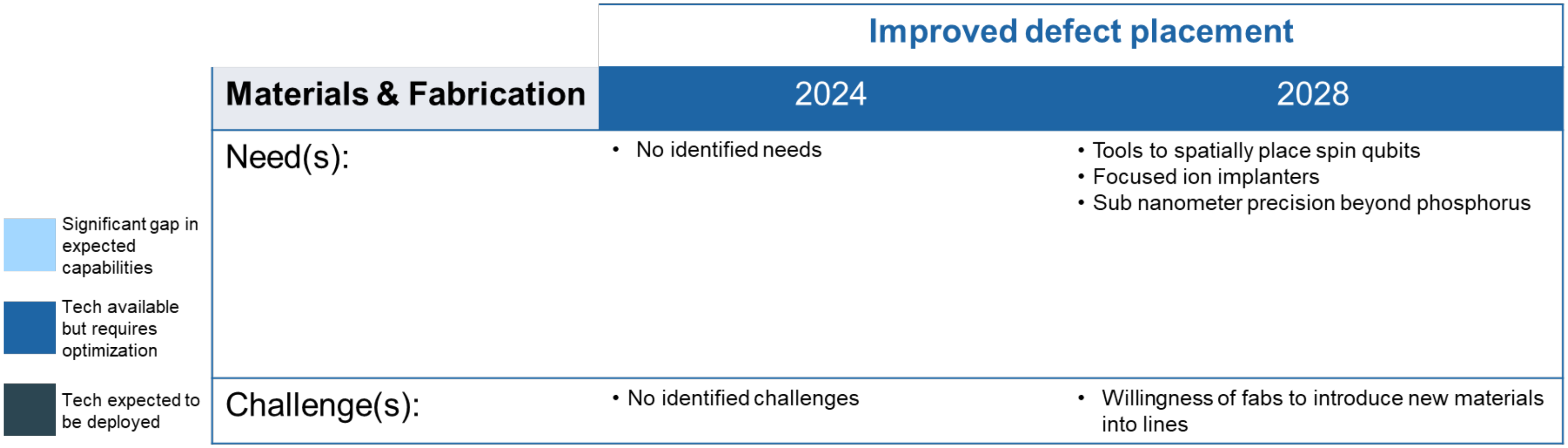
◻ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

	Crystal growth tool availability	
Materials & Fabrication	2024	2028
Need(s):	• Off the shelf reactors • Specialty gases (nitrogen-15, nitrogen-14, ammonia)	• Maintaining effort underway – continued investment in diamond technology • Improved diamond processing
Challenge(s):	• No identified challenges	• Business model challenges (means to prevent others from reproducing systems) • IP protections • Integration of user and crystal maker • Diamond market dominated by gemstones (not suited for technology grade diamonds) • Applications to build up demand / market • Larger areas grown using plasma (how to keep increasing size - adapting reactors to increasing size) • Growing in situ with novel dopant sources (toxic) • Access to more advanced doping techniques • Dealing with toxic gases

Figure 19: Roadmap for crystal growth tool availability



- □ Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

	Improved defect placement	
Materials & Fabrication	2024	2028
Need(s):	• No identified needs	• Tools to spatially place spin qubits • Focused ion implanters • Sub nanometer precision beyond phosphorus
Challenge(s):	• No identified challenges	• Willingness of fabs to introduce new materials into lines

Figure 20: Roadmap for improved defect placement

░ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

	Room temperature packaging	
Materials & Fabrication	2024	2028

Need(s):	• Across all applications, continuous operation reliability and reliability across cold/warm cycles
	  • Reliability across 5 year / 10 year cycles
	  • 50,000 to close to 100,000 hours of operation
	  • Low loss optical IO <0.1 dB/facet
		• Material property availability for packaging temperatures

Challenge(s):	• Continuous operation reliability and reliability across 10 years / 100-200 cycles for computing, 1000 cycles for sensors • Need low loss optical IO <0.02 dB/facet	• Low power dissipation for other devices to accommodate low form factor systems • Incorporation of full full-stack integration • Fabs will need to coordinate with local utility regarding high power reliability • Continuous operation in data system environment; deployment in places where servicing is difficult; industrial level of reliability

Figure 21: Roadmap for room temperature packaging

Electronics

Noise management and shielding was a key topic of discussion for Electronics. When discussing the 2024 needs for this area, shown in Figure 22, TWG participants indicated that the industry lacks sufficient quantum-knowledgeable hardware engineers who can answer questions regarding how their products integrate with quantum systems. They went on to suggest that increasing the availability of multi-disciplinary engineers who can bridge between quantum technology and traditional electronics would help address this challenge. Electronics TWG participants also indicated that better device models (from manufacturers or vendors) that can extrapolate to cryogenic temperatures would be very useful, but that the cost of developing these models and the expected low volume of related business is dissuading suppliers from investing much effort on this. Longer term, TWG participants indicated that investment in new materials and approaches would help manage noise, and that government-funded, university-based research could help here.

New materials would help address a number of related technical challenges, including the need to electrically shield devices without impairing thermal characteristics. Again, the lack of current volumes is keeping vendors from making investments in these areas. Finally, TWG participants indicated that better testing instrumentation will be needed to meet longer term goals in noise management.

On the topic of noise management, PGs discussed the potential for artificial intelligence (AI) to address short- and long-term needs (see Figure 23). TWG participants were less optimistic about the potential of AI to improve noise management. They pointed to the lack of training data and the number of devices that can produce noise—including lasers, microwave sources, and electronics—and the need to better understand device construction, shielding, grounding, and the noise each component produces as a potentially more fruitful way to inform engineering efforts to improve noise conditions. They indicated that improving signal fidelity will require developing approaches for device construction and assembly that are specific to quantum. Currently and into the foreseeable future, the volume of devices is low compared to that of other industries, such as mobile phones, which impedes investment and limits incentives to develop these quantum-specific approaches.

Regarding scalable analog control circuits (Figure 24), TWG participants indicated there are startup companies working on this, but their focus tends to be on small-scale, customized, and instrument-based solutions. Several startups are also working on electronics purpose-built for super-conducting multi-qubit controls (Figure 25), but here again, most solutions are customized. Lack of standards was identified as a barrier to meeting short-term needs. Longer term, the industry is trying to move electronics closer to qubits to improve performance, but this creates challenges as typical electronic components do not perform well below about 100K. Ideally, the industry will develop low-temperature electronics, though TWG participants did wonder where the incentives for this development work will come from.

The final supply chain topic raised by PG participants regarding electronics related to their concern about domestic supply of FPGAs,[1] lasers, and laser controls (Figure 26). TWG participants shared this concern. They suggested ASICs may be a solution in the short term and are hopeful that the 2022 CHIPS and Science Act will provide incentives for developing greater domestic supply of quantum technology components.

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[1] Field-programmable gate arrays.

🟦 Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

	Noise management/shielding	
Electronics	2024	2028
Need(s):	• Understand specific device construction, shielding, grounding, and noise of components • Available or published simulation, modeling devices, and model hardware correlation at cryo temps • Shortened required time and investment to update silicon technology nodes • Better flicker noise in more advanced node	• Shielding contoured to device • Smaller form factor vector magnets • More customized field ranges • Integrable solutions (RF and optical probe stations)
Challenge(s):	• The industry lacks enough quantum-knowledgeable hardware engineers • Data sheets don't always reflect the specs needed to meet needs of quantum • Simulation, modeling devices, and model hardware correlation at cryo temps is important, but little is being published or available from vendors.	• Engineering challenges (multiple parts have noise that needs to be shielded • Lack of quantum volume today thwarts suppliers from making investments • Off the shelf (OTS) vendor components are too costly, lack the shielding, signal fidelity, and low power required to meaningfully scale quantum systems • Quantum industry lacks sufficiently capable test instruments for in situ measurement

Figure 22: Roadmap for noise management/shielding

- ◻ Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

	Noise management/shielding	
Electronics	2024	2028
Need(s):	• AI / data to distinguish noise • Robustness to noise	• AI to distinguish noise from effects of other platform elements (draw out small signals); Software package
Challenge(s):	• Applying microwave / RF control field to defects can induce cross talk with electro-optical detection • Placing components close together • Sensing magnetic fields • External (real world) noise • Signal fidelity needs to improve in all aspects across 4-8 GHz • Shielding materials and techniques, and levels of integration. • Maintain isolation through high-density interconnects: development in materials, processing, and manufacturing	• Engineering challenges (multiple parts have noise that needs to be shielded) • Development costs in the face of low manufacturing volume • For those areas where AI might be useful, there is not enough (training) data yet to help AI determine noise's effects on qubits, etc.

Figure 23: Roadmap for noise management/shielding (AI assisted)

🟦 Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

	Scalable analog control electronics	
Electronics	2024	2028
Need(s):	• Smaller physical packaging (household appliance size) • Less than 10 watts (power per qubit)	• Scalable (1000s of channels with traceability to 10s of 1000s) • Cost-effective laser control electronics (power draw and cost) • Scalable RFSoCs • Tune RF of AOMs – Phase, frequency, amplitude • Sub watt • Hand-held
Challenge(s):	• Volume • Lack of standards	• Low market demand

Figure 24: Roadmap for scalable analog control electronics

🟦 Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Electronics purpose-built for super-conducting multi-qubit controls

Electronics	2024	2028

Need(s):	• Lower cost per channel and optimization of control signal per channel for multi-qubit controls.
	  • $100 per qubit
	• Affordable 1k+ qubit controllers less than ~$1M
	• Common software base
		• Develop cryo-electronics at 1K or 20mK for 1000 qubit controller
		• Controller that performs well at the same temperature as qubit
		• Cost-effective options
		  • Including, lower cost per channel
		• System integration reliability

Challenge(s):	• Cost of electronics scale with the number of qubits	• High cost of developing custom-built models • Devices have low performance below 100K

Figure 25: Roadmap for electronics purpose-built for super-conducting multi-qubit controls

🟦 Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

	Domestic supply of components	
Electronics	2024	2028
Need(s):	• Domestic fabrication of field-programmable gate arrays (FPGAs) • Lasers and laser controls	• Domestic fabrication of field-programmable gate arrays (FPGAs) • Lasers and laser controls
Challenge(s):	• Electronic tracking, electronic off-shoring, and IP offshoring has created a challenge to addressing the need. • Global Supply chain constraints lag in delivery times • International political issues can cause delays/issues in acquiring electronics/ materials. • There are a lack of domestic manufacturers that make major tunable lasers	

Figure 26: Roadmap for a domestic supply of components

Lasers and optics

Figures 27 through 38 present the roadmaps for the 12 Lasers and Optics technology capabilities. Regarding the 2024 needs for on-chip integration (Figure 27), TWG participants expect to need at least two years to develop prototype technologies and another two years to get to production volumes. At the same time, they indicated that not all wavelengths will be available on photonic integrated circuits (PICs). There are several PIC development programs ongoing at the global level that could address some of the needs for on-chip light generation. Progress in this regard may depend on features sizes. While TWG participants expressed optimism regarding progress on PICs from large fabs within the next year, this optimism is for longer wavelengths, predominantly telecom. Research on wavelengths below 1 micron does not appear to be getting significant attention. Integration also depends on the intersection of materials and applications. Photonic integration capabilities exist for materials like Indium Phosphide (InP), Gallium Antimonide (GaSb), and Silicon Monoxide (SiO), but have so far been exploited only for quantum communication applications.

As with many of the technologies addressed in the roadmap, TWG participants indicated that significant market pull will be needed to incentive sufficient technology development. They speculated that emergence of a transformative use case would help to shrink lasers and reduce their cost, and they suggested a government-sponsored grand challenge could help accelerate this process. In a recommendation reminiscent of one made for materials, TWG participants indicated it would be helpful for developers and integrators to consolidate their needs around a specific set of wavelengths to help generate critical mass in demand. Participants indicated that photonic integration is commercially sensible only for applications targeting more than 100,000 units. They also indicated that achieving many of the targets for integrated photonics in Figure 28 will require improvements to packaging technology.

Photodetectors play a ubiquitous role in quantum technology development and PG participants identified several desired improvements in capabilities in Figure 29, efficiency among them. TWG participants expressed reservations about meeting these targets, at least within the 2024 and 2028 target timeframe, indicating that PGs may have to sacrifice specs for deployability.

Regarding quantum interconnection (see Figure 30), TWG participants speculated that connections within a single superconducting chip and between superconducting chips that are close together (i.e., within a few inches of one another) will be achieved by traditional wire. Long distance quantum interconnection will favor optics.

Components are currently available for a wide range of non-telecom wavelength components, and there are production roadmaps for many of these. However, for most, there will be a tradeoff between volume/price and specs. High volume and low cost will only be achievable where there is sufficient market volume for a given specification. Longer term, TWG participants indicate there are numerous ongoing research activities to develop non-telecom wavelength components for use in quantum systems, especially for on-chip lasers. TWG participants expect the on-chip lasers desired for computing to be achievable by 2028 (see Figure 31) but are not sure c-band wavelengths will be available by then. On-chip modulators are also being explored, as are as isolators, switches, and diffraction grating couplers. Non-telecom packaging, however, is still underdeveloped.

Figure 32 highlights needs and challenges related mostly to sensing applications. Here again, TWG participants highlight the lack of demand as a barrier to meeting some of the near-term needs, especially those related to classic scaling issues such as SWaP.[2] They believed the longer-term needs related to pulsed source phase noise, continuous source linewidth, intensity stability, and arbitrary optical waveform generation are technically feasible in time, though it's not clear if that means they are all achievable at scale by 2028. Prospects for the higher repetition rate components of Figure 33 are also unclear. TWG participants indicated that 1 GHz modulators are currently available, but they were less specific about 10 GHz components. For free space communications, needs centered on specific wavelength components available at scale, low cost, and optimized SWaP (see Figure 34). Needed components can be made currently, and demand will determine future scale, which in turn will determine cost. Longer term, there is an R&D challenge to achieve frequency conversion without sacrificing linewidths.

There are select components that PGs would like to see become more portable and available at significantly smaller sizes and energy efficiencies (see Figure 35). TWG participants indicate there are technical paths to achieve some of these needs, but the work is largely in the research stage and some targets, such as VCSELs[3] at wavelengths other than 780 nm, may not be achievable.

In the short term, TWG participants view improving single-photon sources as an engineering challenge, not a physics challenge; they know how to do it, they just need to devote the required level of effort and investment (see Figure 36). They view meeting the long-term targets as largely a matter of finding a business case in which the investment required to meet the stated targets can be justified.

Across most of the discussion of optical components, there was frequent mention of the tradeoff between specs and cost. More narrowly defined specs will lead to lower volumes, which, in turn will lead to higher costs. Regarding the needs described in Figure 37, TWG participants indicated that these needs are generally addressable. Furthermore, some of the longer-term 2028 needs are currently available but in the form of prototype technologies. Again, lack of demand for specific components is expected to be a barrier to supplying what's needed at scale. In some cases, for example, developing the new bandgap materials described in Figure 38 would require tens of millions of dollars, according to TWG participants. For these needs, project participants don't see much progress likely without government funding.

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[2] Size, weight, and power.

[3] Vertical-cavity surface-emitting lasers.

□ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Integration: On-chip light generation for visible and UV

Lasers and Optics	2024	2028
Need(s):	• PIC laser options below 500 nm, from both gain material (e.g., GaN) and waveguide (e.g., Al2O3) material perspectives • Options below 1 micron • Megahertz or faster switching capability • AO or EO integration	• Heterogeneous integration with laser and delivery / sensor with 3 dB loss • 10x increase in distribution channels • On-chip light sources, including visible sources and sources with 100s of milliwatts of output with linewidths less than 100 kilohertz
Challenge(s):	• World foundries of non-silicon visible photonics are not reliable or are not high throughput • Chip-integrated lasers based on primarily telecom-compatible gain materials (e.g., InP or GaAs) and waveguides (e.g., SOI or SiN) are not suitable for <500 nm due to low efficiencies and high losses • Existing fabrication processes aren't consistent across different facilities and have low throughput and long cycle times • Not many options for blue and UV • Optical isolators are needed on chips due to magnets • Getting below 500 nm is difficult • Not enough volume / market demand to make options feasible for commercial development	• Standardization of footprint and layout • Foundries for active PICs don't exist • Current lasers are too big and too expensive • Lack of consensus among developers/integrators around which wavelengths to use

Figure 27: Roadmap for integration: On-chip light generation for visible and UV

🟦 Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Integration: Integrated photonics

Lasers and Optics	2024	2028
Need(s):	• Smaller form factor (space and weight limitations) • Appropriate materials for needed wavelengths • 3D structures (waveguides)	• Ability to handle higher powers (more than 100 milliwatts) • Photonic structures embedded with defect centers (in diamond) or quantum dots • Diamond interfacing with integrated photonics communication to the listed applications (solid-state spin systems broadly; primarily for sensing and computing applications) • Controlled integration into nanostructures for 2 qubits • Efficient coupling into systems • Adapting photonic wire-bonding
Challenge(s):	• Cost per run • PDK usability • 3D structures in labs • Interfacing / mounting / bonding different materials • Learning from other fields (like telecom) for ruggedization (e.g., Does integrating defects into PIC like structures degrade performance? What about surface passivation?)	• Deterministic positioning of defect (NV, SiV, etc.) centers and quantum dots • Broadly usable laser annealing femto second (currently R&D quality / availability) • Bonding materials together • Chemical mechanical polishing for larger diamonds (2-4 inches)

Figure 28: Roadmap for Integration: integrated photonics

- 🟦 Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

	High efficiency photodetectors	
Lasers and Optics	2024	2028
Need(s):	• Single photon detectors that can work at temperatures above 2K • For computing: photodetectors that are >98% efficient • Less than 50 picosecond jitter • Visible, near IR and telecom • Integrating detectors with rest of the system (OEM type device; greater customization ability) • For communications: efficiency needed is determined by bandwidth, temperature, and frequency • Temperature of operation impacts the materials chosen	• Single photon detectors that are 99.5% efficient at cryogenic temperatures • Photodetectors that can work at temperatures above 2K • Less than 50 picosecond jitter • The ability to do photon number resolving measurements
Challenge(s):	• Operating temperature produces a variety of results • Lack of fab-compatible materials needed to scale (primarily in case of SNSPD, TES, and PNRD) • SWaP – hard to get cryo system in small package (rack-mountable)	• Need fab manufacturing improvements to be able to scale: roughness, yield, integration, footprint, layout, temperature coefficient (critical temp vs. operation temp.)

Figure 29: Roadmap for high efficiency photodetectors

🟦 Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Optical interconnection: Long-distance quantum interconnect strategy

Lasers and Optics	2024	2028
Need(s):	• A method for connecting qubits over tiered distances and optically between cryostats that matches the fidelity of qubits and gates • Each chip boundary either can communicate 2 qubits or contains 2-qubit gates	• Need systems comprising 4 chips organized as a square that can either send qubits from one chip to another or perform a multi-gate quantum operation with qubits on different chips • MW-to-telecom and visible-to-telecom frequency transducers that can enable photonic interconnections between physical qubits that are not telecom-compatible

Challenge(s):	• Communications must function in the 100-qubit chips environment
	  • 1 mm - needs a passive circuit design
	  • 1 cm - needs a low-loss connection between adjacent chips
	  • Optical interconnect - needs a transduction strategy
		• Prototyped technology could likely not be integrated into a system (for optics)
		• The existing frequency transductions are mainly at lab demonstration levels and the efficiencies are rather insufficient for manufacturing

Figure 30: Roadmap for optical interconnection: long-distance quantum interconnect strategy

- 🟦 Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

	Components and sources: Non-telecom wavelength components (e.g., filters, splitters, lasers, modulators)	
Lasers and Optics	2024	2028
Need(s):	• Non-telecom chip-integrated components, including: lasers, micro-resonator-based entanglement sources, single-photon emitters, EO and AO modulators, switches, magnet-less isolators, filters, grating couplers, splitters, photodetectors, etc. • Target qubits to fit these components into: trapped ions, nitrogen and silicon vacancy centers, cold atoms	• Heterogeneous integration of the on-chip components listed in the 2024 Needs
Challenge(s):	• Expensive • Not readily available (especially modulators) • Optical loss • Performance • Reliability • Low volume / market demand	• Deterministic single-photon sources • On-chip lasers with >100 mW power at the visible wavelengths • Materials compatibility as it relates to heterogeneous integration of multiple on-chip components

Figure 31: Roadmap for components and sources at non-telecom wavelengths (on-chip and qubit systems)

Components and sources: Non-telecom wavelength components (e.g., filters, splitters, lasers, modulators)

🟦	Significant gap in expected capabilities
🟦	Tech available but requires optimization
⬛	Tech expected to be deployed

Lasers and Optics	2024	2028
Need(s):	• Linewidth of 1 Hz for continuous source for optical clock applications	• On-demand laser source generation / rapidly manufacturable lasers for sensing needs that can arise • New chemicals, new biological samples • Correlates to a laser required to pump single photon sources when required for those applications at non-standard wavelengths
Challenge(s):	• Lack of production scalability (no one laser serves all markets) • Lack of demand • SWaP • Pulsed source issue: phase noise • Continuous source: line width • Intensity stability • Arbitrary optical wave form generator	• Lack of production scalability (no one laser serves all markets) • Lack of demand • SWaP • Pulsed source issue: phase noise • Continuous source: line width • Intensity stability • Arbitrary optical wave form generator

Figure 32: Roadmap for components and sources at non-telecom wavelengths (sensing focused)

🟦 Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Components and sources: Non-telecom wavelength components (e.g., filters, splitters, lasers, modulators)

Lasers and Optics	2024	2028

Need(s):	• Lasers, modulators, or other optic components: 1 GHz repetition rate (should be low-loss interfaces)
	  • May be required to be put into a dilution fridge for transduction and in a vacuum chamber to address atomic systems
		• Lasers, modulators, or other optic components: 10 GHz repetition rate (should be low-loss interfaces)
		  • May be required to be put into a dilution fridge for transduction and in a vacuum chamber to address atomic systems

Challenge(s):	• Production scale • Lack of demand • SWaP • Pulsed source issue: phase noise • Optical wave form generator	• Low-cost (and non-cryogenic), high-repetition-rate high spectral brightness single or entangled photon sources

Figure 33: Roadmap for components and sources at non-telecom wavelengths (high repetition rate devices)

🟦 Significant gap in expected capabilities

🔷 Tech available but requires optimization

⬛ Tech expected to be deployed

Components and sources: Non-telecom wavelength components (e.g., filters, splitters, lasers, modulators)

Lasers and Optics	2024	2028
Need(s):	• 780 nm components for free-space communications • High-repeition-rate, high-brightness entangled photon sources with MHz-level linewidths that are compatible with quantum memory wavelengths (e.g., 606, 637, 737, 780 nm)	• Need efficient single photon c-band to 775-795 nm band conversion (communications)
Challenge(s):	• Production scale • Lack of demand • SWaP • Pulsed source issue: phase noise • Optical wave form generator	• Low-cost (and non-cryogenic), high-repetition-rate single photon sources • Lack of off-the-shelf options

Figure 34: Roadmap for components and sources at non-telecom wavelengths (communications)

▢ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Components and sources: Downscaled and ruggedized lasers for fieldable tech

Lasers and Optics	2024	2028
Need(s):	• Stable 532 and 514 nm, especially power stable • 590 nm lasers • VCSELs at other than 780 nm • Visible to near IR • Low SWaP lasers for Rydberg sensing applications • Low SWaP lasers for atomic clocks applications	• Order of magnitude smaller and more energy efficient • Handheld • 532 nm VCSEL
Challenge(s):	• Typically exist as larger systems • Tech is currently lab based • Need stable environments • Have space limitations • Have temperature issues • Power consumption • No off-the-shelf solution for tunability within wavelength range • SWaP	• Cooling • Thermal management • Physical / commercial challenges • Power delivery

Figure 35: Roadmap for components and sources: Downscaled and ruggedized lasers for fieldable tech

■ Significant gap in expected capabilities

■ Tech available but requires optimization

■ Tech expected to be deployed

Components and sources: Generation, sources, and integration of single photons

Lasers and Optics	2024	2028

Need(s):	• Generation rates in MHz (>1 MHz) or mega photon pairs/second
	  • g(2) <10% at non-cryo temps (though some applications may have more stringent requirements)
	  • Integrated device emission efficiency >50%
	• Scatter mitigation >100 dB
	  • Depends on Chi 2 or Chi 3
	• Low device variability/reproducibility
	• Quantum dots
		• Electrically driven single photon sources, N>2 entangled states, and photon-state generation
		• Generation rates of >10 GHz (single photons or entangled photon pairs/second)
		  • g(2) <1% at non-cryo temps
		  • Integrated device emission efficiency >90%
		  • Stretch goal: High-rate quantum entanglement sources of spectrally pure photons, producing entangled pairs >100 GHz with high fidelity >0.99*
		• Scatter mitigation >120 dB (Depends on Chi 2 or Chi 3)

Challenge(s):	• High scalability requires heterogenous integration • Scatter mitigation and mitigation of all parasitics • Deterministic vs. non-deterministic control of sources • Wavelength, specs for source laser needed for photons depends on the application • Market pull	• High scalability requires heterogenous integration • Scatter mitigation and mitigation of all parasitics • Deterministic vs. non-deterministic control of sources • Excess loss / source to wave guide coupling efficiency • Material identification • Market pull

Figure 36: Roadmap for components and sources: Generation, sources, and integration of single photons

◻ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Components and sources: Compact, reliable, and fast photonic/optical components (isolators, modulators, fiber components, nonlinear optics, shutters) at UV to IR wavelengths

Lasers and Optics	2024	2028
Need(s):	• Both non-integrated and integrated components • UV robust optical fibers • Isolators, modulators, fiber components, nonlinear optics, shutters • Frequency conversion (non-linear optics)	• Disparate wavelength combiners/splitters (e.g., 480 nm and 780 nm) • 100s of milliwatts • 5 years continuous use without bleaching • 5-10x reduction in current packaging size • Integrated components • Longevity at UV wavelengths • Control of individual beams • Expanded availability of multi-channel AOMs • UV fiber splitters • Physical packaging of a complete modulation system for a specific ion species/isotope
Challenge(s):	• Mitigation of stray magnetic fields from optical isolators • Miniaturization of optical isolator components • Low loss at relevant wavelengths	• Material specific issues at UV, such as bleaching • Longer timeframe for funding (3-5 years) • Magnitude of funding; demand is low compared to other industries • Lack of attention to interoperability of research for different types of neutral atoms and trapped ions • Cost • Market demand

Figure 37: Roadmap for components and sources: compact, reliable, and fast photonic/optical components (isolators, modulators, fiber components, nonlinear optics, shutters) at UV to IR wavelengths

Components and sources: Compact, reliable, stable, high-power free space laser sources with specific wavelengths and tunable wavelengths

- ◻ Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

Lasers and Optics	2024	2028
Need(s):	• A laser lifetime of 10 years • Hz level stability, in particular for Calcium ion Qubits • Compact footprint per power (visible or UV) • More accessible vertical integration in development • Maintain linewidths • Maintaining power and stability in smaller systems	• Cost and reliability (cost per hour, cost per power, 10s of kHz linewidth, -55 to -125 C) • Downscaled (size, power) • Ruggedized • Wavelengths for excitation of new defects • Ability to do linewidth narrowing below 10 kHz • Absolute locking below 100 mHz
Challenge(s):	• There is no single solution to this need • Although the lasers can be built in house, development is restricted due to the amount of time required for each step in the development of the laser source • Available laser sources have a large footprint • Different lasers needed for each defect • Performance specs vary by application	• Materials: bandgaps at blue/UV for direct diode generation (CW lasers) • Reduced maintenance • Right gain media (tunable bandgaps) • Growth of the right gain media • Semiconductor alloy growth challenges • Ways to tune bandgaps (strain-induced, electrical tuning of bandgaps) • Frequency conversion sources on-chip • Market demand

Figure 38: Roadmap for components and sources: Compact, reliable, stable, high-power free space laser sources with specific wavelengths and tunable wavelengths

Cryogenic and vacuum systems

Cryogenic packaging was highlighted as a key need across different applications of quantum technology, including packaging that can survive many cycles from room temperate to millikelvin temperatures over long periods of time. TWG participants highlighted the diversity of packaging types as the key challenge to meeting the packaging needs shown in Figure 39, and also indicated that precise specifications for cryogenic packaging have not yet been determined. Regarding the greater knowledge sharing described in Figure 40, TWG participants are amenable to more sharing in principle, but any shared information must be clearly and narrowly defined and there must be a clear rationale for its sharing, one that does not jeopardize any supplier’s competitive position.

As they did with cryogenic packaging, TWG participants indicated they need more information on needs to address the ultra-high vacuum chamber/pump system needs described in Figure 41. They do not see a movement towards standardization within the 2024–2028 timeframe of the roadmap.

As indicated in Figure 42, PG participants highlighted several long-range needs regarding cryogenic, vacuum, and thermal management systems, and most of the TWG participant perspective was also focused on the longer term. Primary among the challenges they identified for meeting these needs was the diversity of applications and the different solutions they foresee being required for each. They also indicate that Helium-3 will be needed to address many of these needs.

- □ Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

	Cryogenic Packaging	
Cryogenic and Vacuum Systems	2024	2028

Need(s):	• Across all applications, continuous operation reliability and reliability across cold/warm cycles (i.e., zero to low maintenance, tolerant and functional in different operating conditions)
	  • Room temp to mK
	  • Reliability across 5 years / 10 cycles
	  • Low loss optical IO <0.1 dB/facet
	    • Eventually mdB loss levels per facet for optical I/O
		• Continuous operation reliability and reliability across 10 years / 100-200 cycles for computing, 1000 cycles for sensors
		• Milspec is deployed in the field for 10 years
		  • Need low loss optical IO <0.02 dB/facet)

Challenge(s):	• High expense at colder temperatures • Material property availability for packaging temperatures • Limited data at lower temperatures	• Needs material that can withstand target metrics • Low power dissipation for other devices to accommodate low form factor systems • Incorporation of full stack integration • Need for CTE matching over full temperature range for cryo packaging • Fabs will need to coordinate with local utility RE: high power reliability

Figure 39: Roadmap for cryogenic packaging

◻ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Greater knowledge sharing of dilution fridge/cryostat specification data

Cryogenic and Vacuum Systems	2024	2028
Need(s):	• Way for system integrators to obtain knowledge of common components, cable types, connector types, etc. and specs of a dilution fridge to provide to suppliers and standardize setup • Need knowledge of cooling power and the heat load per qubit, especially a heat map of the mixing chamber plate • More domestic dil fridge providers	• Continued information sharing of common components and specs to provide dilution fridge providers of the functional profile needed, especially as the profile changes over time
Challenge(s):	• Getting all system integrators on the same page and willing to share their specs due to a lack of pull from integrators for consolidation of needs	• Needing to scale everything in the dilution fridge (e.g., wires, physical space, cooling capacity) as number of qubits increase

Figure 40: Roadmap for greater knowledge sharing of dilution fridge/cryostat specification data

□ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Ultra-high vacuum chambers/pump systems

Cryogenic and Vacuum Systems	2024	2028
Need(s):	• Reliable commercial processes for bonding/ soldering (metal to glass, metal to metal) • Expand capabilities to integrate systems with other components and swap components (off the shelf solutions) • Quick turnaround vacuum systems • Yields close to 1 for new processes/seals • For cold atoms, need vacuum of ≤10^-8 torr that can be maintained for a long time with a small (inch-scale) pump.	• Expanded/improved processes for pre-qualifying vacuum chambers
Challenge(s):	• No small UHV systems that are mass manufacturable; challenge of bonding UHV chambers • Lack of places to source UHV systems from • Lack of federal support and funding for scaling and infrastructure • Niche market • Lack of R&D funding for developing new processes • Lack of standardized configuration	• Small market size will not justify investment in innovation • Lack of standardized configuration

Figure 41: Roadmap for ultra-high vacuum chambers/pump systems

- ▢ Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ■ Tech expected to be deployed

	Improved reliability and SWaP and reduced complexity of cryogenic, vacuum, and thermal management systems	
Cryogenic and Vacuum Systems	2024	2028
Need(s):	• Field deployable cooling (communication and computing) (i.e., usable in an operational environment it wasn't designed for)	• Cryo systems that fit cube sat size or line card size (could do for optically cooled); ideally air cool using line voltage (wall AC) • Rack mountable (standard electronics rack, less than 8u) • Operating temperature below 1k that does not require He3 • Systems that can operate continuously and don't need to be recharged • Optical access for probing spin qubits • Technologies with temperature ranges that suit cooling methods • Methods to integrate electronic and cryogenic systems (hardware) • Greater than 1 mW cooling power • Portability • Temperature stability
Challenge(s):	• No identified challenges	• SWaP – hard to get cryo system in small package • Different specs needed depending on application

Figure 42: Roadmap for improved reliability and SWaP and reduced complexity of cryogenic, vacuum, and thermal management systems

Control Systems

The role of standards was featured in the discussion of control systems needs. TWG participants acknowledged that having better standards would help them meet the short-term needs described in Figure 43, but they fear that standards could slow innovation. TWG participants indicated that the focus of specs for scalable controls is shifting from radio frequency (RF) and mechanical issues to thermal regulation issues. A key challenge to meeting the longer-term needs is the challenge of coax cabling. Channel counts in the thousands is not considered achievable with coax cabling, though currently, that's the technology the technician workforce is familiar with.

For components that allow integration of spin systems (see Figure 44), PGs proposed codesign of technology with customers for specific applications. The TWG acknowledged the potential benefits of codesign in addressing customer needs but also highlighted the fact that customer-specific codesign would tend to work against the desire for standardization and off-the-shelf equipment. As an alternative, TWG participants proposed setting standards to create compatibility across products. In this regard, they cautioned against setting standards too early and getting the industry "stuck" with a set of suboptimal standards. They suggest focusing on a small set of key standards that are "not too restrictive" but can nevertheless pull the industry toward a degree of commonality.

TWG participants agreed that technician usable systems compose an important goal, though they pointed out that a level of skill is needed for technicians, by definition. They suggest that there will likely always be areas of deeper expertise required to integrate components (see Figure 45). Longer-term, they suggest reskilling existing CMOS[4] test engineers and providing them with technology that has been designed with features to facilitate testing and quality control.

Cryogenic technology is ubiquitous in quantum system development and so is the need for fast device testing and validation at cryogenic temperatures. TWG participants described a number of challenges associated with meeting the needs described in Figure 46, including lack of standards around testing, diversity in protocols for different types of qubits, and lack of an adequate testing workforce. Longer term, TWG participants indicated that cryogenic testing will require new solutions for things like dilution fridge cabling.

In comments reminiscent of those made regarding dilution fridge and cryostat specification data, PG participants cite lack of shared data as a short- and long-term challenge to creating better tools for system and device modeling. TWG participants agreed with the need to address this challenge and indicated that better tools will come in the short term from better communication between fab teams, design teams (of control electronics and qubits, separately), EDA[5] tool developers, and physicists (who understand electromagnetic effects). They suggested existing semiconduction design tools, which are used to design chips with billions of transistors, could be modified for use with qubits. Longer term, they indicated that achieving more accurate modeling will require government investment in research or a significant industry player to address the challenge. TWG participants believe it is possible to meet the 2028 needs of Figure 48, but doing so will require defining the electronics that need to be at low temperatures, how cold these low temperatures need to be, how close components will need to be, and what their dimensions will be.

Figure 49 describes two control-related needs, spin state readout and long-term controls for microwave cavities. TWG participants focused mostly the long-term microwave cavity needs,

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[4] Complementary metal-oxide-semiconductor

[5] Electronic design automation

indicating that progress is being made toward the bandwidth range targeted for microwave cavities. QTMR participants saw no fundamental barriers to meeting the stated 2028 needs. The same optimism was expressed for addressing the 2028 needs described in Figure 50 for FPGA feedforward hardware.

░ Significant gap in expected capabilities

▓ Tech available but requires optimization

█ Tech expected to be deployed

Scalable control systems, including scalable analog control electronics

Control Systems	2024	2028
Need(s):	• Customizable off the shelf solutions • Uniformity of equipment • Frequency resolution (pulse speed: mega vs. giga) • Price per channel • Standards among existing manufacturers	• Modular solutions that address system-level needs, including single system-level controller solutions • Scalable to larger channel counts (1000s with traceability to 10s of 1000s) at low cost per channel • Cost-effective laser control electronics (power draw and cost) • Scalable RFSoCs • Tune RF of AOMs – Phase, frequency, amplitude • Sub watt • Hand-held (primarily applicable to QC) • Higher bandwidth solutions and smaller form factors
Challenge(s):	• No base set of specs / existing standards that allow vendors to make a system quickly/efficiently, leading to the development of systems with different specs	• No market for a single device (for one-off use) • Niche market / low market demand • Funding for open-source software

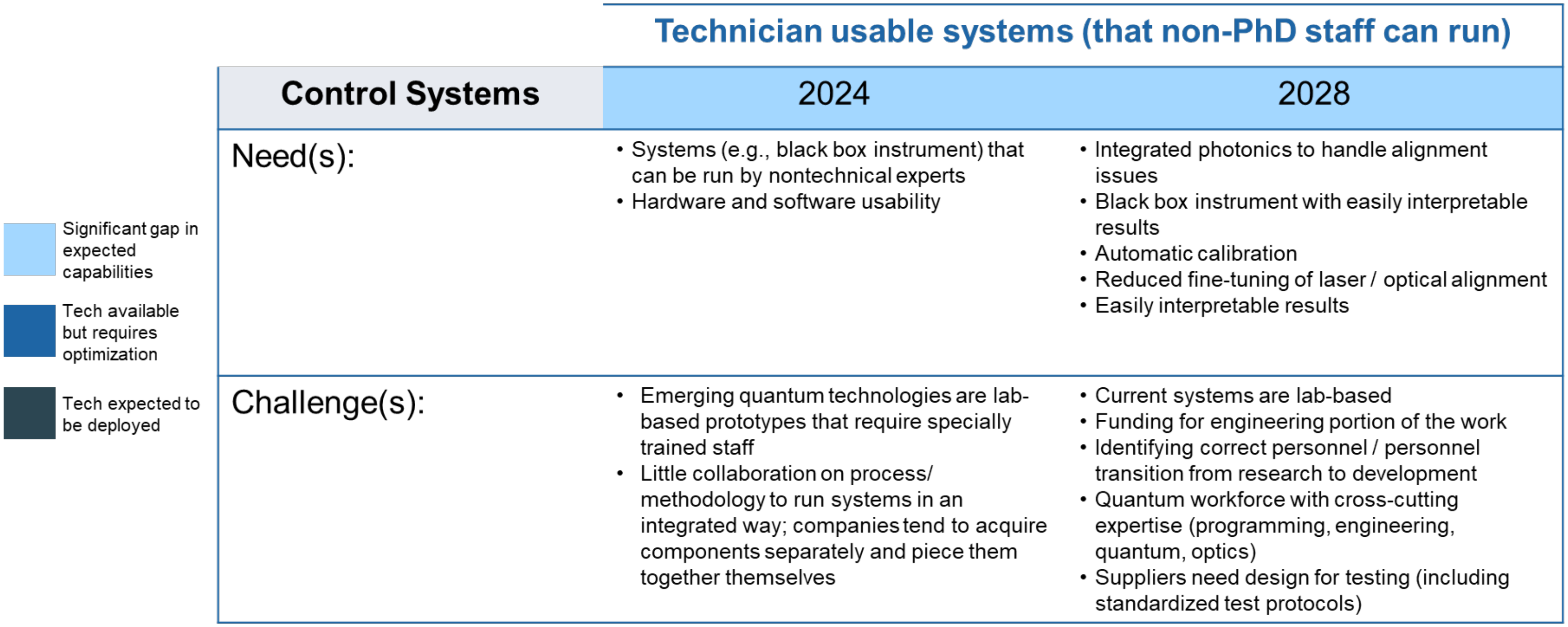
Figure 43: Roadmap for scalable control systems, including scalable analog control electronics

- 🟦 Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

Components that allow integration of spin systems into technologies

Control Systems	2024	2028
Need(s):	• Codesign around specific technologies / application • R&D in shared environment (i.e., microscopes that use defects as local probes)	• Codesign around specific technologies / application • R&D in shared environment (e.g., microscopes that use defects as local probes) • Standardization around component specifications
Challenge(s):	• Isolated development environments • Codesign hinders ability to produce off-the-shelf control electronics	• Isolated development environments • Narrow field / limited market

Figure 44: Roadmap for components that allow integration of spin systems into technologies



🟦 Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

	Technician usable systems (that non-PhD staff can run)	
Control Systems	2024	2028
Need(s):	• Systems (e.g., black box instrument) that can be run by nontechnical experts • Hardware and software usability	• Integrated photonics to handle alignment issues • Black box instrument with easily interpretable results • Automatic calibration • Reduced fine-tuning of laser / optical alignment • Easily interpretable results
Challenge(s):	• Emerging quantum technologies are lab-based prototypes that require specially trained staff • Little collaboration on process/ methodology to run systems in an integrated way; companies tend to acquire components separately and piece them together themselves	• Current systems are lab-based • Funding for engineering portion of the work • Identifying correct personnel / personnel transition from research to development • Quantum workforce with cross-cutting expertise (programming, engineering, quantum, optics) • Suppliers need design for testing (including standardized test protocols)

Figure 45: Roadmap for technician usable systems

▢ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Cryogenic temperature fast device testing and validation

Control Systems	2024	2028
Need(s):	• For cryogenic temperature testing (e.g., qubit parameters): An intermediate point between 100 mK and 1 K • Specifically, need ways to calibrate and then do (and standardize) testing • Options: Test houses, partnerships with universities (all are using separate testing standards at this point)	• For cryogenic temperature testing: technology for <1 K stage that doesn't require a dilution fridge and can thermal cycle more quickly 100 mK (or ideally 20 mK) wafer-level prober to qualify qubits
Challenge(s):	• Identifying the best path for frequency prediction • Combining precision and throughput without destroying JJs • Standardized test protocols needed to test systems don't exist (challenge because qubit types are still being tested) • Expense/funding: Who's paying for it, providers or users? • Lack of broad standards makes it difficult to advance, but creating standardized protocol for all different types of qubits is challenging • Challenge of optimizing qubits • Workforce: Who's running tests? What quals do they need to run tests? • Test equipment systems (AWGs) are needed – complexity and cost issue	• Identifying the best path for frequency prediction • Doing wafer probing with high precision and throughput without damaging devices • Technology will be different 5 years from now, so it'll need a different solution (e.g., dilution fridge cabling)

Figure 46: Roadmap for cryogenic temperature fast device testing and validation

Tools for system and device modeling

Control Systems	2024	2028

Need(s):	• More standardized or open-source documentation of individualized microwave modeling (i.e., cavity QED calculations)
	• Need standard device modeling solution that can be applied elsewhere
	  • Simulating on-chip is important (with EM effects)
	  • Need to scale up to hundreds of qubits
		• Extracting coupling capacities and microwave model characteristics with 5% accuracy of measurement
		• A common language for evaluating modeling methods and their accuracy

Challenge(s):	• Lack of bandwidth for adopting a common language • Little pull from the field for this information to be published/shared • Companies view modeling methods as proprietary	• Lack of access to industry data due to its proprietary nature

◻ Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

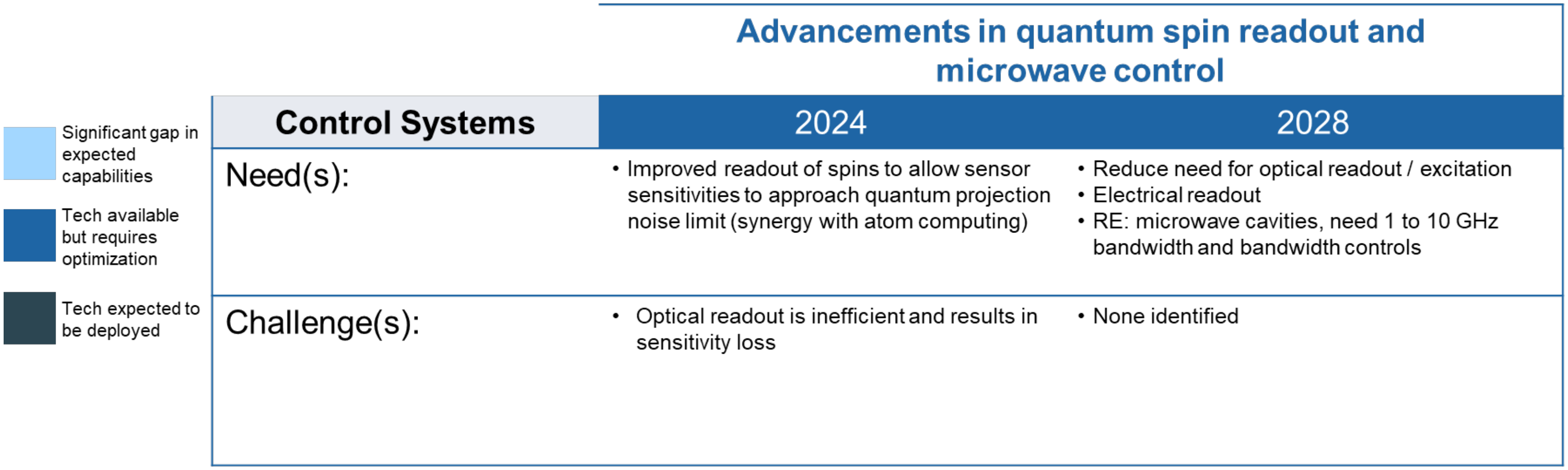
Figure 47: Roadmap for tools for system and device modeling

□	Significant gap in expected capabilities	
🟦	Tech available but requires optimization	
■	Tech expected to be deployed	

	Low temp operation (in situ control electronics)	
Control Systems	2024	2028
Need(s):	• No identified needs	• Deployable systems • Application and spin-system dependent (operate across application range) • Defects in 2D materials need to be at colder temperatures • Technologies with temperature ranges that suit cooling methods • Need to define how many electronics need to be at cold temps vs. how many don't need to be and how cold the temp needs to be

Challenge(s):	• No identified challenges	• Making smaller cryo systems
		  • Difficult to bring many digital electronics close to qubits.
		  • Technology needs to be scaled down, which involves high cost
		• Bringing electronics into fridge requires research

Figure 48: Roadmap for low temp operation (in situ control electronics)



Advancements in quantum spin readout and microwave control

- ▢ Significant gap in expected capabilities
- 🟦 Tech available but requires optimization
- ⬛ Tech expected to be deployed

Control Systems	2024	2028
Need(s):	• Improved readout of spins to allow sensor sensitivities to approach quantum projection noise limit (synergy with atom computing)	• Reduce need for optical readout / excitation • Electrical readout • RE: microwave cavities, need 1 to 10 GHz bandwidth and bandwidth controls
Challenge(s):	• Optical readout is inefficient and results in sensitivity loss	• None identified

Figure 49: Roadmap for advancements in quantum spin readout and microwave control

- ■ Significant gap in expected capabilities
- ■ Tech available but requires optimization
- ■ Tech expected to be deployed

	FPGA feedforward hardware	
Control Systems	2024	2028
Need(s):	• DC to 10 GHz bandwidth • Analog and digital outputs • Internal timing mechanisms up to 200 MHz • 64 channels • Python APIs	• DC to 10 GHz bandwidth • Analog and digital outputs • Internal timing mechanisms up to 200 MHz • 64 channels • Python APIs
Challenge(s):	• No identified challenges	• No identified challenges

Figure 50: Roadmap for FPGA feedforward hardware

Testbeds

PG participants identified two areas of need for Testbeds: cloud accessible systems, described in Figure 51, and testbeds that provide characterization hardware for specialized components, described in Figure 52. The testbed technology category was one for which the project team facilitated joint discussion involving both PG and TWG participants. Much of this joint discussion focused on the need for white box testbeds over black box facilities. White box testbeds offer researchers and developers a higher degree of control, customization, and visibility. Such testbeds would be helpful for experimental research, algorithm development, and for understanding the detailed operation of quantum systems. Participants pointed to the National Quantum Information Science Research Centers (NQISRCs) funded by the U.S. Department of Energy (DOE) Office of Science as an example of white box centers that are publicly accessible to researchers from private companies and other entities.

Acknowledging that testbed access is expensive, participants proposed facilitating broader access via government support that was awarded on a competitive basis. They warned that if the award system was not set up properly, however, such a program might wind up supporting entities that already enjoy access to quantum R&D facilities and that any such government program should be geared toward providing access to new entrants that lack resources.

Regarding testbeds to support characterization hardware for specialized components (see Figure 52), participants were less certain about how such facilities could be made available in the short run, especially for smaller developers. Much of the discussion focused on software being developed for characterization tools. Several tools are working in this area, but the developers involved are not working in a way that could be called cooperative and so the prospects for common testbed facilities are not clear.

- ■ Significant gap in expected capabilities
- ■ Tech available but requires optimization
- ■ Tech expected to be deployed

	Cloud accessible systems	
Testbeds	2024	2028
Need(s):		• Accessible to users for research (limit need to build own system) • Test component level items (experimental protocols, optimization software, error correction schemes, make sure works in cryogenic system)
Challenge(s):		• Federal funding • Maintaining systems • Expanding existing systems

Figure 51: Roadmap for cloud accessible systems

🟦 Significant gap in expected capabilities

🟦 Tech available but requires optimization

⬛ Tech expected to be deployed

Characterization hardware for specialized components

Testbeds	2024	2028
Need(s):	• Know fundamental capabilities and performance of hardware • Cryogenic, RF, narrow linewidth laser, PIC • Lower barrier to entry, don't have startup capital to purchase items they need • Have good clock, narrow linewidth laser, cryogenic system available regionally for researchers/small businesses that need access to those items a handful of times • Support from federal government	• Access to characterization tools and equipment not available to individual users • Rapid cryogenic characterization • Rapid cryogenic sample exchange
Challenge(s):	• Business case	• No identified challenges

Figure 52: Roadmap for characterization hardware for specialized components

Future work

In reflecting on our approach for developing QTMR and what might be needed in the quantum technology industry when this roadmap is due for an update, the SRI team has a few recommendations for a Version 2.0. First, we recommend each quantum application (i.e., communications and networking, computing, sensing) develops its own roadmap. The specific metrics and needs vary drastically by application, and we expect this to become even more true as each application progresses. Relatedly, within each application-specific roadmap, we recommend keeping needs organized by platform rather than by technology area. As this roadmap was focused on manufacturing, it was logical to organize needs by technology when presenting them to manufacturers and suppliers for their input. However, as with applications, we expect needs to become more platform-dependent over time.

Another recommendation for a future quantum technology roadmap is to involve manufacturers earlier in the process. On the few occasions when we organized meetings between integrators and manufacturers, rather than meeting with each group separately, we found the opportunity for direct dialogue to be highly valuable. Often, the specifications that integrators provided were not sufficiently detailed or were less important to manufacturers. The back-and-forth communication enabled manufacturers to obtain the specifications they actually need and learn the integrators' priorities so that the manufacturers can better align with industry. Thus, we recommend planning for more of these opportunities from the beginning of the roadmap development process.

Lastly, we recommend doing more intentional outreach to key players in the industry, on both the integrator and supplier sides. In particular, a next iteration should seek more international involvement. Many countries have unique specializations, and not including experts from international regions can hinder the utility and comprehensiveness of the roadmap.

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- Cryomech
- Doppler Systems, LLC
- DRS Daylight Solutions
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