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The GARD RF Roadmap Update: Community Input and Preview

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U.S. DEPARTMENT
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The 2017 RF GARD Roadmap



The US GARD Program

- The General Accelerator Research & Development (GARD) Program is a unique US Department of Energy Office of Science resource that supports **high-impact R&D in Accelerator Science and Technology** for broad, cross-office accelerator-based sciences (HENP, BES, NNSA and FES) at National Laboratories and universities (from <https://indico.classe.cornell.edu/event/2526/contributions/3437/attachments/2036/2787/CBB-Presentation-07162025F.pptx>)
- GARD also supports test facilities – ATO, AWA, NLCTA (RF test facility), etc.
- In short: GARD is the “beating heart” of accelerator R&D in the US
- GARD supports the operation of the US Particle Accelerator School, a key resource for the accelerator workforce

HENP = High Energy and Nuclear Physics

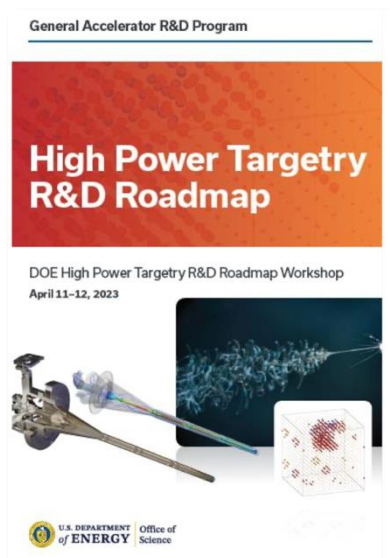
BES = Basic Energy Sciences

NNSA = National Nuclear Security Administration

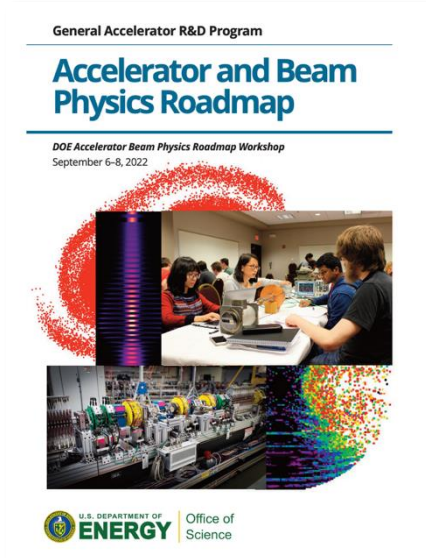
FES = Fusion Energy Sciences

GARD Thrusts and Roadmaps

The GARD program has five thrusts, each with their own guiding roadmaps



- **PST:** Particle Sources and Targets



- **ABP:** Accelerator and Beam Physics



- **RF:** RF Acceleration Technology



- **SCM:** Superconducting Magnets and Materials



- **AAC:** Advanced Accelerator Concepts

Decadal GARD roadmaps outline R&D priorities and milestones to aim for

RF GARD Roadmap

- RF GARD Roadmap was released in 2017
- Lots of exciting progress since then!
- Need new milestones to aim for
- It is time for an update to the roadmap



Following R&D successes, it is time for Update to 2017 RF Roadmap

Highlights of Achievements from 2017 Roadmap



High Precision RF Controls

Marble applied to LCLS-II & PIP-II, with new AI/ML effort under Genesis



New Techniques for Field Emission

Advent of SRF cleanroom robotics and use in PIP-II module assembly



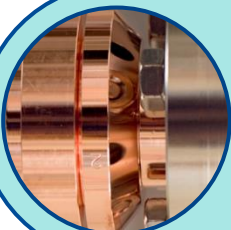
$Q > 3e10$ at $E_{acc} > 35$ MV/m

Advances in doping, novel mid-T bake. Novel RF sources support efficiency.



Nb₃Sn Multicell Cavities and Cryomodules

9-cells, 5-cells, 4 K cryomodules for CEBAF and more



Short Pulse $E_{acc} > 300$ MV/m

Demonstrated at few-ns pulse lengths



$R_{sh} > 200$ M Ω /m

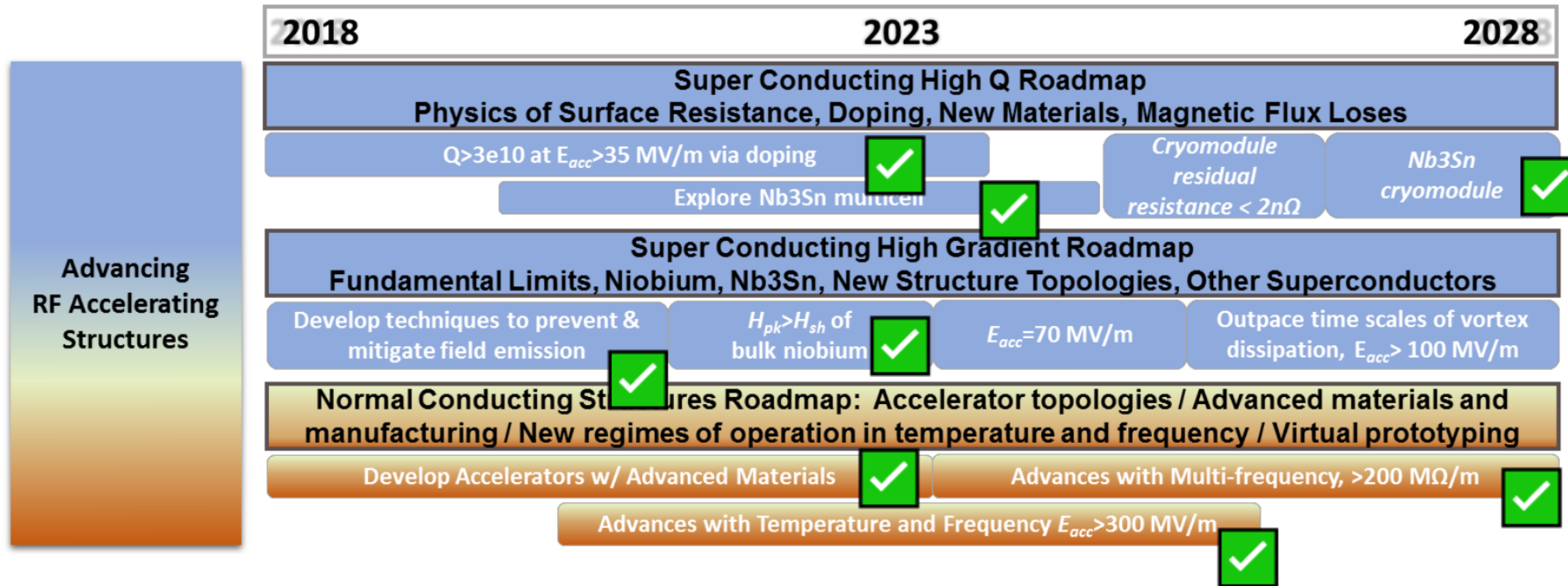
Up to 350 M Ω /m with cold copper.

Selected milestones achieved from the 2017 RF GARD roadmap



Highlights of Achievements from 2017 Roadmap

Overview plot of 2017 RF GARD roadmap, noting milestones achieved in recent years



D. Bafia et al., “New insights on nitrogen doping,” <https://doi.org/10.18429/JACoW-SRF2019-TUFUA4>

S. Posen et al., “Advances in Nb₃Sn superconducting radiofrequency cavities towards first practical accelerator applications,” <https://doi.org/10.1088/1361-6668/abc7f7>

G. Ereemeev et al., “Demonstration of $= 10 \text{ MV m}^{-1}$ with Nb₃Sn cavities in a cryomodule,” <https://doi.org/10.1088/1361-6668/ade82d>

C. Narug et al., “Successful cleanroom installation of PIP-II SSR2 coupler using robotic arm,” <https://doi.org/10.18429/JACoW-LINAC2024-MOPB056>

A.D. Cahill et al., “High gradient experiments with X-band cryogenic copper accelerating cavities,” <https://doi.org/10.1103/PhysRevAccelBeams.21.102002>

W.H. Tan et al., “Nanosecond Radio-Frequency Pulse Driven Photogun for Very Hard X-ray Free-electron Laser,” <https://doi.org/10.48550/arXiv.2511.07592>

Some examples – others have achieved these milestones too!



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RF Roadmap Update Process



Community Input Process – Satellite Meetings

Getting the word out about the Roadmap Update, collecting input



NAPAC Satellite Meeting August 2025

- ESPPU - EU - June 2025 - <https://agenda.infn.it/event/44943/overview>
- USMCC - US - Aug. 2025 - <https://indico.uchicago.edu/event/479/>
- NAPAC - US - Aug. 2025 - <https://indico.jacow.org/event/97/overview>
- SRF - Tokyo - Sept 2025 - <https://ribf.riken.jp/SRF2025/index.html>
- CW and High Average Power RF Workshop - Sept. - US - <https://indico.cern.ch/event/1415344/>
- LLRF Workshop - US - Oct. 2025 - <https://www.jlab.org/conference/LLRF25>
- LCWS - Spain - Oct. 2025 - <https://agenda.linearcollider.org/event/10594/>
- Pulsed High Power RF Sources Workshop - Italy - Nov. 2025 - <https://indico.psi.ch/event/16728/>



Community Input Process – Virtual Workshops

Focus on 4 subtopics: NCRF, SRF, RF sources, RF Controls – recordings of the zoom meetings are available at <https://indico.slac.stanford.edu/event/10359/> – huge thanks to conveners!

- **Normal Conducting RF** - John Power (ANL), Evgenya Simakov (LANL)
 - Date: Jan. 20th, 2026 (full day)
 - Indico: <https://indico.slac.stanford.edu/event/10356/>
- **Superconducting RF** - Matthias Liepe (Cornell University), Anne-Marie Valente (JLab)
 - Date: Feb. 5th, 2026 (full day)
 - Indico: <https://indico.slac.stanford.edu/event/10358/>
- **RF Sources** - Galen Aymar (SLAC), Alireza Nassiri (ANL), John Moss (ORNL)
 - Date: Feb. 11th, 2026 (half day)
 - Indico: <https://indico.slac.stanford.edu/event/10357/>
- **RF Controls** - Philip Varghese (FNAL) Alex Ratti (LBL)
 - Date: Feb. 27th, 2026 (half day)
 - Indico: <https://conferences.lbl.gov/event/2419/>



Community Input Process – In-Person Workshop

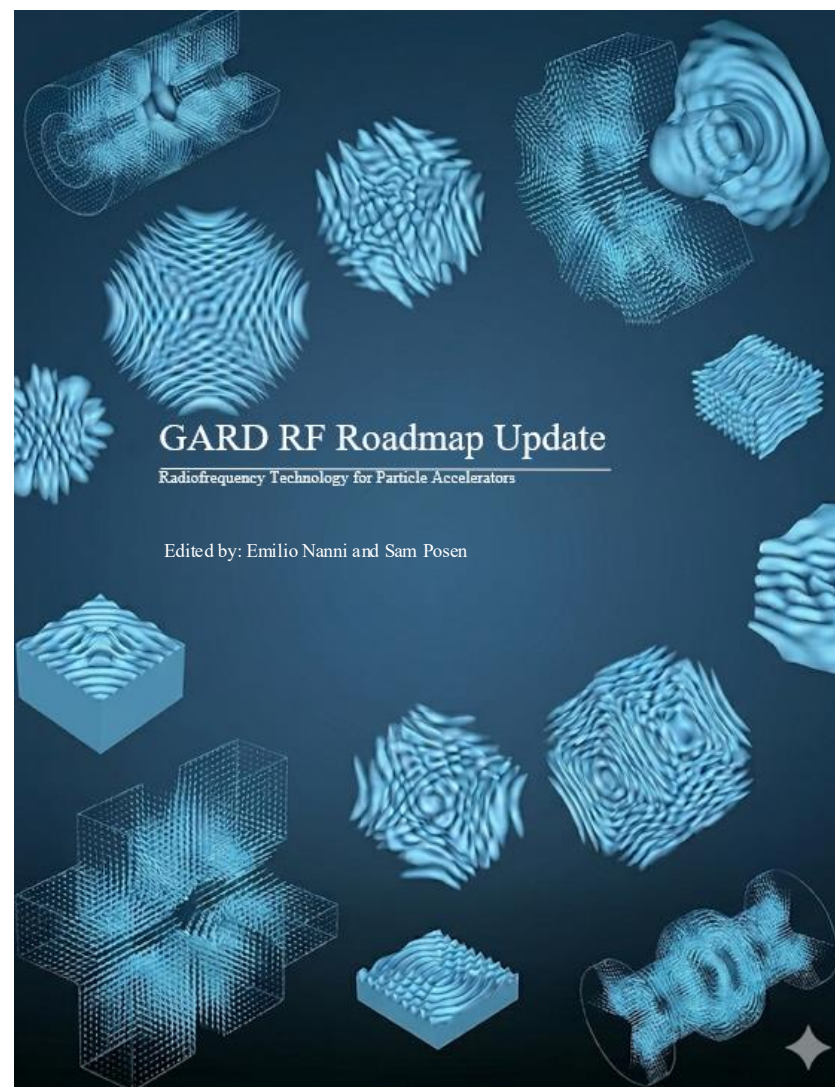
In-Person Workshop at SLAC with summaries from subtopic conveners, first pass at decadal milestones, lots of time for discussion

- March 3-4, 2026 - <https://indico.slac.stanford.edu/event/10359/>



GARD RF Roadmap Update 2026

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Comparison to 2017 Roadmap

- More constrained budgetary environment – must deliver on major international and domestic commitments
 - Disciplined near-term prioritization of R&D directions is essential
- FCC-ee is on the horizon and this roadmap update will be critical to set the stage for US role in the project
 - RF systems will be key for FCC-ee (like magnets have been to LHC). R&D efforts for efficiency, particularly high Q_0 will be essential: Nb₃Sn at 4 K, high Q at 600-800 MHz, Nb/Cu, high efficiency klystrons
- More integrated across subtopics (e.g. SRF + NCRF), sharper focus on RF controls
- Something that hasn't changed: RF R&D has consistently focused on impact, tailoring efforts to where it supports priorities, in ways that really move the needle
 - Enabling new accelerators, supporting existing machines, creating new opportunities for benefits to science and society by leveraging SRF technology

Roadmap focuses on impactful advances that support priorities



High Impact Areas

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1. Revolutionize **RF controls** to enable highly efficient pulsed RF, ultra-reliable operations, and autonomous controls using AI/ML
2. Deploy advanced tools for **reliable, high performance operation** of SRF cavities, including cleanroom robotics and in-situ techniques for field emission
3. Dramatic improvement in **RF sources**, including in efficiency and cost using new concepts and manufacturing technologies
4. **Revolutionary cavities** for fast ramping and beam manipulation
5. Novel platforms for **high-gradient high-brightness injectors**
6. Enhance performance of **Nb₃Sn cavities** and demonstrate their advantage in first applications
7. Understanding the limits of material and structure performance for **transformational increases in gradient and efficiency**
8. Support the RF accelerator ecosystem, including **workforce development**, and synergistic supply chain and **industry** partnership

High Impact Areas carefully selected to prioritize attention in key efforts



Table: Benefits to Projects and Operations

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			RF Controls	Field Emission Reduction	RF Sources	Revolutionary cavities	High-gradient high-brightness injectors	Nb3Sn	Transformational increases in gradient and efficiency	RF accelerator ecosystem
Facilities that are operating or in construction, and their future upgrades	HENP	PIP-II	✓	✓						✓
	HENP	ATLAS	✓	✓				✓	✓	✓
	HENP	CEBAF	✓	✓		✓	✓		✓	✓
	HENP	FRIB	✓	✓					✓	✓
	HENP	SNS	✓	✓	✓	✓				✓
	BES	LCLS	✓	✓	✓		✓			✓
	BES	Synchrotron Light Sources	✓			✓	✓	✓	✓	✓
	NNSA	LANSCE/LAMP	✓		✓	✓	✓			✓
Proposed future facilities	HENP	ACE	✓	✓		✓				✓
	HENP	EIC	✓	✓		✓	✓	✓	✓	✓
	HENP	FCC-ee	✓	✓	✓		✓	✓	✓	✓
	HENP	Muon Collider	✓	✓	✓	✓		✓	✓	✓
	BES	Future Light Source	✓			✓	✓	✓	✓	✓
	BES	Compact FELs	✓	✓	✓	✓	✓	✓	✓	✓
	FES	Fusion Neutron Source	✓	✓	✓			✓		✓
	Ind.	ADS	✓	✓	✓	✓		✓	✓	✓
	Ind.	Compact Industrial Accelerators	✓	✓	✓			✓	✓	✓

High Impact Areas enable facilities – in operation, construction, and future



Table: GARD R&D Facilities

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	RF Controls	Field Emission Reduction	RF Sources	Revolutionary cavities	high-gradient high-brightness injectors	Nb3Sn	Transformational increases in gradient and efficiency	RF accelerator ecosystem
SRF cavity processing facility								
Coating systems								
Cleanroom assembly								
Vertical cavity test facilities								
Horizontal cavity test facilities								
Cryomodule test facilities								
Materials science laboratory								
Advanced prototyping and fabrication								
RF source test stands								
NLCTA								
AWA								
Synergistic facilities								
International facilities								

Activity requires moderate use of facility

Activity requires extensive use of facility

Facilities are critical to R&D efforts, also complimentary to other activities in facilities



Benefits to HENP and Beyond

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RATORY

How Success in the GARD RF Roadmap Benefits High Energy and Nuclear Physics and the Broader DOE Mission

High Energy and Nuclear Physics (HENP)

While there will be advantages across the Office of Science for GARD RF, HENP will be the strongest beneficiary. The roadmap targets impactful improvements for HENP's flagship next-generation accelerators PIP-II and EIC. During a critical time for laying groundwork for the FCC-ee collaboration, the roadmap positions the US to play a key role. In the next decade, HENP's existing user facilities will rely heavily on the SRF linacs PIP-II, FRIB, CEBAF, and ATLAS, so operational cost reductions and improvements to reliability for SRF linacs will be highly impactful. The roadmap also sets a foundation for the future of HENP accelerator-based science through transformational improvements to performance. These benefits are drawn from all four RF subareas of superconducting RF, normal-conducting RF, RF sources, and RF controls, and increasingly from their integration, since the gain from a higher-Q or higher-gradient cavity is realized only with the controls that hold it stable and the RF source that powers it efficiently.

Pulsed operation of PIP-II. Being able to operate PIP-II in pulsed mode at times when cw beam is not needed could save millions of dollars per year in RF power and cryogenic costs. Doing so requires exquisite control of piezoelectric tuners and low-level radiofrequency (LLRF) systems. GARD efforts invoking AI/ML show promise towards enabling this key capability.

Improved operational reliability. SRF accelerators like PIP-II, EIC, FRIB, CEBAF, and ATLAS often want to achieve as much energy gain per cavity as possible. Low-cost AI-enhanced RF controls can provide superior accelerator performance including reduced trips and improved up-time when operating SRF cavities close to stability limits.

Autonomous operation and faster commissioning. Beyond individual feedback loops, the roadmap targets RF systems that tune, diagnose, and protect themselves. Direct-RF-sampling architectures on RFSOC-class hardware reduce the cost and complexity of the control system itself, while model-based and AI/ML methods for anomaly detection, fault classification, and predictive maintenance shorten the path from installation to reliable beam. For projects at the scale of PIP-II and EIC, where hundreds of cavities must be brought into specification, shortening commissioning and reducing the specialized effort needed to run the RF is a direct schedule and cost benefit; the same tools extend the productive life of the installed systems at existing facilities.

Improved performance of existing facilities. Field emission can degrade SRF cryomodules, leading to regular rebuilds as part of operations. Cleanroom robotics have already been implemented in the PIP-II project, which show promise to substantially reducing refurbishment costs while simultaneously improving performance. AI/ML for computer vision will be critical for alignment, but requires small-scale development and demonstration before operational deployment. Another key area of research for supporting operating facilities is in-situ methods for addressing field emission, particularly plasma cleaning.

Nb₃Sn revolution. Nb₃Sn SRF cavities have made enormous performance improvements under GARD, and are now proceeding to first prototype applications including compact accelerators, ion linacs, and isolated cryomodules (e.g. energy adjustment, isotope separation, harmonic

cavities). Continued progress in reproducibility and performance will make Nb₃Sn the material of choice for large-scale science applications such as FCC-ee.

Position the US to play a key role in FCC-ee. CERN has sought out U.S. RF expertise and capabilities for enabling FCC-ee. Investments in both directed R&D and general R&D efforts in relevant areas will be critical in the next few years. U.S. strength in Nb₃Sn as a result of GARD efforts will be foundational, and there are major opportunities in RF sources, the injector complex, controls, and auxiliaries.

Novel crab cavities for EIC. The EIC brings opportunities for innovation in crab cavities to provide strong deflecting voltages while still fitting in the confined interaction regions. Novel cavity shapes can improve luminosity, building on experience gained from HL-LHC.

Widely Tunable SRF cavities. Rapid cycling synchrotrons typically use normal conducting cavities for acceleration due to the large tuning requirement. Innovation in widely tuneable SRF cavities could enable the use of SRF in RCS applications, such as Fermilab's Main Injector, bringing the benefits of high gradients—and therefore fewer cavities—and energy efficiency.

Magnetic field-tolerant high Q cavities. Progress has been promising in recent years in achieving high Q in multi-tesla magnetic fields, for example through the use of Nb₃Sn or HTS coatings on cavities. Magnetic field-tolerant high Q cavities are promising for photoinjectors, ion linacs, a muon collider, and applications beyond accelerators (e.g. dark matter search).

Novel injectors. High-brightness photoinjectors and high-gradient, high-charge injector linacs can transform how electron, positron and ion beams are generated for HENP. This is enabled by dramatic increases in performance for normal-conducting RF structures with demonstrated cathode fields of 400 MV/m in short-pulse operation, and cryogenic copper injectors are advancing toward sustained operation near 300 MV/m with strongly reduced breakdown. Higher-gradient, higher-charge injector linacs may address the positron-production and damping-ring bottlenecks that drive the cost of collider injector complexes, including FCC-ee. The same platform supports the demanding source and cooling-beam requirements of the EIC.

Transformational improvements in performance. Transformational advances in accelerating gradient and Q can enable the next generation of HENP accelerators, as they have many times before. GARD research in alternative materials beyond Nb₃Sn, layered heterostructures, high-gradient copper cavities, and Nb/Cu will be crucial to bring new understanding to material and structure limits.

Efficient, affordable RF power. RF sources set both the wall-plug power and a large fraction of the capital cost of every HENP accelerator. High-efficiency klystrons, permanent-magnet and multi-beam device concepts, solid-state amplifier arrays exceeding 60% efficiency, and RF pulse compression together offer efficiency gains that convert directly into operating-cost savings at EIC, any future collider where power consumption is a defining constraint, and retroactively on deployed accelerators as rf sources require replacement. Advanced manufacturing, including additive manufacturing of source components, promises shorter lead times and lower unit cost. The long-term goal is RF power on demand: architectures that scale in both power and frequency so that a facility can specify the RF it needs rather than design around what the market happens to supply.

Alleviation of supply chain bottlenecks. The next generation of frontier accelerators including EIC and FCC-ee need a reliable supply chain for stable, long-lifetime high power RF sources, as

well as couplers and other RF auxiliaries. Supporting the U.S. RF industry ecosystem in the coming decade can help HENP facilities obtain these components free from supply chain bottlenecks and unpredictable cost increases.

U.S. Strategic Partnership with CERN

CERN is a uniquely important partner for HENP with shared interest in the Future Circular Collider (FCC-ee), the High-Luminosity LHC, and the broader technology base for future colliders. U.S. leadership in high-Q cavities, efficient RF sources, and advanced controls positions the community to contribute materially to CERN's flagship programs while benefiting from CERN's own developments.

Efficient RF sources for large-scale colliders. RF power efficiency is decisive for a machine the scale of FCC-ee, where wall-plug power is a defining constraint. New high-efficiency device concepts such as permanent magnet devices, multi-beam IOTs and high efficiency sources, illustrates a coordinated international push toward the highest-efficiency sources. Progress on these devices lowers the operating cost and energy footprint of the next generation of colliders.

High-Q superconducting cavities and cryomodules. The high-Q0 SRF technology and cryomodule expertise developed through the last decade of U.S. R&D position the community to play a leading role in designing and building high-Q cavities and efficient cryomodules for FCC-ee. Continued advances in surface treatments, Nb₃Sn, and cavity fabrication and cost reduction feed directly into the affordability and performance of a future circular collider's RF system.

RF controls for demanding operational modes. Future CERN machines impose control challenges that are shared with U.S. projects. FCC and HL-LHC require operation across a wide range of voltage requirements, handled through techniques such as reverse-phase operation. The direct-RF-sampling platforms, precision feedback, and AI/ML tools advanced under the roadmap are directly relevant to these needs, and collaborative development accelerates progress for HENP and CERN.

Beam-manipulation and collider RF systems. The demanding cavity systems required for future colliders, including crab cavities, higher-order-mode damping, and beam-loading compensation for high-current beams, represent a shared technical frontier. Advances in cavity architecture, high-power couplers, and low-noise controls developed collaboratively benefit both CERN's programs and the U.S. collider efforts they parallel.

Basic Energy Sciences (BES)

The next decade of GARD RF will directly advance the DOE BES mission, whose accelerator needs are concentrated in the light sources and ultrafast-science facilities including LCLS-II and LCLS-II-HE, storage-ring improvements and upgrades (APS-U, ALS-U, NSLS-II), ultrafast electron diffraction, and an emerging class of compact radiation sources. Progress across superconducting RF, normal-conducting RF, RF sources, and RF control has significant benefits for all of these facilities.

Brighter beams. The brightness of a light source is set at its injector, and both RF technologies are advancing the state of the art. High-gradient normal-conducting photoinjectors offer a path to

R&D milestones from roadmap connect to benefits to top priorities

GARD Roadmap Update & FCC-ee

- CERN and the US HEP community share an interest in the energy frontier including HL-LHC, FCC-ee, and the broader technology base for future colliders.
- U.S. strengths in high-Q cavities, efficient RF sources, and advanced controls positions the community to contribute materially to CERN's flagship programs while benefiting from CERN's own developments, including substantial synergy with EIC.
 - **High-Q superconducting cavities and cryomodules:** High- Q_0 SRF technology and cryomodule expertise position the US to play a leading role in designing and building high-Q cavities and efficient cryomodules. A US Nb_3Sn initiative could enable Nb_3Sn SRF to be a part of the baseline for FCC-ee with substantial benefits for infrastructure and cryogenic energy savings.
 - **Efficient RF sources for large-scale colliders:** New high-efficiency device concepts such as permanent magnet devices, multi-beam IOTs and high efficiency sources can lower the operating cost and energy footprint of the next generation of colliders.
 - **RF controls for demanding operational modes:** FCC and HL-LHC require operation across a wide range of voltage requirements, handled through techniques such as reverse-phase operation. Direct-RF-sampling platforms, precision feedback, and AI/ML tools advanced under the roadmap are directly relevant to these needs, and collaborative development accelerates progress for the US and CERN.
 - **Beam-manipulation and collider RF systems:** Advances in crab cavities, higher-order-mode damping, and beam-loading compensation for high-current beams developed collaboratively benefit both CERN's programs and the U.S. collider efforts they parallel.





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Final Thoughts



Summary

- **GARD RF Roadmap update is reaching a full draft**
- Major progress since 2017 roadmap, amazing to see the milestones that have been achieved
- Community input through satellite meetings, virtual meetings on 4 subtopics, in-person meeting at SLAC
- In the near term, RF GARD investments are tightly aligned with mission-driven priorities, including near term efforts that will support PIP-II operations
- R&D efforts with major impact for FCC-ee include Nb₃Sn SRF for high Q at 4 K, ~800 MHz high Q development, and high efficiency RF sources, with substantial synergies with ongoing EIC efforts



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