SRF Ecosystem

Cavity Fabrication, Preparation, and Test Facility Needs for the U.S.

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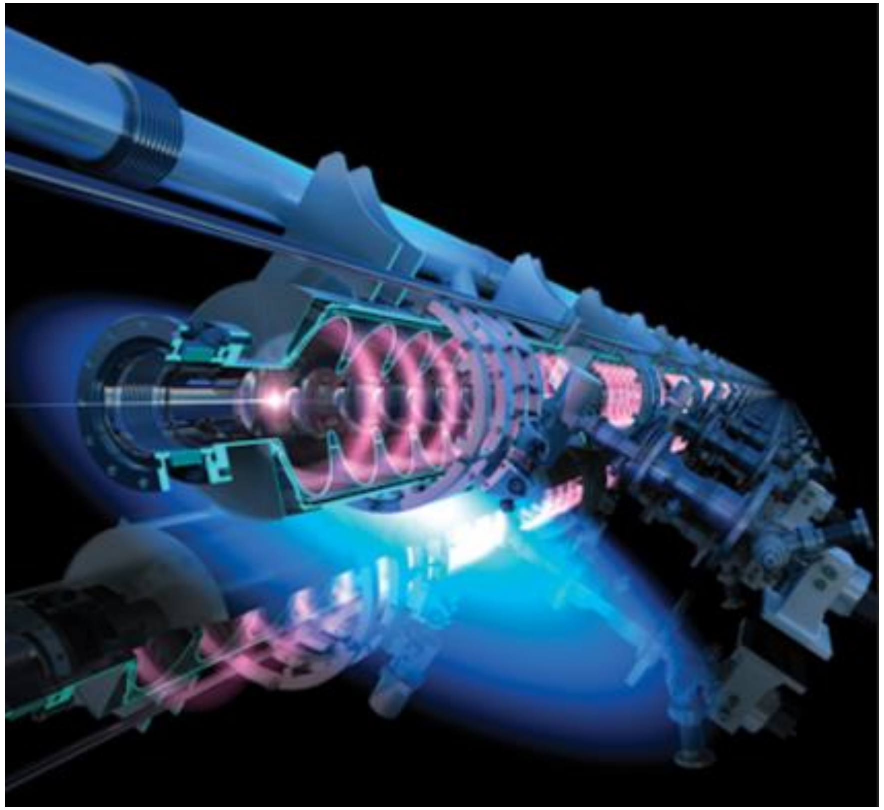
Overview & Strategic Context

- Global & US Landscape: Large-scale projects drive demand for high-performance SRF infrastructure
- US initiatives range from high-energy physics (Colliders) to applied accelerators (Isotopes)
  - Future SRF demand increases in scale, complexity, and concurrency
  - Future accelerators are mostly facility-throughput limited, not physics-limited
- Ecosystem Gaps:
  - Facility readiness directly drives cost, schedule, and workforce sustainability



SRF technology readiness is no longer the limiting factor

Drivers of Future SRF Facility Demand

Energy-frontier colliders

- ILC: ~16 km of 1.3 GHz cavities. Demands mass-production capacity.
- FCC: 91 km tunnel. Needs 400/800 MHz cavities, strong HOM damping, and Nb/Cu materials.
- Muon Collider: Long-term concept (~10 TeV). Unique challenges in muon cooling and strong magnetic fields

Intensity-frontier CW proton drivers and upgrades

- PIP-III / ACE (Fermilab): Potential multi-MW upgrade to PIP-II linac (e.g., 8 GeV). Requires high-capacity testing.

Advanced FELs and next-generation light sources

- LCLS-II HE upgrades

Industrial and applied SRF accelerators

- Medical Isotopes: Turnkey SRF linacs for Mo-99 production (e.g., Niowave).
- EUV Lithography: High-power FELs (>10kW) for next-gen semiconductor manufacturing.
- Environmental: Compact, conduction-cooled accelerators for wastewater treatment and sterilization.

Drivers of Future SRF Facility Demand

- Order-of-magnitude increases in cavity counts (for collider-scale machines)
- Parallel production and processing of multiple cavity families (1.3 GHz, 650MHz, 400/800MHz, low-β structures)
- Higher Q_0 CW Operation (longer processing cycles, tighter contamination control, more retesting)
- Concurrency (fabrication, processing, testing, assembly for multiple program at once)
- New materials and processing workflows (R&D breakthroughs)

High Impact R&D as a Facility Driver

Emerging directions impose new facility requirements:

- High-Q high-gradient via surface engineering -> material analysis
- Nb_3Sn and new materials -> new heath treatments and coating infrastructure, cryogen free conduction cooling
- Nb/Cu thin film -> deposition systems, material analysis
- Field emission mitigation -> plasma processing and advance diagnostics
- New cavity shapes -> modular, flexible infrastructure

High Impact R&D actively reshape facility needs

Current US SRF Facility Ecosystem

- Distributed network of specialized lab facilities
- World-leading but tightly coupled to active projects
- Optimized for qualification, not for national-scale throughput
- Limited surge capacity and limited long-duration test capability

Facility	SRF Capabilities & Infrastructure	Major SRF Projects / Programs
Jefferson Lab (TJNAF)	Cavity processing, cleanroom assembly; Vertical Test Area for cavities and materials; Cryomodule assembly & testing	CEBAF 12 GeV ops; LCLS-II HE; SNS PPU; EIC and NP SRF R&D; Nb_3Sn prototype module; this-film and materials R&D
Fermilab (FNAL)	Cavity processing, Multiple vertical test stands; Cryomodule Test Facility (CMTS) for full modules; FAST accelerator (SRF test beamline)	LCLS-II HE; PIP-II; ILC; SRF R&D (high Q, flux expulsion, materials); SRF Quantum Computing R&D
SLAC	SRF linac operations; Cryoplant and module support infrastructure; Developing in-house maintenance and test capability for 1.3 GHz modules	LCLS-II ops; LCLS-II-HE; CRMF
Oak Ridge (ORNL)	SRF linac operations; Cryogenic test stand for spare/modified cavities; On-site tunnel for additional cryomodules	SNS Proton Power Upgrade; Second Target Station (planned, may require further SRF energy upgrade)
Brookhaven (BNL)	SRF infrastructure for NSLS-II; Collaboration with JLab for cavity processing and R&D	Electron-Ion Collider, NSLS-II ops
Argonne (ANL)	Cavity fabrication (niobium forming, EB welding in partnership); Surface prep labs (BCP cleaning, HPR); Vertical test dewar; ATLAS cryomodules (in-situ testing)	ATLAS; PIP-II; R&D on low-β cavity designs
MSU/FRIB	Full production facility for low-β cavities: cleanrooms, chemistry (BCP), vacuum furnace; Multiple test cryostats; Module assembly line	FRIB heavy-ion linac (324 cavities across 46 cryomodules, operational 2022); FRIB upgrade studies (more QWR/HWR for higher energy)
Cornell University	SRF R&D labs at CLASSE: cavity processing, cleanroom and vertical test dewars; cryomodule test area	CBETA ERL ops; Prototype SRF injector and linac for future ERL light source; SRF R&D
Niowave, Inc.	Commercial SRF fabrication (niobium cavity forming, EB welding) on small scale; In-house processing (HPR, 800°C furnace) for prototypes; SRF cryomodules for isotope production	Turn-key SRF linacs for medical isotopes (e.g. Mo-99 production); SBIR projects (e.g. high-Q nitrogen-doped cavities, novel geometries, conduction cooling)
General Atomics	Partners with labs (JLab) on SRF prototyping; Developed a horizontal cryostat for conduction-cooled cavity tests using commercial cryocoolers	Demo of a 952 MHz conduction-cooled cavity in 2024; Collaborative R&D on next-gen SRF systems
C.F. Roark & Other Vendors	Niobium cavity fabrication (deep-drawing, machining, electron-beam welding) – no in-house chemistry or cleanroom; U.S. source for niobium raw material (ATI Metals) exists but cavity grade remains internationally competitive	Supplied >100 cavities for FRIB (via Roark); Smaller contracts for prototype cavities (often partnering with labs for processing and testing)

Fabrication Capabilities – Current Reality

- Niobium forming and EB welding primarily via vendors with lab oversight
- Fermilab, Jlab and others provide process development and acceptance testing
- Limited domestic cavity industrial base

Facility	Fabrication
JLab	Limited
FNAL	
SLAC	
ORNL/SNS	
BNL	
ANL	Limited
MSU/FRIB	
Cornell	
Industry	Limited

There is no single U.S. company provides end-to-end cavity production

Processing & Preparation Facilities – Current Reality

- High-β cavity processing mainly at FNAL and Jlab
- Low-β cavity processing mainly at MSU and ANL
- Nb_3Sn and thin-film capability at JLab, Cornell and FNAL
- Facilities are:
  - optimized for active flagship projects
  - highly subscribed
  - capacity-limited for exploratory or parallel workflow
- Processing steps are serial, labor-intensive, and rework-prone

Facility	Processing (EP/BCP/HPR/Furnace)
JLab	√
FNAL	√
SLAC	
ORNL/SNS	
BNL	√
ANL	√
MSU/FRIB	Low-β
Cornell	√
Industry	

Processing is one of the most important bottleneck

Cold Test & Validation Facilities – Current Reality

- Vertical test stands distributed across FNAL, JLab, ANL,MSU, Cornell
- Cryomodule test facilities at FNAL, JLab, ORNL, BNL, Cornell
- Key limitations:
  - Cryomodule test facilities are very specific for cryomodule types
  - Cryogenic plants sized for single-program operation
  - Long cooldown/warmup cycles dominate cadence

Facility	VTS (2 K)	Cryomodule Test
JLab	√	√
FNAL	√	√
SLAC	Under development	Under development
ORNL/SNS		√
BNL		√
ANL	Low-β	
MSU/FRIB	Low-β	
Cornell	√	√
Industry		

Under concurrent demand queues grow nonlinearly and retest cycles propagate delays upstream

Strengths & Gaps of Current Ecosystem

- The US SRF ecosystem provides end-to-end technical capability:
    - fabrication know-how shared between industry and labs
    - world-class surface processing protocols
    - high-capacity testing infrastructure

- No single U.S. company offers end-to-end cavity production (forming → surface processing → clean assembly) at production scale.
- Bottlenecks in surface processing, clean assembly and cold test capacity.
- Highly specialized workforce concentrated at a few labs/university.

Enhance Domestic Fabrication

- RISK: fragmented domestic capability increases dependence on international vendors and introduces schedule fragility.

Closing the Gap

- Shared SRF fabrication and test facilities with industry to lower entry barriers
- Establish a shared SRF innovation center enabling industry access to advanced infrastructure without large capital barriers.
- This will enable parallel cavity production beyond single-lab capacity and will reduce single-facility risk

Processing & Testing Facility Expansion

- RISK: under concurrent demand, queues grow nonlinearly and propagate schedule delays across programs.

Closing the Gap

- Expand processing and cold-test capacity where bottlenecks dominate
- Add redundancy to cryogenic
- Treat facilities as national user assets
- Enable concurrent programs without queue-driven delays
- Shift from project-optimized infrastructure to programmatic capacity

Workforce Development

- RISK: scaling future programs becomes workforce-limited rather than technology-limited.

Closing the Gap

- Facilities as workforce and innovation hubs
- University–lab–industry training pipelines
- Embedded training within operational SRF facilities
- Develop transferable process expertise, not project-specific knowledge

Evolution of the SRF Ecosystem

Phase 1 — Project-driven infrastructure (historical model)

Facilities built to support individual flagship projects
Specialized capabilities concentrated at few labs
Sequential project execution enabled reuse of infrastructure
Limited industrial participation beyond fabrication

Phase 2 — Programmatic infrastructure (today)

Multiple SRF-intensive programs emerging simultaneously
Facilities optimized for existing missions but approaching capacity limits
Increased reliance on shared expertise and cross-lab collaboration
Workforce and infrastructure beginning to limit scalability

Phase 3 — Industrial-scale SRF ecosystem (future needs)

Parallel production across multiple facilities and industry partners
Redundant processing and cold-test infrastructure
Facilities operating as national user assets
Integrated workforce pipelines across labs, universities, and industry

Roadmap

0-5 years

- Stabilize and modestly expand existing lab facilities
- Relieve processing and cold-test bottlenecks
- Launch design of national SRF facility strategy
- Demonstration facilities for Nb_3Sn and cryogen-light SRF

5-10 years

- Construct shared fabrication and test facilities
- Enable domestic industrial-scale cavity production
- Establish national reliability and system test infrastructure
- Support concurrent major SRF projects

10+ years

- Collider-scale SRF production readiness
- 4 K SRF and conduction cooling mainstream
- Persistent US SRF industrial and facility base
- Facilities operating as national user infrastructure

Summary

- The U.S. SRF ecosystem is technically strong but structurally capacity-limited
- Future accelerator programs shift the limiting factor from technology to infrastructure
- Key system risks
  - Schedule fragility due to limited fabrication diversity
  - Nonlinear delays under concurrent demand
  - Workforce scaling becomes limiting before technology maturity
- Strategic direction
  - Transition from project-driven infrastructure → programmatic national capacity
  - Expand processing and cold-test throughput with redundancy
  - Strengthen domestic industry integration
  - Treat workforce development as infrastructure

Future SRF programs will be infrastructure-limited unless facility capacity and workforce pipelines evolve now.

Back-Up