Integrated US SRF Program for FCC-ee

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For Program Partner Institutions

Integrated US SRF Program for FCC-ee

US Strategic Participation in the FCC-ee Nb SRF Development

1. Motivation / introduction
2. Proposed Scope
3. Proposed Timeline

US Rapid Development Program for Nb_3Sn SRF Technology

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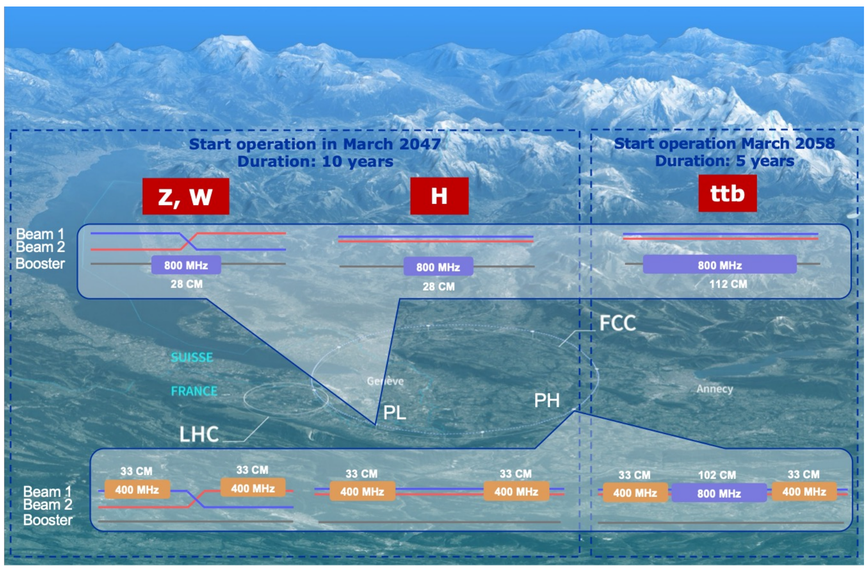
FCC-ee SRF Layout and Specifications

- 400 MHz 2-cell cavities: 10.6 MV/m, Q_0~3×10^9 @ 4.5K
- Or 600 MHz 2-cell cavities: 14 MV/m ($t\bar{t}$: 20.5 MV/m), Q_0~3×10^{10} @ 2K
- 800 MHz 6-cell cavities: 5-17 MV/m ($t\bar{t}$: 20.5-23 MV/m), Q_0~3×10^{10} @ 2K



Collider (point H)	Z	W	ZH
Frequency [MHz]		600	
Number of cells / Cav. per CM		2 / 4	
Temperature [K]		2	
RF voltage - E_{acc} [MV-MV/m]		6.94 – 13.89	
Q_0		3.0 x 10^{10}	
R/Q [Ohm]		150	
# of cryomodules		72	

Collider	$t\bar{t}$	
Frequency [MHz]	601.19	801.5
Number of cells / Cav. per CM	2 / 4	6 / 4
Temperature [K]	2	2
RF voltage - E_{acc} [MV-MV/m]	10.25 – 20.5	22.76 – 20.5
Q_0	3.0 x 10^{10}	3.0 x 10^{10}
R/Q [Ohm]	150	630.4
# of cryomodules	72	72

Booster initial layout equal to reference scenario

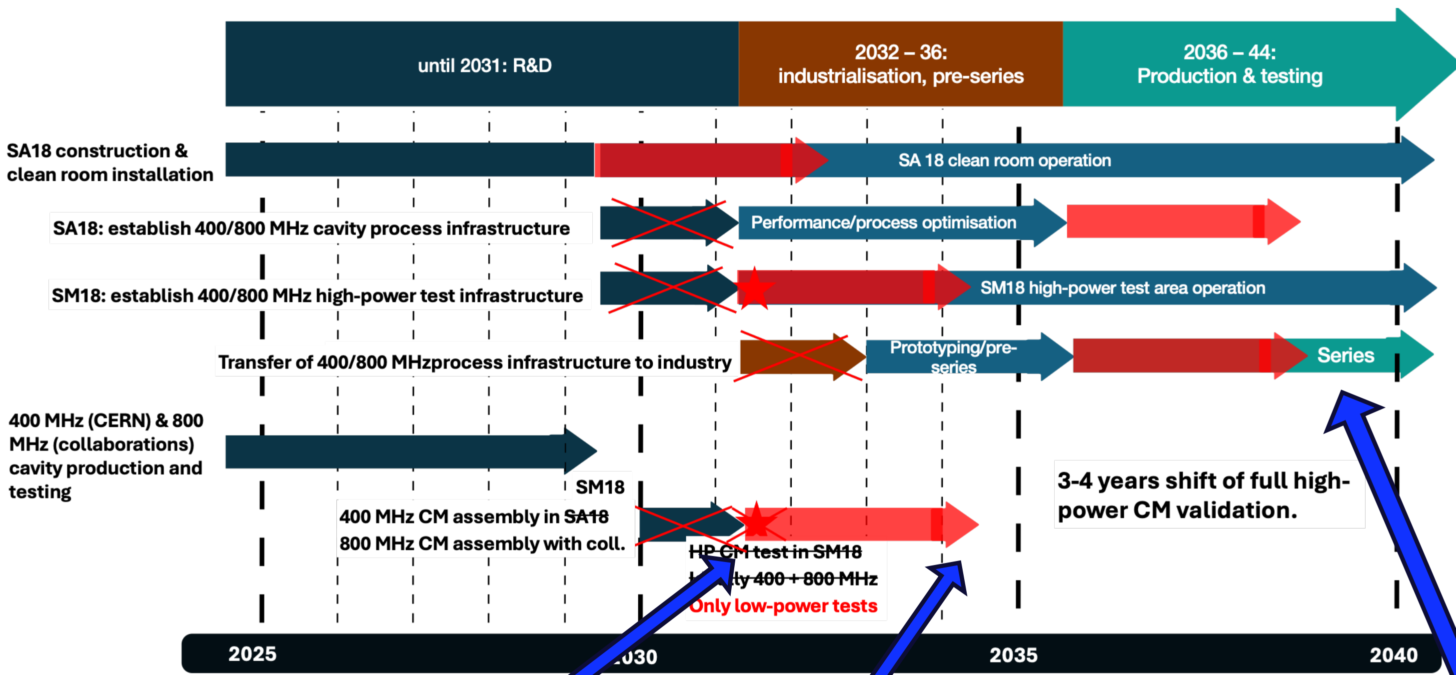
Booster (point H)	Z	W	ZH
Frequency [MHz]		801.5	
Number of cells / Cav. per CM		6 / 4	
Temperature [K]		2	
RF voltage - E_{acc} [MV-MV/m]	5.4 - 4.9	12.6 - 11.45	17.6 – 16.9
Q_0		3.0 x 10^{10}	
R/Q [Ohm]		630.4	
Duty cycle	0.55	0.23	0.14
# of cryomodules		28	

Booster	$t\bar{t}$
Frequency [GHz]	801.58
Number of cells / Cav. per CM	6 / 4
Temperature [K]	2
RF voltage - E_{acc} [MV-MV/m]	25.51 – 22.98
Q_0	3.0 x 10^{10}
R/Q [Ohm]	630.4
Duty cycle	0.086
# of cryomodules	98

FCC-ee SRF Roadmap

Slide credit: Adopted from
F. Gerigk, FCC Week 2026

~8 years till full power CM test; ~ 12 years till start of CM production



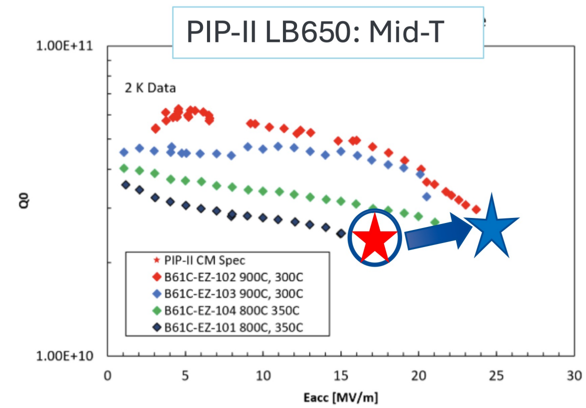
Low power CM testing ~2031

Full power CM testing ~2034

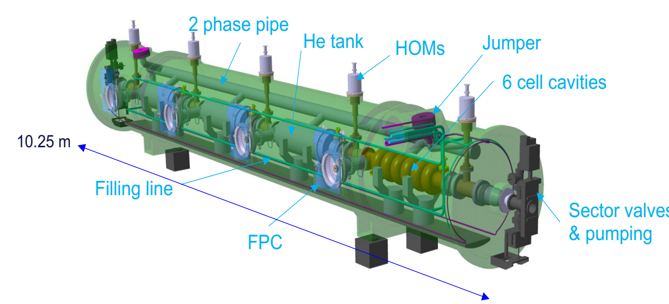
CM production start ~2038

U.S. Superconducting RF R&D Leadership

- **U.S. is a leader in SRF science and technology**
  - LCLS-II high-Q (nitrogen doping) and cryomodules (FNAL, TJNAF, SLAC, Cornell)
  - PIP-II high-Q cavity and full system development (FNAL)
  - EIC SRF (TJNAF, BNL)
  - FRIB SRF (MSU)
  - LHC crab cavity development (FNAL, TJNAF)
  - SNS Energy Upgrade (TJNAF, SNS)
  - General SRF R&D (GARD): high Q, high gradient, Nb_3Sn…
- **U.S. is well positioned to take on SRF R&D leadership for FCC-ee**
  - 800 MHz cavity and prototype cryomodule development (FNAL)
  - High Q_0 R&D (FNAL, TJNAF, ANL, Cornell)
  - Breakthrough Nb_3Sn R&D (Cornell, FNAL, TJNAF)
- Beyond FCC-ee, continued **SRF R&D highly relevant for other future accelerator projects, e.g., EIC, FRIB energy upgrade, industrial accelerators…**
- FCC-ee **SRF R&D aligns well with the U.S. long-term priorities**.
- **Continued focus on SRF R&D** with sustained support and investment **critical for future colliders and workforce development**



High-Q_0 SRF cavity process R&D



FCC-ee 800 MHz prototype cryomodule design at Fermilab

Integrated US SRF Program for FCC-ee

Our vision:

- Establish a **nationally coordinated effort** on SRF
  - Like the U.S. LHC Accelerator Research Program(LARP) collaboration on LHC magnet development
- Well-aligned with (updated) DOE GARD RF Roadmap => see Sam's talk
- Focused on high-impact for FCC-ee and the US accelerator program
- Closely coordinated with CERN
- Funded via US FCC-ee support and DOE GARD
- Proposed US Institutional participation: ANL, Cornell, JLab, Fermilab,…

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US Strategic Participation in the FCC-ee Nb SRF Development

- **CERN FCC-ee leadership wants the US to contribute in the area of SRF**, and to ramp up our engagement as much as possible.
- The **HENP budget remains constrained** due to the imperative to deliver on major commitments (HL-LHC, LBNF/DUNE, PIP-II).
- US FCC-ee activity at this time must be scoped in this context.

⇒ **Small, strategic program** proposed here for US institutions.

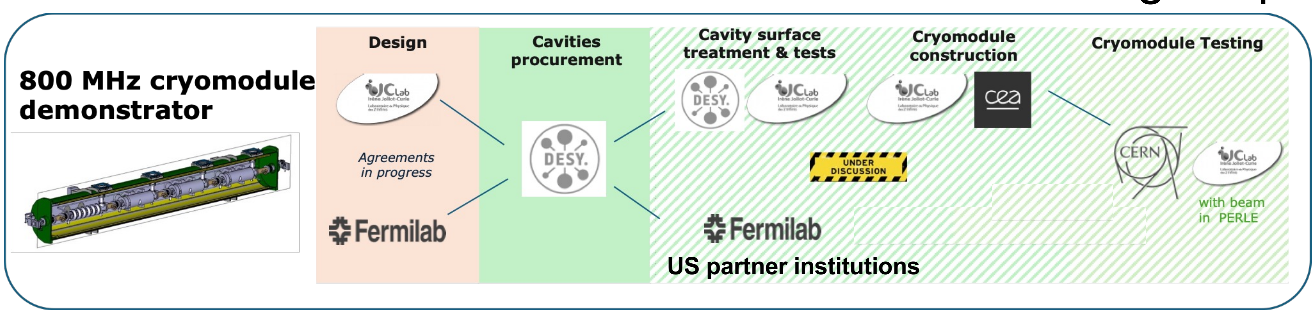
⇒ Program carefully designed to **align with CERN's priorities**.

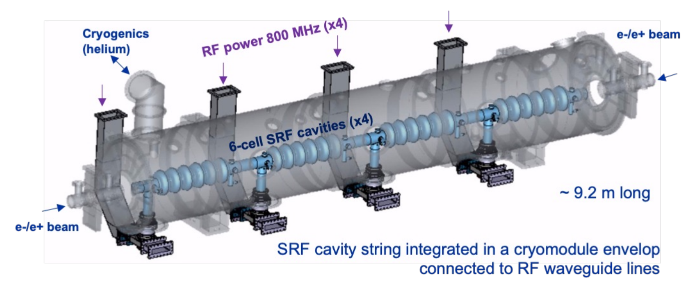
⇒ Gives the US a chance to make **meaningful contributions to ongoing FCC-ee accelerator efforts.**

⇒ Program is aimed to show US commitment and position the US to play a significant role should CERN give the green light in 2028, all while **maintaining a limited budget**.

FCC-ee Nb SRF Development Program

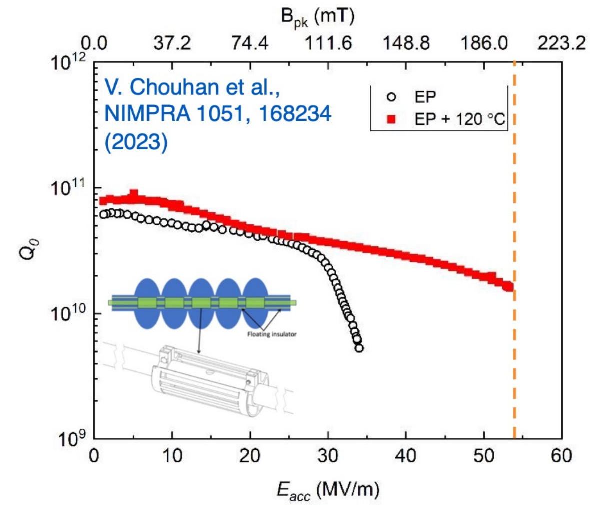
- SRF system where CERN has sought outside contributions so far has been the 800 MHz cryomodules.
- Through the INFRA-TECH 2026 European call, **European institutions plan to build an 800 MHz FCC-ee cryomodule demonstrator**.
  - CERN, IJCLab, CEA, ESS, DESY, HZB
  - **Not realistic building a prototype module in the US at this time.**
- **But: Opportunity to contribute to a European prototype cryomodule, leaning on US strengths in high-performance SRF.**
  - Makes the US an intellectual and technological partner in this development.

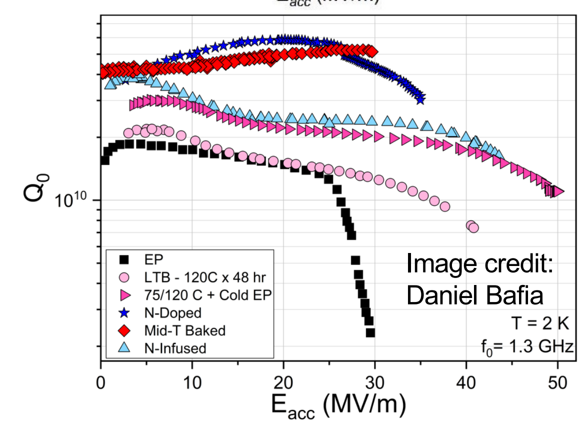




US Capability and Experience for FCC-ee Nb SRF Development

- 800 MHz modules: bulk niobium cavities requiring high Q at medium fields.
  - ⇒ **FCC 800 MHz cavity performance goals are challenging but seem within reach of current advanced techniques with focused R&D.**
- **US leadership and capability in high Q, high gradient cavities and cryomodules is highly relevant here:**
  - N-doping breakthrough development
  - Low-T and mid-T heat treatment development
  - Optimized EP development
  - LCLS-II, LCLS-II HE, PIP-II





Proposed Scope: Overview

- **Perform high Q process R&D at 800 MHz.**
- **Transfer optimal processing steps to 800 MHz 6-cell cavities.**
- **Treat and test 800 MHz cavities for prototype cryomodule**
- **TBC: Weld helium tanks to prototype module cavities and retest.**
- **TBC: Design of 800 MHz cavity frequency tuner and test.**

Note: This 800 MHz high-Q Nb development is relevant for FCC SRF in the 600 – 800 MHz range.

<u>Deliverable:</u> 4 qualified, jacketed 6-cell 800 MHz cavities with tuners, plus 1 spare.

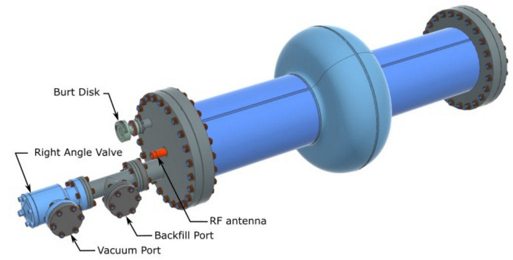
CERN FCC-ee leadership voiced strong support for this proposed US scope.

Proposed Scope: Details

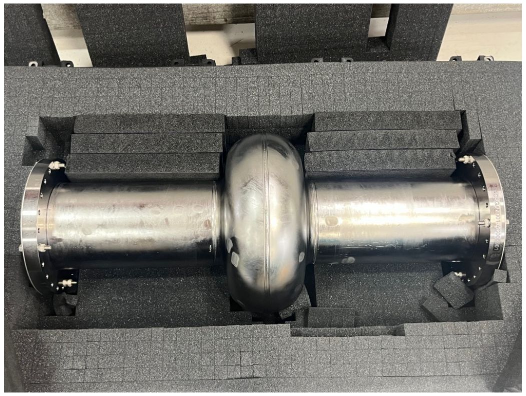
Perform high Q process R&D at 800 MHz:

Goal: Determine best treatment process at 800 MHz.

- Note: 800 MHz sits between the PIP-II (650 MHz) and LCLS-II (1300 MHz) frequencies.



- Fabricate 3 to 4 single-cell 800 MHz cavities (in addition to those provided by CERN).
- Conduct systematic single cell 800 MHz cavity treatment optimization.
  - E.g., EP baseline, followed by mid-T at various temperatures.
  - Cross-US-facility performance validation.
- Process R&D primarily funded by GARD.



Proposed Scope: Details (cont.)

Transfer optimal processing steps to 800 MHz 6-cell cavities.

- Five 6-cell 800 MHz prototype cavities to be sent to the US from Europe for high Q and high gradient treatment.
- Tooling and infrastructure preparations for 800 MHz cavities
- Perform a limited number of treatment cycles to establish optimal steps.

Treat and test 800 MHz cavities for prototype cryomodule

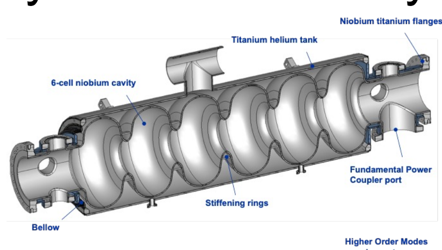
- Using optimized process, perform treatment of 4+1 cavities.

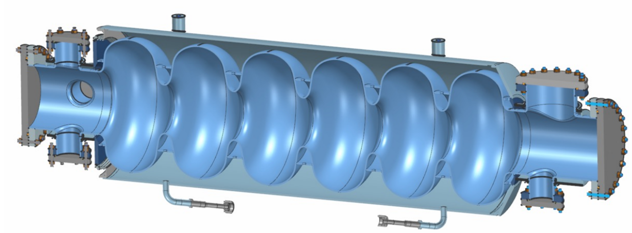
TBC: Weld helium tanks to prototype module cavities and retest.

- Tanks provided by European partners

TBC: Design of 800 MHz cavity frequency tuner and test.

- Use FNAL experience in cavity tuners to modify existing design to 800 MHz cavity and test with cavity.





Timeline

Task	FY27	FY28	FY29	FY30
800 MHz single-cell fabrication	■	■		
800 MHz single-cell high Q process R&D	■	■	■	
Tooling and infrastructure preparations		■	■	
Receive 800 MHz 6-cell cavities from CERN			■	
Treatment and vertical performance testing of 800 MHz 6-cell cavities			■	■
Helium tank welding and final test				■
Frequency tuner development		■	■	■
Send qualified, jacketed 6-cell 800 MHz cavities to CERN for module assembly				■

FCC-ee go/no-go decision

✓ **Cavity delivery in time for string and cavity assembly of 800 MHz cryomodule by European partners planned for CY 2030/31.**

Some Notes on Cost (for the proposed initial scope)

- **Smooth ramp up in funding assumed with limited funds before go/no-go decision**
  - Estimate: Initial ~$200k/year, ramping up to ~$500k+/year
  - Detailed bottom-up budget estimate currently under development with partner institutions (ANL, Cornell, Jlab, Fermilab)
- Costs will be **augmented by synergistic efforts**, including existing R&D efforts under GARD as well as internal lab funds.
  - Indication of support and buy-in for participation in the FCC-ee program.
- The program would **leverage existing investments in treatment and testing facilities** at labs and universities.

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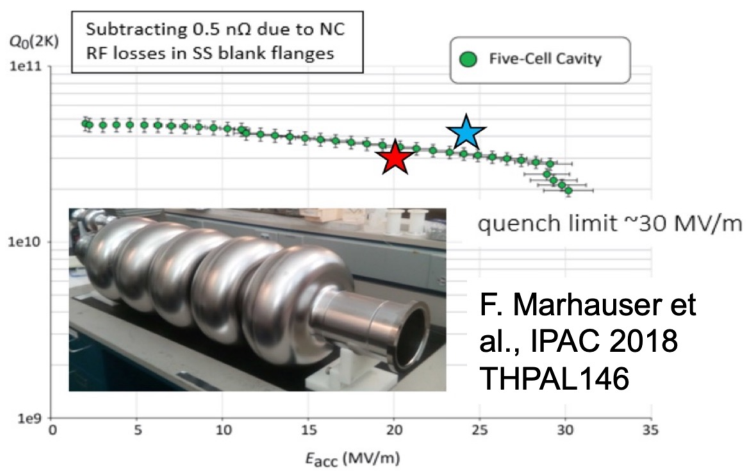
Nb_3Sn Breakthrough

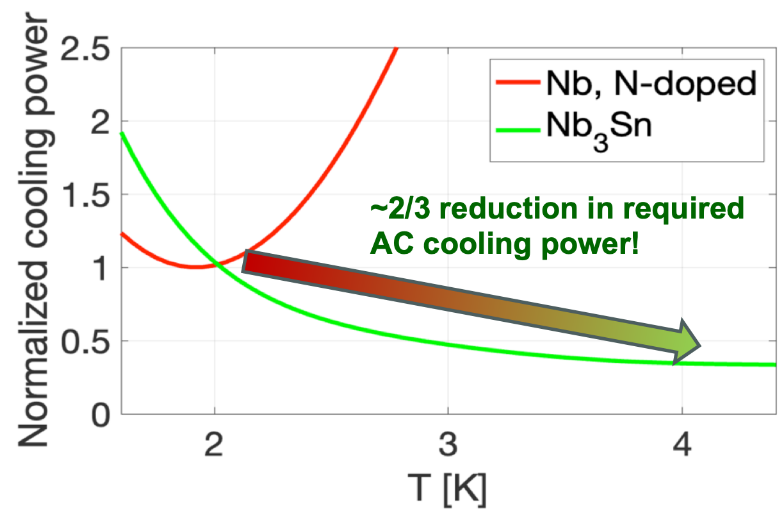
- **Nb_3Sn is a transformative material option for SRF (T_c=18K vs 9.2K).**
- **Nb_3Sn SRF breakthrough achieved by US institutions, supported by DOE HEP, especially HEP GARD (Cornell, FNAL, JLab).**
- **Key benefit: SRF operation at 4.5K instead of 2K with similar Q_0.**

$\Rightarrow$ **Factor of 3 to 4 times higher overall efficiency!**

Prototype cavity (800 MHz)



F. Marhauser et al., IPAC 2018 THPAL146



Nb_3Sn Benefits for FCC-ee

- **Using 4.5K Nb_3Sn in SRF systems offers 3 significant advantages compared to using Nb:**
  - **Higher cryogenic efficiency, meaning that a smaller cryoplant can be used, reducing infrastructure costs.**
  - **Smaller cryogenic plan requires less power, lowering operating costs.**
  - **Cryogenic system at 4.5 K reduces operational risk.**

- **Factor of ~3 reduction in carbon footprint for cryo!**
- **Translates into cryoplant construction cost savings of several tens of $M and 10-year operating cost reduction of the order of $100M.**

Nb_3Sn State of the Art Performance

1.3 GHz

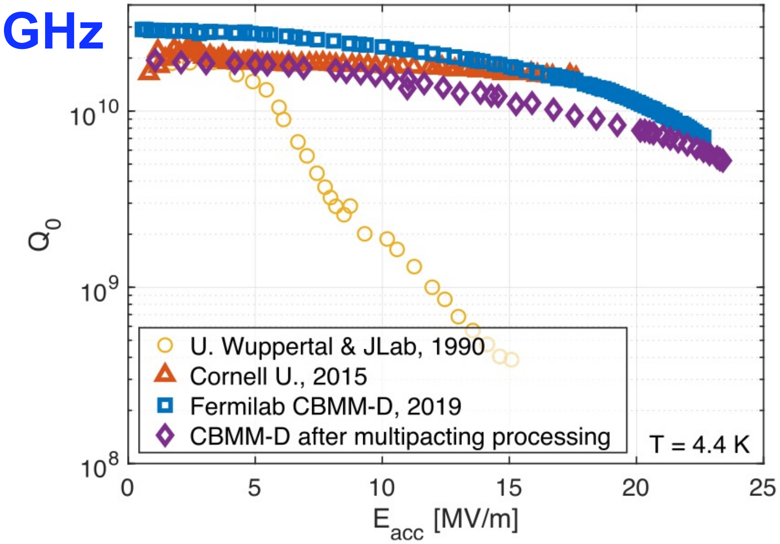


Figure 9. Performance of 1.3 GHz single cell cavity CBMM-D before and after processing (top) and comparison to a selection of previous 1.3–1.5 GHz single cell cavities (data from [24, 35]) at 4.4 K (bottom). Supercond. Sci. Technol. 34 (2021) 025007

650 MHz

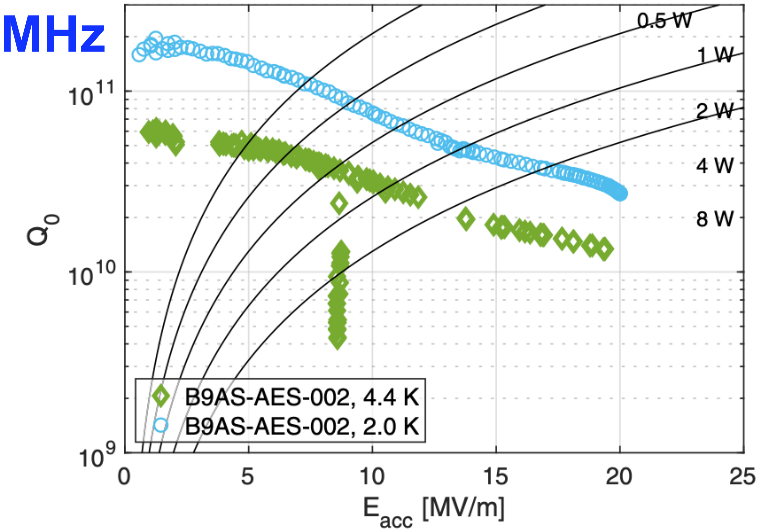
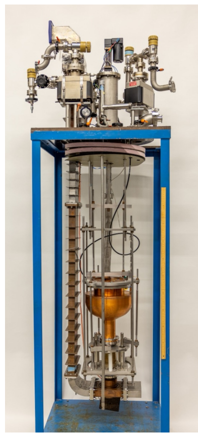


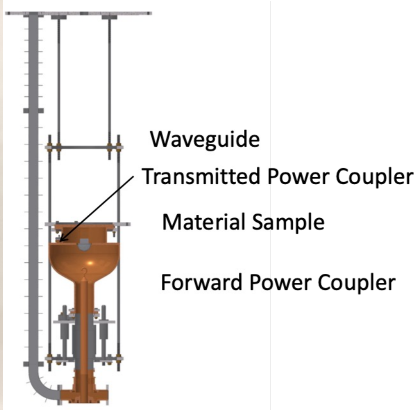
Figure 10. Performance of 650 MHz single cell cavity B9AS-AES-002. The multipacting at 9 MV m^{-1} was processed during the test. Supercond. Sci. Technol. 34 (2021) 025007

Gradients 20+ MV/m on single-cell cavities, meeting FCC-ee needs

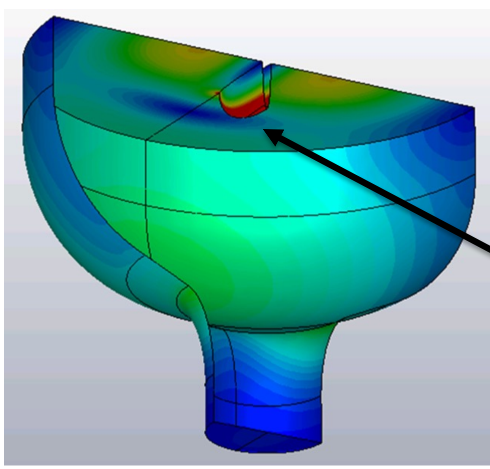
$Q_0 > 10^{10}$ at 4.5K

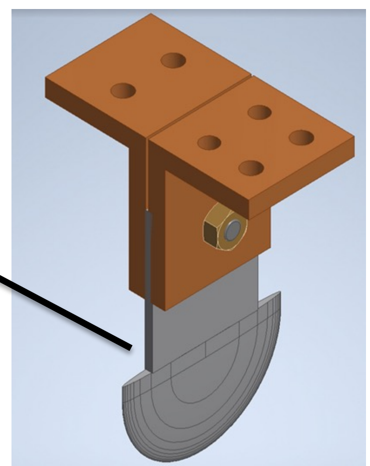
Nb_3Sn Field Potential Demonstration at Cornell

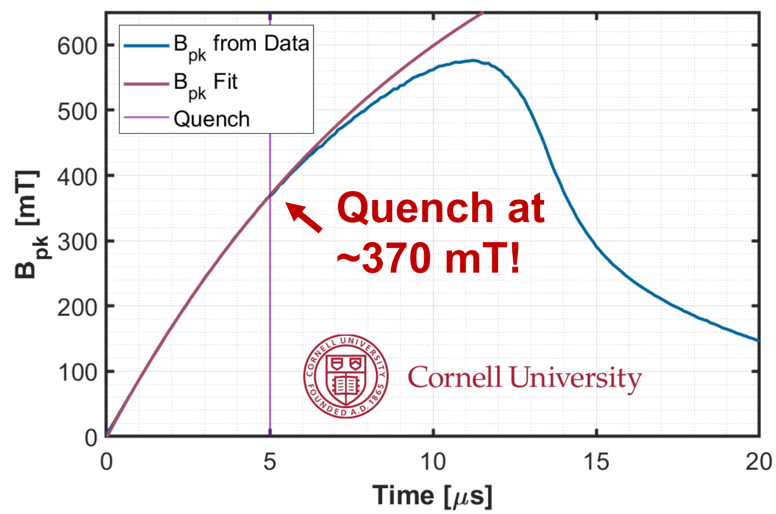




- **Reached ~400 mT (corresponding to ~100 MV/m) in short-pulse RF operation on a Nb_3Sn coated sample, 2x Nb limit.**
- **Highest RF magnetic field achieved on a superconductor**

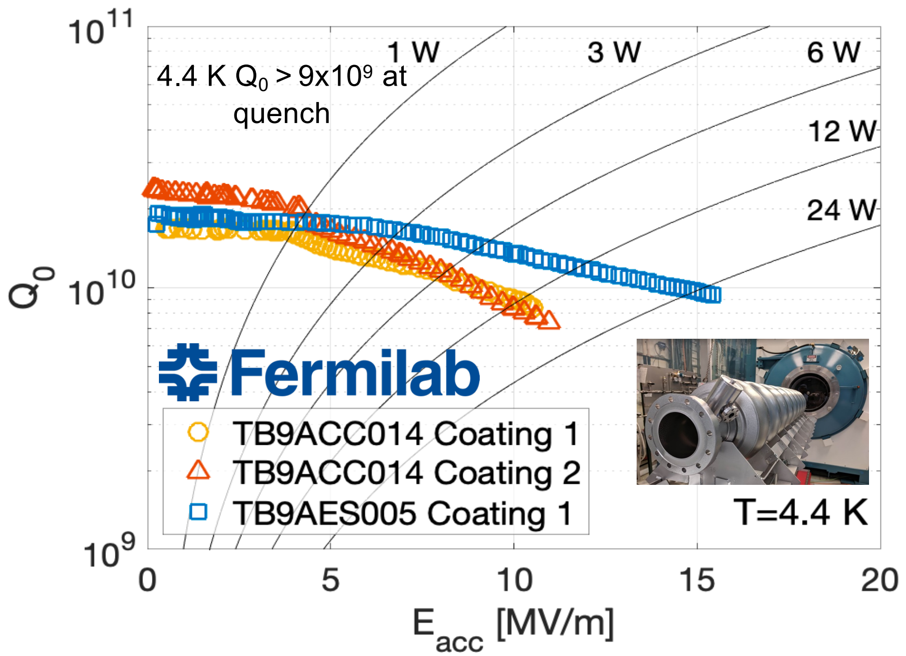




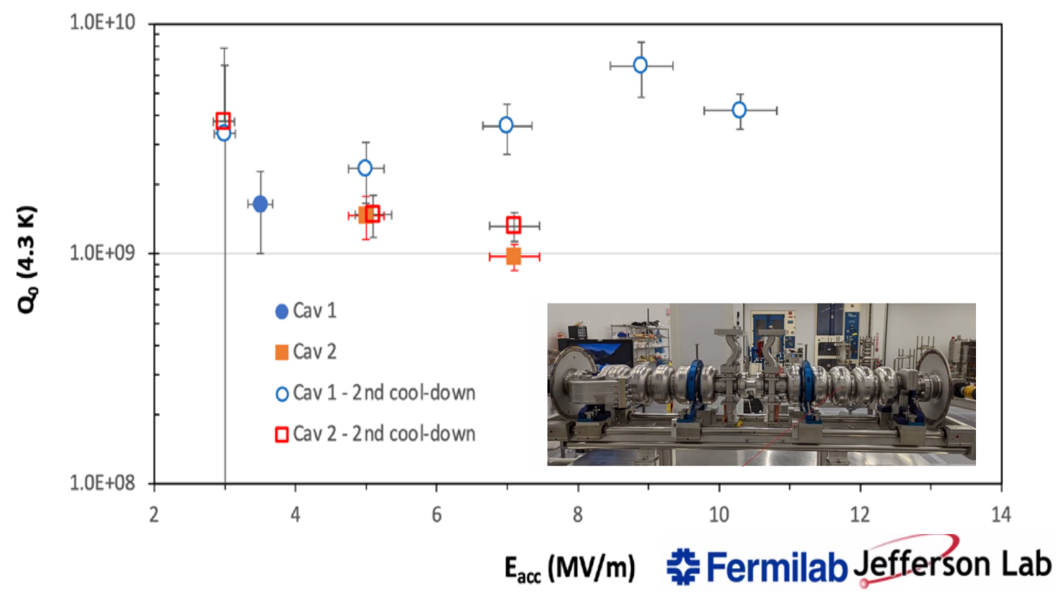


Towards Applications: Practical Nb_3Sn Cavities

Fermilab: 9-cell 1.3 GHz cavities



CEBAF-style quarter module using Nb_3Sn 5-cell cavities



>15 MV/m with Q_0~10^{10} at 4.4K on accelerator structures!

=> Becoming an option for accelerator projects!

US Rapid Development Program for Nb_3Sn SRF Technology

- **So far: Individual U.S. Nb_3Sn SRF research programs**
  - **Coating process developments and breakthrough performance demonstrations, with 1-cell cavity performance approaching FCC-ee needs**
  - **More development efforts are needed now to demonstrate performance in a cryomodule.**
  - **If higher Q_0 values are obtained in those demonstrations, the Nb_3Sn benefits will be similarly improved.**

- **Now: Need a <u>coordinated</u> effort involving all key US players in this development to fully develop Nb_3Sn technology at the cryomodule level and to demonstrate project readiness.**

US Rapid Development Program for Nb_3Sn SRF Technology

- **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.**
- **Benefits reach far beyond FCC-ee:**
  - Lower construction and operating costs for SRF driven lights sources, neutron sources, muon collider…. **Revolution in SRF technology**
  - **Nb_3Sn enabling technology for taking SRF into industrial settings**
    - Conduction-cooled, cryocooler-based Nb_3Sn SRF
    - Nb_3Sn highly beneficial and sought-after technology for large industrial accelerators, for example for semiconductor lithography and subcritical reactors.
  - **Program would cement U.S. leadership in (Nb_3Sn) SRF technology with huge benefits to all further SRF driven accelerators.**

Nb_3Sn Program Specifics

- 3 major program parts:
  1. **Enabling Nb_3Sn R&D**
     - Coating optimization (at FCC frequencies)
     - Transfer to multi-cell cavities (at FCC frequencies)
     - Nb_3Sn cavity technology R&D (handling, tuning, tank welding…)
  2. **Nb_3Sn Coating Scale-Up and Industrialization**
     - Dedicated Nb_3Sn coating facility development and deployment
     - Multiple coating facilities for cross-checking between institutions (as was done for N-doping development for LCLS-II)
     - Technology transfer and licensing to industry

Nb_3Sn Program Specifics

3. Prototype Cryomodules

- **Approach:** Program sized to providing data needed to support baseline change of FCC-ee from Nb SRF to Nb_3Sn SRF
- FCC cavity coating and performance testing at multiple institutions
  - 20 cavities at given frequency to demonstrate performance yield
  - **Goal:** Consistent performance demonstration meeting FCC specs
- Nb_3Sn prototype cryomodue(s) design, production, assembly and test
  - **Goal:** Lower frequency (600/650 MHz) prototype fully tested by CERN's ~2034 target
  - **Goal:** Higher frequency (800/1300 MHz) prototype fully tested in time for ttbar upgrade

12-Year Timeline

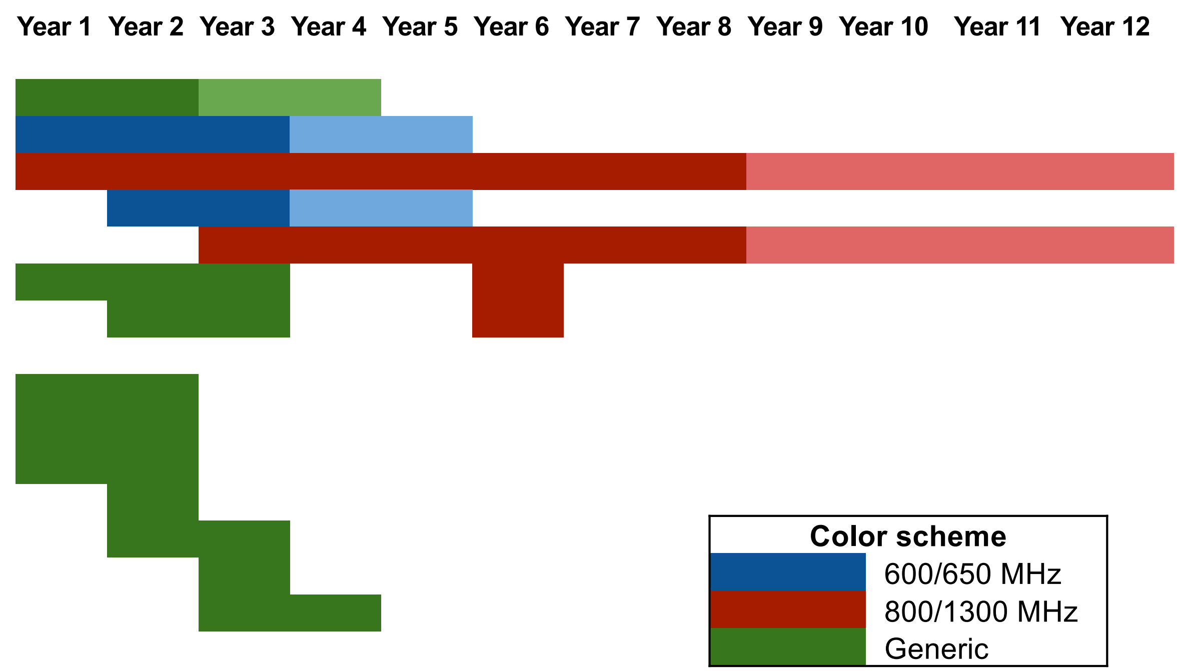
Area **Tasks**

Enabling R&D

- Substrate optimization and specification R&D
- Single cell 600 MHz R&D
- Single cell 800 MHz R&D
- Multicell 600 MHz R&D
- Multicell 800 MHz R&D
- Tuning/handling development
- Helium tank integration development

Nb3Sn Coating Scale-Up and Industrialization

- Design furnace
- Set up facility for prototype furnace – utilities, space, etc.
- Deploy, commission, and debug first furnace
- Set up facilities for subsequent furnaces
- Build subsequent furnaces (2)
- Technology transfer & licensing to industry



12-Year Timeline (Cont.)

Area **Tasks**

Prototype Cryomodule

Cavity production (20 of each frequency)
Cavity coating at multiple US facilities
Consistent performance demonstration

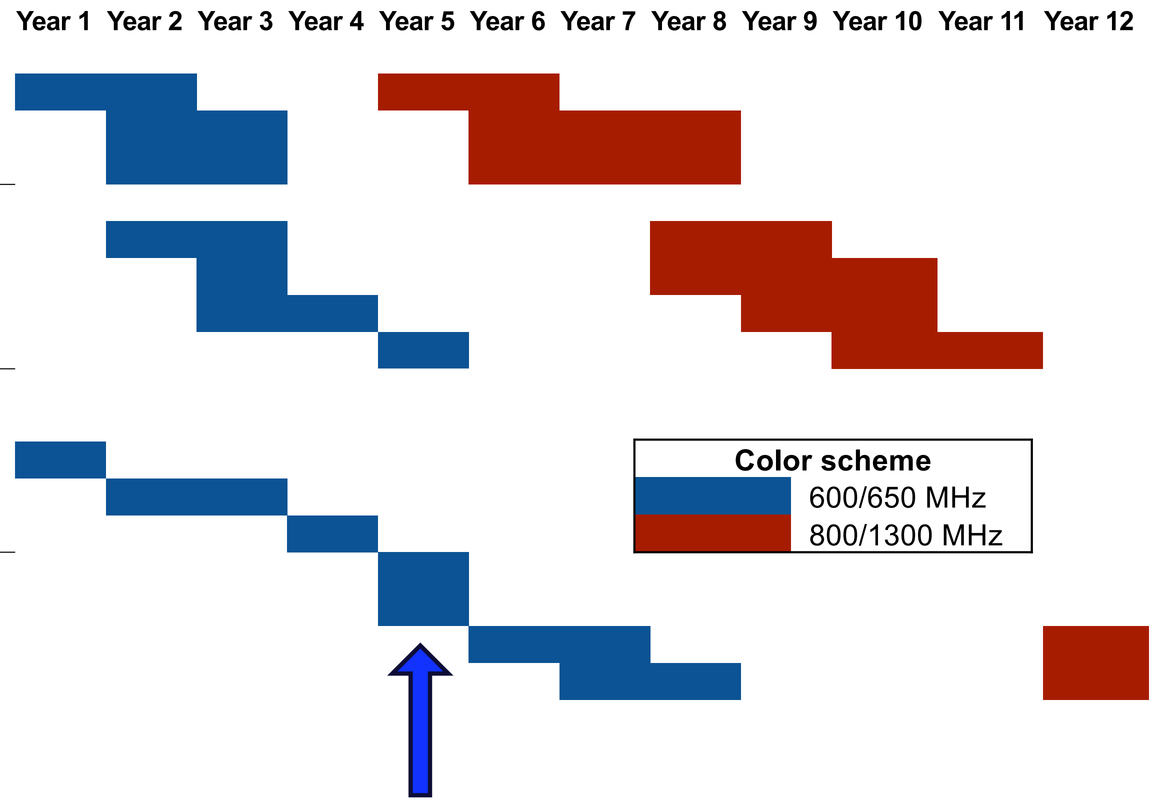
Alternative 1 (new 4K CM Design)

New 4K cryomodule design
Horizontal tests for design verification
Full scale prototype 4 K cryomodule production
Full scale prototype 4 K cryomodule test

Alternative 2 (Usage of existing PIP-II "650MHz" Design)

"650 MHz" cryomodule Procurement
"650 MHz" cryomodule Production
"650 MHz "cryomodule Test

Transportation testing
Microphonics studies as needed
High current beam test at Cornell
Integrated cryomodule test at CERN



Meets CERN timeline for (low-power) CM testing in 2031

Some Notes on Cost

- **Major multi-institution U.S. initiative**, similar to magnet program of the the U.S. LHC Accelerator Research Program (LARP) collaboration (~$6M/year in 2000 era dollars).
- Working on putting together detailed budget estimate, including **alternative options / budget scenarios.**
  - (a) Rapid program to impact FCC-ee baseline covering two RF frequencies or (b) single-frequency timeline that leads to prototype to impact ttbar upgrade.
  - (a) New 4.5K Nb_3Sn FCC cryomodule design or (b) use of existing PIP-II module design.
  - Flexible to adjust to final FCC-ee frequency choice.

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Key Takeaways

- ✓ **Exciting opportunities for the US for leadership in high-impact SRF technology development**
  - ✓ **Opportunity to contribute to a European prototype cryomodule, leaning on US strengths in high-performance SRF**
    - Shows US commitment and positions the US to play a significant role should CERN give the green light in 2028, all while maintaining a limited budget.
  - ✓ **US Rapid Integrated Development Program for Nb_3Sn SRF Technology**
    - Major initiative that would be transformative for future SRF accelerators, including FCC-ee

Thank you for your attention!