R&D towards an 800 MHz cryomodule

Sam Posen

FCC Week

June 2023

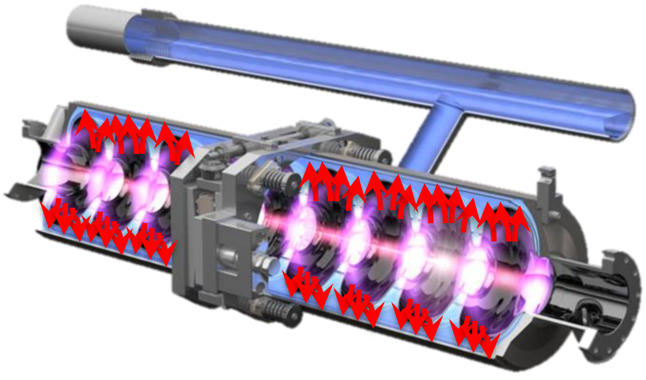
Overview

- High Q_0 for FCC-ee
- 800 MHz Cavity Studies
- Fermilab Cryomodule Design & Production
- Summary

1. **High Q_0 for FCC-ee**
2. 800 MHz Cavity Studies
3. Fermilab Cryomodule Design & Production
4. Summary

Impact of Q_0 -> Cryogenic Infrastructure, Operating Cost

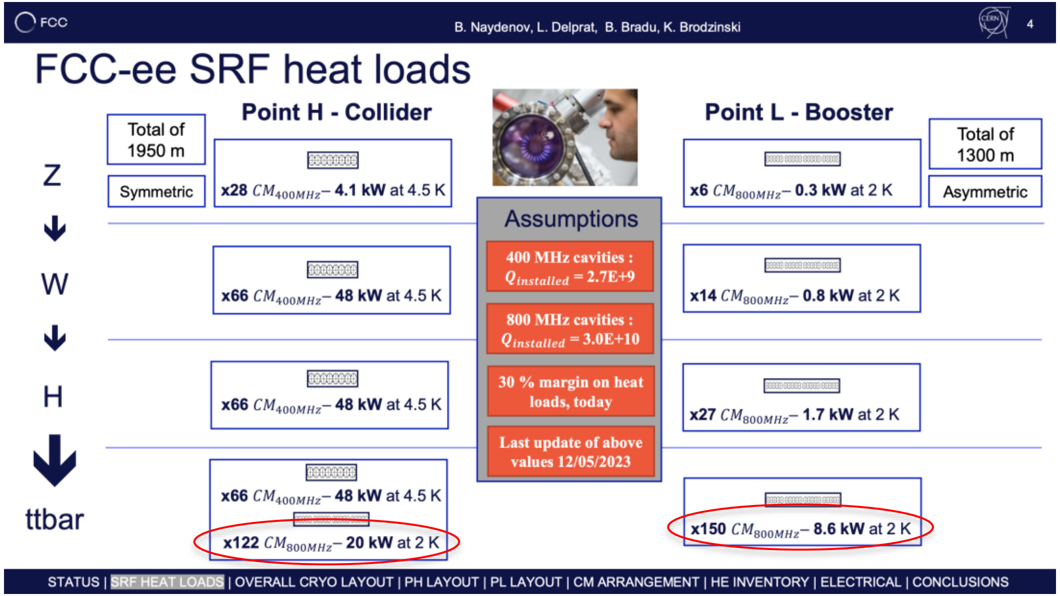
- Quality factor of cavities determines heat deposited at cryogenic temperatures
  - Especially important for high duty factor RF (particularly CW)
- Heat deposition at cryogenic temperatures determines the size of cryoplant needed
  - **Cost** → up-front infrastructure cost and longer term operating costs
  - **Sustainability** → Optimization of ~100 nm of cavity inner surface can have a big impact on footprint of cryogenic systems
- 2 K inverse coefficient of performance is ~800 W/W



Cryoplant mage from CERN

High Q_0 for FCC-ee 800 MHz Systems

- Focusing on 800 MHz systems (bulk niobium)
- Bulk niobium high Q_0 treatments include nitrogen doping, mid-T bake, Nb_3Sn
- Flux expulsion also important to consider

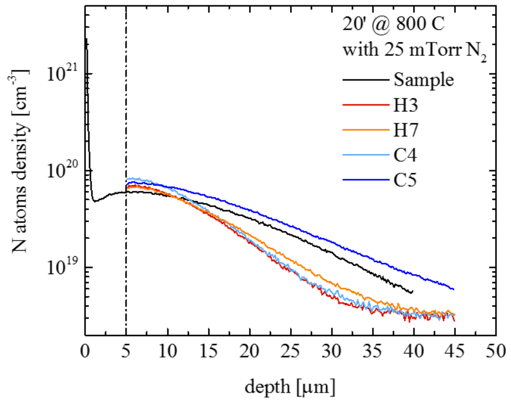


Slide from B. Naydenov, CERN

Fermilab

Nitrogen Doping

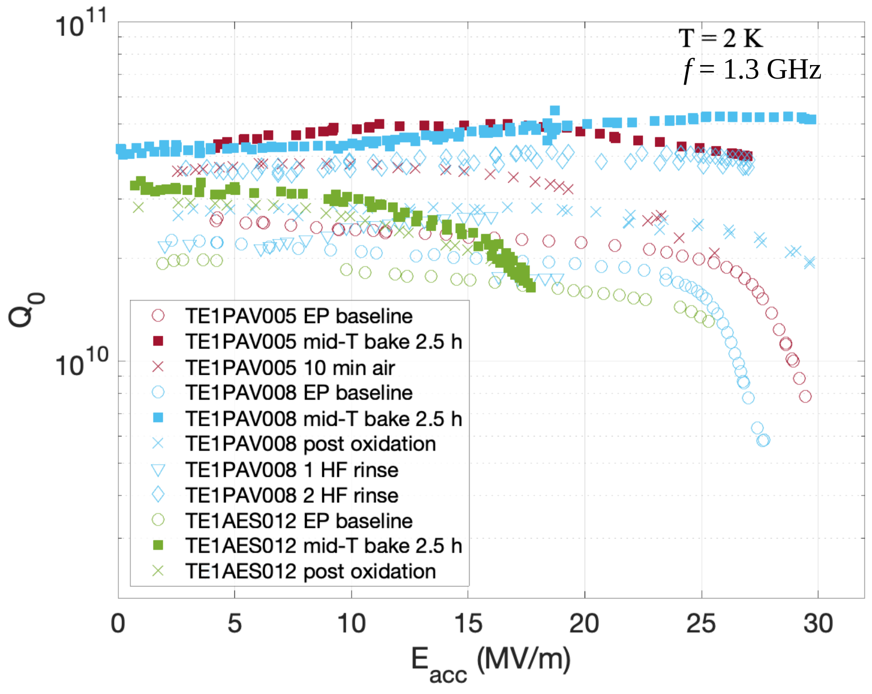
- Cavity is heat treated in vacuum at ~800 C
- Small nitrogen pressure injected into furnace for a few minutes
- Creates nitrogen interstitials as well as surface layer of niobium nitride (poorly superconducting)
- NbN removed via electropolishing of a few micrometers
- Now industrialized and used for LCLS-II production cavities
- Previous state of the art was $Q_0 \sim 1.5\text{x}10^{10}$; N-doping made it possible to have LCLS-II Q_0 specification of $2.7\text{x}10^{10}$

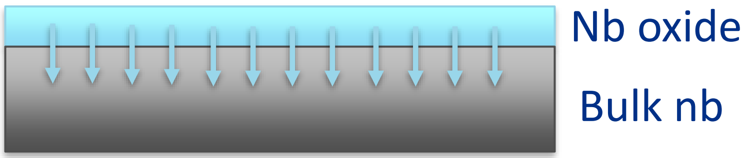


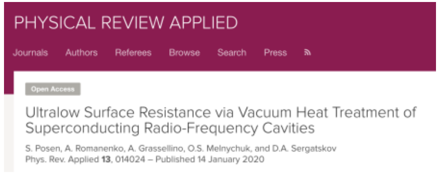
Fermilab

Medium Temperature (mid-T) Bake

- Cavity is heat treated typically in the range ~300-400 C: above low temperature bake, and below high temperature degas
- Best understood mechanism is that oxide dissociates and oxygen impurities diffuse into RF layer, creating interstitials
- Similar to nitrogen doping, but without additional electropolishing step – simpler, and less prone to non-uniform EP, can be important for larger cavity geometries






PHYSICAL REVIEW APPLIED

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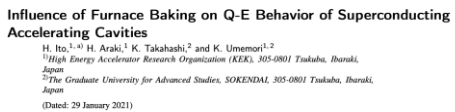
Ultralow Surface Resistance via Vacuum Heat Treatment of Superconducting Radio-Frequency Cavities

S. Posen, A. Romanenko, A. Grassellino, O.S. Melnychuk, and D.A. Sergatskov
Phys. Rev. Applied **13**, 014024 – Published 14 January 2020


Influence of Furnace Baking on Q-E Behavior of Superconducting Accelerating Cavities

H. Ito,[1,a)] H. Araki,[1] K. Takahashi,[2] and K. Umemori[1,2]
[1)] *High Energy Accelerator Research Organization (KEK), 305-0801 Tsukuba, Ibaraki, Japan*
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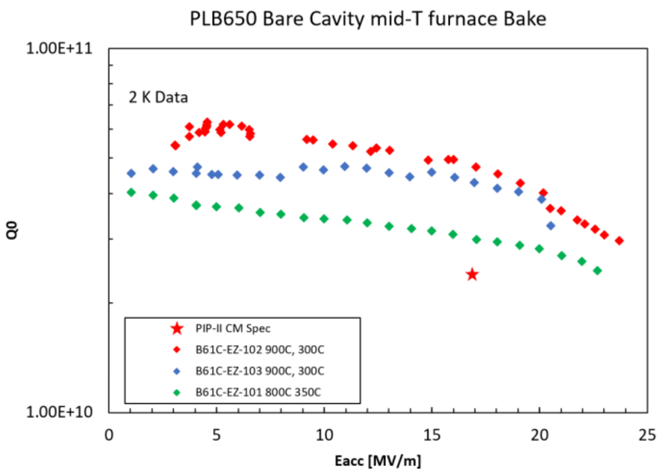
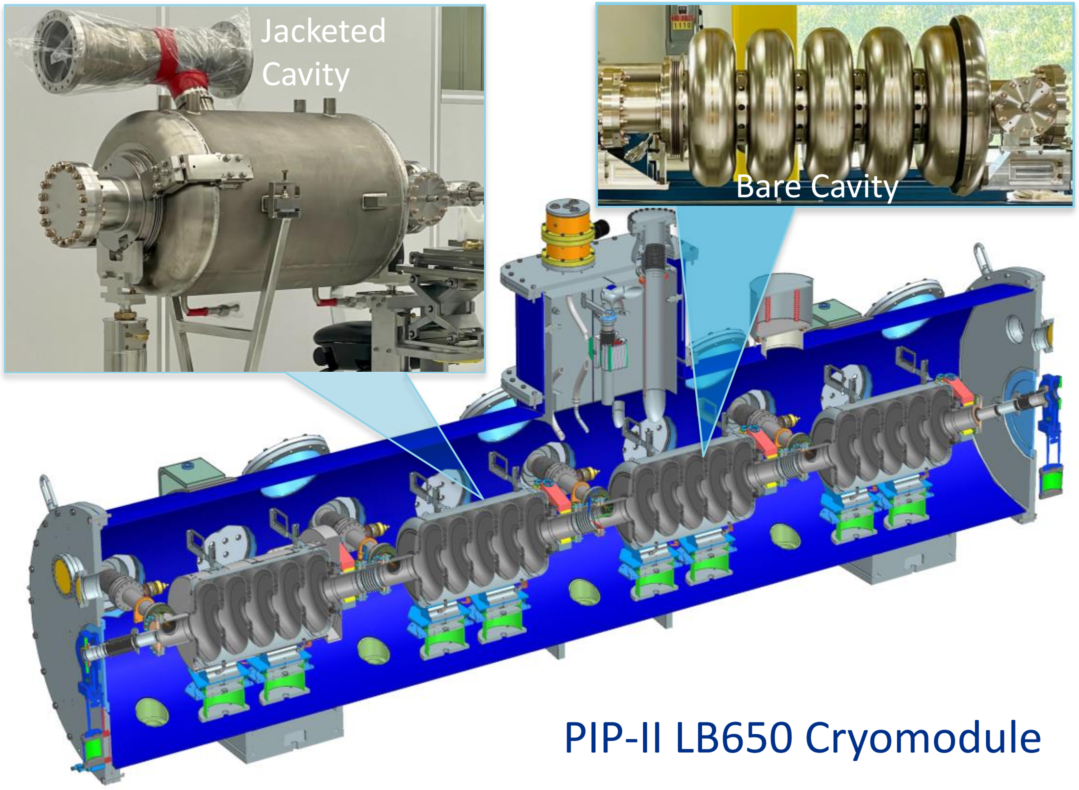
(Dated: 29 January 2021)

Mid-T Bake for PIP-II LB650 Cryomodule

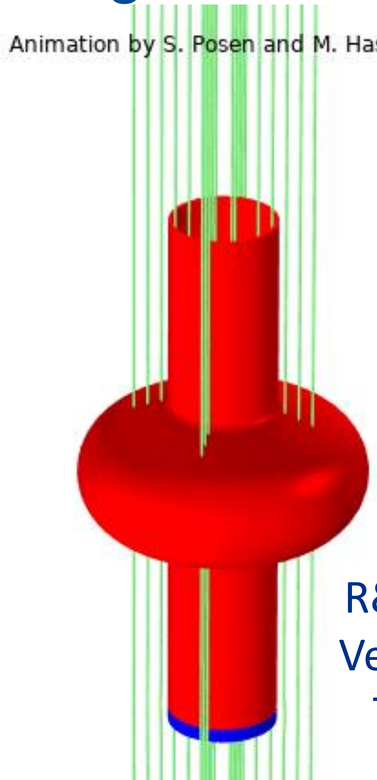
- High Q recipe using Mid-T furnace baking was endorsed by a review committee and adopted for LB650 cryomodules





PIP-II LB650 Cryomodule

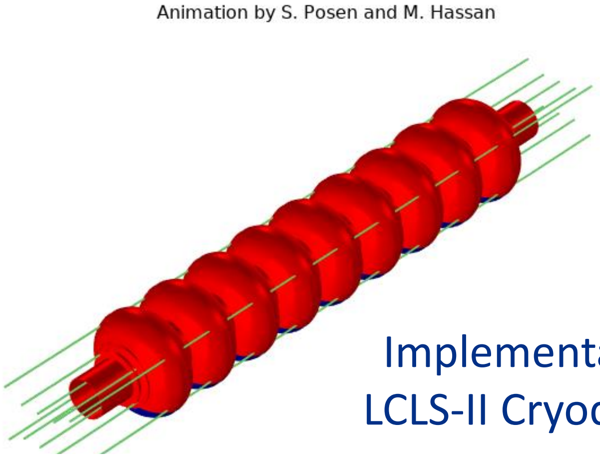
Magnetic Flux Expulsion



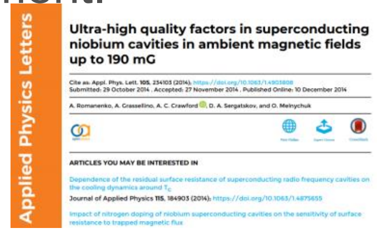
- Meissner Effect – niobium tends to expel applied magnetic flux
- well below T_c
- However, flux can become trapped in superconductor during cooldown, and trapped flux degrades Q_0
- Large impact on LCLS-II CM Q_0. In-situ demag of cryomodules to reduce ambient field also results in improvement.

R&D in Vertical Test

Ambient magnetic field during cooldown



Implementation in LCLS-II Cryodmodule


Applied Physics Letters

Ultra-high quality factors in superconducting niobium cavities in ambient magnetic fields up to 190 mG

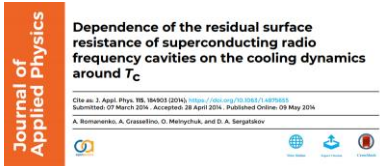
Cite as: Appl. Phys. Lett. 105, 234103 (2014); https://doi.org/10.1063/1.4903808
Submitted: 29 October 2014 . Accepted: 27 November 2014 . Published Online: 10 December 2014

A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk

ARTICLES YOU MAY BE INTERESTED IN

Dependence of the residual surface resistance of superconducting radio frequency cavities on the cooling dynamics around T_c
Journal of Applied Physics 115, 184903 (2014); https://doi.org/10.1063/1.4875655

Impact of nitrogen doping of niobium superconducting cavities on the sensitivity of surface resistance to trapped magnetic flux


Journal of Applied Physics

Dependence of the residual surface resistance of superconducting radio frequency cavities on the cooling dynamics around T_c

Cite as: J. Appl. Phys. 115, 184903 (2014); https://doi.org/10.1063/1.4875655
Submitted: 07 March 2014 . Accepted: 28 April 2014 . Published Online: 09 May 2014

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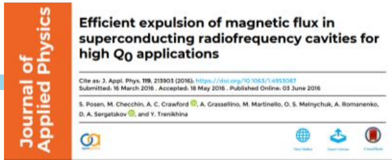

Journal of Applied Physics

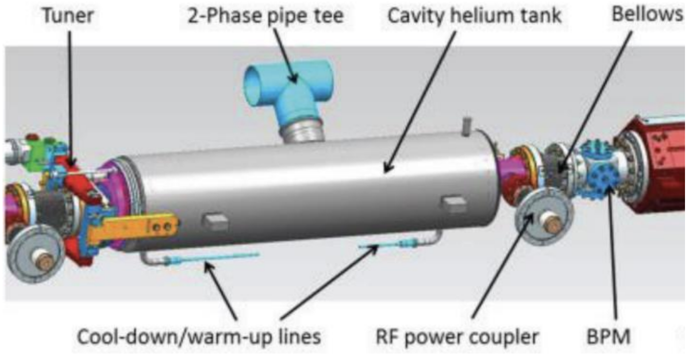
Efficient expulsion of magnetic flux in superconducting radiofrequency cavities for high Q_0 applications

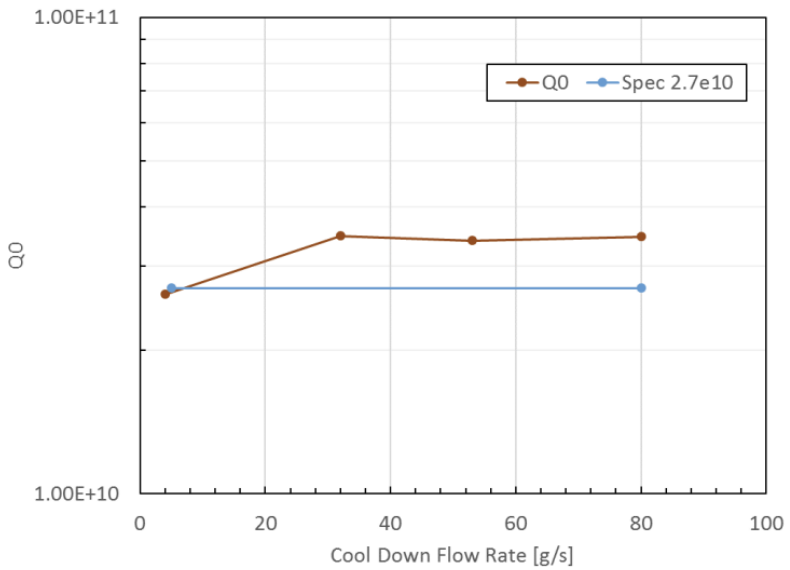
Cite as: J. Appl. Phys. 119, 213903 (2016); https://doi.org/10.1063/1.4953087
Submitted: 16 March 2016 . Accepted: 18 May 2016 . Published Online: 03 June 2016

S. Posen, M. Checchin, A. C. Crawford, A. Grassellino, M. Martinello, O. S. Melnychuk, A. Romanenko, D. A. Sergatskov, and Y. Trenikhina

Flux Expulsion and LCLS-II

- High Q_0 depends on:
  - High massflow cooldown to create spatial thermal gradient to expel flux (each CM has its own JT valve)
  - Careful heat treatment of cavities (typically ~900 C) to achieve high expulsion
- 3×10^{10} is achieved in the linac





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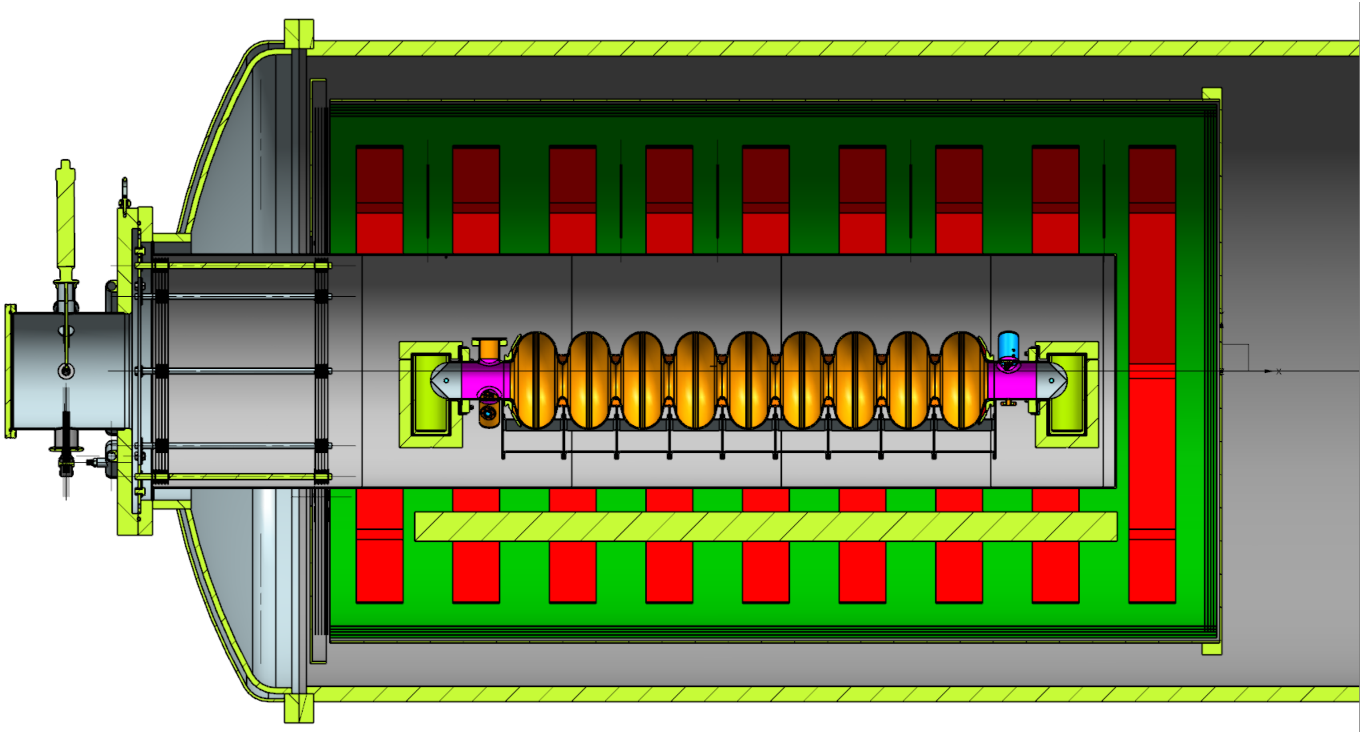
Operational experience from LCLS-II cryomodule testing

To cite this article: R Wang *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **278** 012187

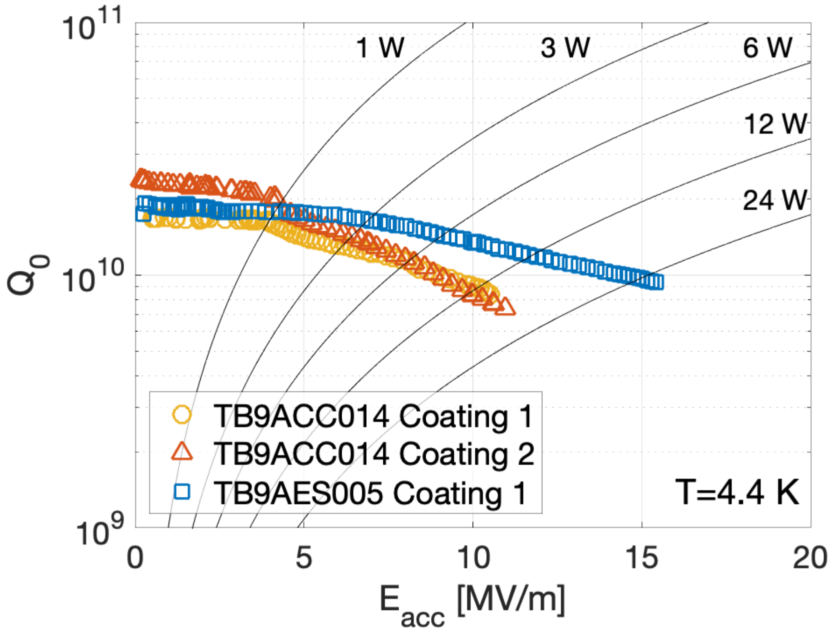
Fermilab Nb_3Sn Coating System

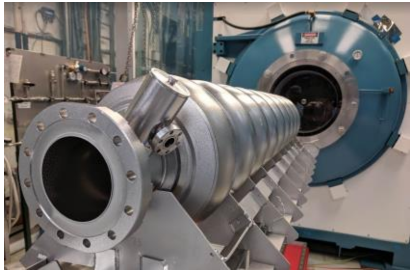


First and only Nb_3Sn coating chamber capable of coating 1.3 GHz 9-cell cavities or 5-cell 650 MHz cavities

Nb_3Sn Coating – Possibility for 4 K Operation

- Inverse coefficient of performance substantially (~3x) better at 4 K than at 2 K
- Advantages for efficiency, avoids subatmospheric helium and cold compressors
- Still under development, but promising results for bare multicells





Includes correction for stainless steel flanges 2x0.8 nΩ

Nb_3Sn-coated 9-cell cavities TB9ACC014 and TB9AES005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Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications

S Posen[1], J Lee[1,2], D N Seidman[2,3], A Romanenko[1], B Tennis[1], O S Melnychuk[1] and D A Sergatskov[1]

Published 11 January 2021 • © 2021 The Author(s). Published by IOP Publishing Ltd

Superconductor Science and Technology, Volume 34, Number 2

Citation S Posen *et al* 2021 *Supercond. Sci. Technol.* **34** 025007

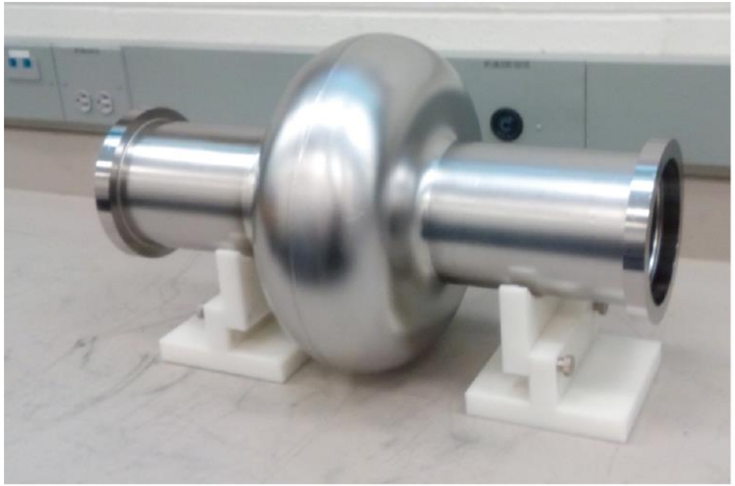
Fermilab

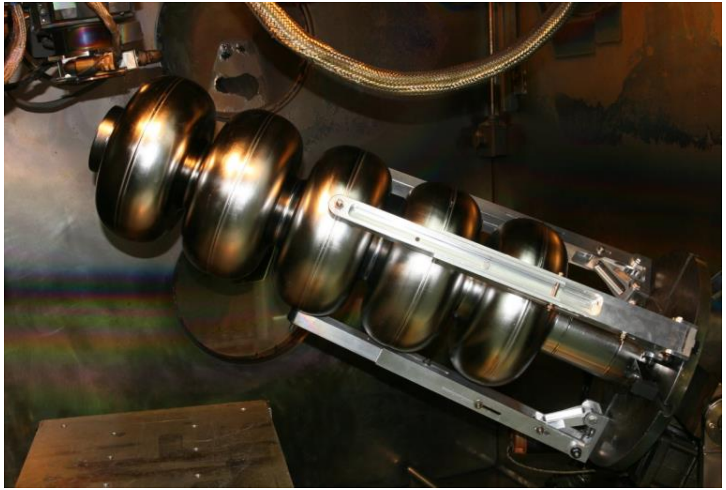
1. High Q_0 for FCC-ee
2. **800 MHz Cavity Studies**
3. Fermilab Cryomodule Design & Production
4. Summary

Prototype 800 MHz Cavity R&D

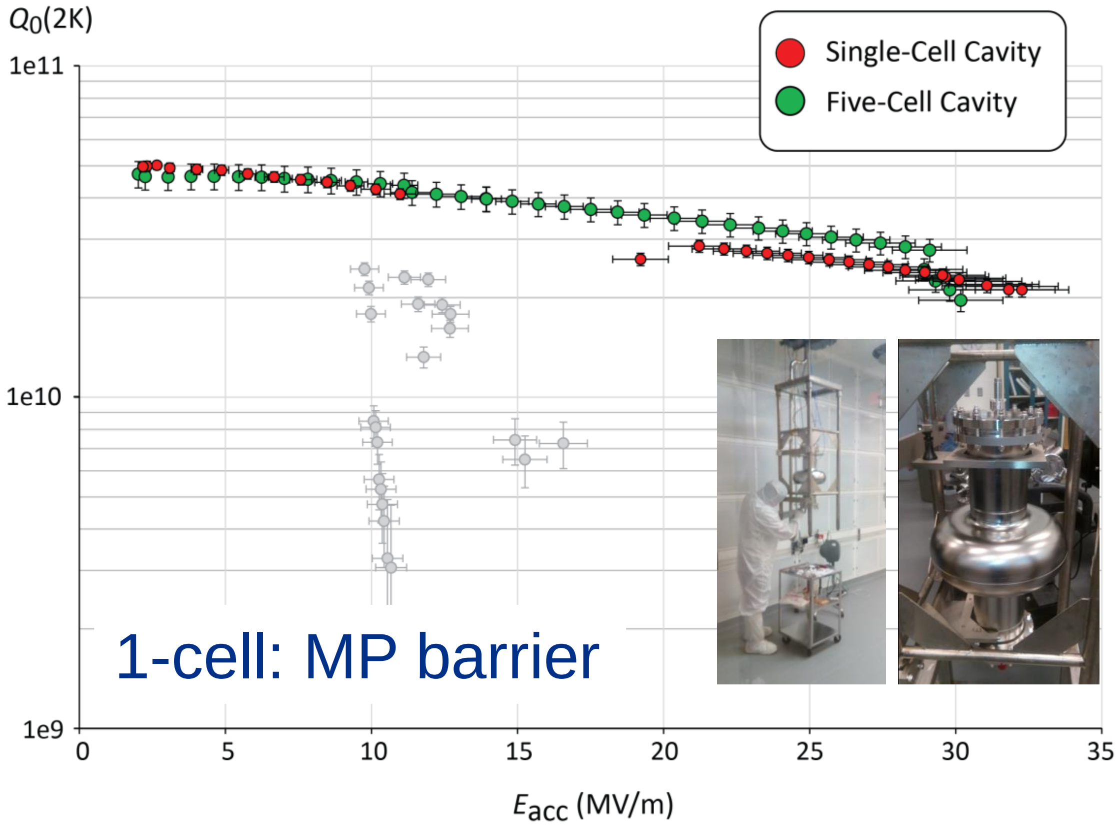
From Frank Marhauser, FCC Week 2018

- 1-cell and 5-cell 800 MHz cavities were fabricated, treated, and tested by JLab
- Copper cavities were also fabricated (not discussed here)
- 5-cell cavity does not have additional ports (e.g. coupler, HOM, pickup)





800 MHz Cavity Testing at JLab

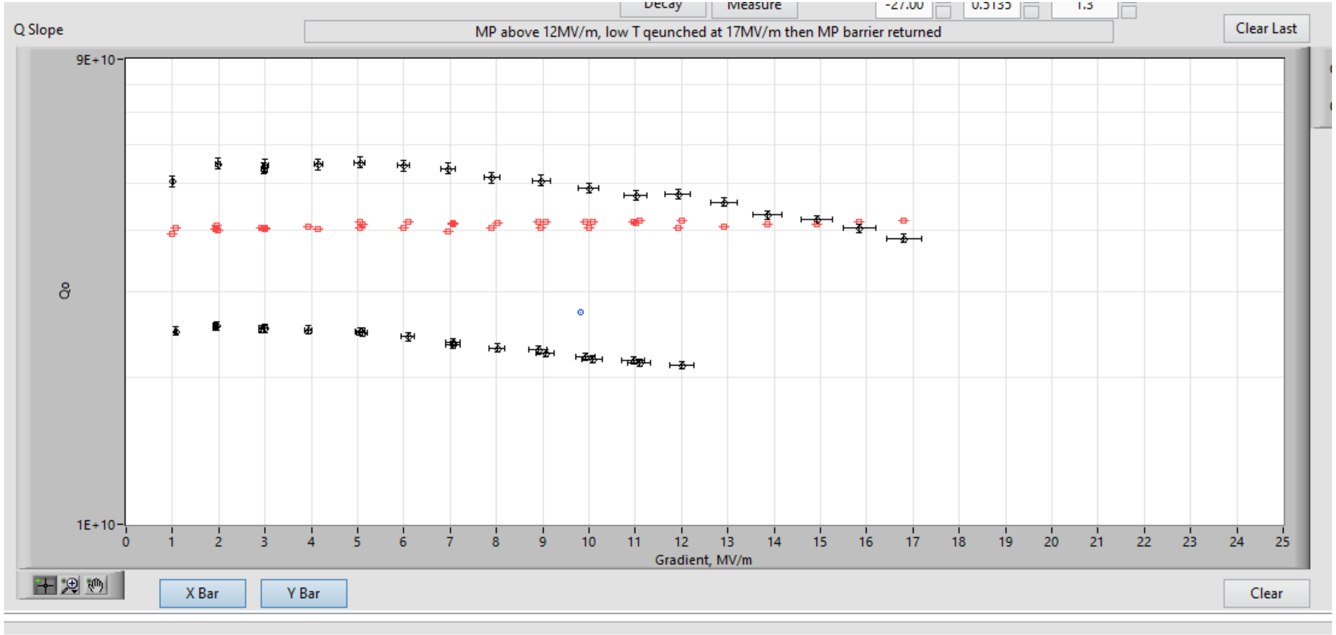


- Both cavities had quite good performance in initial testing, reaching ~30 MV/m with Q_0 in the range of 2-3x10^{10} at 2.0 K
- Continued processing of single cell (including electropolishing) led to degradation – cavity limited by multipacting

From Frank Marhauser, FCC Week 2018

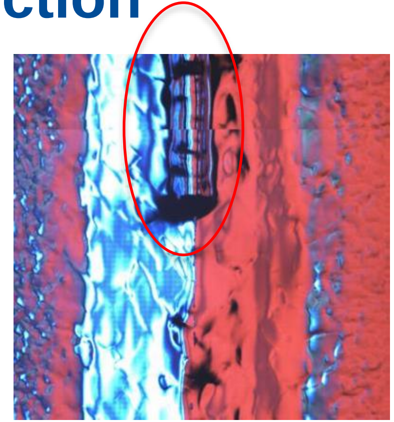
1-Cell 800 MHz Cavity Testing at Fermilab

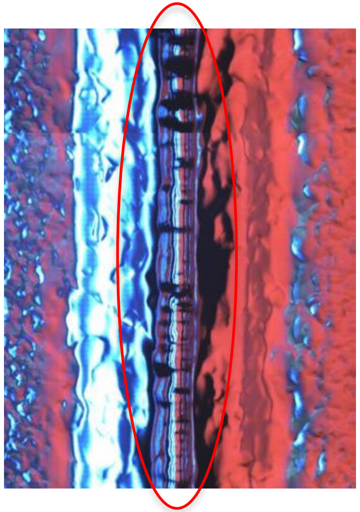
- Cavity was sent to Fermilab – testing in March 2023 confirmed multipacting limit, unable to process or 'jump' over – similar to JLab post-EP result

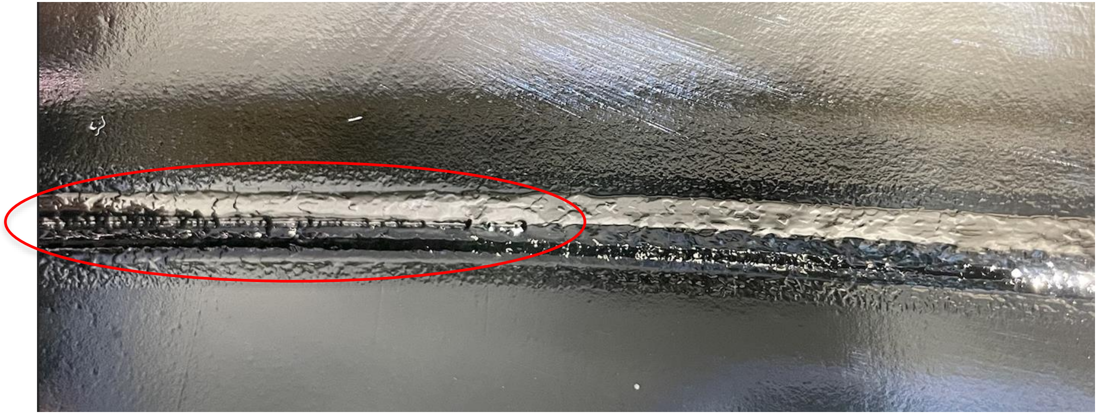


1-Cell 800 MHz Cavity Inspection

- Boroscope inspection revealed substantial defect at equator weld, likely worsened by EP
- Defect visible by eye on interior
- Replica shows ~1 mm ridge, indicating a trench on cavity
- Expected to be cause for strong multipacting
- Currently discussing if fix is possible
  - Deep mechanical polishing
  - Reweld may be possible but risk of blowout
- Meanwhile working on 5-cell

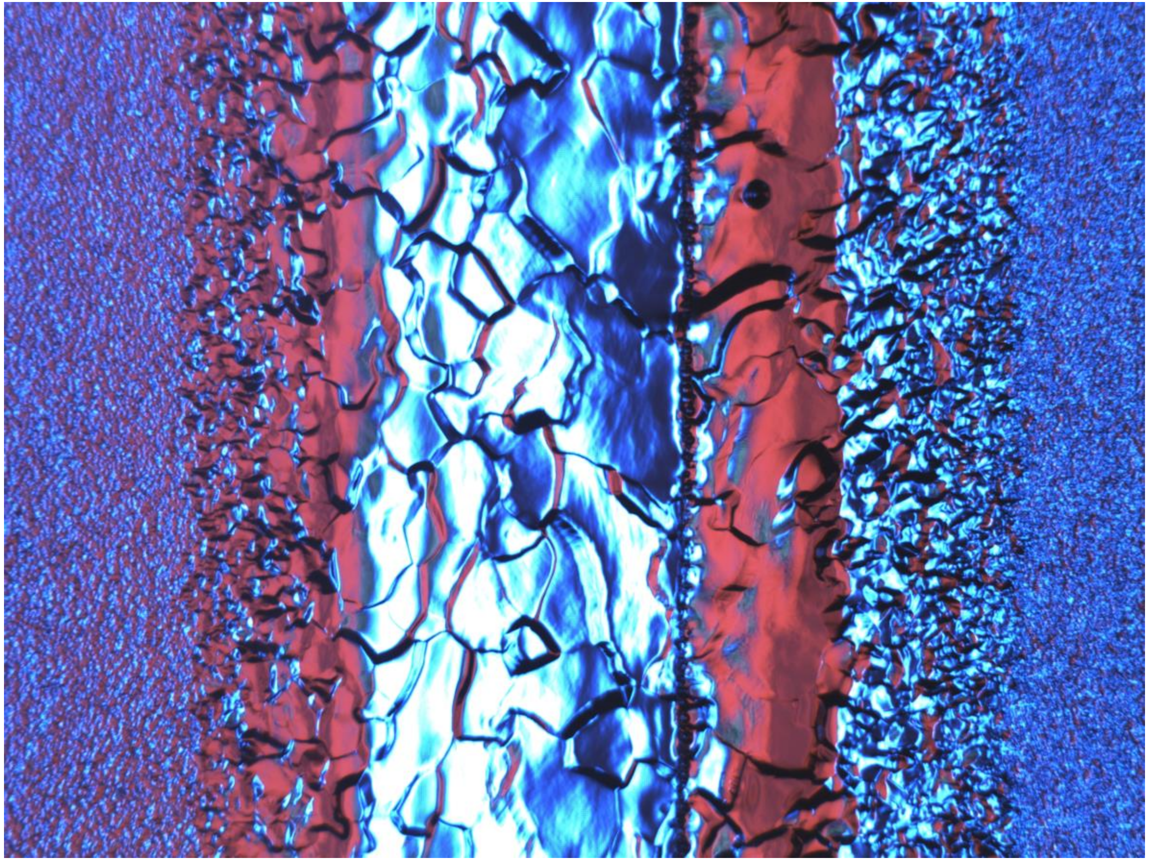






5-Cell 800 MHz Cavity Inspection

- 5-cell cavity recently arrived at Fermilab
- Optical inspection shows some signs of incomplete welds, but not as bad as 1-cell
- Possibly some etching in previous EP based on inspection – plan to use lessons from FNAL 650 MHz experience to try to improve further



5-Cell 800 MHz Cavity Testing at Fermilab

- Working now on preparation of 5-cell for baseline testing
- If successful, possible next steps include studies with mid-T bake, EP using 650 MHz lessons learned, additional mid-T bake temperatures
- Nb_3Sn coating may also be tried, but lack of stiffening rings on 5-cell cavity may be a challenge – Nb_3Sn is brittle, and 1100 C heat treatment makes Nb substrate soft (1-cell would be preferable for Nb_3Sn if it can be recovered)

1. High Q_0 for FCC-ee
2. 800 MHz Cavity Studies
3. **Fermilab CM Design & Production**
4. Summary

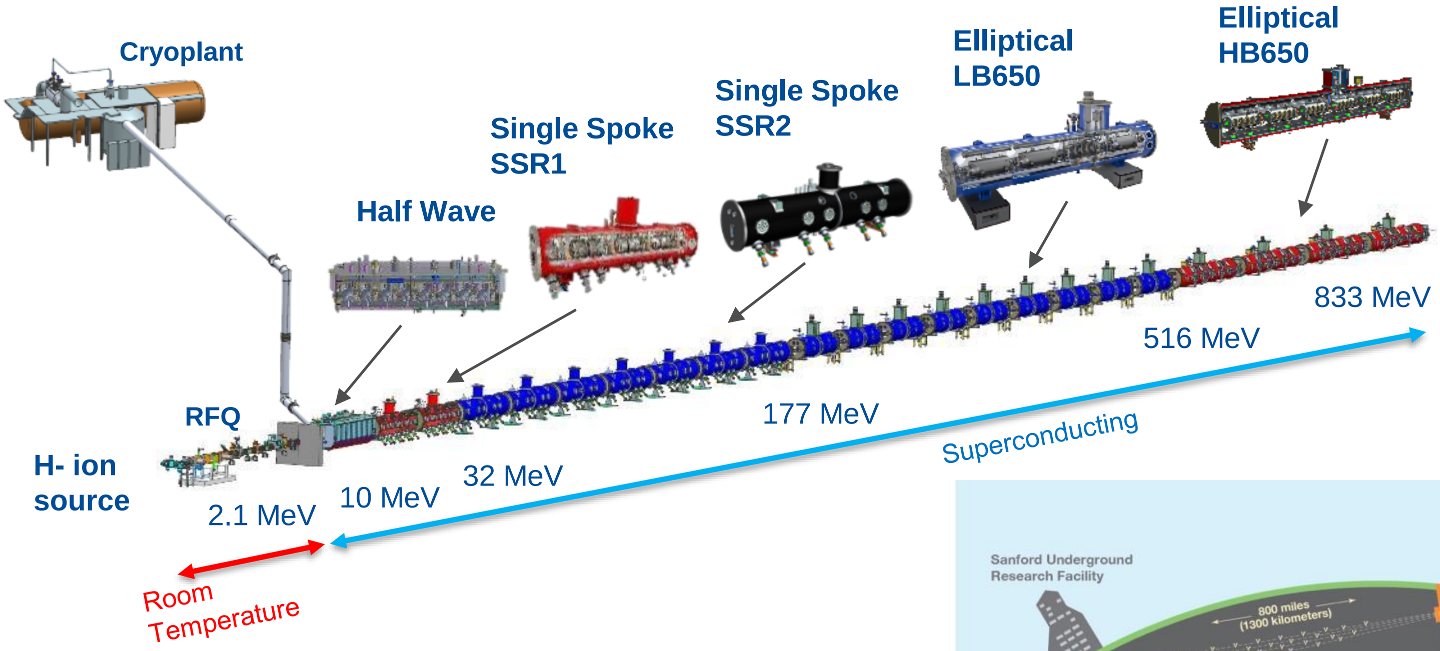

Assembly in semiconductor-grade cleanroom
Fermilab - LCLS-II Cryomodule Assembly

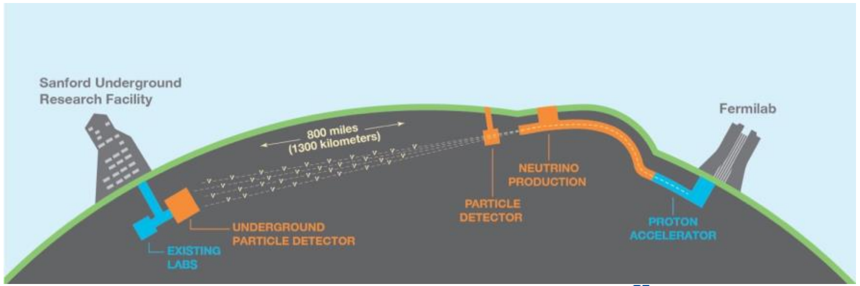
LCLS-II and LCLS-II-HE

- ILC-like CMs, but operating in CW mode, nitrogen-doped cavities
- FNAL high Q SRF R&D is critical: N-doping, flux expulsion
- LCLS-II was the first large-scale SRF CM production for Fermilab
- Designed, built, tested, and delivered 1.3 GHz & 3.9 GHz CMs
- **Fermilab cryomodule results exceed specifications**
  - (17) 1.3 GHz cryomodules: average energy gain/CM = 158 MV (spec 128 MV), average $Q_0 = 3x10^{10}$ (spec $2.7x10^{10}$)
  - (3) 3.9 GHz cryomodules: average energy gain/CM = 46.5 MV (spec 41 MV), average $Q_0 = 3.45x10^9$ (spec $1.5x10^9$)
- LCLS-II commissioning now underway, with Fermilab experts participating – performance is very promising so far
- LCLS-II-HE: ~20 more CMs from FNAL, R&D was critical to achieve high-Q at higher gradients ~21 MV/m
- **In summary**: substantial 1.3 GHz CM production experience, excellent performance, FNAL R&D advances were critical

PIP-II superconducting CW linac

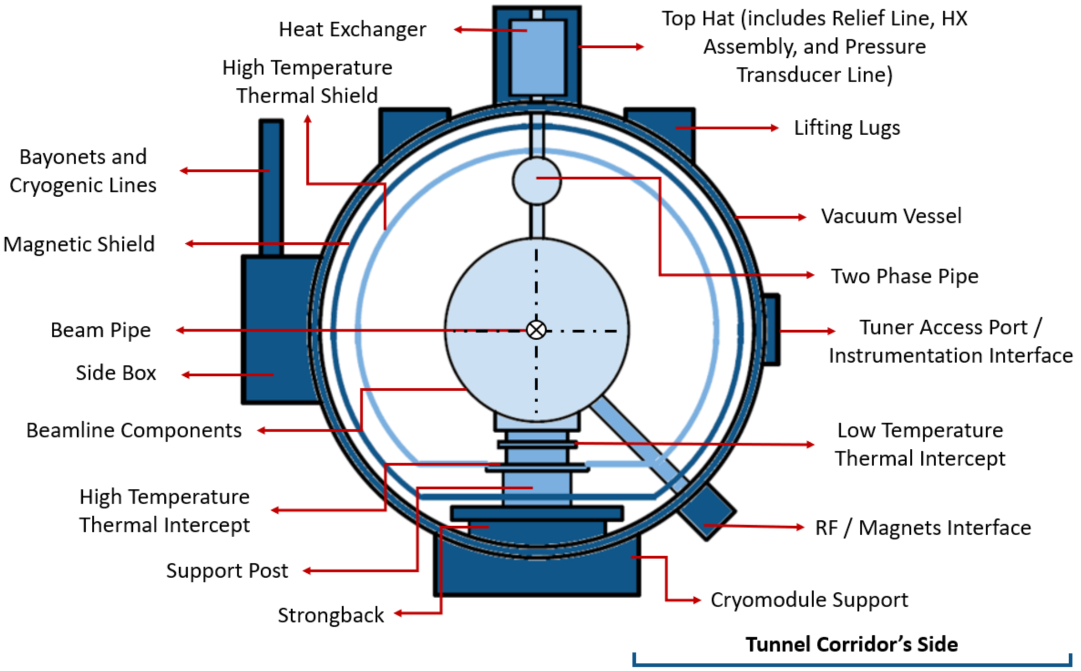
- PIP-II linac is technically complex, state of the art superconducting RF accelerator





Fermilab

PIP-II style cryomodule



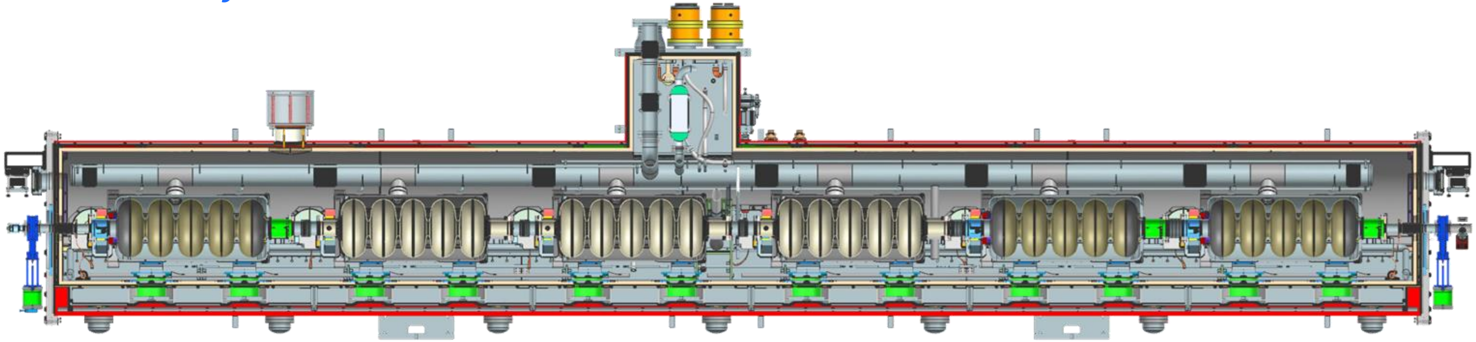
The **"Strongback"** serves as the coldmass **foundation** for PIP-II cryomodules.

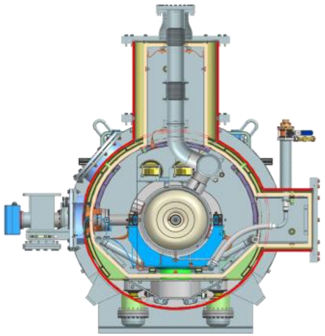
It will support all the elements of the beamline, shielding, and piping from below. This will enable the entire coldmass to be assembled and aligned as a unit which is then inserted into the vacuum vessel during final assembly.

Maintaining the **strongback at room temperature** will help to minimize axial movement of the cold elements during cooldown, which will reduce the displacement of couplers, current leads, and many of the internal piping components.

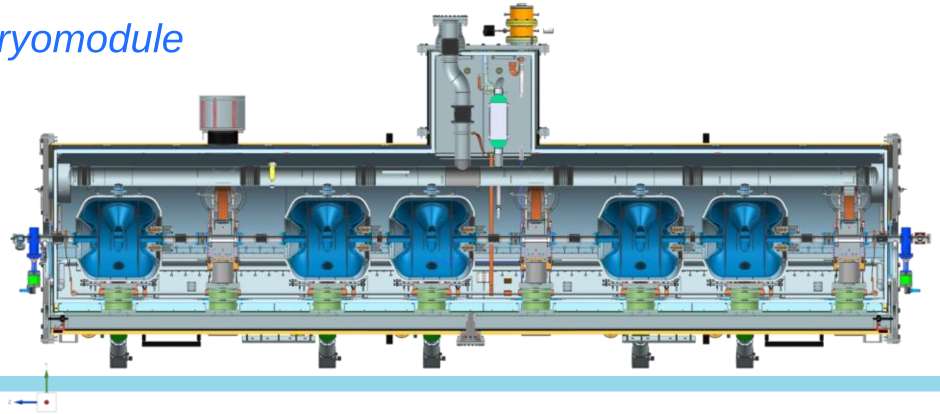
PIP-II style cryomodule

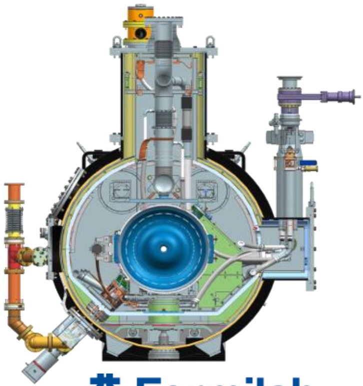
- *HB650 cryomodule*





- *SSR2 cryomodule*





Cryomodule String Assembly

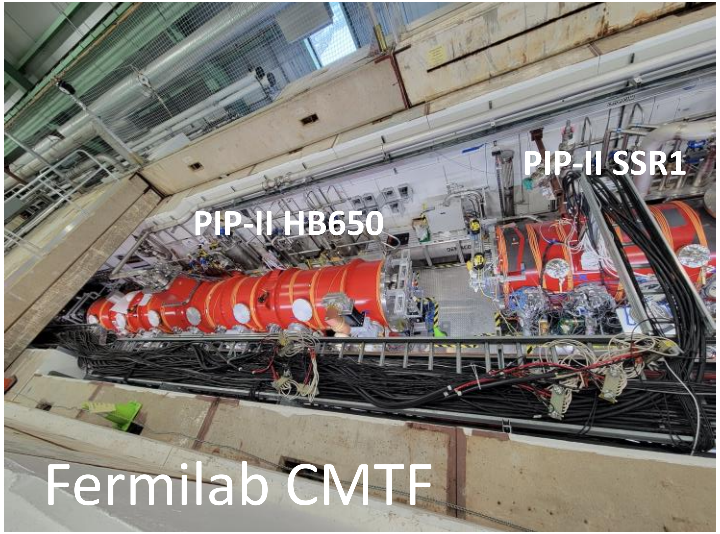
- New cleanroom was commissioned last year to allow PIP-II CM assembly in parallel to LCLS-II
- Designed to be compatible with both PIP-II cryomodules and 1.3 GHz ILC-like cryomodules
- Crucial for PIP-II, but new infrastructure will be available after PIP-II

Slide by O. Pronitchev

New SRF String Assembly Cleanroom with PIP-II HB650 String

Cryomodule Testing

- Cryomodule test stands at the Fermilab Cryomodule Test Facility (CMTF) characterize cryomodule performance prior to installation in the tunnel
- Cryogenics, pumps, RF power, shielding, instrumentation, DAQ



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4. **Summary**

Summary

- High Q_0 is impactful for power consumption and infrastructure cost of FCCee cryogenic system, particularly at highest energy configurations
- State-of-the-art SRF cavity treatments such as mid-T bake and Nb_3Sn can help enable high Q at gradients relevant to FCCee
- Fermilab SRF team has substantial experience at frequencies near (above and below) 800 MHz, now working on 800 MHz cavities built by JLab
- Fermilab SRF team has key experience from PIP-II and LCLS-II including cryomodule design and production; facilities are capable for FCCee 800 MHz CMs