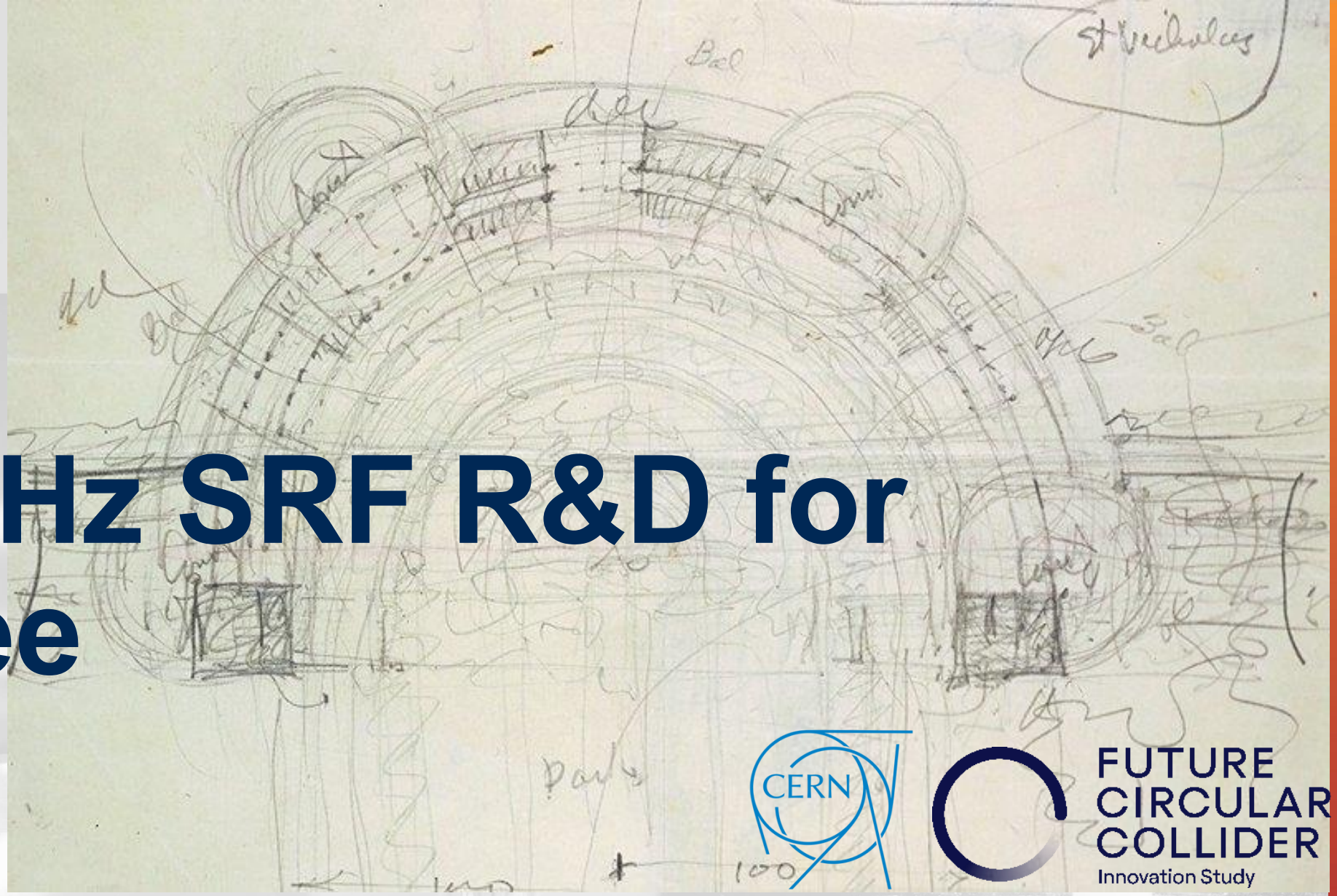
Fermilab

August 25, 2025

800 MHz SRF R&D for FCC-ee

Kellen McGee
FNAL



CERN

FUTURE CIRCULAR COLLIDER
Innovation Study

FERMI NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT of ENERGY
Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

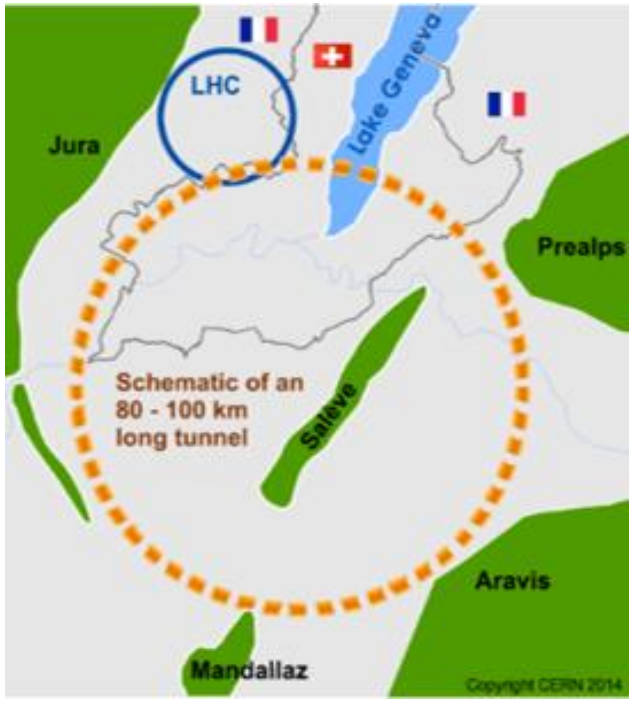
MONONA TERRACE
A Public Place by Frank Lloyd Wright

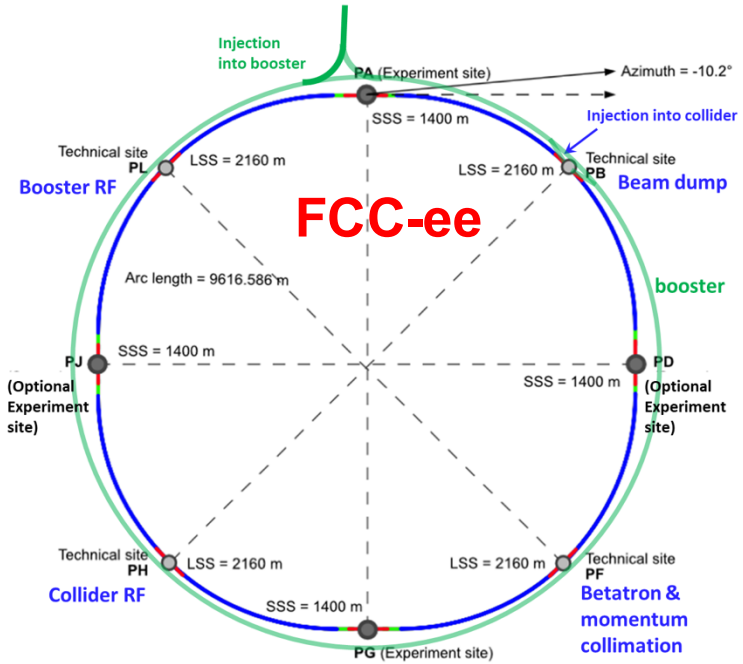
FCC week: 2025

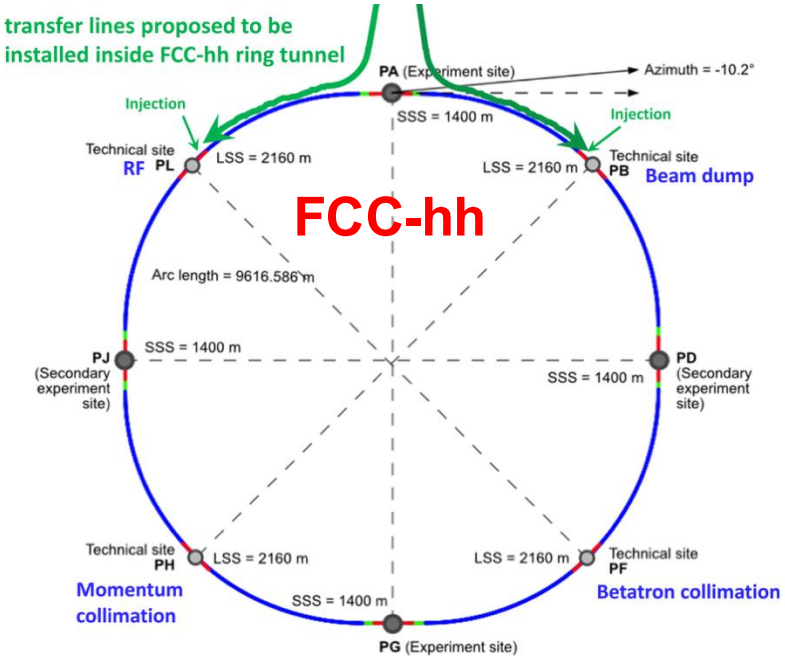
- FCC Feasibility Study has been concluded with the submission of the Feasibility Study Report to the ESPP, as requested by CERN Council.
  - Volume 1: Physics, Exp, Detectors (280p) https://arxiv.org/abs/2505.00272
  - Volume 2: Accelerators, technical infrastructure, safety (627p) https://arxiv.org/abs/2505.00274
  - Volume 3: Civil Engineering, Infrastructure, sustainability (357p) https://arxiv.org/abs/2505.00273
- A coherent baseline design for the FCC integrated programme has been developed, including a well-advanced territorial implementation scenario, in line with desired CE construction start by 2032/33.
- FCC-ee design level enables moving towards technical design and prototyping phase, well aligned with overall schedule and towards preparing input for potential project decision by 2027/28.
- ”FCC-ee: Your questions answered” –A. Blondel, P. Janot, ed. et al. https://arxiv.org/pdf/1906.02693

FCC integrated program – scope and timeline

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme maximising the physics opportunities
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







2020 - 2045 | 2045 - 2065 | 2070 - 2100

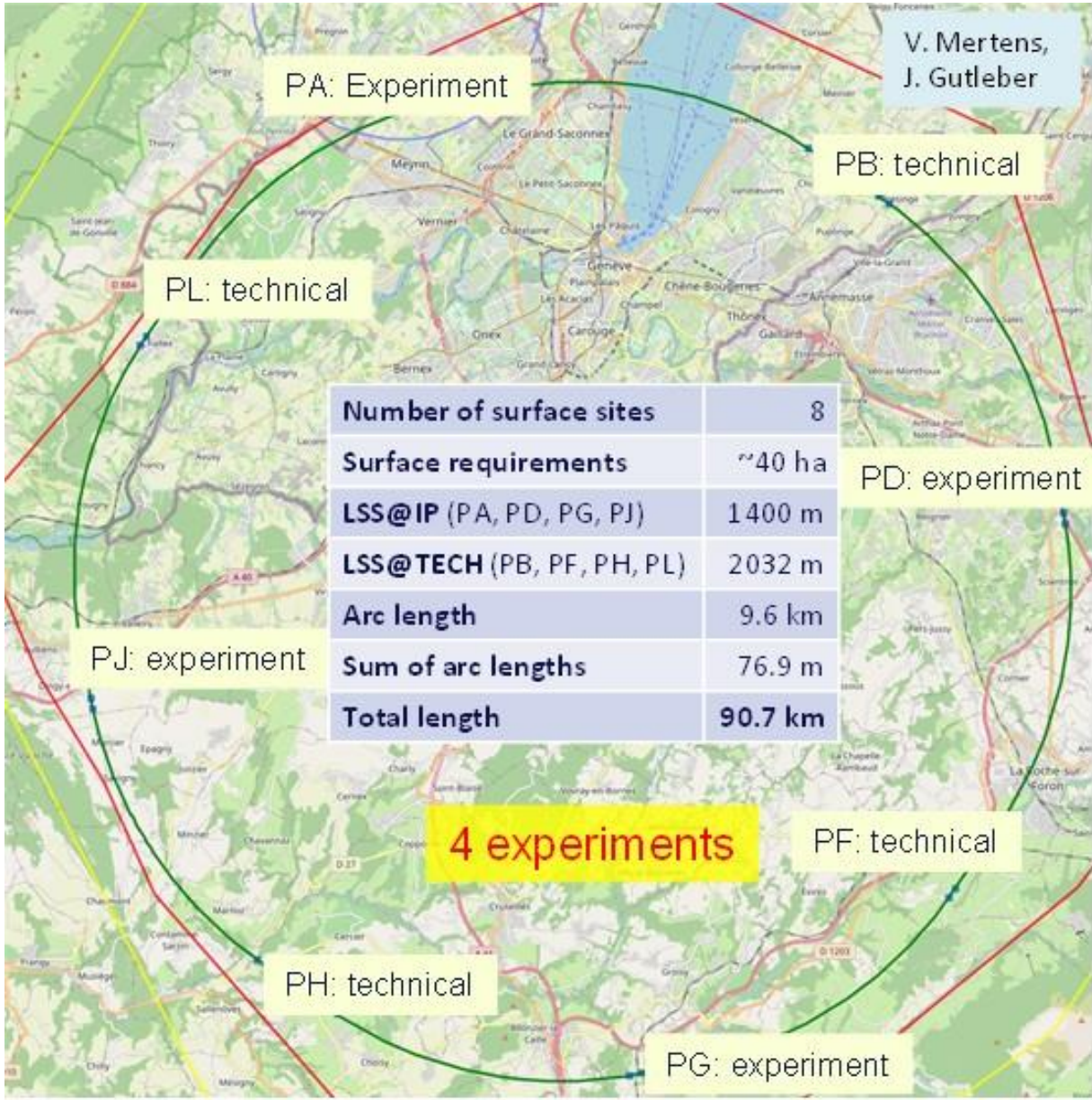
Reference layout and implementation: PA31 - 90.7 km

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

Overall lowest-risk baseline:
90.7 km ring, 8 surface points,
4-fold symmetry

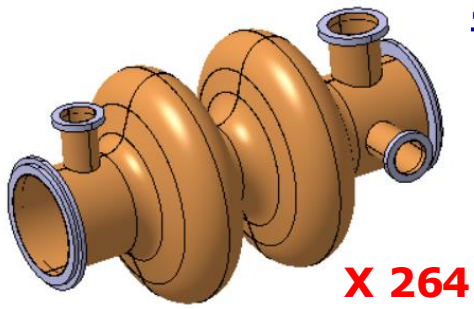
Reference layout was the basis for:

- **Surface sites optimisation** and **land reservation** with host states CH and FR
- **Environmental initial-state study**



FCC-ee RF system – key technology, R&D ongoing

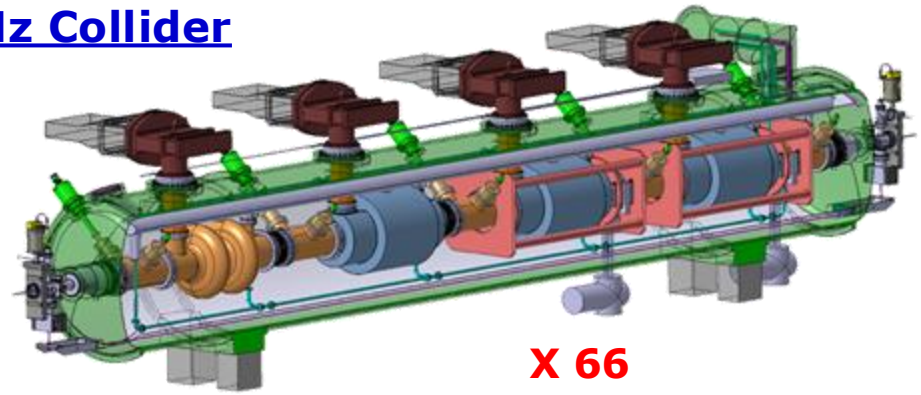
400 MHz Collider



X 264

Superconducting elliptical cavity

- 400 MHz, 2-cell, copper Nb coated
- 1.5 m. long



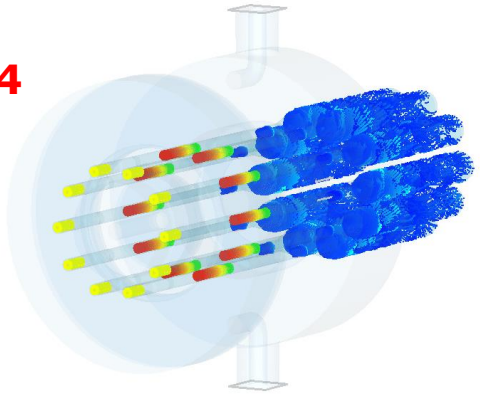
X 66

400 MHz Cryomodule

Power source: Multibeam Tristron

- Very efficient ~90 % ! <<OPEX
- 3 m long
- 50 kV
- 500 kW, CW

X 264



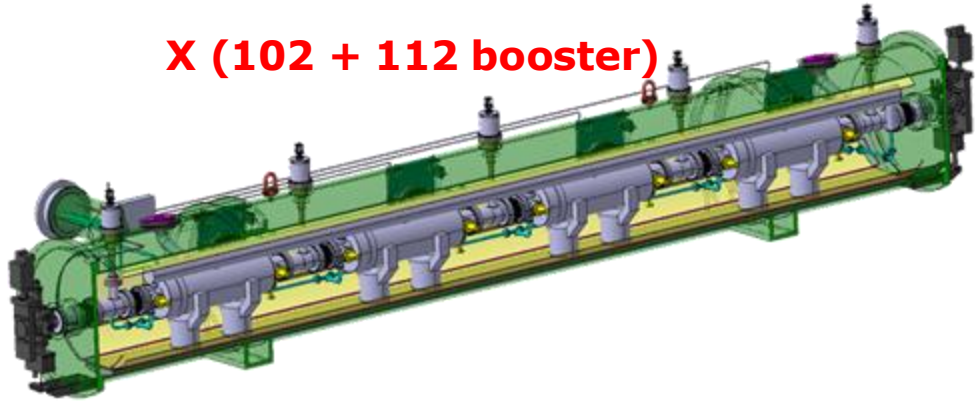
X 204

+ 448 x 10 kW SSA booster

800 MHz Collider + Booster

X (408 + 448 booster)

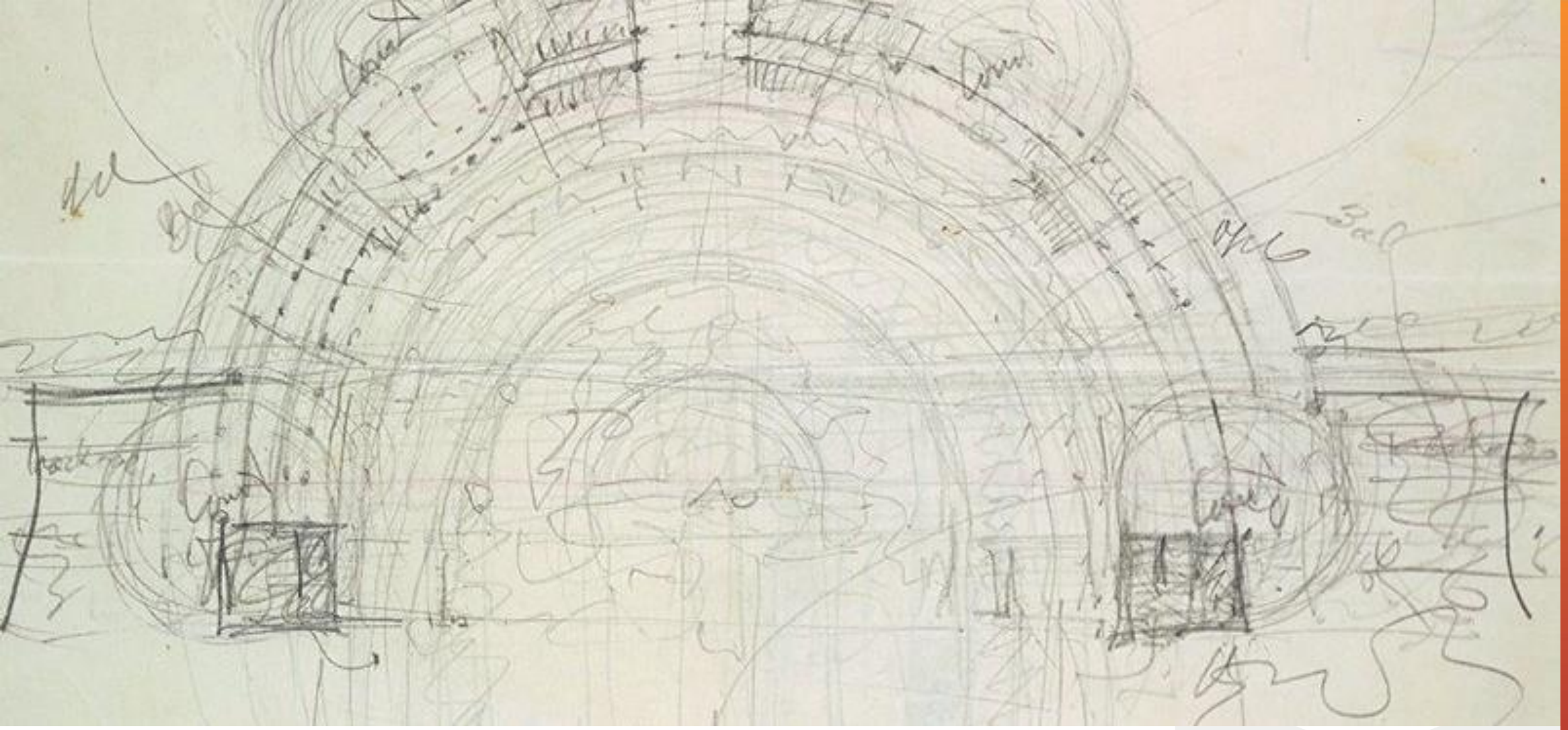
X (102 + 112 booster)



800 MHz Cryomodule

Superconducting elliptical cavity

- 800 MHz, 6-cell, bulk Nb
- Nb_3Sn if R&D is successful



800 MHz SRF cavities and surface processing

01

FUTURE CIRCULAR COLLIDER
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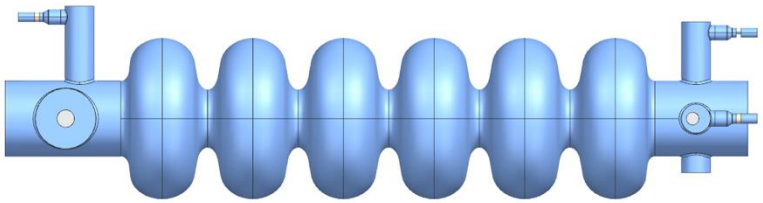
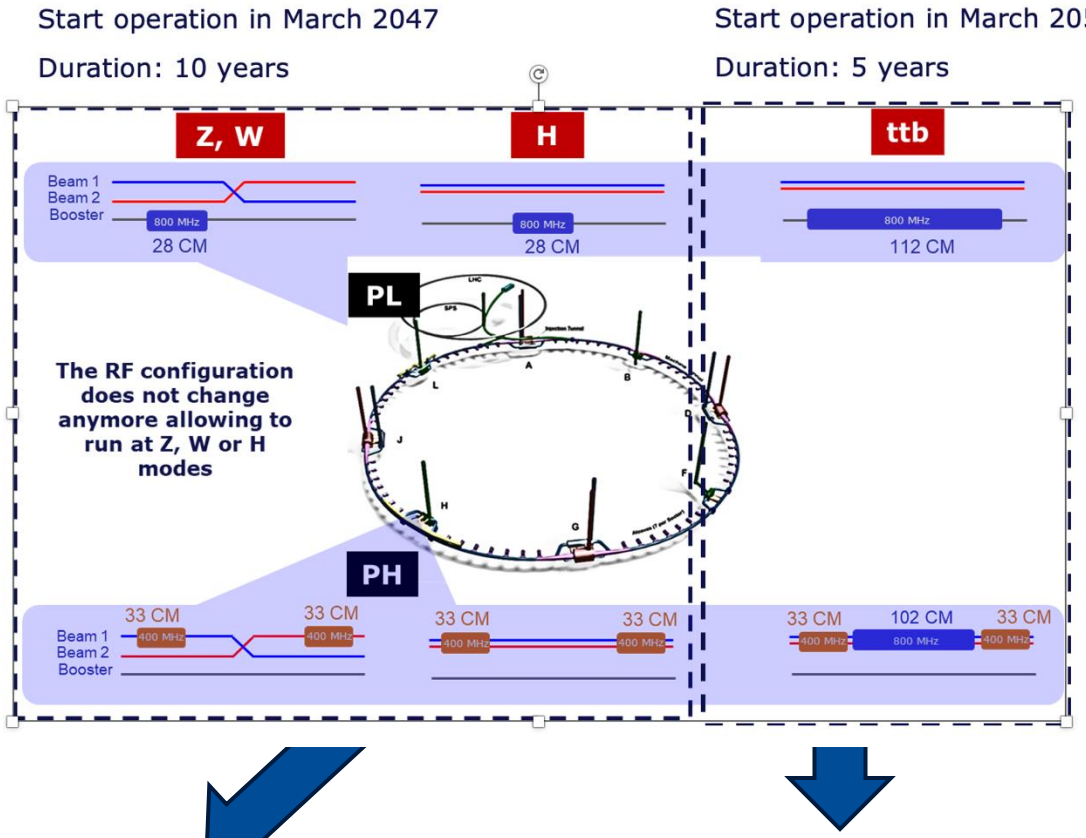
FERMI NATIONAL ACCELERATOR LABORATORY

800 MHz SRF for FCC-ee

Introduction

- 800 MHz, 6-cell cavity performance goals
  - Operation: Q0 = $3x10^{10}$ at E_{acc} = 20 MV/m
  - Vertical test: Q0 = $3.8x10^{10}$ at E_{acc} = 24.5 MV/m
- Phase 1: Z,W, and H operating points
  - High-current machine: higher-order mode excitation
  - Reverse phase operation enables Z,W, and H OPs
- Phase 2: TTb operating point
  - High-gradient machine





Booster: 112 cavities/28 CM

Booster	Z	W	ZH
	RPO	RPO	
Total RF voltage [MV]	80	401.9	1961
Beam current [mA]	16.2	6.2	2
RF Frequency [MHz]	801.58		
Operating temp. [K]	2		
Cavity voltage at extraction [MV]	5.6	13.5	17.5
# cell/cavity	6		
Eacc [MV/m]	4.9	12	15.6
Q0	3E+10		
Max RF power [kW]	42		
Coupling QL	1E+07		
# CM (with 4 cav/CM)	28		
# cavities	112		

448 booster + 408 collider = 856 cavities/214 CM

	ttb collider		ttb booster
	2 beams		1 beam
Total RF voltage [MV]	2098	9202	10180
Beam current [mA]	10		0.4
RF Frequency [MHz]	400.79	800.58	
Operating temp. [K]	4.5	2	
Cavity voltage [MV]	7.95	22.5	22.8
# cell/cavity	2	6	
Eacc [MV/m]	10.6	20.1	20.3
Q0	2.7E+9	3E+10	
RF power [kW]	78	195	8.9/12.7
Optimum coupling QL	4.5E+06	4.1E+06	9.2E+07/2.7E+07
# CM (with 4 cav/CM)	66	102	112
# cavities	264	408	448

800 MHz SRF for FCC-ee

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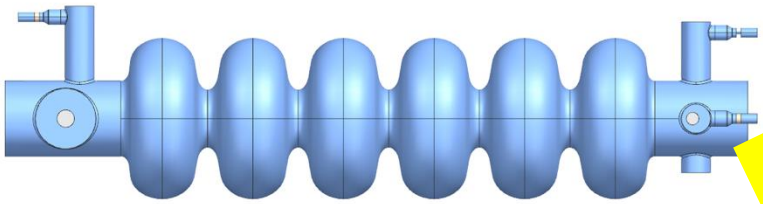

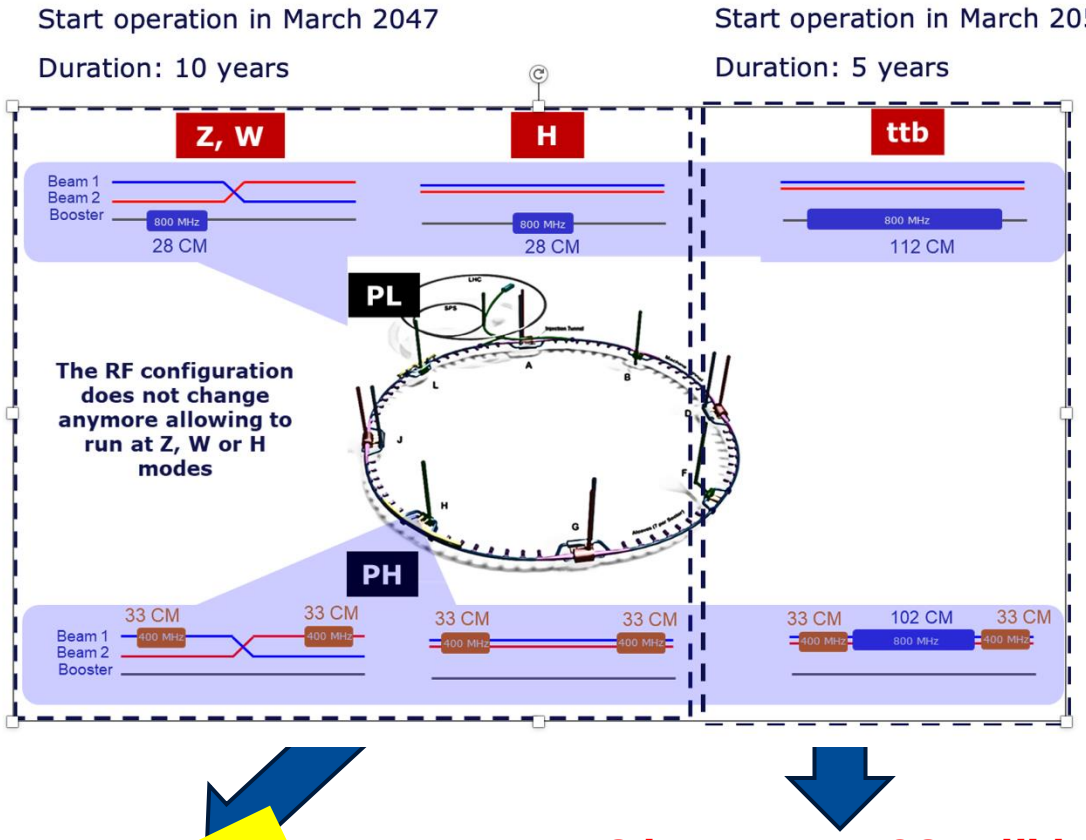

Booster: 112 cavities/

~~370 CM, ~1,500 cavities~~

Booster	Z		ZH
Total RF voltage [M		401.9	1961
Beam current		6.2	2
RF Frequ		801.58	
Ope		2	
	5.6	13.5	17.5
vity		6	
[MV/m]	4.9	12	15.6
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Coupling QL		1E+07	
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# cavities	264	408	448

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Reaching high Q0

Recent advances in high-Q high-gradient SRF cavities

- N-doping[1]

"2/0" N-doping: Bulk EP, High T (degassing+stress release) bake, light EP, N-Doping (2min doping/0min annealing), Post-doping+cold EP, HPR+VT assembly, RF test.

  - 2012-13 FNAL: Doubled Q, reversed R_{BCS} dependence on E_{acc}
  - Industrialized at 1.3 GHz to deliver LCLS-II

[1] A. Grassellino et al, *Supercond. Sci. Technol.* **26**, 102001 (2013).

- Medium temperature baking[2,3]

Bulk EP, High T (degassing+stress release) 800-950C 3h, light EP, mid-T furnace bake 300C 3h, HPR, VT assembly, RF test.

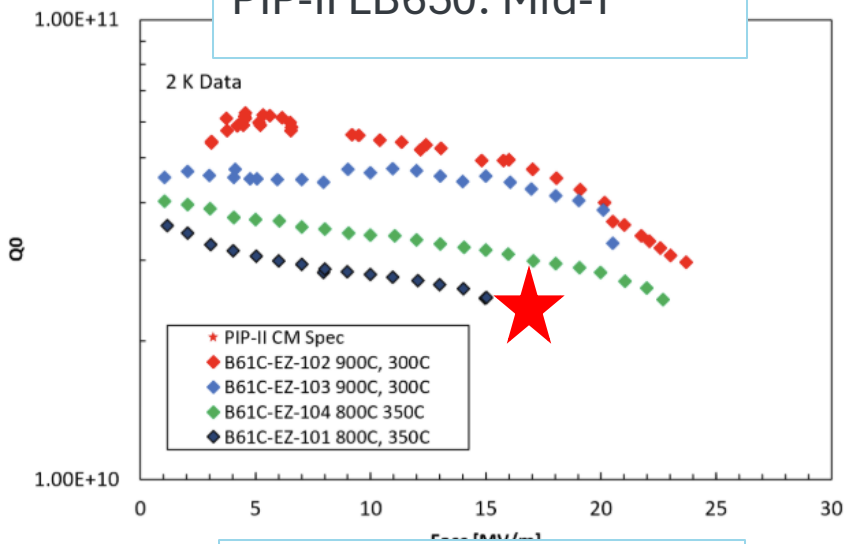
  - Simple one-step chemical processing (FNAL)
  - 300C, 3-hour bake dissolves the native oxide layer and diffuses oxygen into the niobium bulk
    - Mechanism not fully understood, but seems to have traits in common with N-doping, despite differences in diffusion depth: See H. Hu, Hu, Hannah. "Decoupling of Nitrogen and Oxygen Impurities in Nitrogen Doped SRF Cavities." , Jun. 2024.

[2] S. Posen, et al., *Phys.Rev.Applied.*, Volume 13, Issue 1, Jan 2020 (FNAL)
[3] H. Ito, et al., *Prog of Theor. and Exp. Phys.*, Volume 2021, Issue 7, July 2021

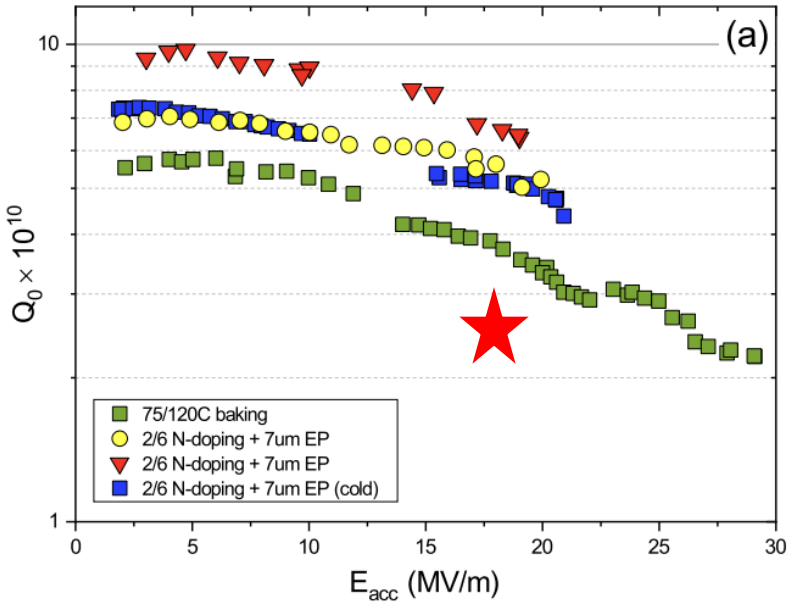
- Sensitivity to trapped magnetic flux increases in both cases
  - "Sensitivity" measures the amount of residual resistance generated per unit of trapped magnetic flux
  - "Increased sensitivity" means your accelerator is more vulnerable to the effects of trapped flux
    - Mitigation strategies include fast cooldown, improved magnetic hygene

Technical perspective: SRF

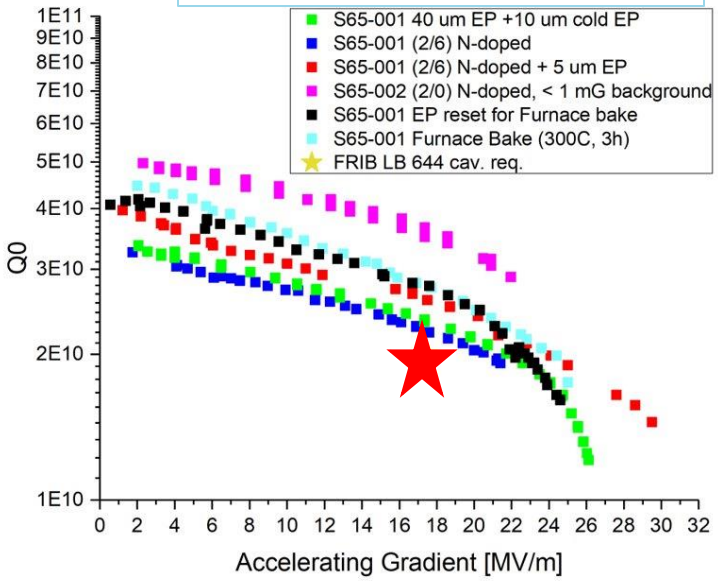
PIP-II LB650: Mid-T

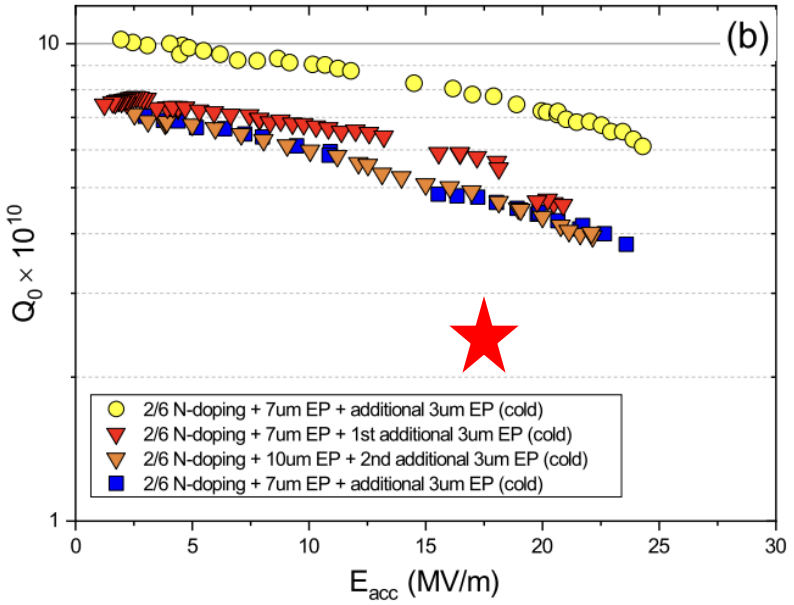


PIP-II HB650: N-doping



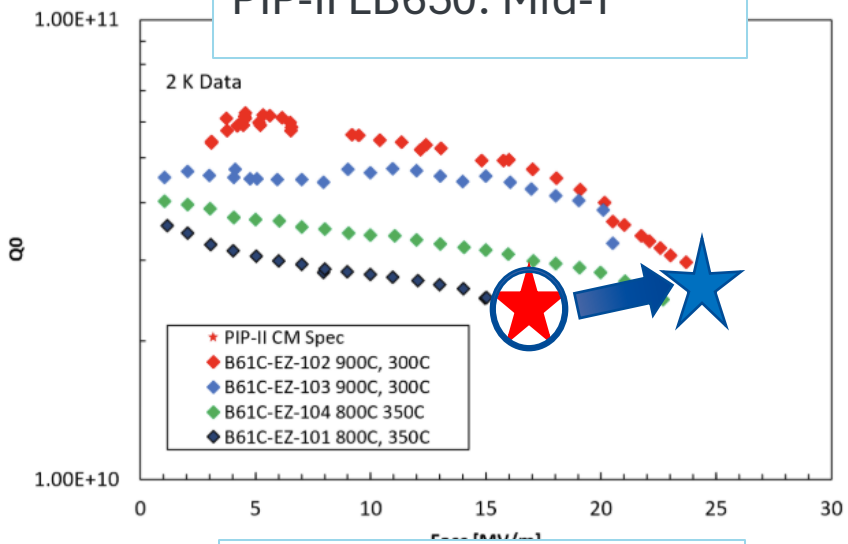
FRIB 644 MHz: various



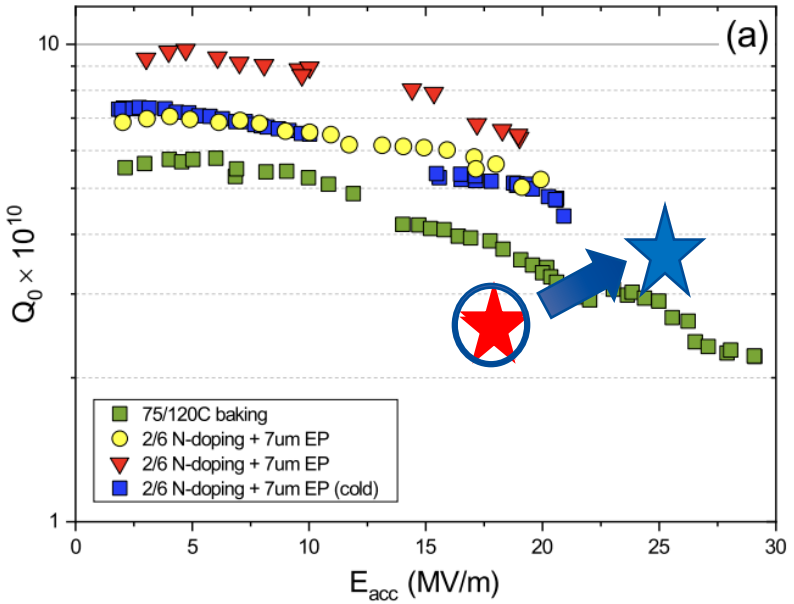


Technical perspective: SRF

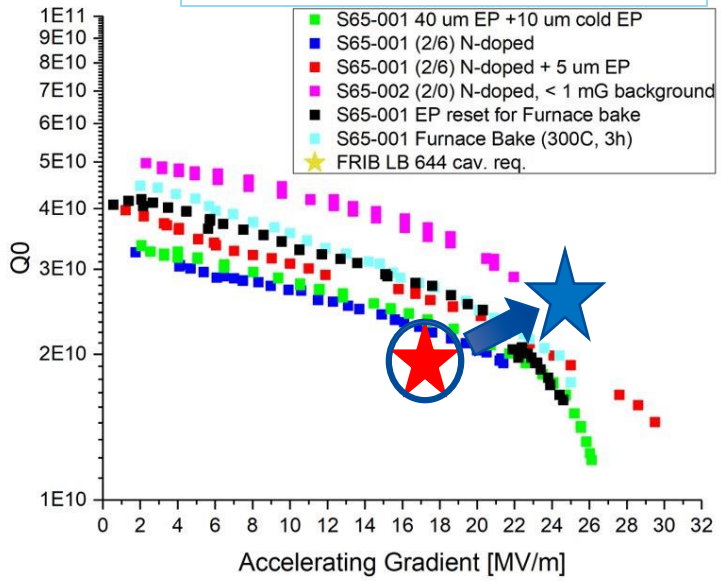
PIP-II LB650: Mid-T

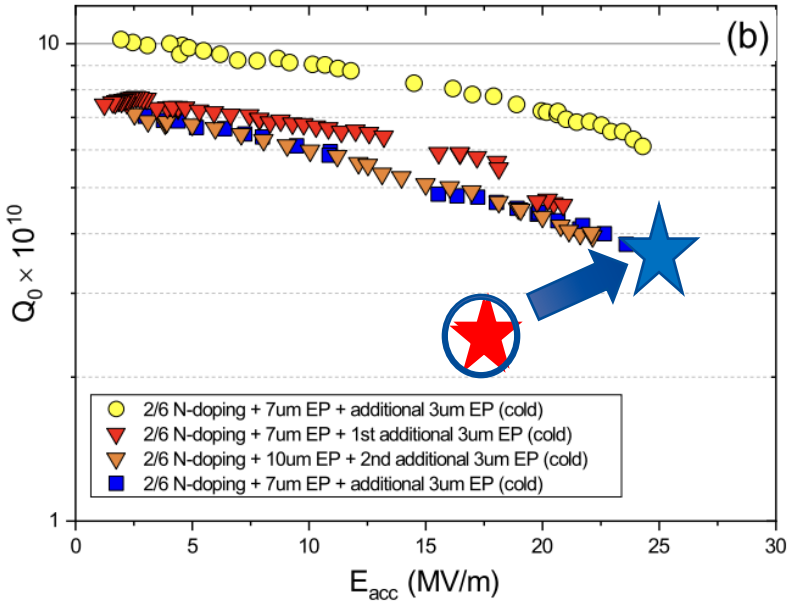


PIP-II HB650: N-doping



FRIB 644 MHz: various

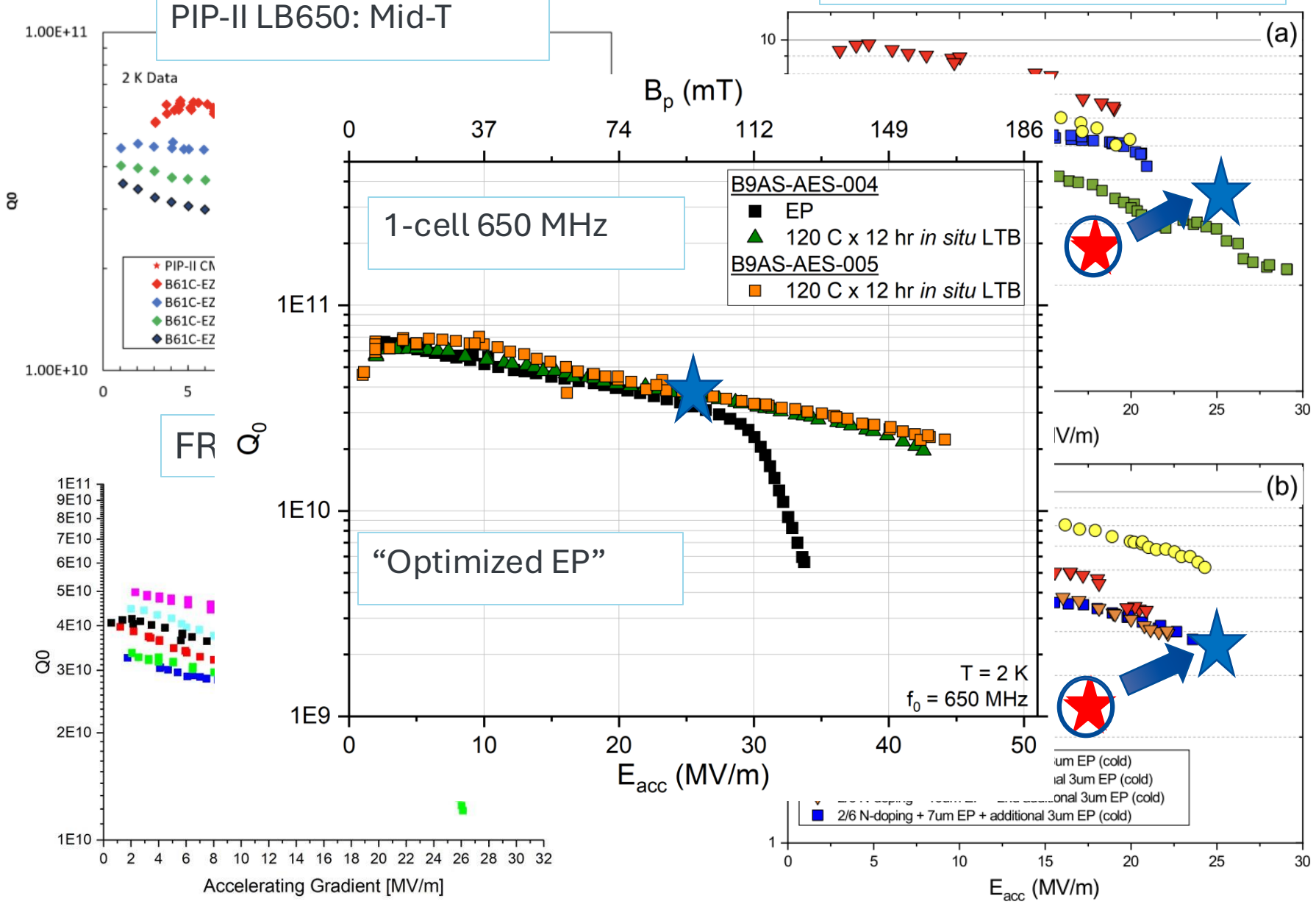




Technical perspective: SRF

PIP-II LB650: Mid-T

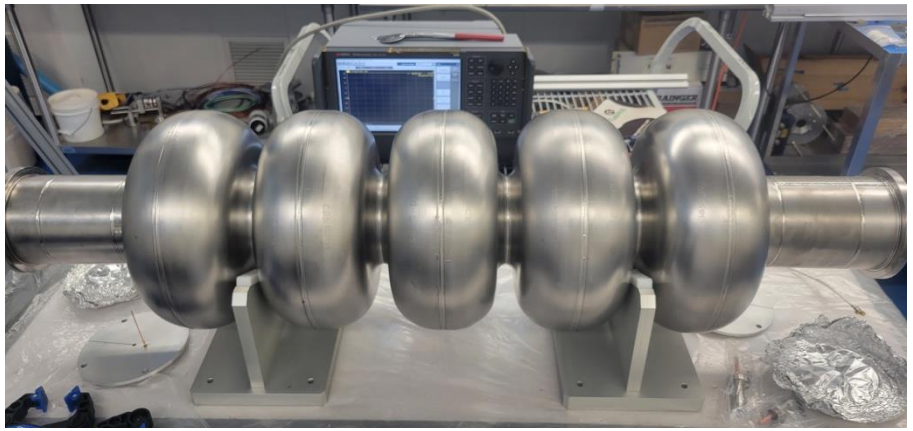
PIP-II HB650: N-doping



800 MHz 5-cell cavity

First experiments

- Cavity fabricated at JLab, currently at FNAL
- High-power RF cold-test baseline electropolish
  - Q_0~3x10^{10} at 25 MV/m
  - Quench at 27 MV/m
- Explore advanced techniques for >26% improvement in Q_0
  - Mid-T baking **complete 7/2025!**
    - **Cold-test expected Fall 2025**
  - N-doping?
  - Nb3Sn (future)



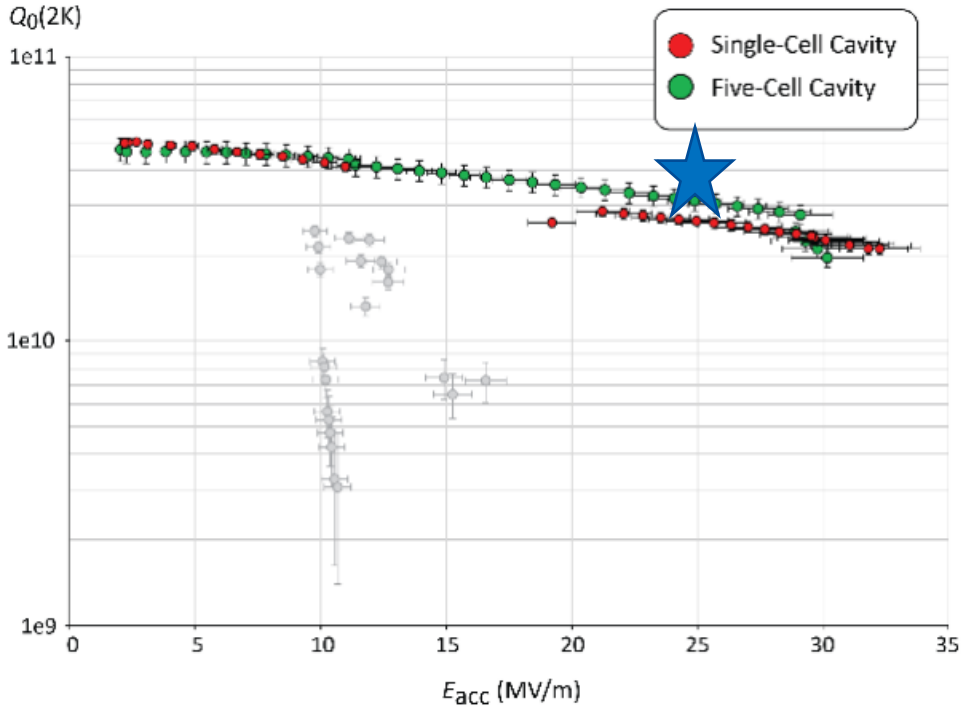


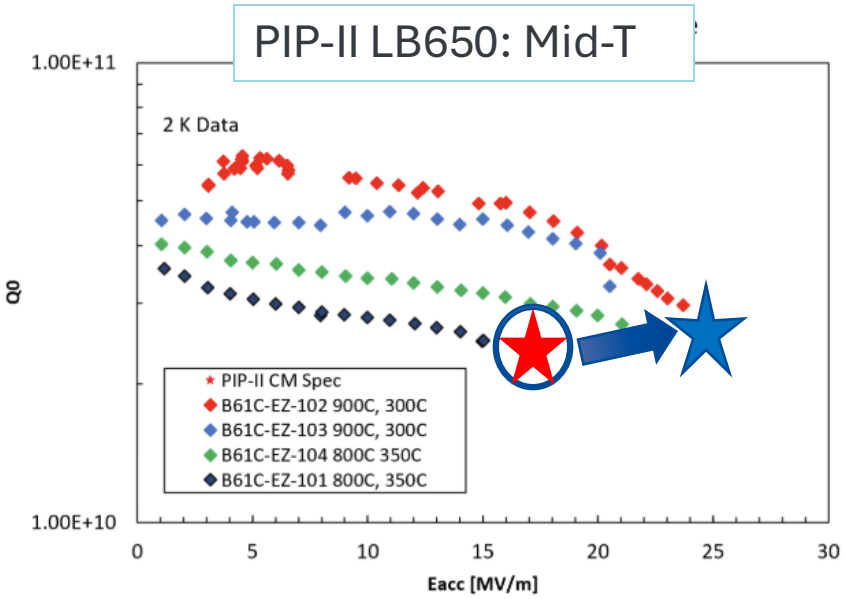
Figure 4: Combined VTA results for the five-cell and single-cell cavity as measured at 2 Kelvin.

F. Marhauser et al. *802 MHz ERL Cavity Design and Development (cern.ch)* *IPAC 2018* **THPAL146**

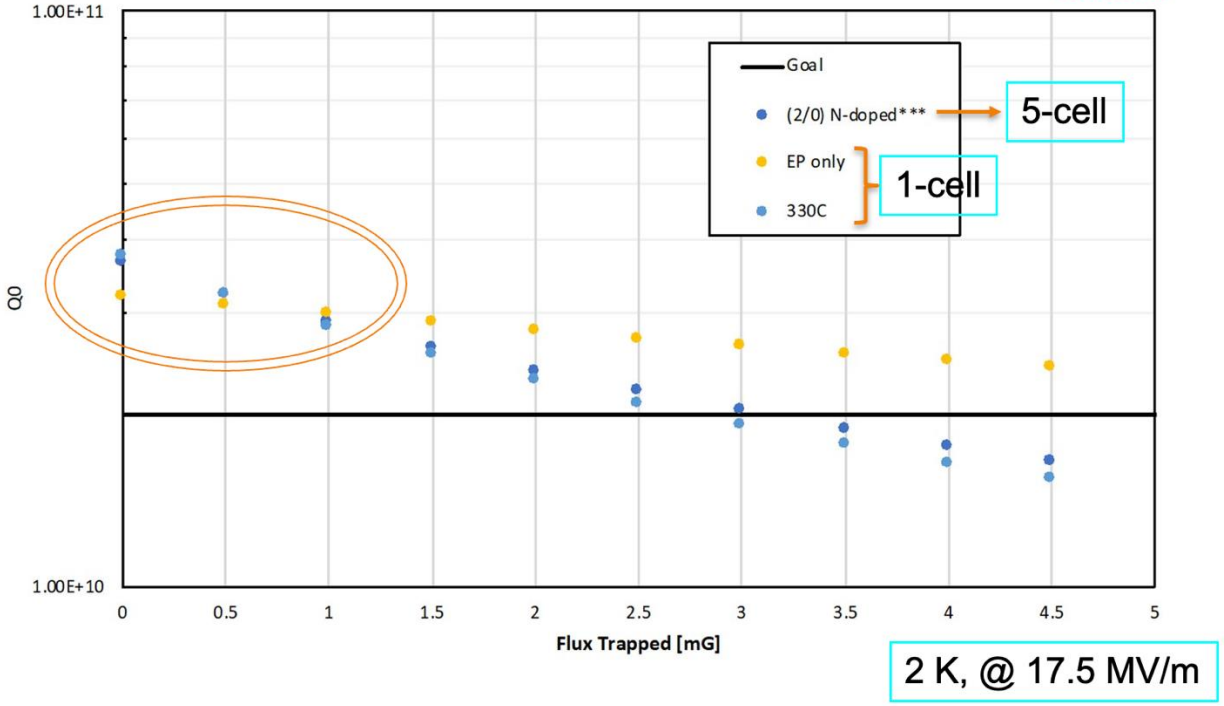
Production challenges

Magnetic flux trapping and implications

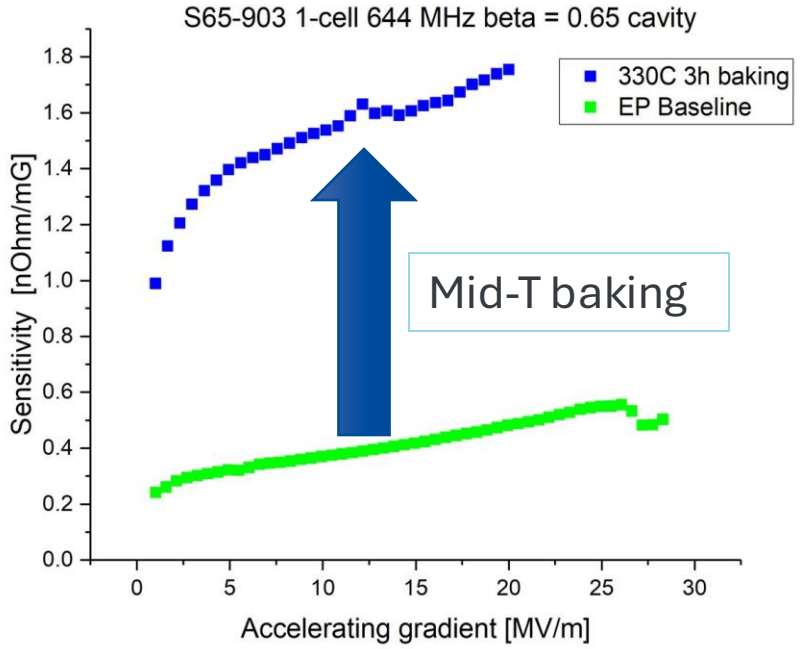
- Flux trapping degrades Q!
  - Varies within Nb batches
  - Highly correlated with Nb texture
  - Difficult/impossible to control at the Nb vendor level

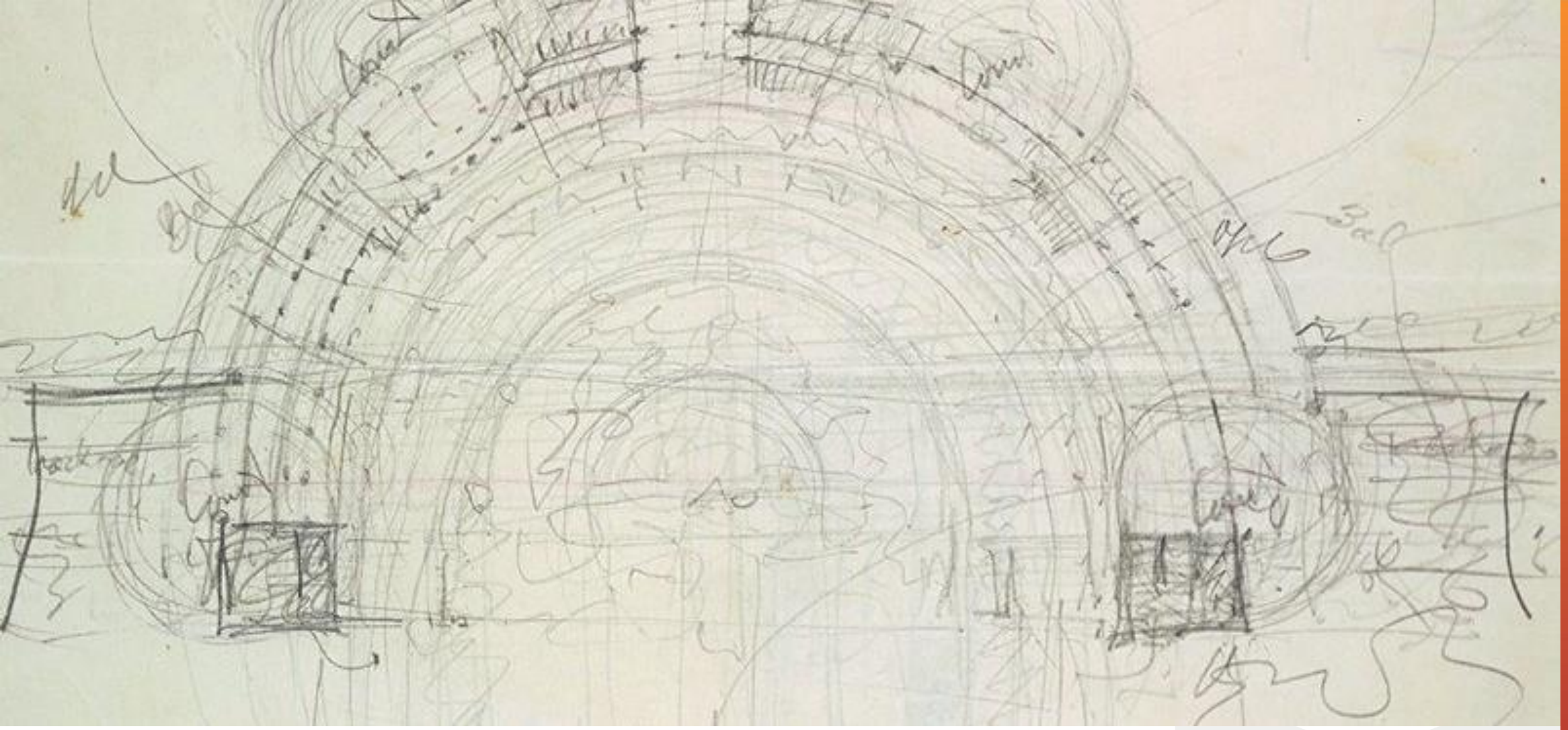


*Tokyo-Denkai material



2 K, @ 17.5 MV/m





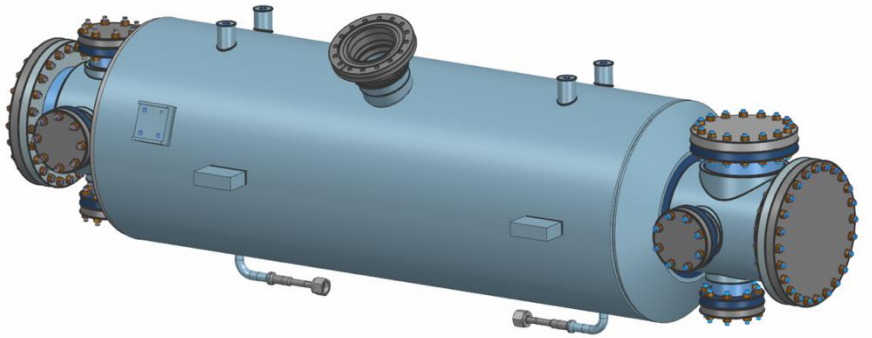
Mechanical design and analysis of 800 MHz cavities and cryomodules at FNAL

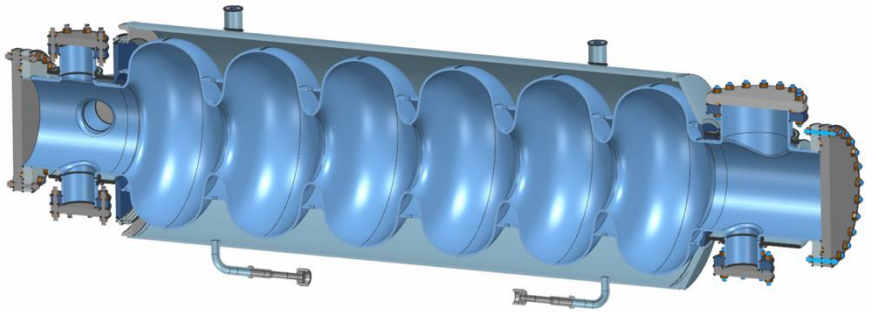
02

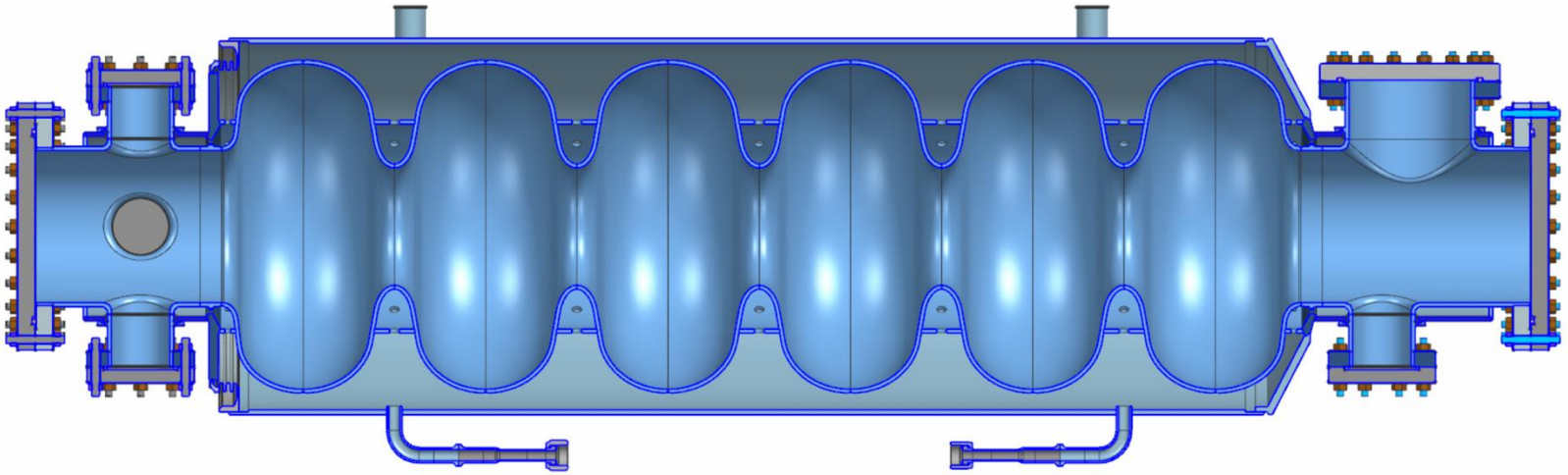
3D Model and planned analysis

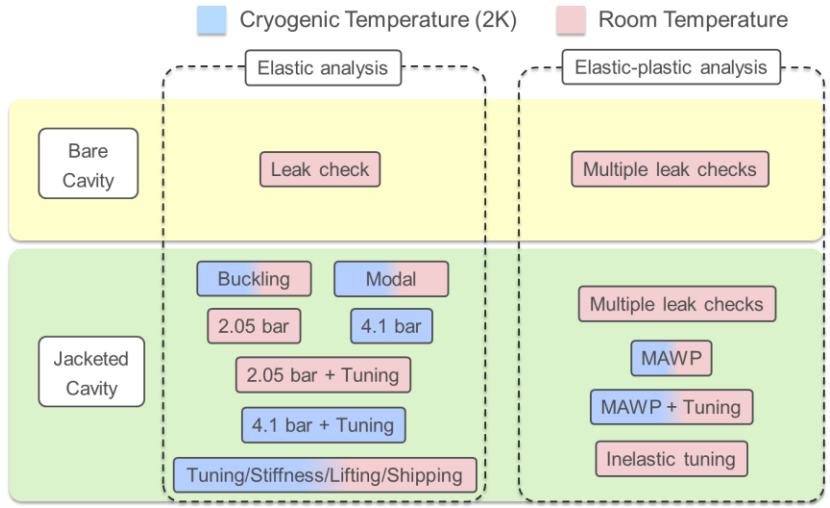
Mattia Parise, FNAL

- Cavity mechanical design and jacket integration underway!
  - The MAWP primarily determined using design-by-analysis per Part 5 of Division 2 of ASME boiler and pressure vessel code. Part 4 is used to verify the FEA, guide the design of the bellows and openings, and set minimum thicknesses for the main shell and cavity ends
  - Additional analysis, specific to SRF cavities, are carried out to check tunability and structural stability during leak checks.





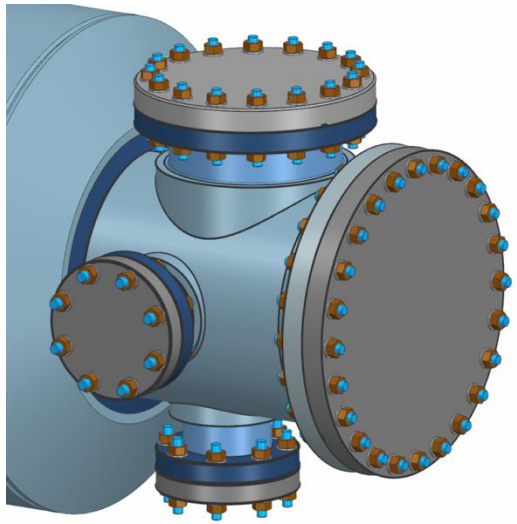


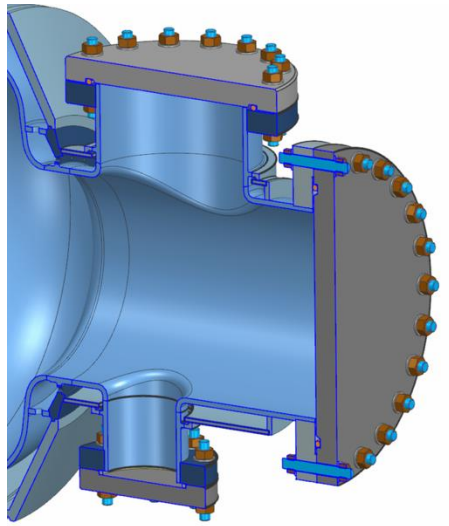


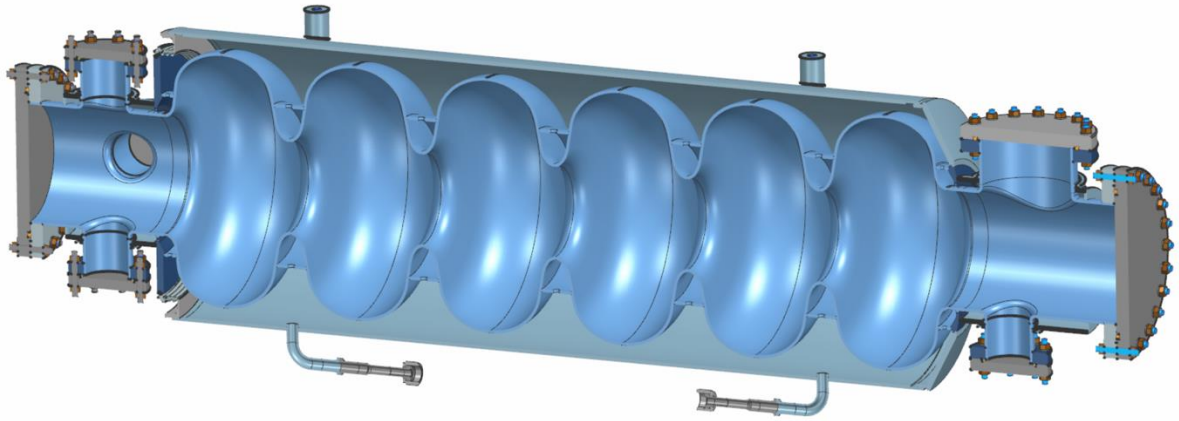
3D Model and planned analysis

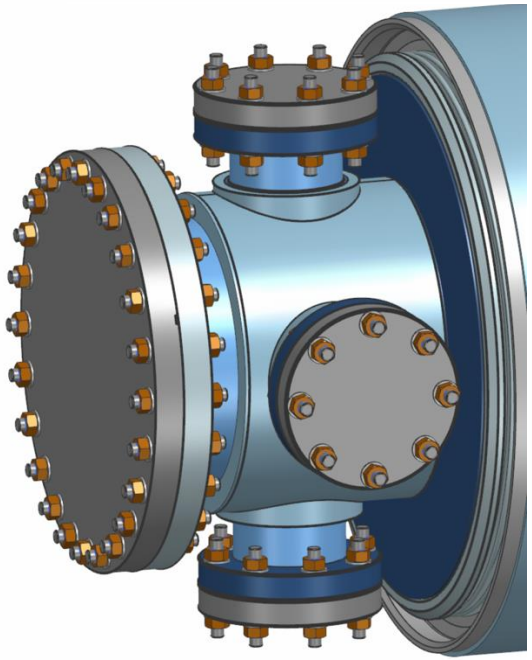
Mattia Parise, FNAL

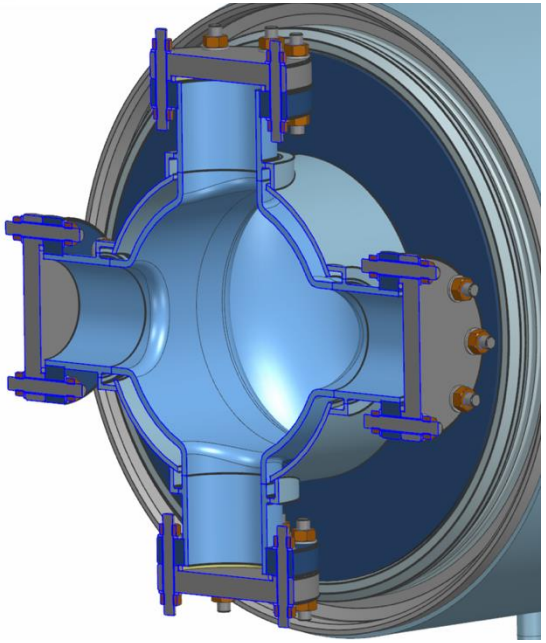
- Progress on conceptual mechanical designs
  - Complex higher order mode (HOM) port design
  - Single cavity design for booster and collider
  - Potential need for active cooling on the HOM ports, studies ongoing
- Detailed weldmap, fabrication plans to be optimized







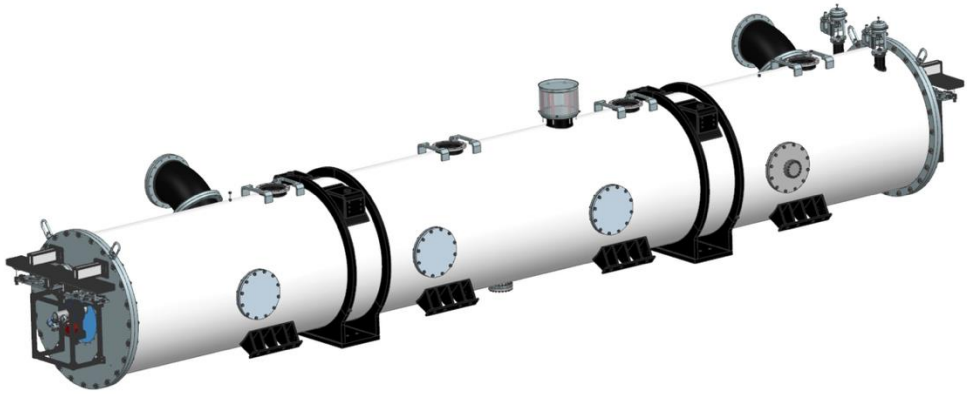




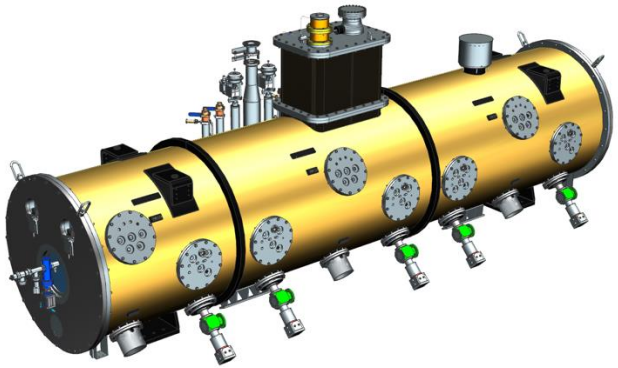
Preliminary design of FCC 800MHz Cryomodule

Vincent Roger, FNAL

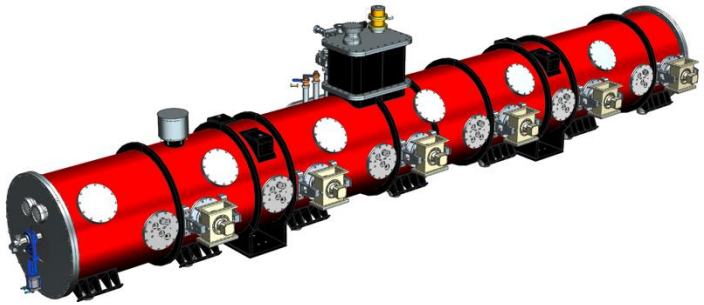
- The FCC 800 MHz CM design is based on SSR2 and HB650 PIP-II CMs with the following main differences:
  - Heat exchangers and valves are integrated into the Cryogenic Distribution System (CDS).
  - A "Jumper" will be used to interface with CDS through welded connection into the tunnel (no u-tubes).
  - Couplers are actively cooled with helium.



FCC 800 MHz cryomodule



PIP-II SSR2 cryomodule



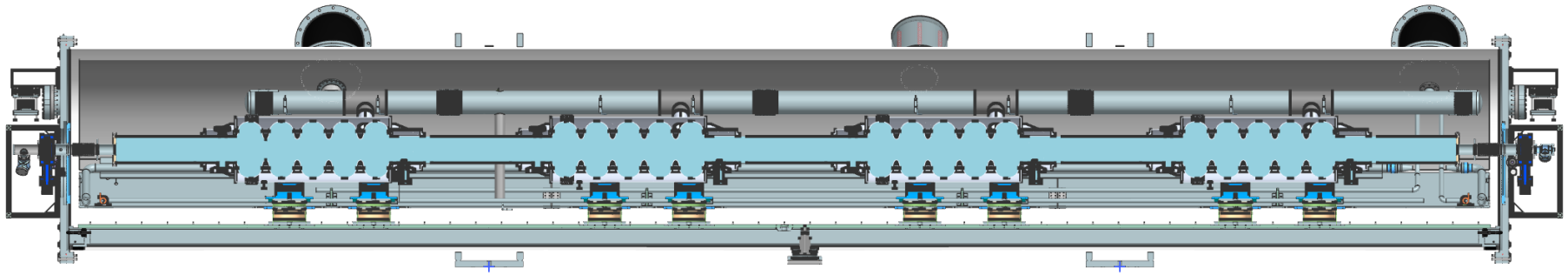
PIP-II HB650 cryomodule

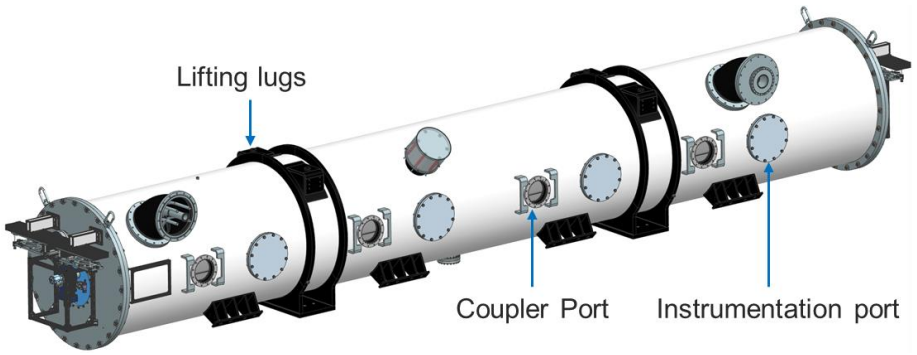
"Final Design of the Pre-Production SSR2 Cryomodule for PIP-II Project at Fermilab", V. Roger et al., Proceedings of LINAC 2022
"Design of the 650 MHz High Beta Prototype Cryomodule for PIP-II at Fermilab", V. Roger et al., Proceedings of SRF 2021

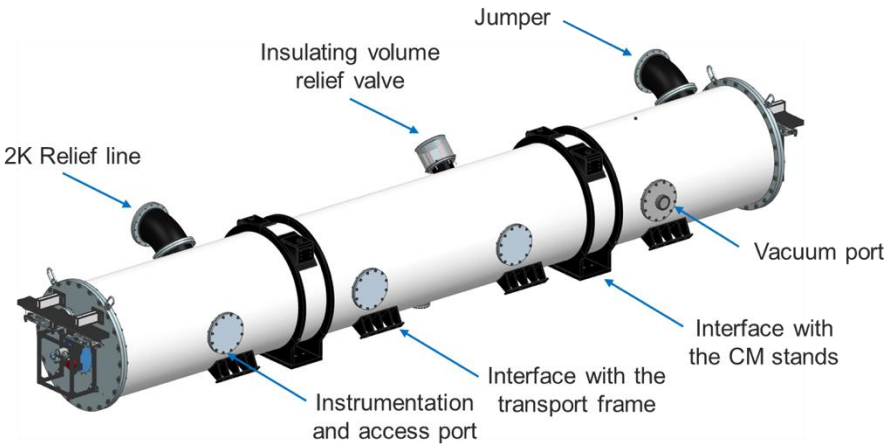
Preliminary design of FCC 800MHz Cryomodule

Vincent Roger, FNAL

- The fine segmentation is the current baseline configuration for the FCC 800 MHz cryomodule- draws heavily on PIP-II.
- The connections to cryogenics and relief lines are made through “jumpers”, welded connections.



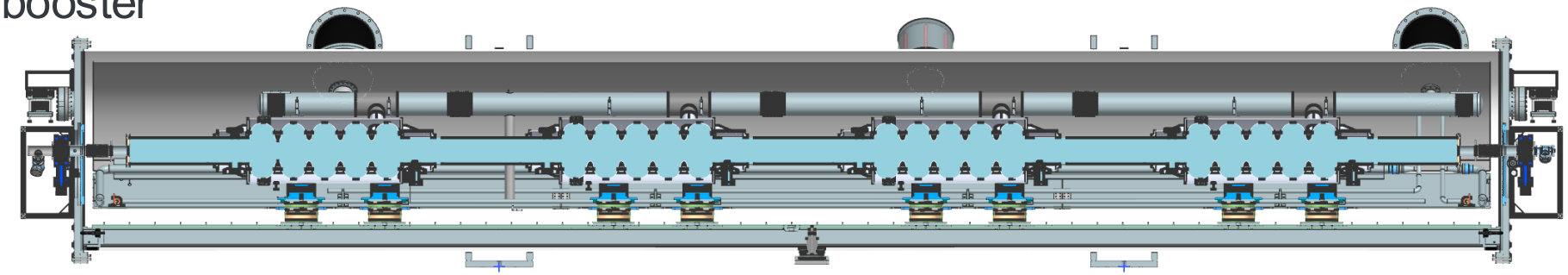


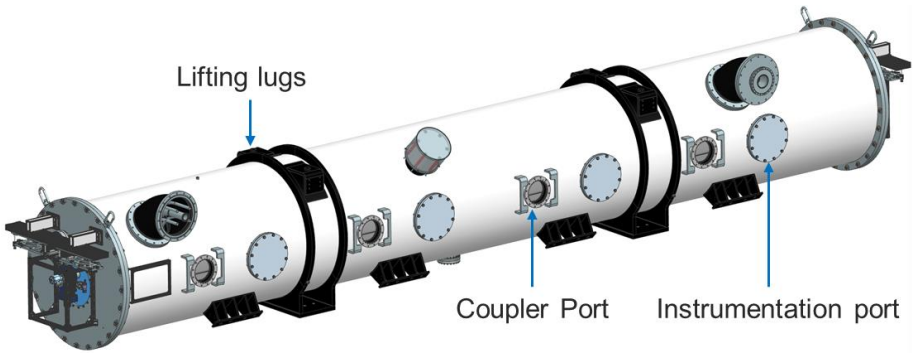


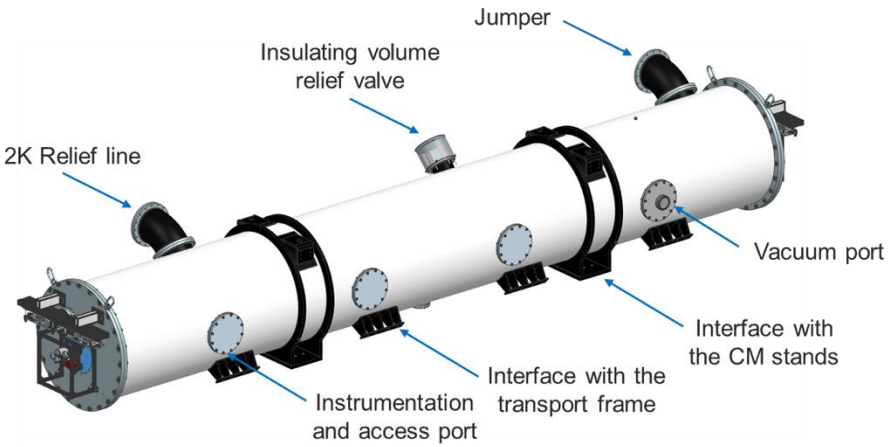
Preliminary design of FCC 800MHz Cryomodule

Vincent Roger, FNAL

- Through collaborative efforts with CERN, this design aligns with the functional, technical and interface requirements.
- Fits within the dimensional envelopes for the two different locations in the accelerator: collider and booster

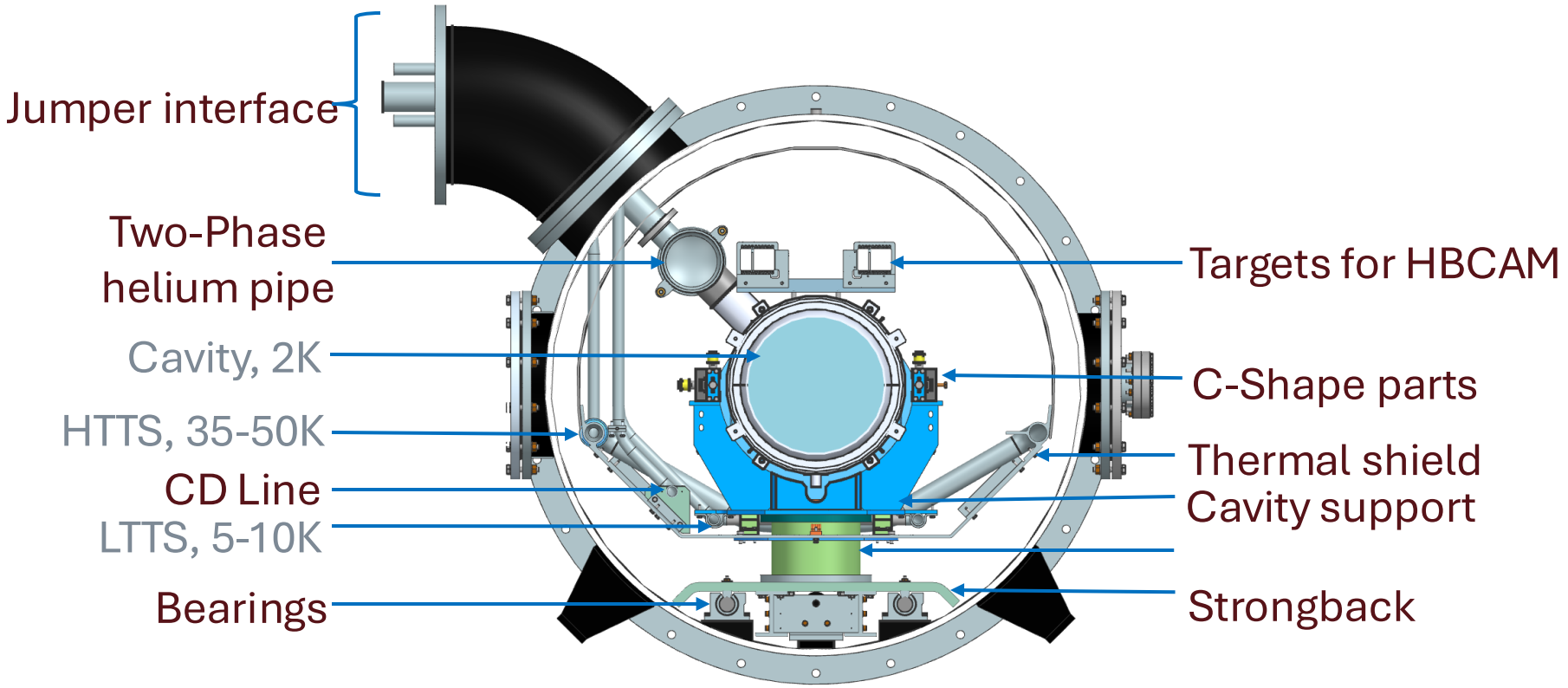






Preliminary design of FCC 800MHz Cryomodule

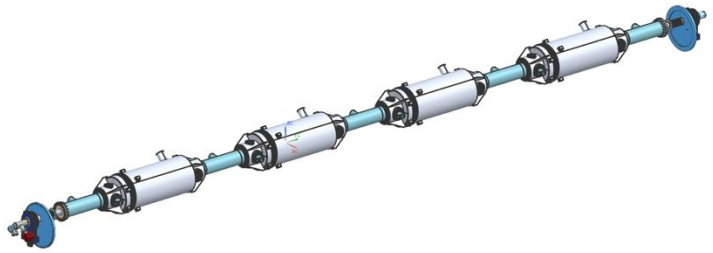
Cross-section



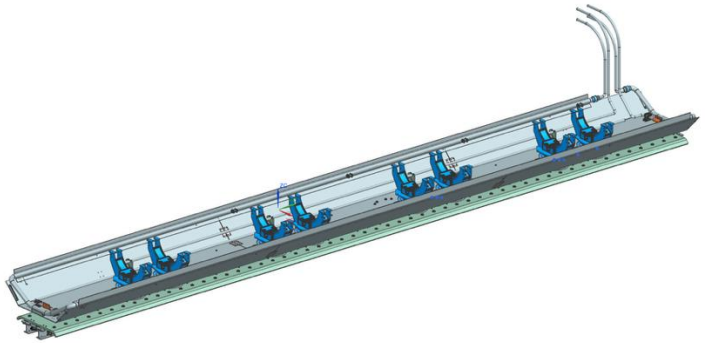
FCC 800MHz cryomodule assembly phases

Based on PIP-II assembly process

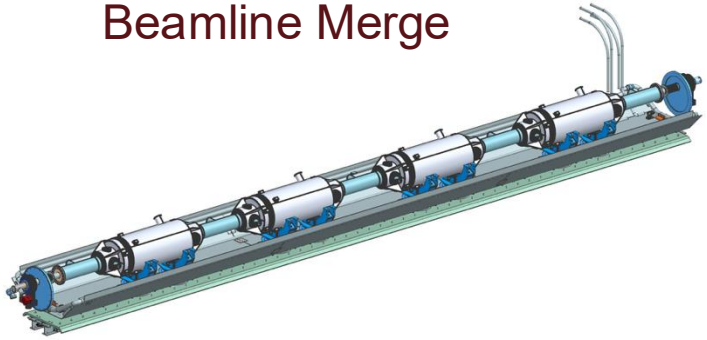
Phase 1a: Beamline assembly in the cleanroom



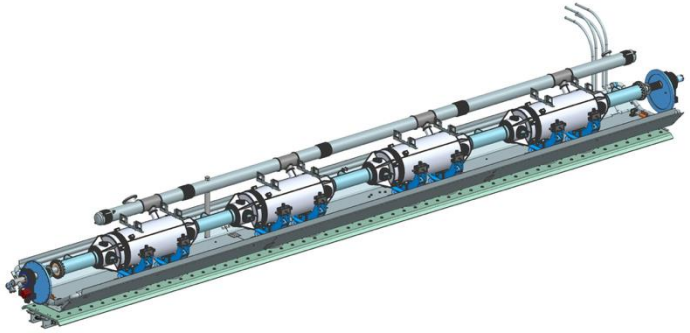
Phase 1b: Strongback Assembly



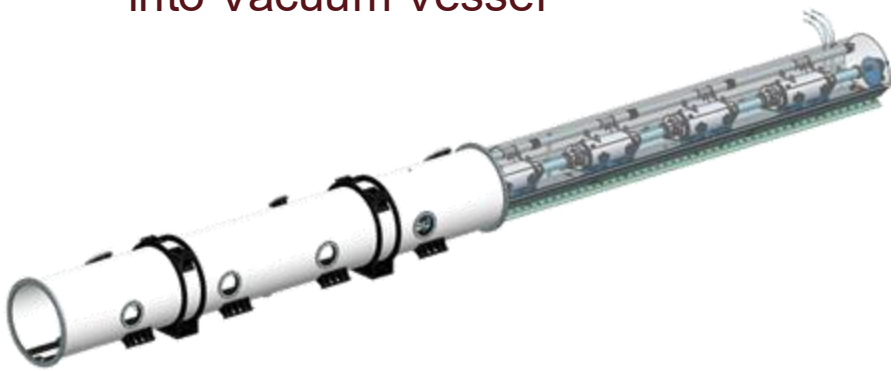
Phase 1c: Strongback and Beamline Merge



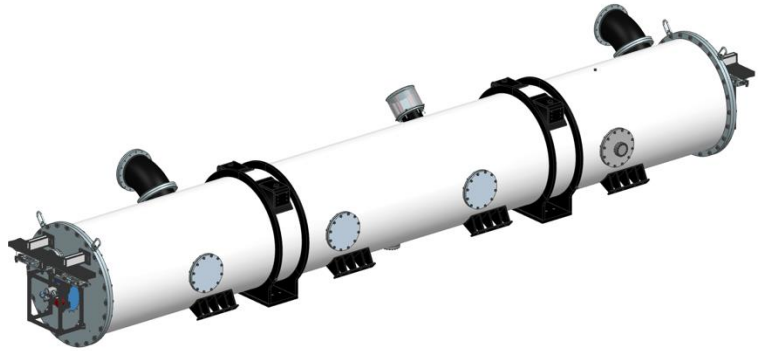
Phase 2: Coldmass Assembly



Phase 3: Insertion of Coldmass into Vacuum Vessel



Phase 4: Finalization and Quality controls



800 MHz SRF for FCC engineering next steps

- Need to establish pressure vessel code before engaging in any serious structural design (ASME code vs PED regulations)
- Determine need/feasibility of fast cooldown design
- Choose coupler cooling schemes - heatload management
- FNAL is writing preliminary technical specifications, RF, mechanical interfaces
- CERN fabricating 1-cell Nb cavities w/FNAL mechanical design
  - 1-cell program for developing and optimizing surface processing technique
- Full jacketed cavity mechanical design progressing

Summary

- FCC 800 MHz cavity performance goals are challenging but seem within reach of current advanced techniques
- 800 MHz SRF R&D program well underway at FNAL
  - 5-cell mid-t bake RF test planned/ 1-cell fabrication @ CERN
- 800 MHz CM design underway at FNAL+CERN
  - Active and fruitful collaboration ongoing
  - Funding support on US side remains a challenge, and timing is becoming critical
- FNAL currently writing preliminary technical specifications, RF, mechanical interfaces for CERN

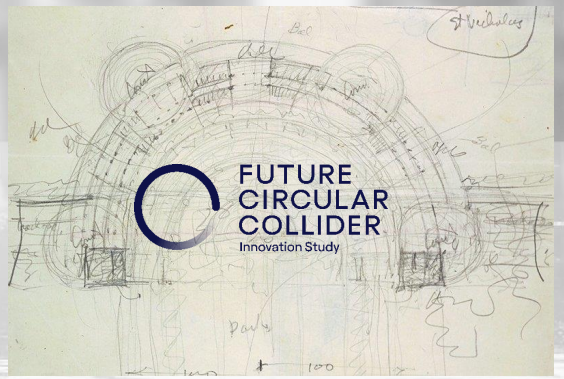
Thanks and credit to our CERN SRF R&D colleagues:

Vittorio Parma, Calum Sharp, Fabien Cottenot, Franck Peauger, Karin Canderan, Marc Timmins, Marco Garlasche, Sebastian Calvo, Shahnam Gorgi-Zadeh

Fermilab

FermiFORWARD

U.S. DEPARTMENT of ENERGY



MONONA TERRACE

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