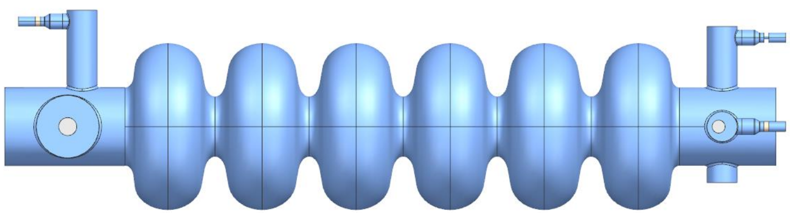
800 MHz SRF cavity and cryomodule developments at FNAL towards FCC

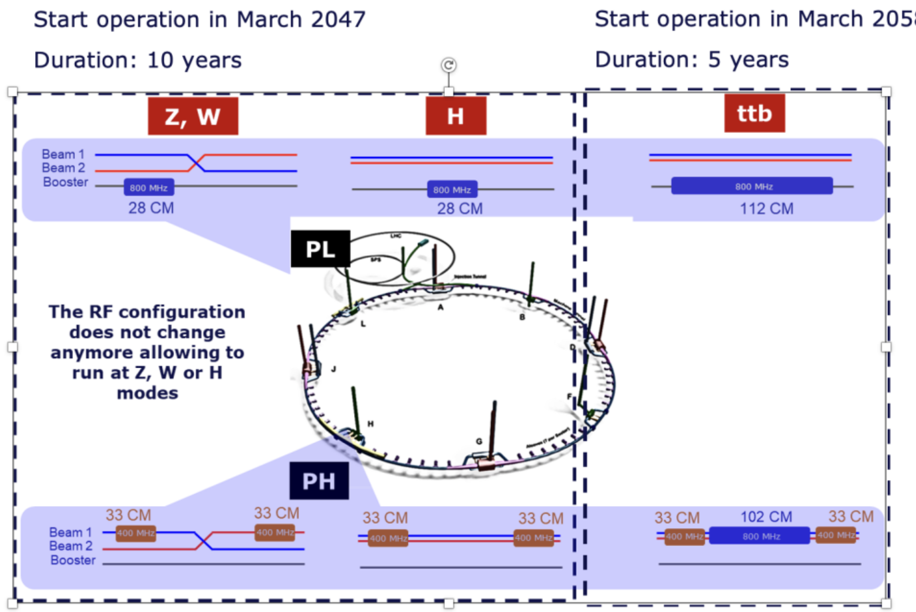
Kellen McGee, FNAL
21 May 2025
FCC week, Vienna

1. SRF Cavities and Surface processing

800 MHz SRF for FCC-ee

- 800 MHz, 6-cell cavity
  - Op: E_{acc} = 20 MV/m, Q0 = 3e10
  - VT: E_{acc} = 24.5 MV/m, Q0 = 3.8e10
- Bulk Nb: EP+Mid T?





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]	[illegible]		[illegible]
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

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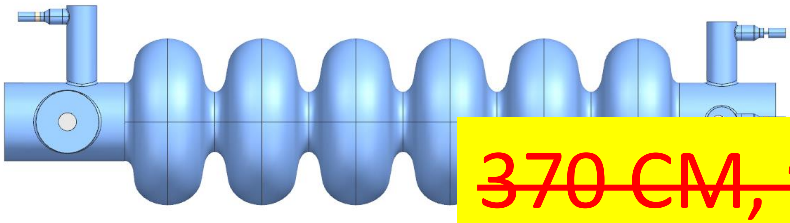

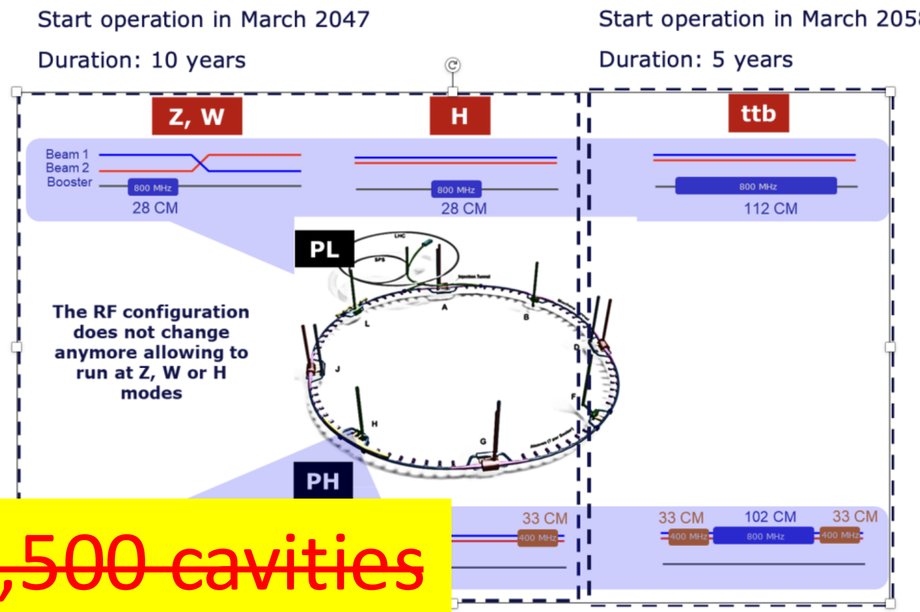

~~370 CM, ~1,500 cavities~~

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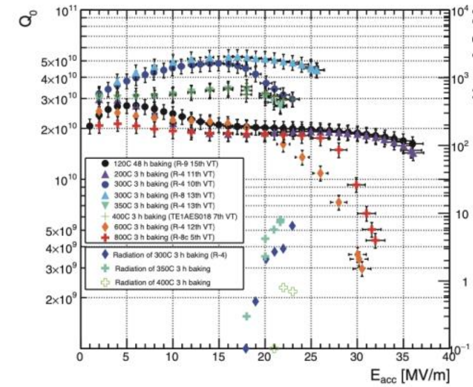
How to reach High Q?



- Furnace/medium temperature bake[2,3,4]
  - Simpler method: no N-profusion, no post-EP
  - Oxygen diffusion can reproduce effects of N-doping at 1.3 GHz

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

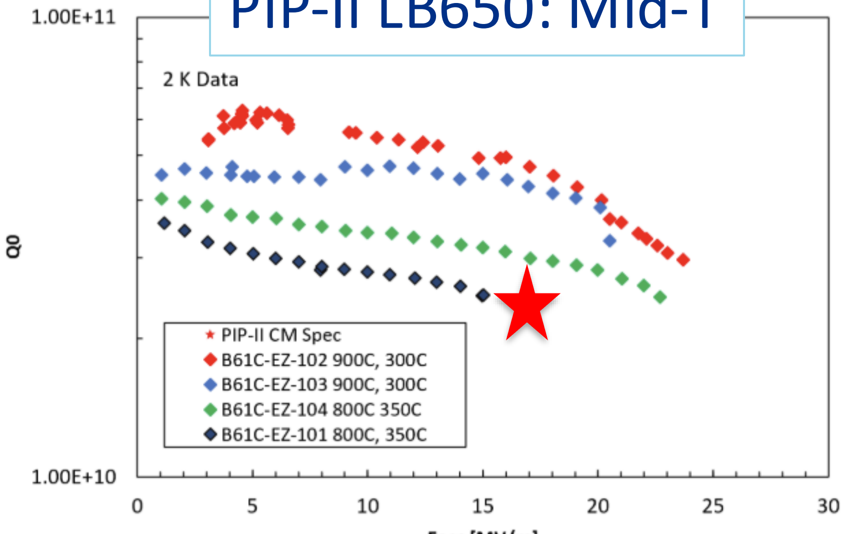
- N-doping[1]
  - 2012-13 FNAL: doubled Q, reversed R_{BCS} dependence on E_{acc}
  - Industrialized at 1.3 GHz and used to deliver LCLS-II

“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.

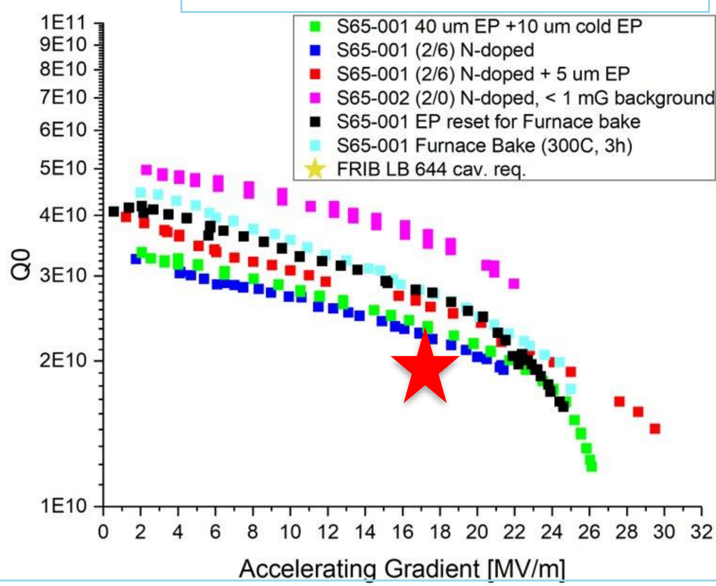
[1] A. Grassellino et al, *Supercond. Sci. Technol*. **26**, 102001 (2013).
[2] H. Ito, et al., *Prog of Theor. and Exp. Phys.*, Volume 2021, Issue 7, July 2021
[3] E.M. Lechner, et al., *Appl. Phys. Lett.* ***119,*** 082601 (2021). [4] D. Bafia, TU1A, LINAC’22

Multicell production cavities

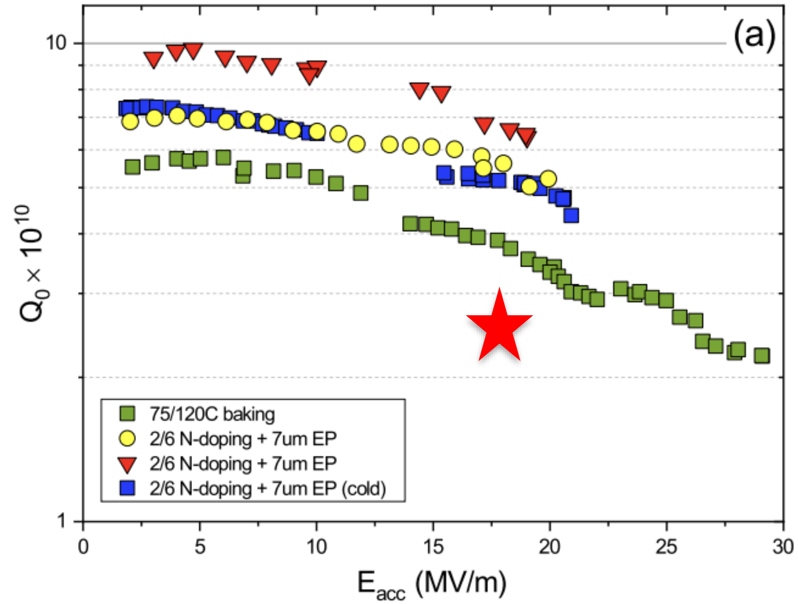
PIP-II LB650: Mid-T

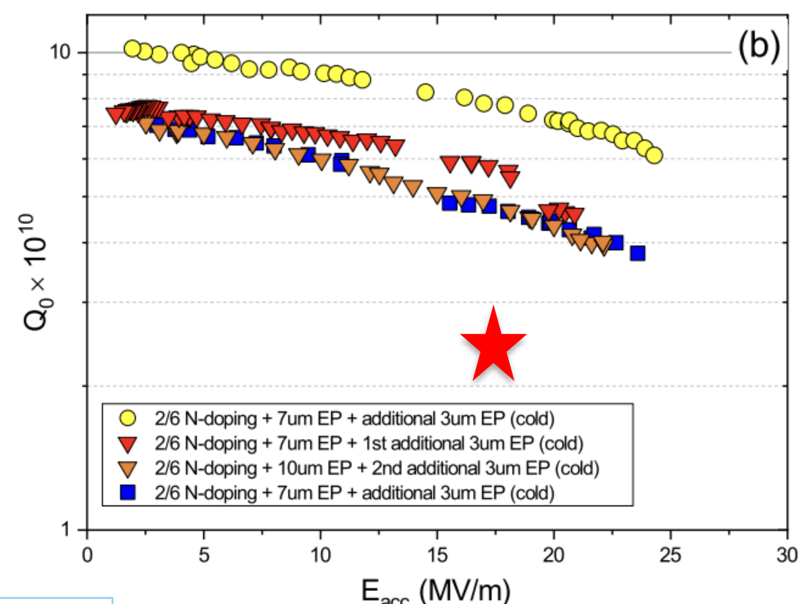


FRIB 644 MHz: various



PIP-II HB650: N-doping





Note: ESS cavities (704 MHz) are off-scale @ 5e9

Multicell production cavities

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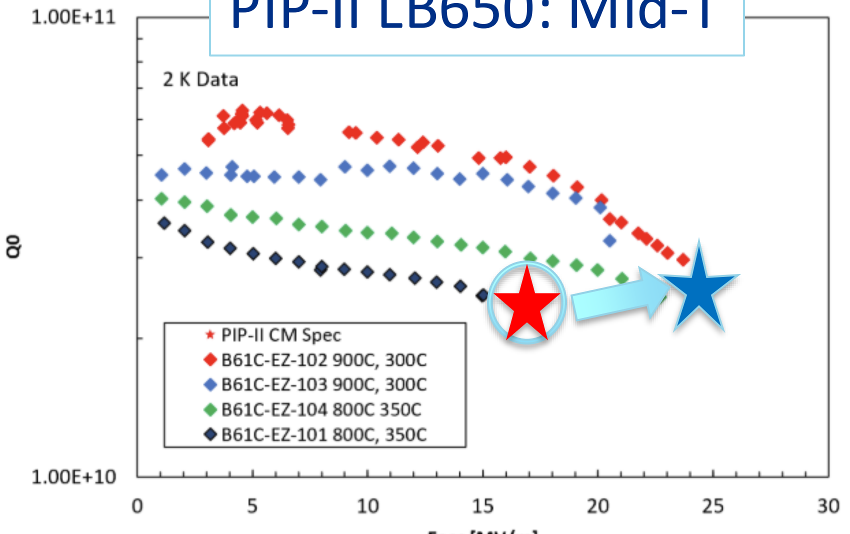
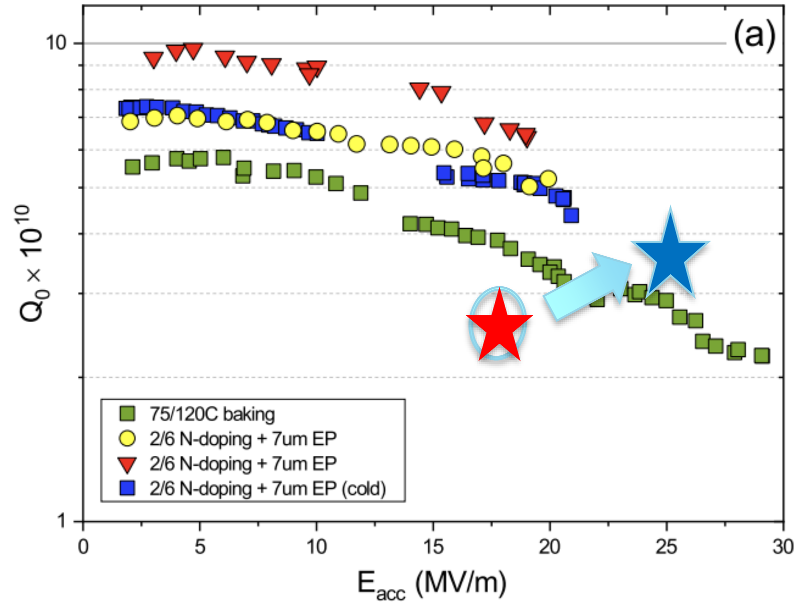
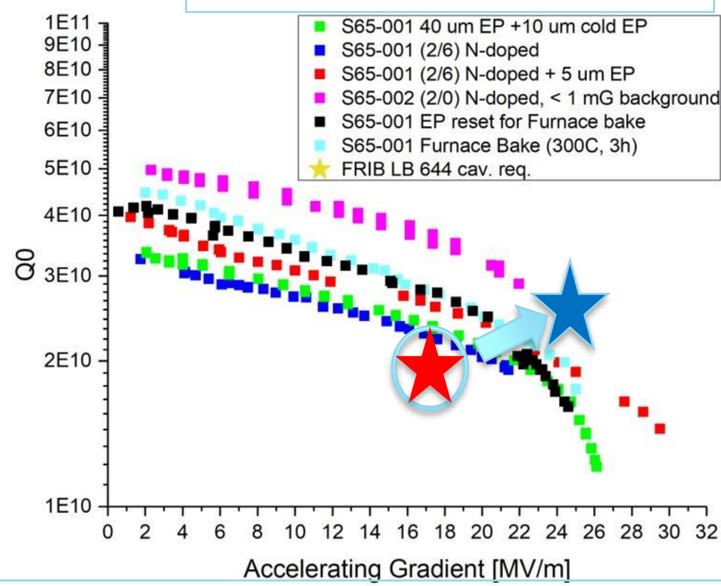
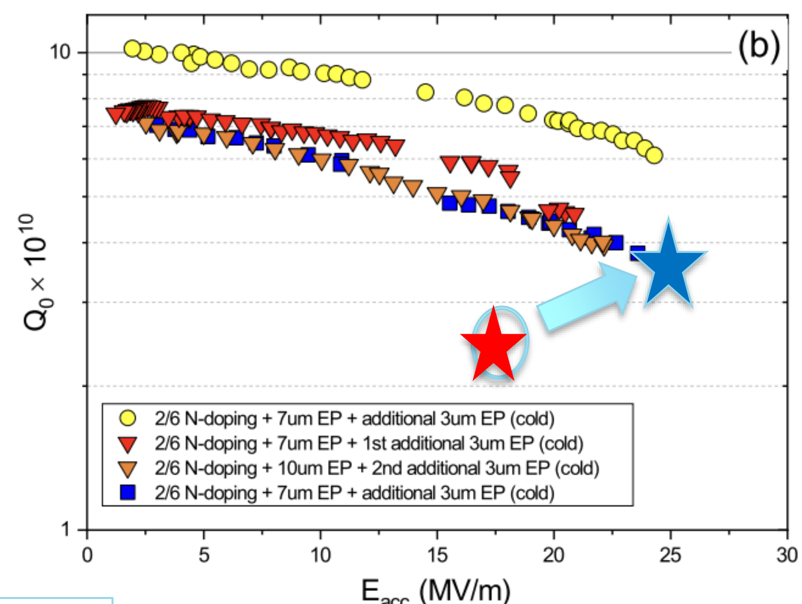


PIP-II HB650: N-doping



FRIB 644 MHz: various





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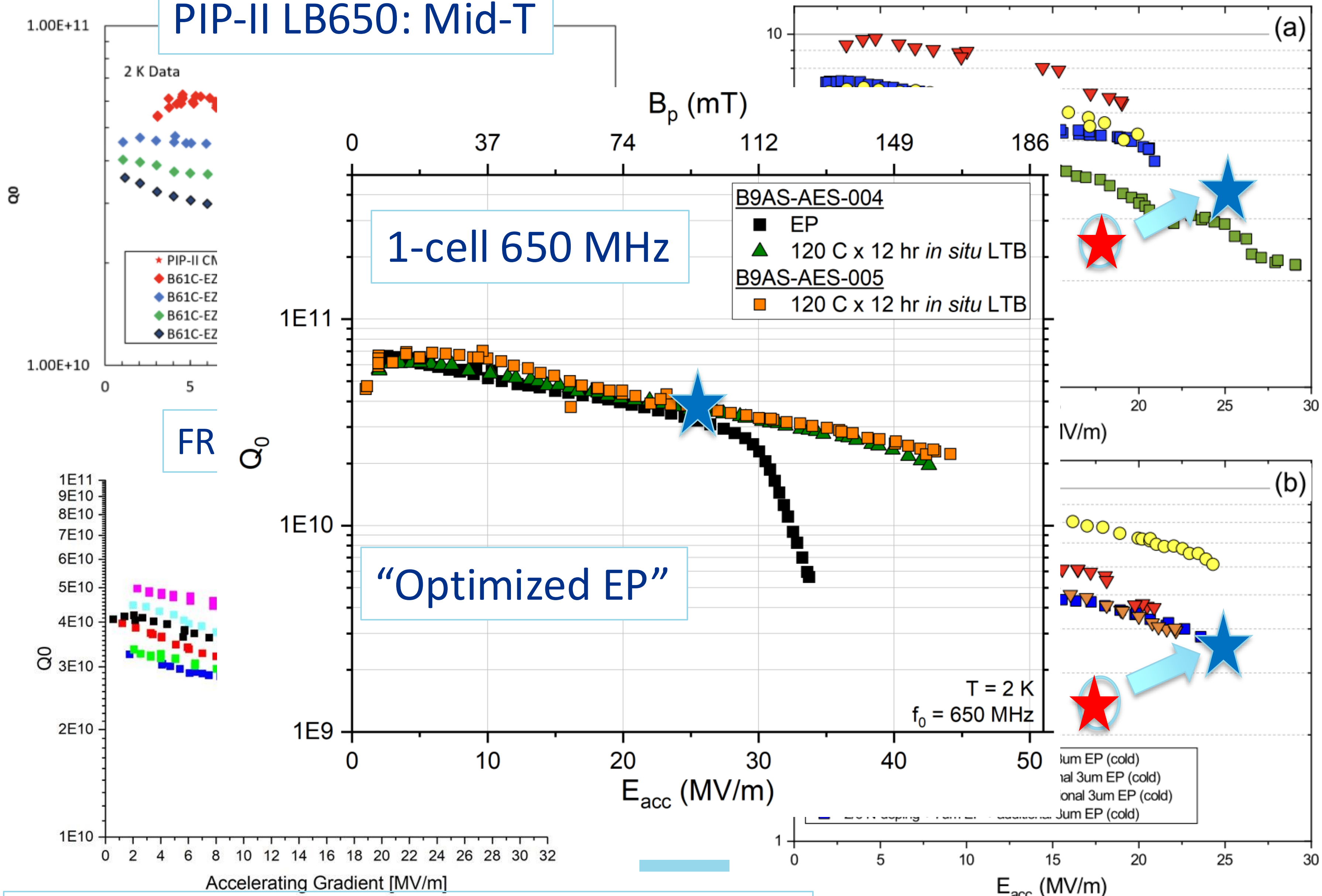
Multicell production cavities

PIP-II HB650: N-doping

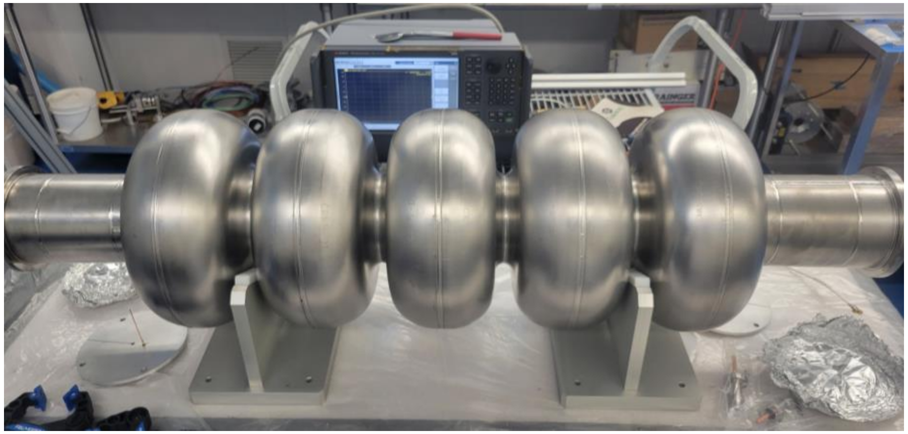
PIP-II LB650: Mid-T



Note: ESS cavities (704 MHz) are off-scale @ 5e9

800 MHz 5-cell 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 **underway!**
  - N-doping?
  - Nb3Sn (future)



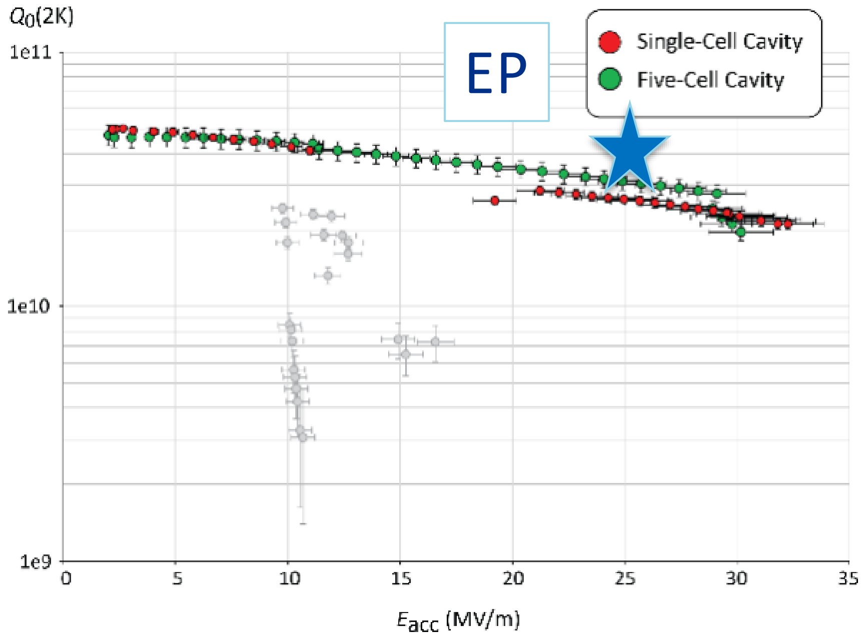
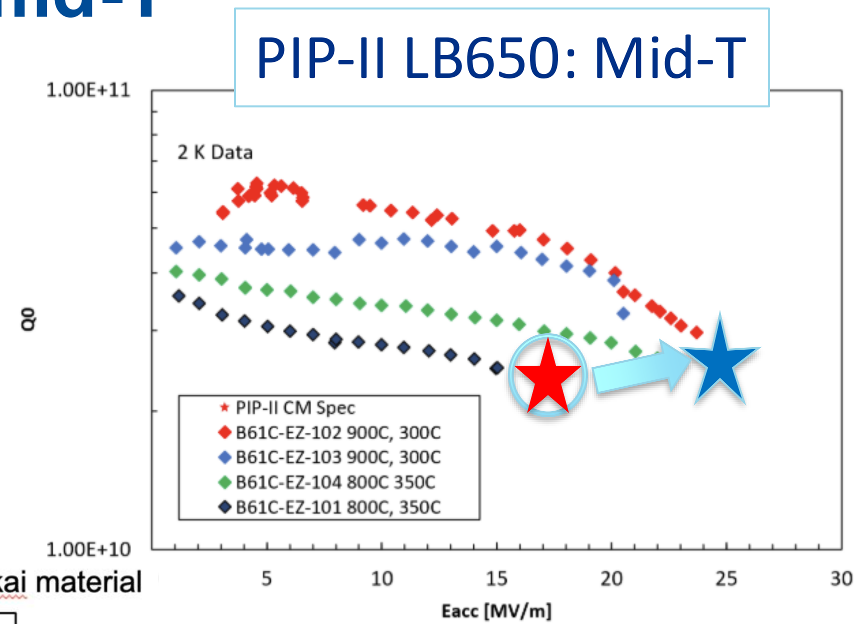


Figure 4: Combined VTA results for the five-cell and single-cell cavity as measured at 2 Kelvin.

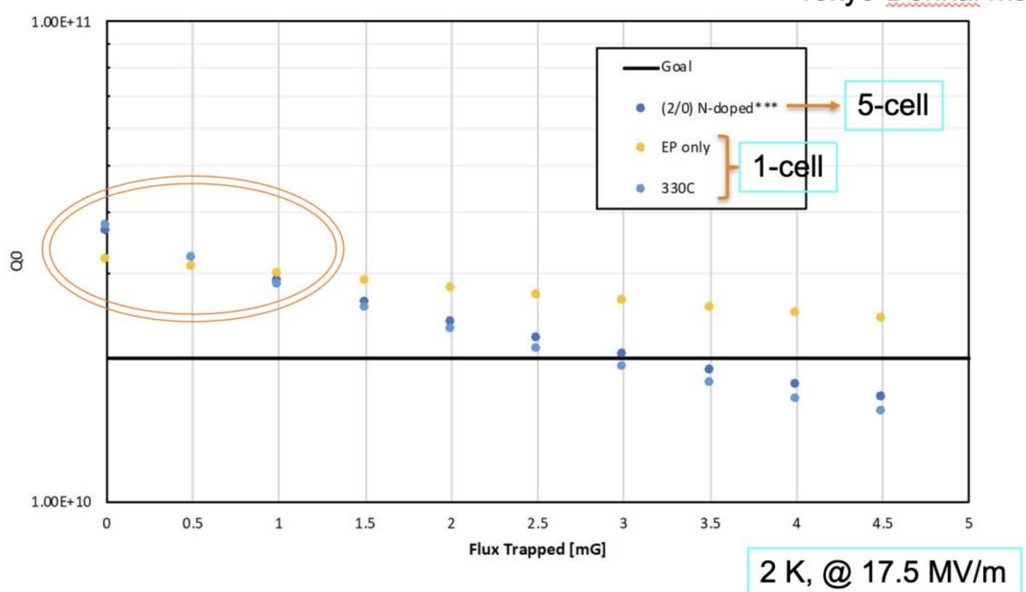
F. Marhauser et al. 802 MHz ERL Cavity Design and Development (cern.ch) *IPAC 2018* THPAL146

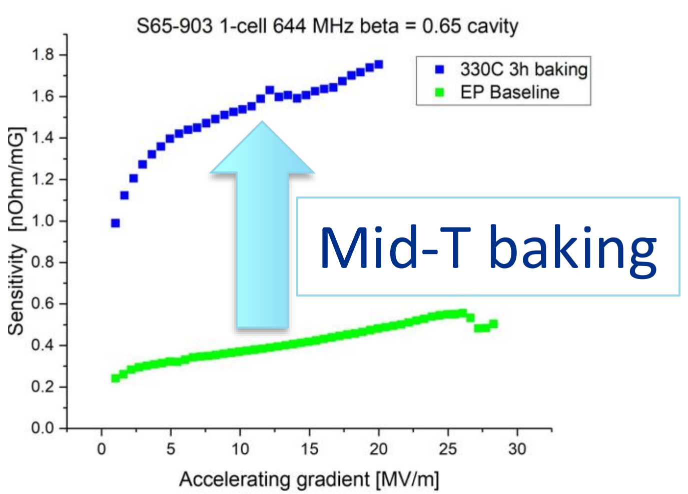
Production challenges for mid-T

- Flux trapping degrades Q!
  - Varies within Nb batches
  - Highly correlated with Nb texture: vendor oven temp uniformity?



*Tokyo-Denkai material





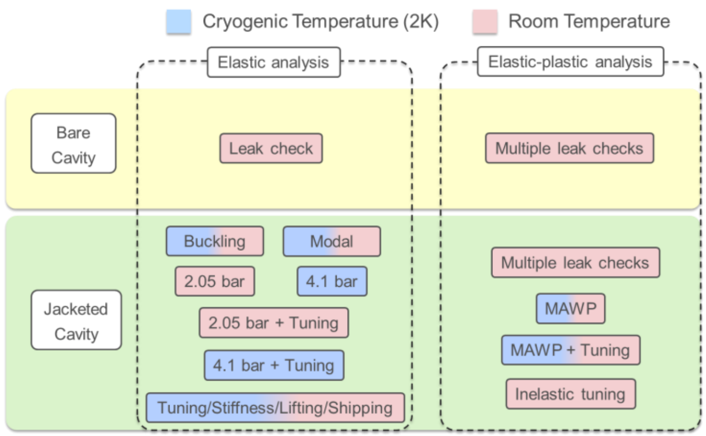
2. Mechanical Design & Analysis of Cavities and Cryomodules

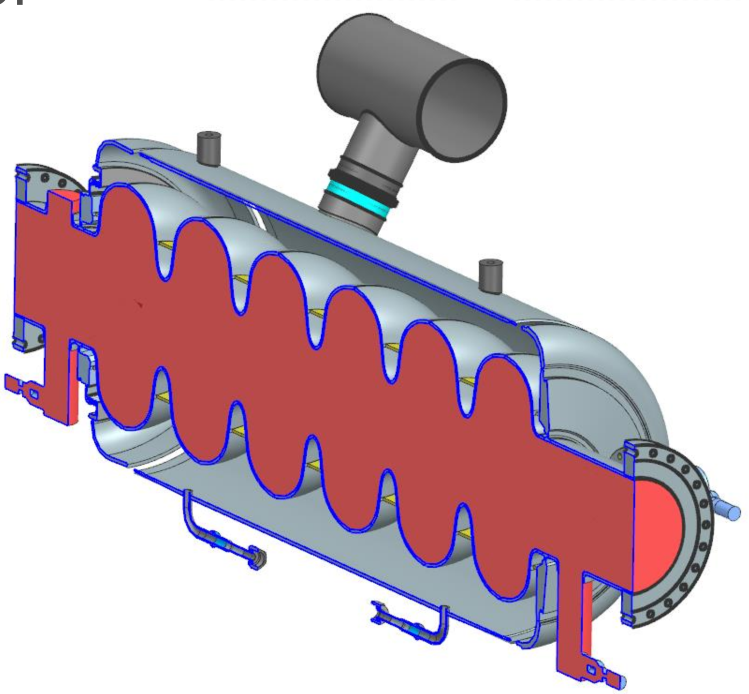
3D model and planned analysis – FNAL

M. Parise

- 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

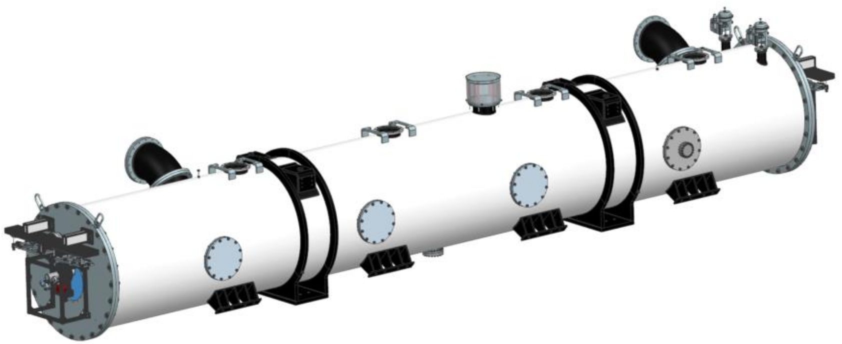
- Additional analysis, specific to SRF cavities, are carried out to check tunability and structural stability during leak checks.



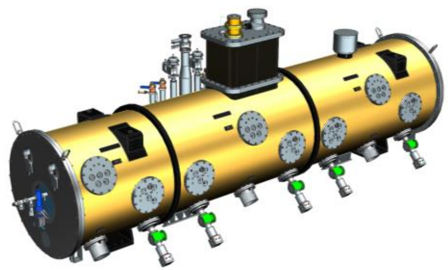


Preliminary design of FCC 800MHz Cryomodule

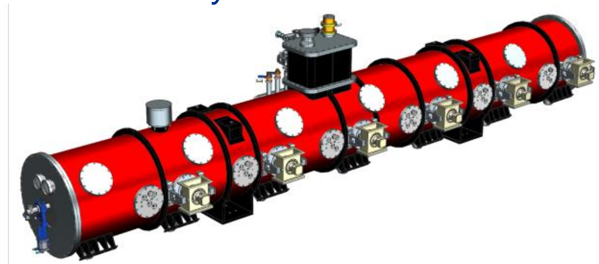
- The FCC 800 MHz CM design is based on SSR2 and HB650 PIP-II CMs with the following main differences:
  - Heat exchangers and valves are integrated into the Cryogenic Distribution System (CDS).
  - A “Jumper” will be used to interface with CDS through welded connection into the tunnel (no u-tubes).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



FCC 800 MHz cryomodule



PIP-II SSR2 cryomodule



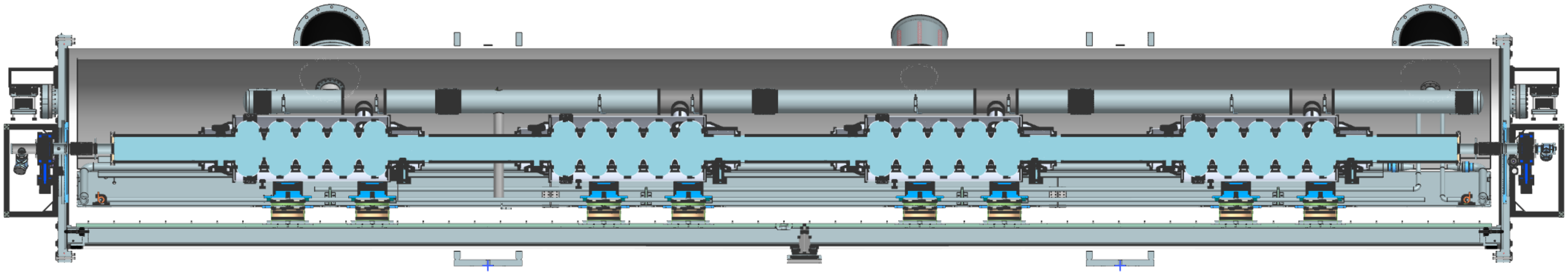
PIP-II HB650 cryomodule

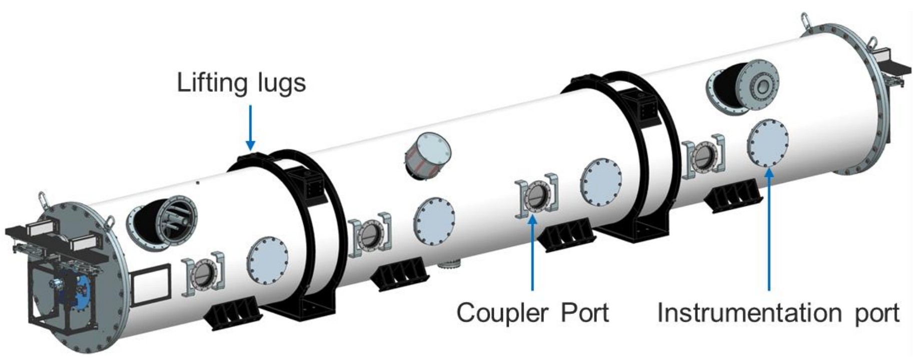
“Final Design of the Pre-Production SSR2 Cryomodule for PIP-II Project at Fermilab”, V. Roger et al., Proceedings of LINAC 2022

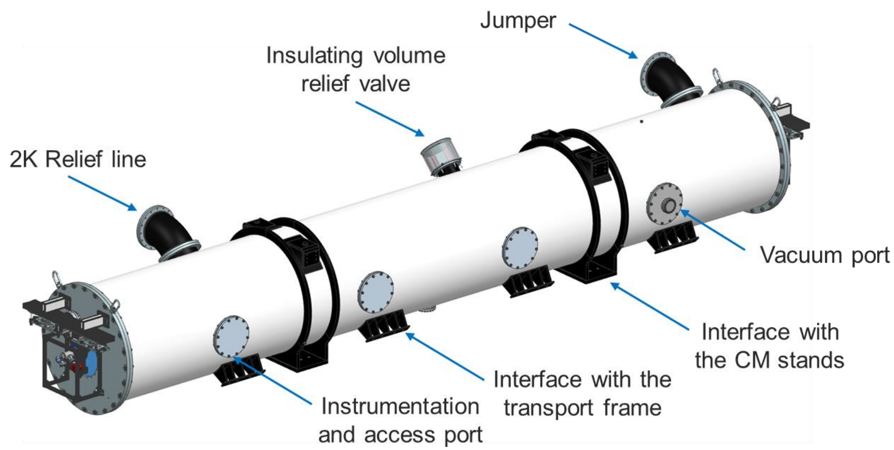
“Design of the 650 MHz High Beta Prototype Cryomodule for PIP-II at Fermilab”, V. Roger et al., Proceedings of SRF 2021

Preliminary design of FCC 800MHz Cryomodule

- The <u>fine segmentation</u> 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.

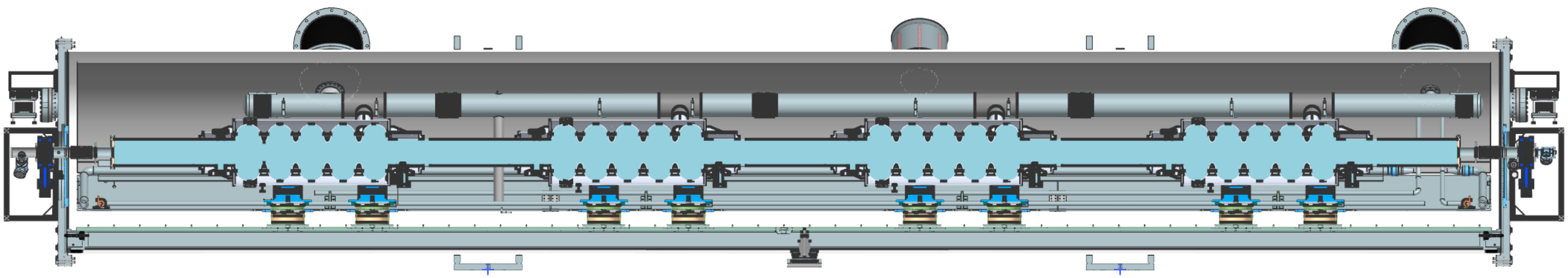


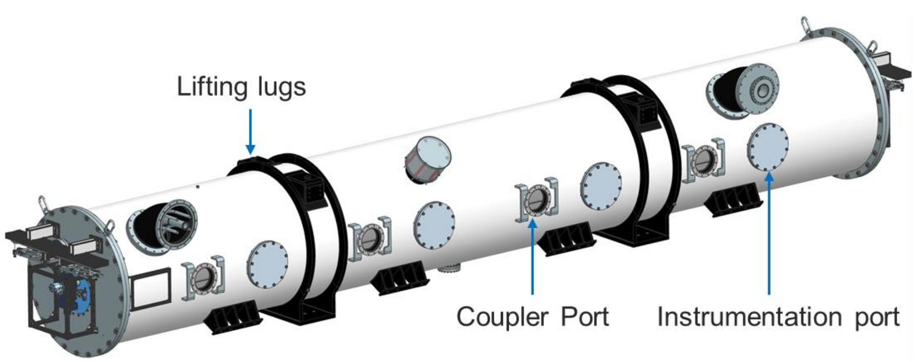


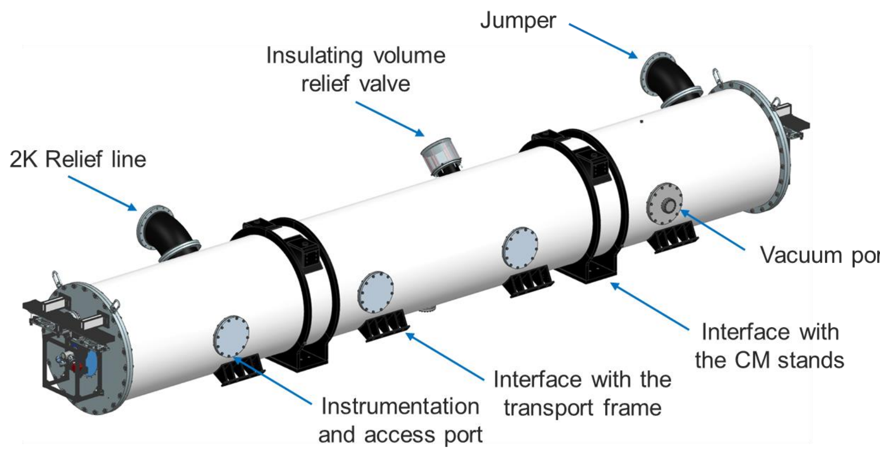


Preliminary design of FCC 800MHz Cryomodule

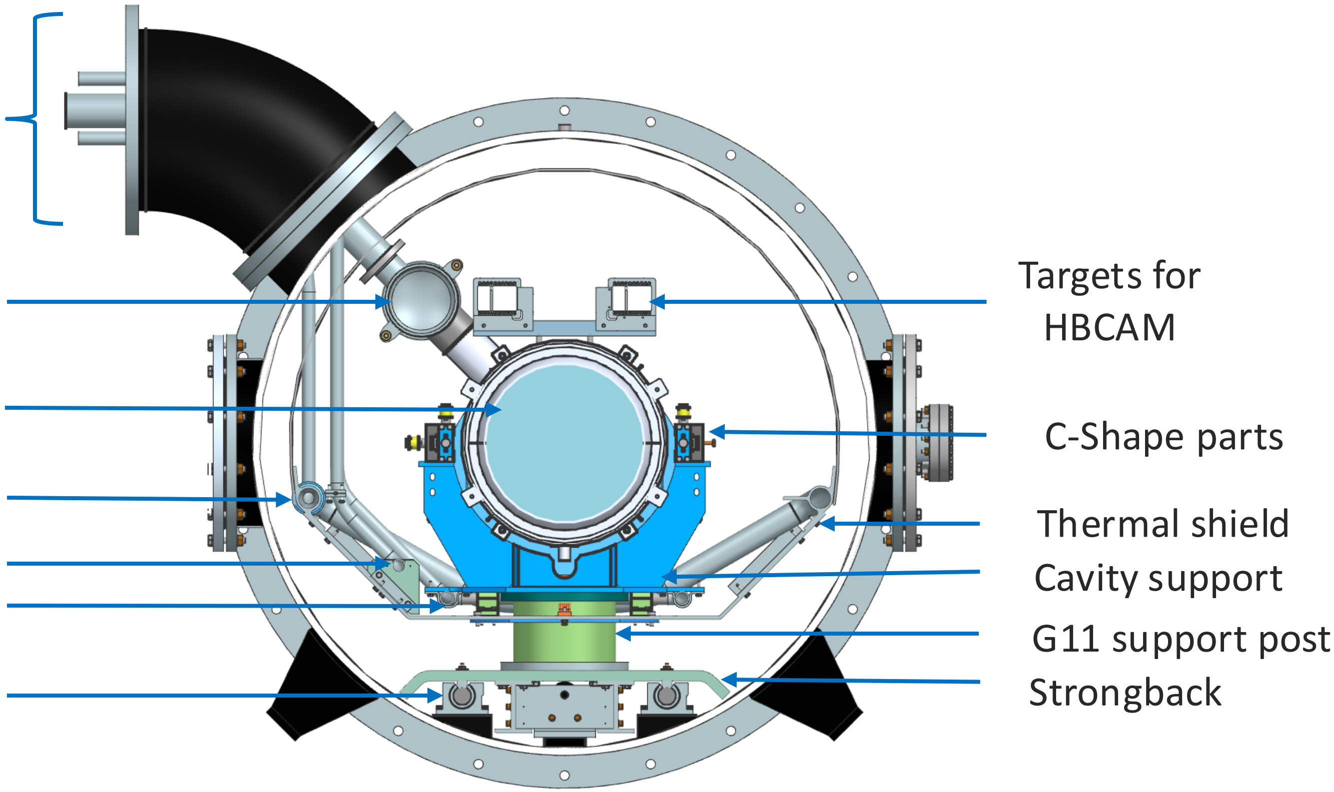
- Through collaborative efforts with CERN, this design aligns with the functional, technical and interface requirements.
  - Fits within the dimensional envelopes for the two different locations in the accelerator: collider and booster





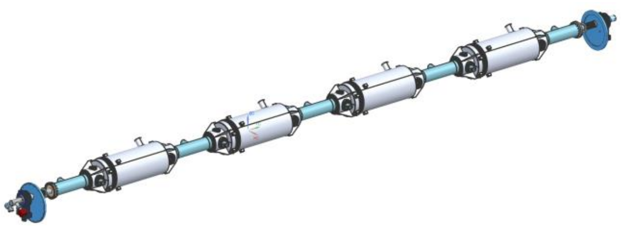


Preliminary design of FCC 800MHz Cryomodule - Cross section

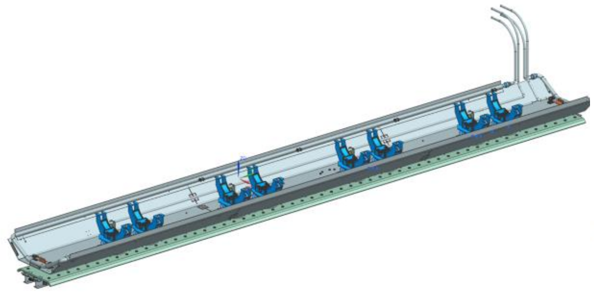


FCC 800MHz cryomodule assembly phases

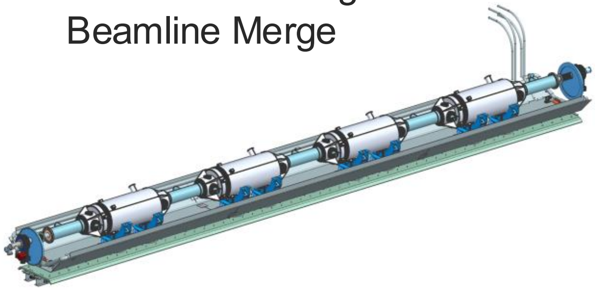
Phase 1a: Beamline assembly in the cleanroom



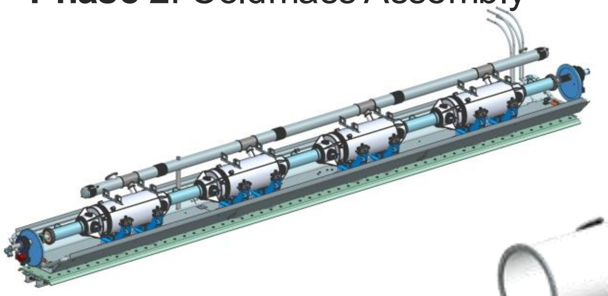
Phase 1b: Strongback Assembly



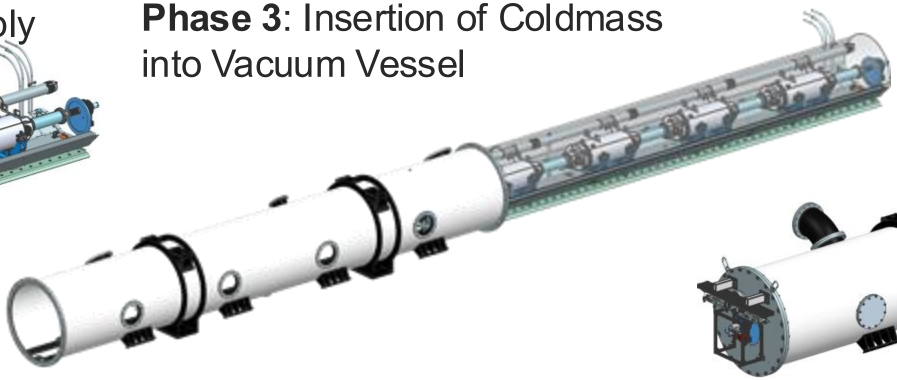
Phase 1c: Strongback and Beamline Merge



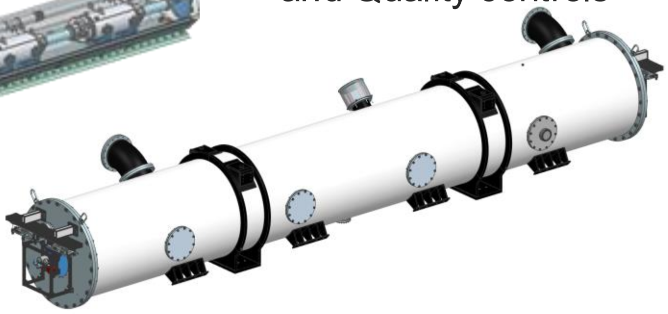
Phase 2: Coldmass Assembly



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

Summary

- FCC 800 MHz cavity performance goals are challenging but seem within reach of current advanced techniques
- 800 MHz 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, but funding support on US side remains a challenge
- FNAL currently writing preliminary technical specifications, RF, mechanical interfaces for CERN

Thanks and credit to CERN colleagues:

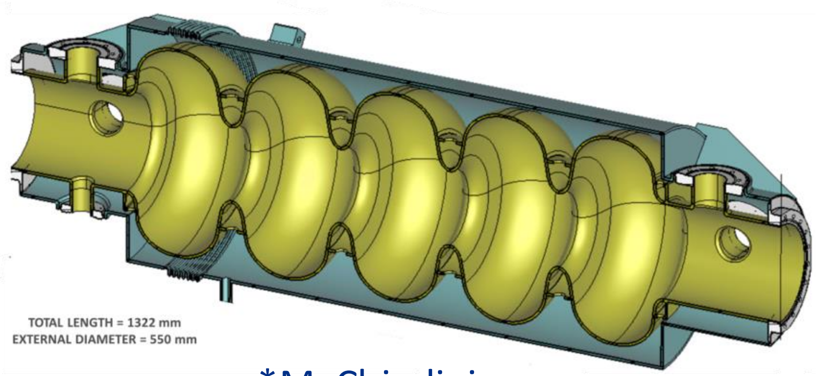
Vittorio Parma, Calum Sharp, Fabien Cottenot, Franck Peauger, Karin Canderan, Marc Timmins, Marco Garlasche, Sebastian Calvo, Shahnam Gorgi-Zadeh

Questions?

Backup

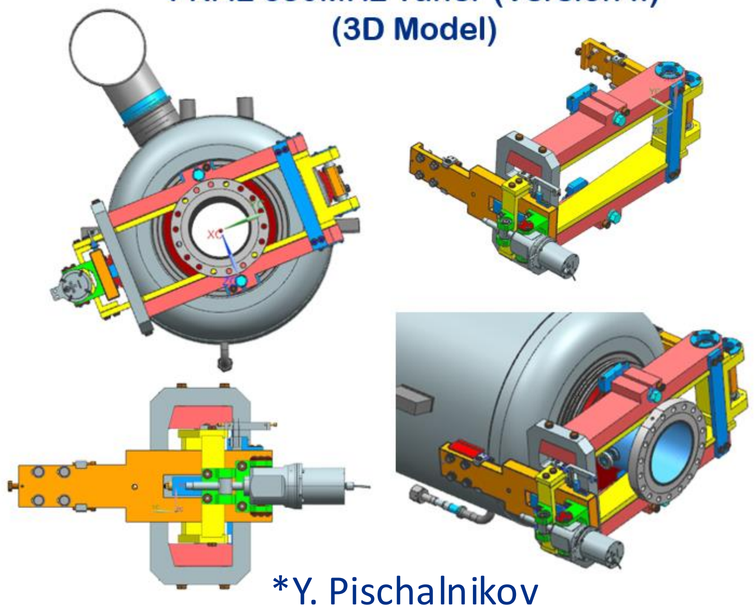
Integrated jacketed cavity + tuner design

- Initial design proposed by CERN
- FNAL contributing based on PIP-II,LCLS-II
- Tuner design to be based on modified FNAL 650 MHz double-lever tuner
  - FNAL has unique experience manufacturing/QA testing these in production quantities



*M. Chiodini

FNAL 650MHz Tuner (Version II)
(3D Model)



*Y. Pischalnikov