Development and Performance of Spoke Resonators for Project X

* Attention, this is a model, we did not cut a real cavity

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on behalf of the

Fermilab SRF Development Group

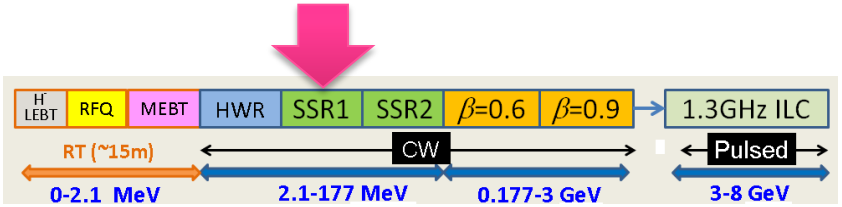
Outline

- Spoke Cryomodules in Project X
- SSR1-SSR2 Cavity Design
- Cavity Fabrication
- Processing
- VTS Qualification
- Jacketing
- Tuner

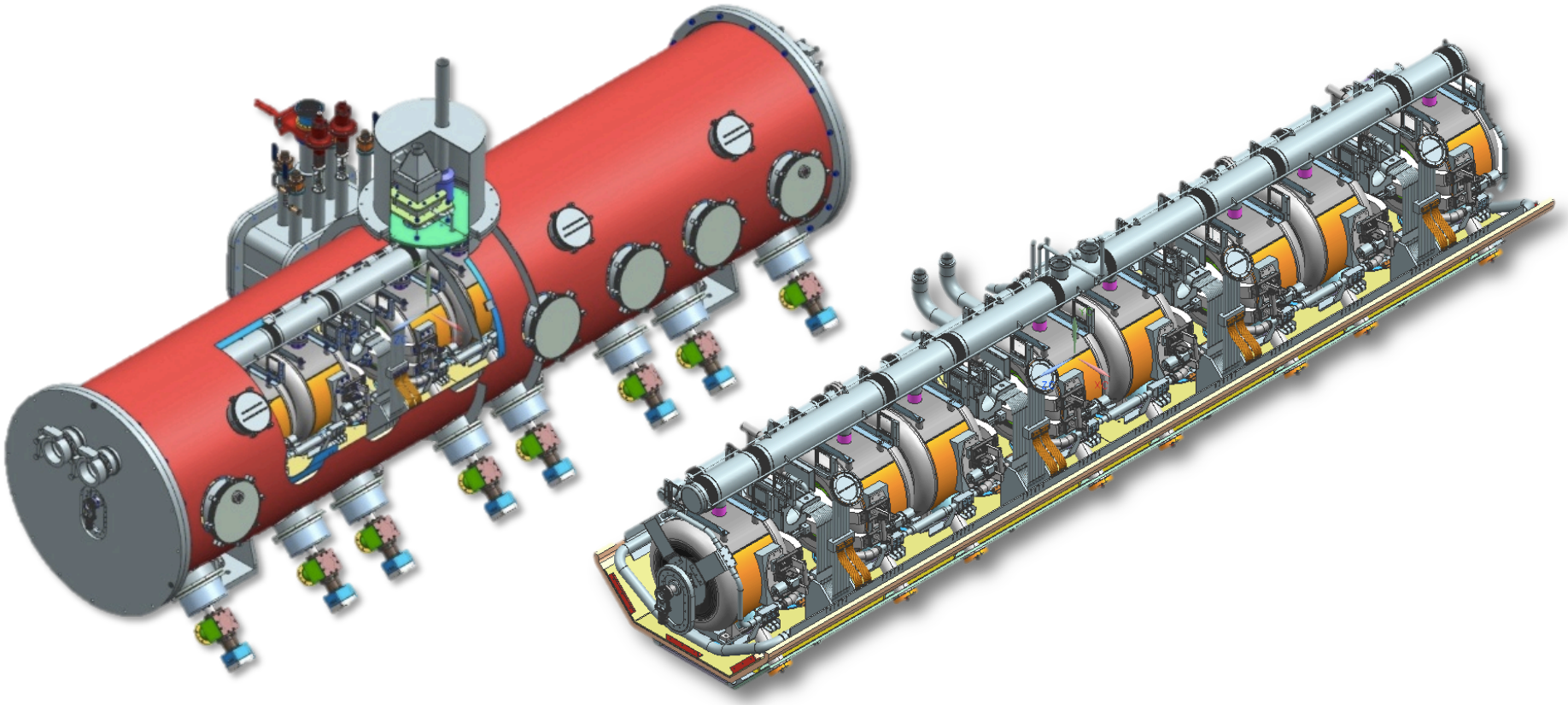
The first production SSR1

The first jacketed SSR1

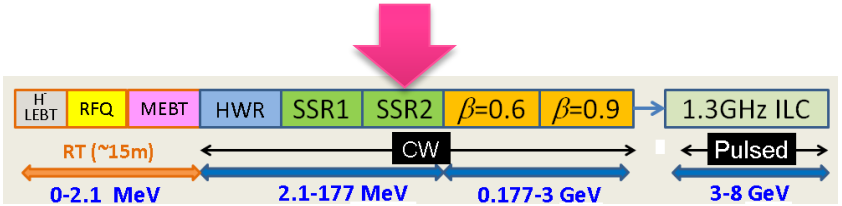
SSR1 Cryomodules



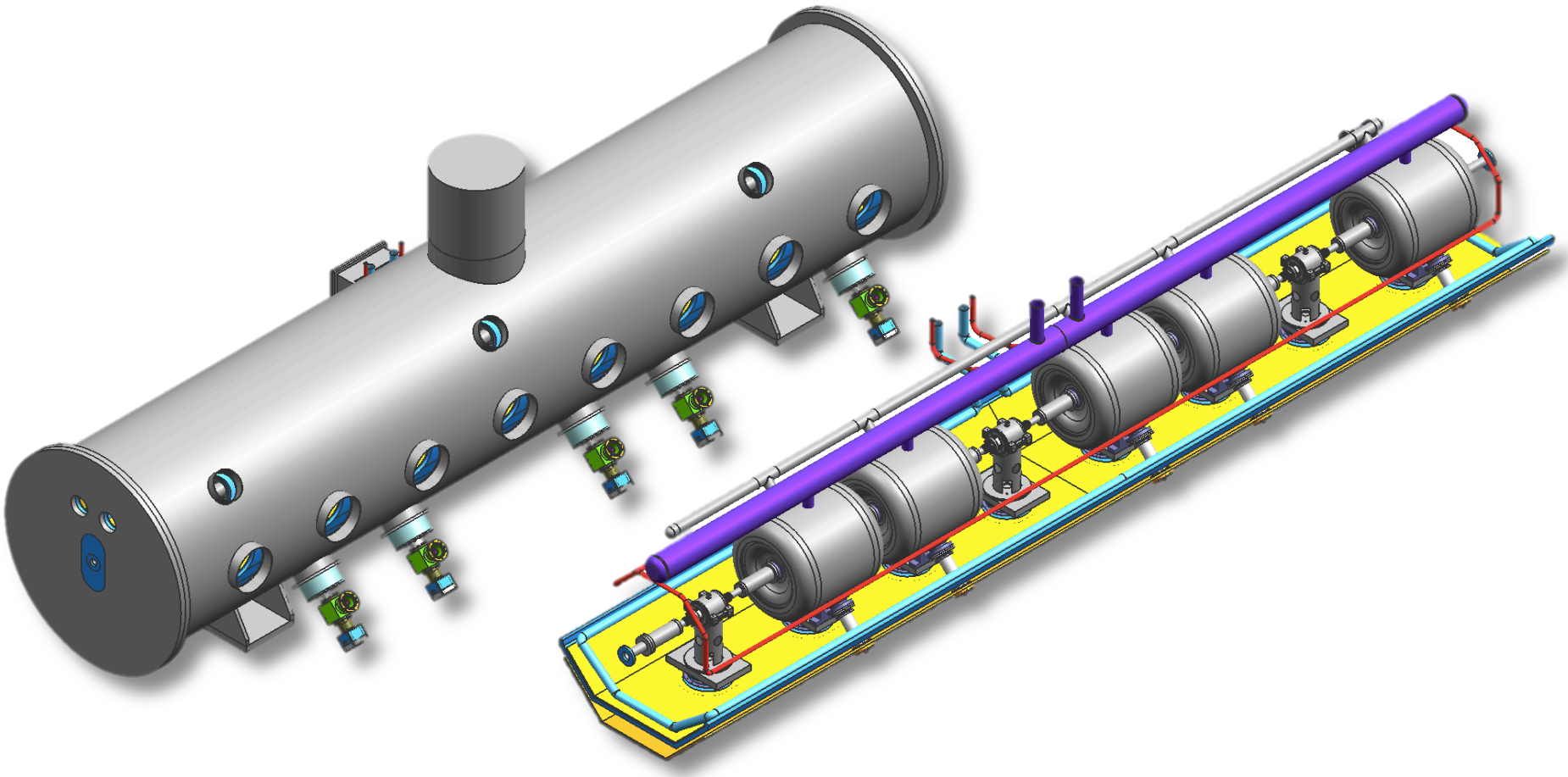
SSR1
2 CMs – 5.2 m
8 Cav/ea



SSR2 cryomodules

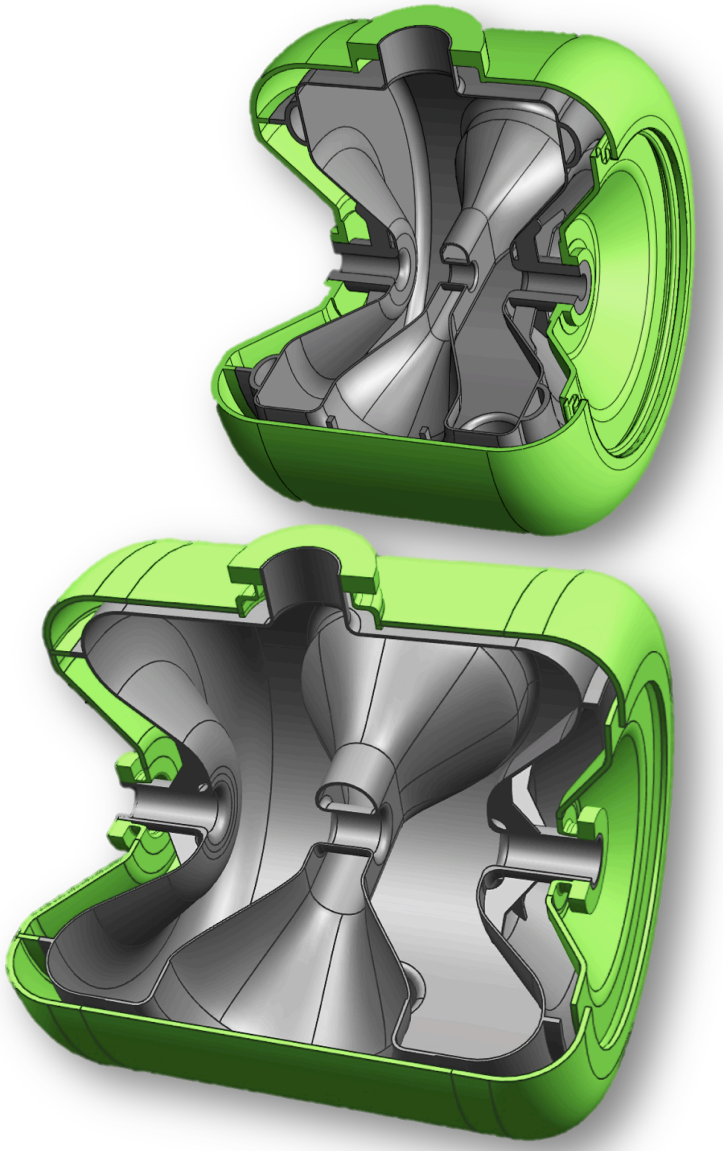


SSR2
7 CMs – 6.5 m
5 Cav/ea

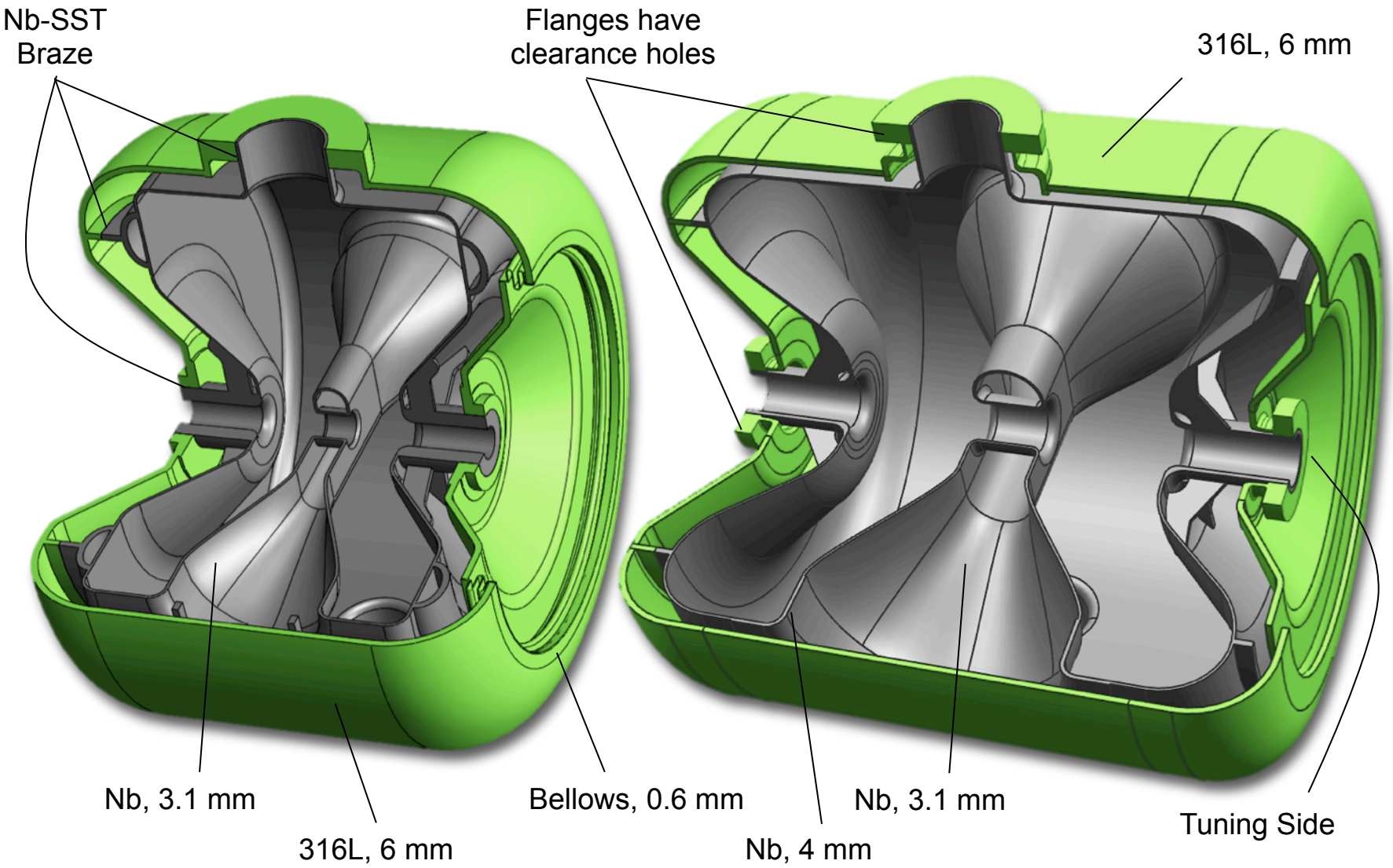


SSR1 and SSR2

	SSR1	SSR2
β	0.222	0.515
E_p/E_{acc}	3.84	3.53
B_p/E_{acc}	5.81 mT/(MV/m)	6.25 mT/(MV/m)
Aperture	30 mm	50 mm
Diameter	492 mm	560.8 mm
L_{EFF} (βλ)	205 mm	475 mm
G	84 Ω	118 Ω
R/Q	242 Ω	275 Ω
Oper. Gradient	12 MV/m	11.2 MV/m
Q_0 at E_{acc}	> 0.5 10^{10}	> 1.2 10^{10}
Operating B_{MAX}	70 mT	70 mT
Operating E_{MAX}	46 MV/m	40 MV/m
Tuning constant	40 N/kHz	90 N/kHz
Sensitivity	< 25 Hz/torr	< 25 Hz/torr
P (RT, CT)	2 bar, 4 bar	2 bar, 4 bar

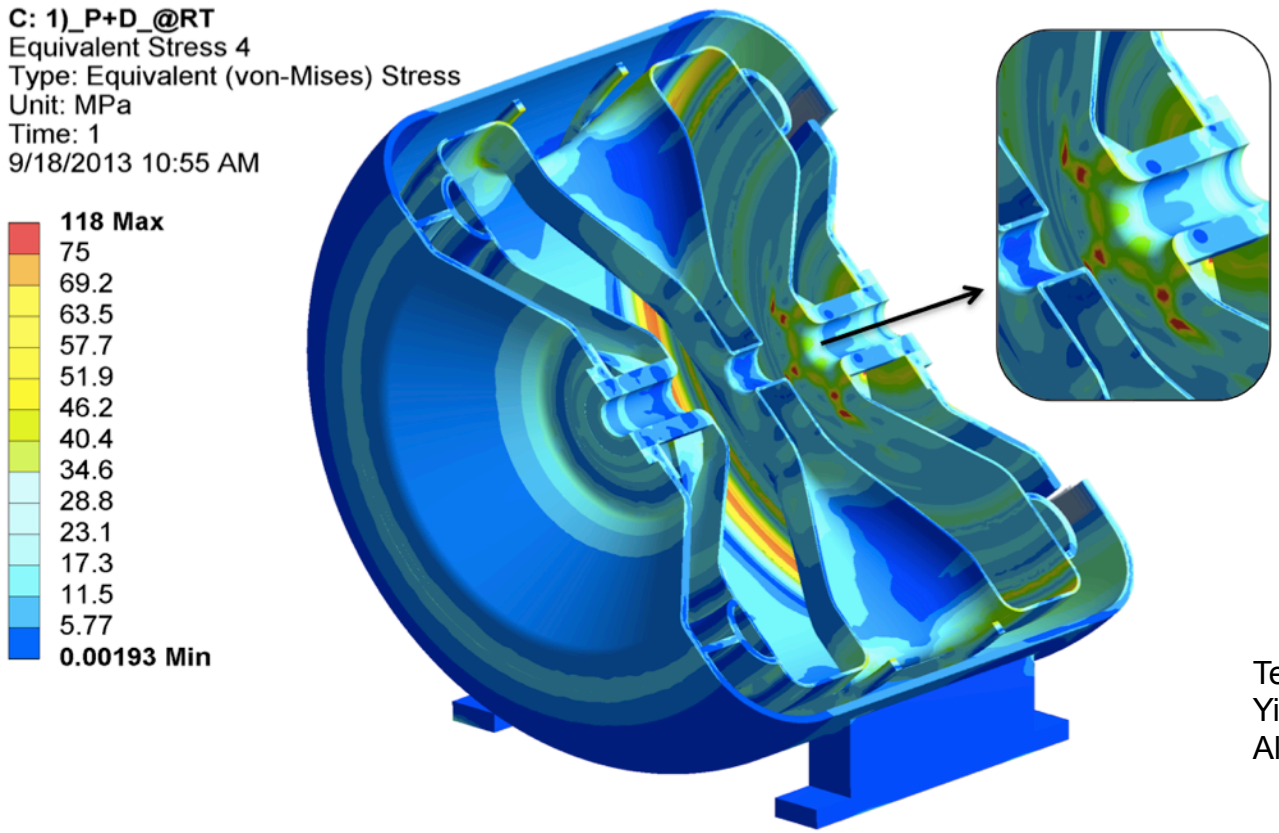


SSR1 and SSR2 – a closer look..



Pressure Safety

- We designed spoke resonators to reach 2 bar (RT) and 4 bar (CT) meeting applicable US safety codes, ASME, B&PV, for complex shapes extensive FEA necessary
- Von Mises stresses may appear higher than yield in certain locations (see image), don't be scared, depending on the specific case, it may be OK!



Tensile tests on Nb batch
Yield limit 75 MPa
Allowable 47 MPa

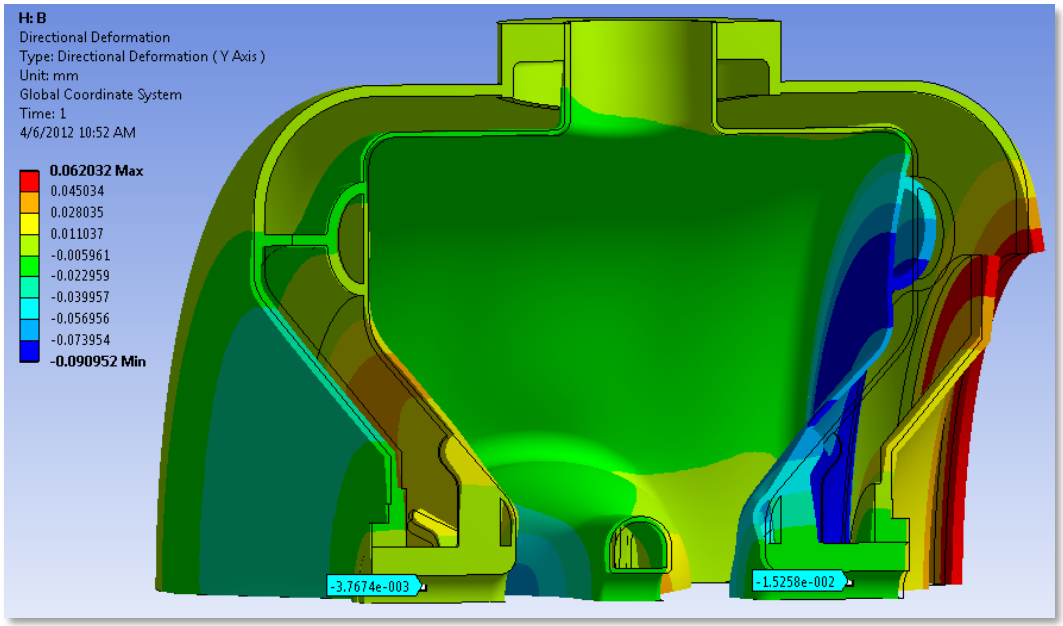
Reduction of Pressure Sensitivity

It is possible to reduce sensitivity without increasing rigidity

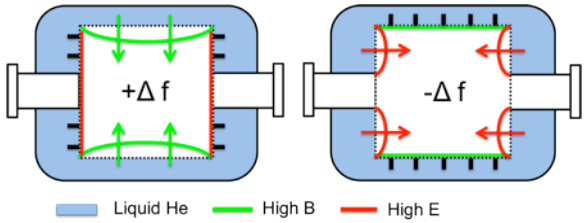
Bare cavity, free interfaces, df/dp ~ 600 Hz/torr (sim & meas)

Jacketed cavity, free interfaces df/dp ~ 0 Hz/torr (sim), ~ 10 Hz/torr (meas)

Ease of tuning 39 N/kHz (bare), 40 N/kHz (jacketed)



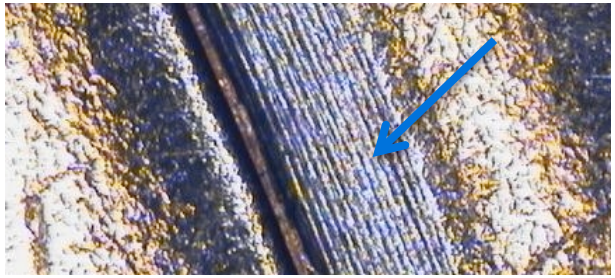
- Deformations with 1 atm pressure: 90 microns on cavity
- Beam pipes are free, but move only few microns
- Bellows diameter optimized



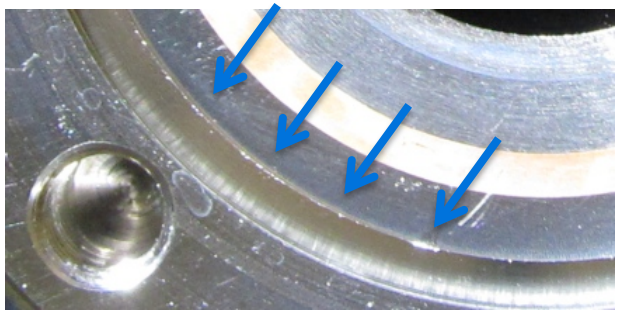
- Deformations in high E and B regions balance out resulting in a small frequency shift (Slater's Theorem)

From ConFlats to Aluminum Seals

- Sealing unreliable/non-repeatable
  - 100% leak tight during incoming QC using regular Ag-coated screws
  - Success rate 75% per flange (~ 30%) using clean Si-Bronze screws
- Machining/damaging
  - Inaccurate machining of sealing surfaces, high roughness (see photo)
  - Flanges are machined and welded to cavity in early stages of fabrication, prone to damaging (see photo)
- Generators of Cu-particulates
  - Sharp (and rough) knife edge able to detach copper particulates from gasket when disassembled, unacceptable for SRF applications
- Switch to DESY-Tesla Aluminum Seals
  - flanges of existing cavities will be reworked, conflats will not be used anymore in SRF applications, custom-machining of conflats will be avoided in all applications



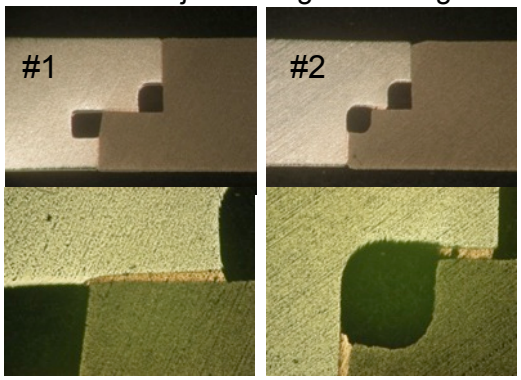
Magnification of a copper gasket after disassembly. The imprint left by the knife edge shows rough machining grooves.

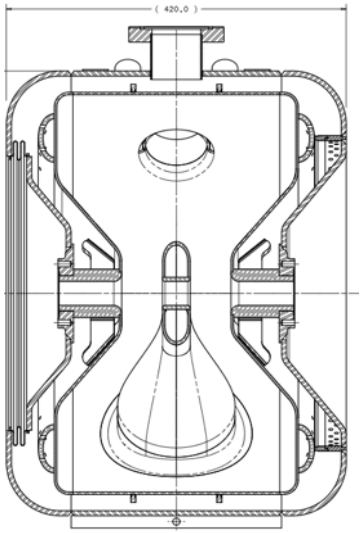


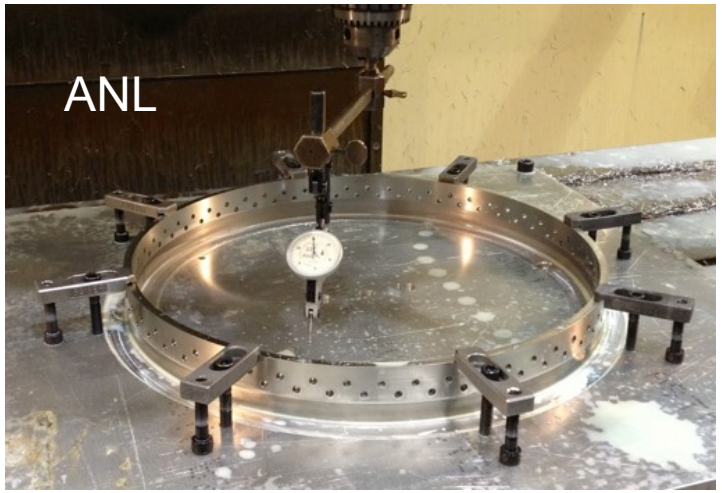
Magnification of a knife edge showing extensive damage

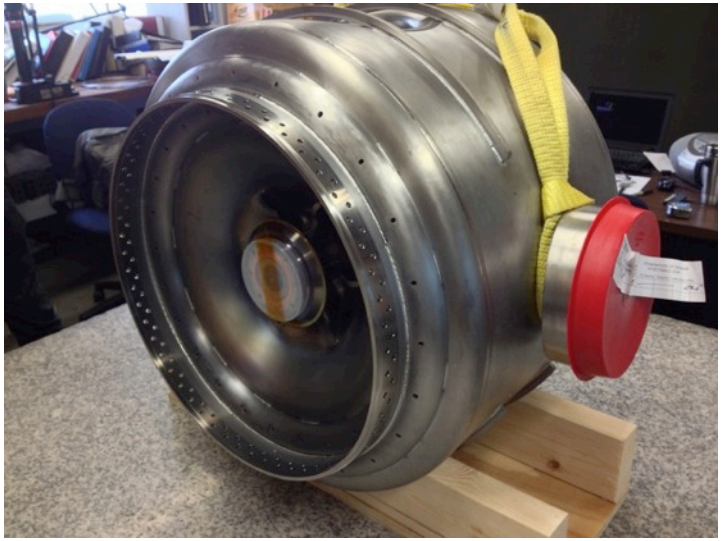
Brazed transition rings

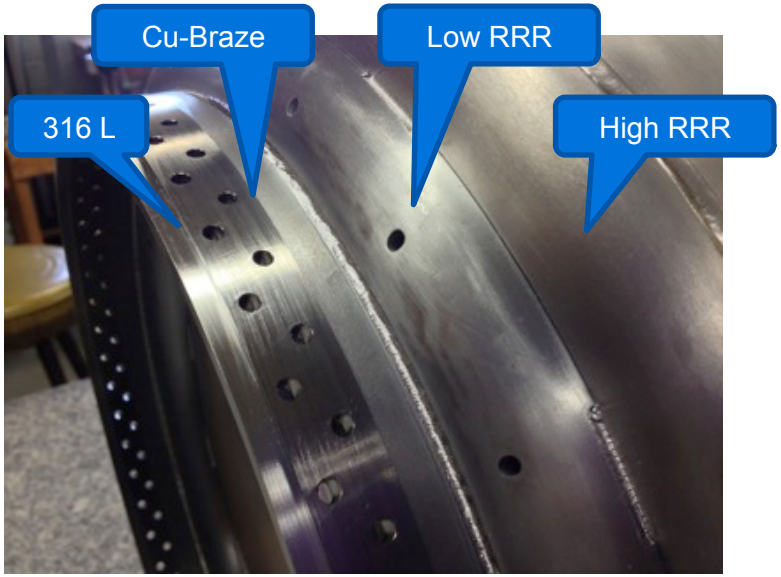
Two different joint designs investigated







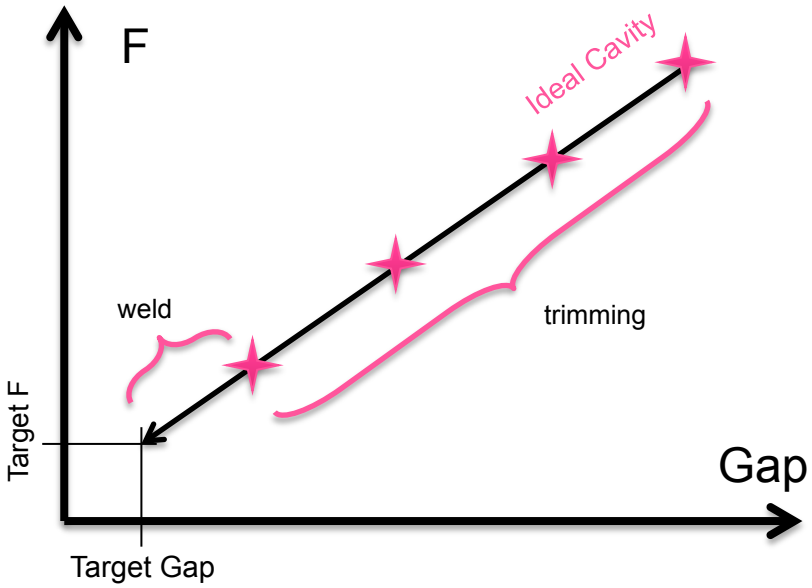


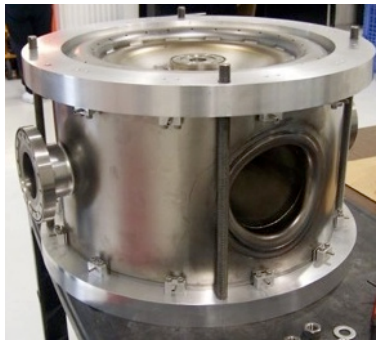


Adjusting Frequency

- Frequency is adjusted by trimming the outer conductor incrementally, before final equator welds.
- Ideal cavity will hit target frequency and gap size

Operation	Shift (kHz)	Freq. (MHz)
End-wall Welding	Negligible	323.975
BCP (120-150 μm)	+ 160	324.135
BCP (20-30 μm)	+ 40	324.175
Ring + Jacketing	+ 500	324.675
BCP (20-30 μm)	+ 40	324.715
Cool-down	+ 385	325.100
Tuner Engaged	- 100	325.000

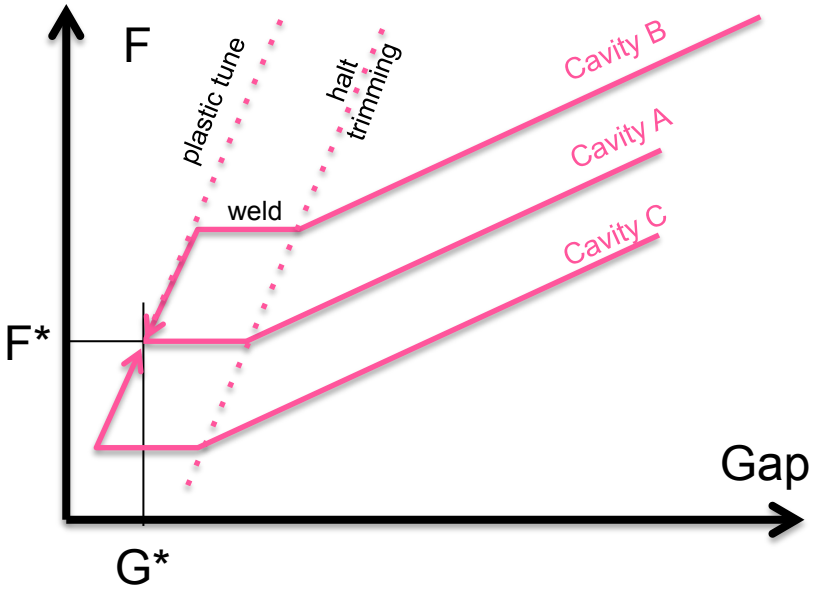


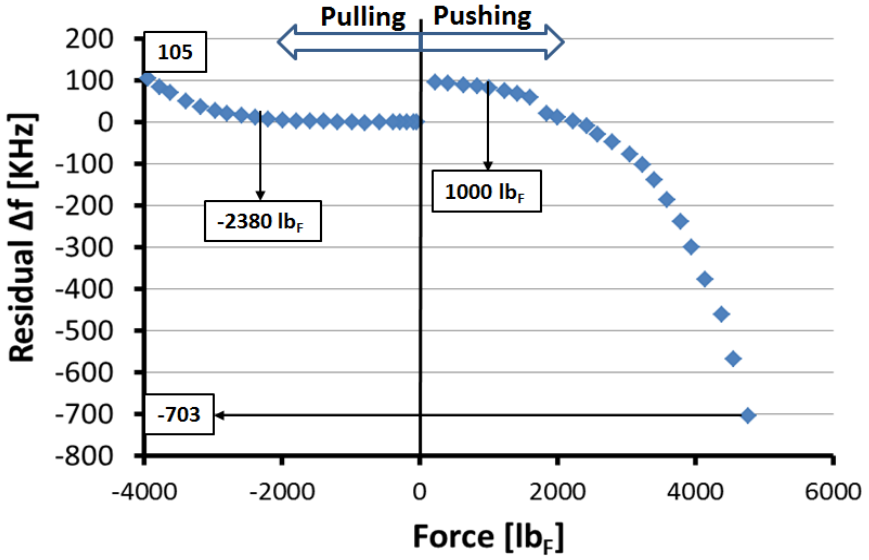


Adjusting frequency and gap size independently

- Frequency AND gap size can be achieved by using wisely the plastic tuning process.
- Trimming should be interrupted at the crossing of the "halt trimming" line, not at a fixed frequency

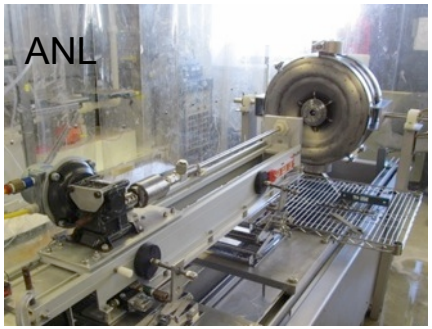
kHz/mm	measured (avg)
trimming	345 (320-370)
plastic tune	465
elastic tune	585

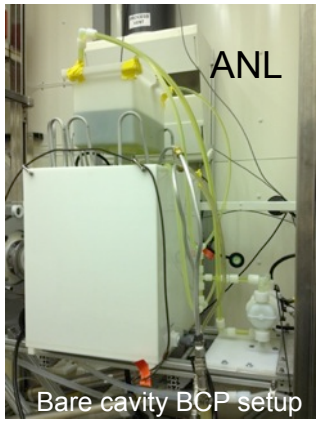




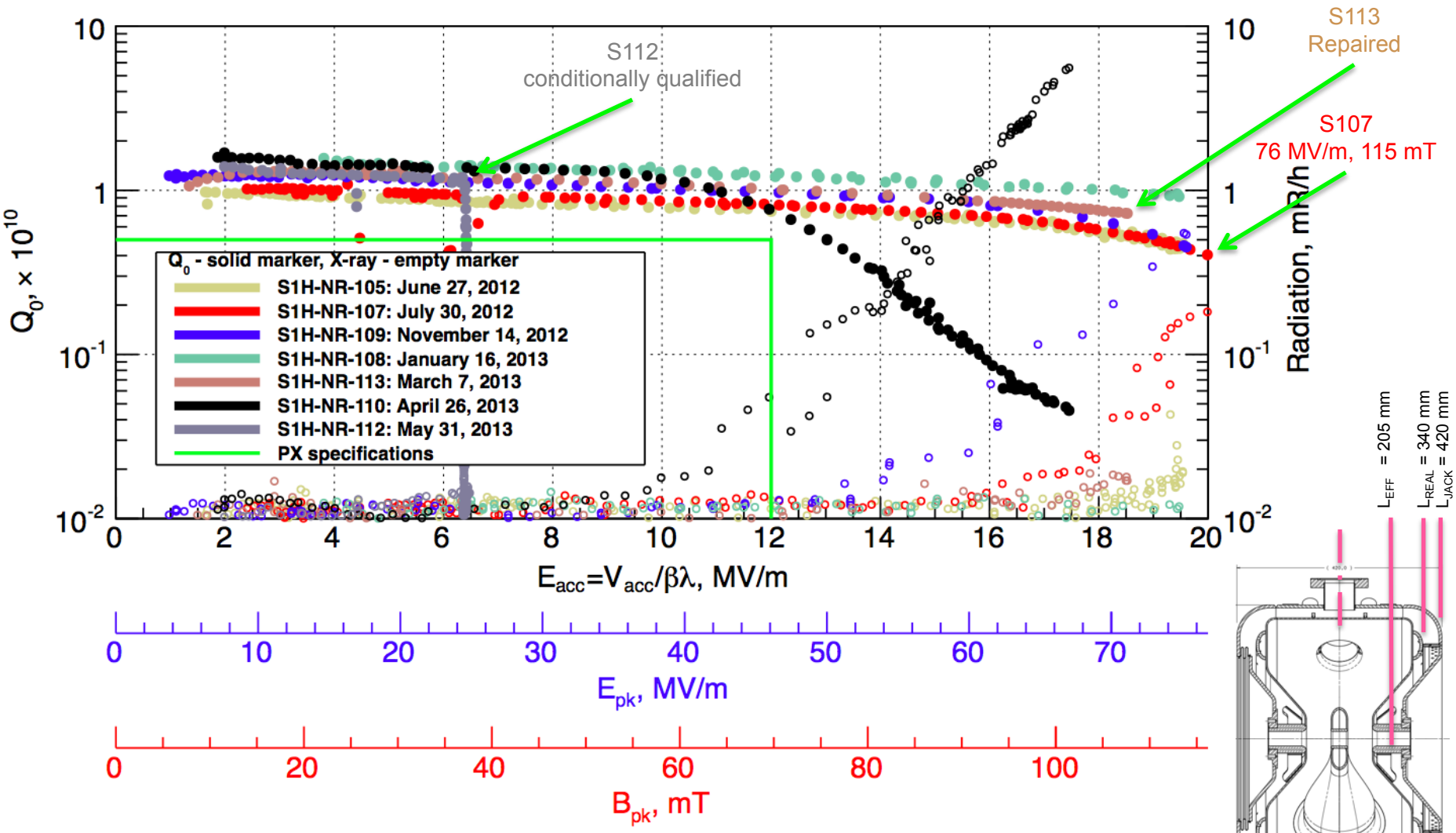
Processing/Testing steps (ANL, FNAL)

1. Inspection – RF & Optical
2. BCP 120-150 μm (flip half-way)
3. HPR
4. 600 °C, 10 h (< 5°C/min ramp rate)
5. RF Tuning
6. BCP 20-30 μm
7. HPR (horiz + vert)
8. Assemble
9. Evacuate + 120 °C, 48 h
10. Vertical Test
11. Helium Vessel Dressing
12. HPR
13. BCP 20-30 μm
14. HPR
13. Assemble
14. Evacuate + 120 °C, 48 h
15. Horizontal Test
16. Ready for String

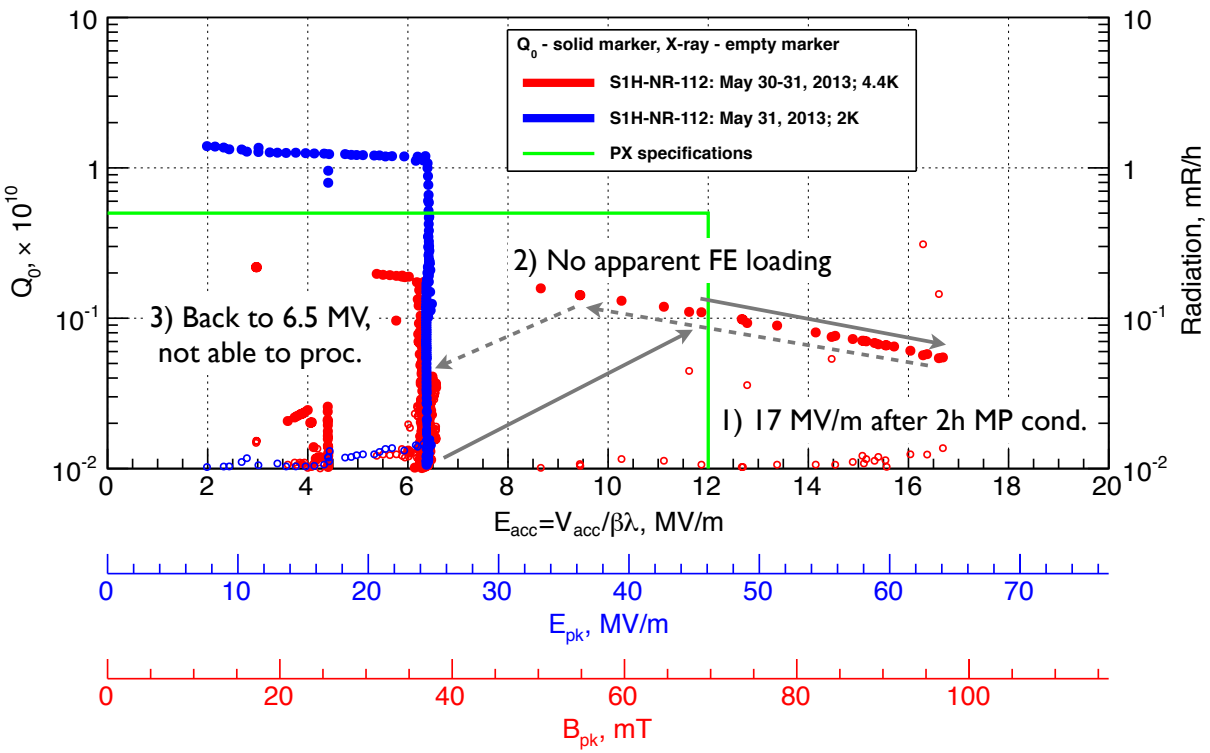




VTS Qualification



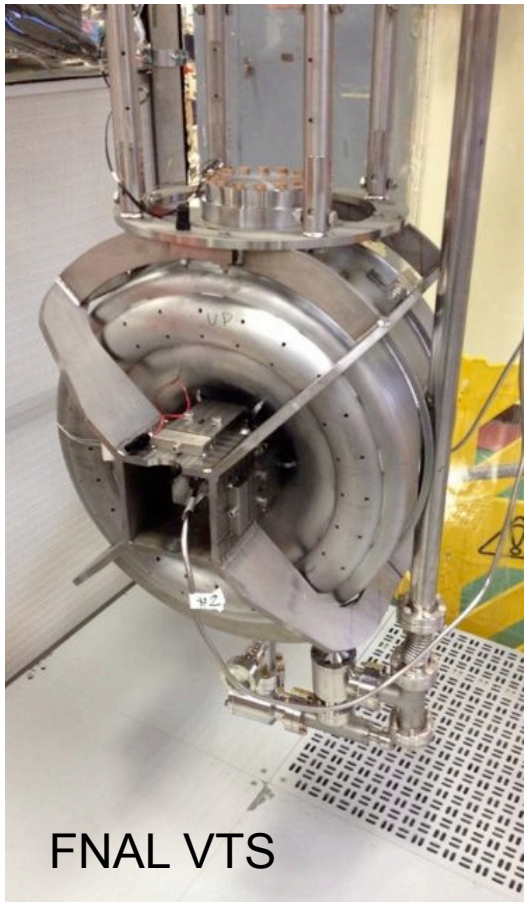
VTS Qualification – cont.



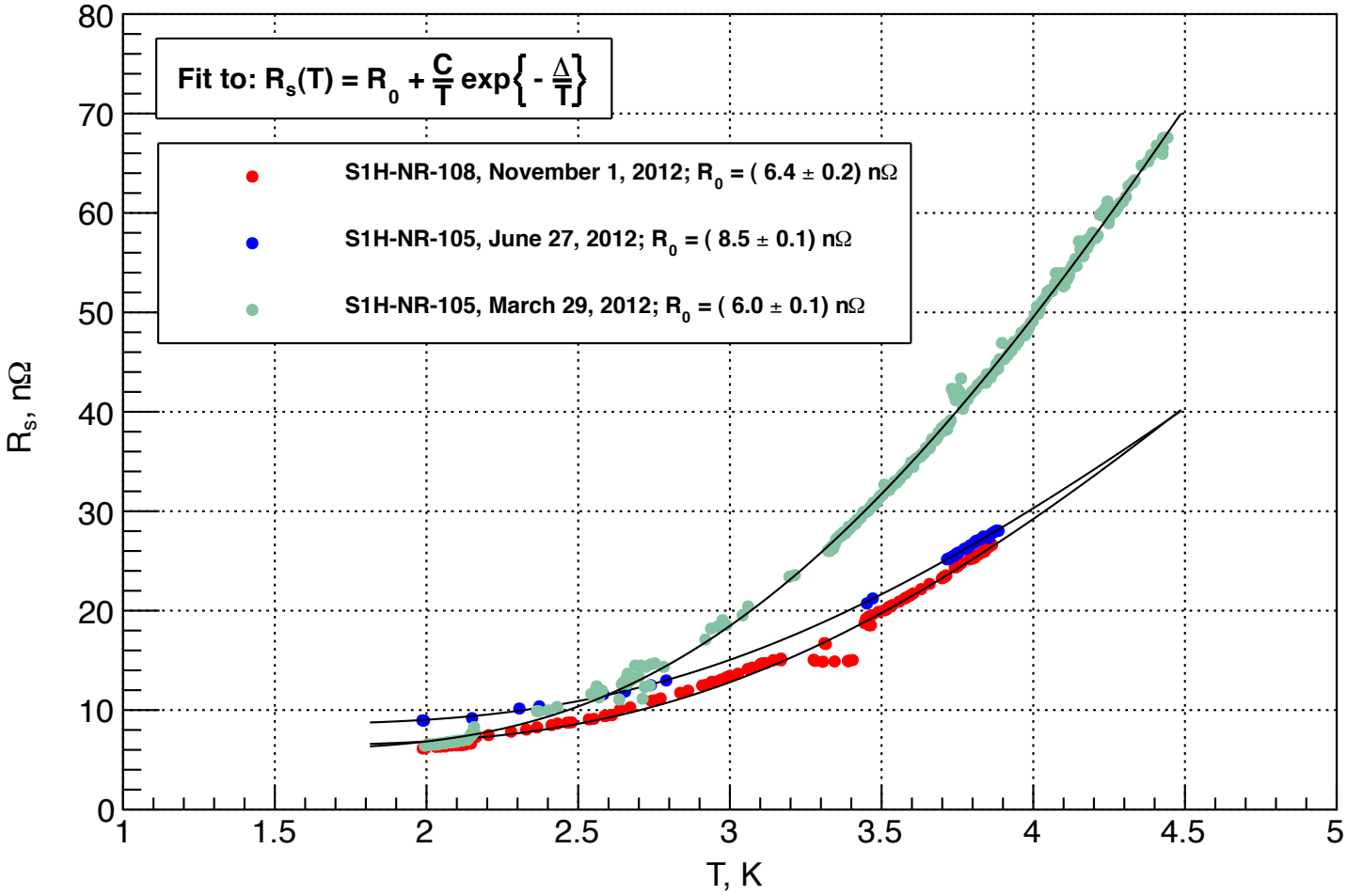
Cavity	E_{MAX} – Q_0 at 12 MV/m	Status
S105	19.5 MV/m – 0.8 10^{10}	Qualified at 2nd pass
S107	21.7 MV/m – 0.8 10^{10}	Qualified at 1st pass
S109	19.6 MV/m – 0.98 10^{10}	Qualified at 1st pass
S108	21.3 MV/m – 1.2 10^{10}	Qualified at 2nd pass
S113	18.5 MV/m – 1.0 10^{10}	Qualified at 1st pass
S110	17.3 MV/m – 0.77 10^{10}	Qualified at 2nd pass
S112	17* MV/m – 1.2 10^{10}	Qualified conditionally

*at 4.4K, limited by multipacting

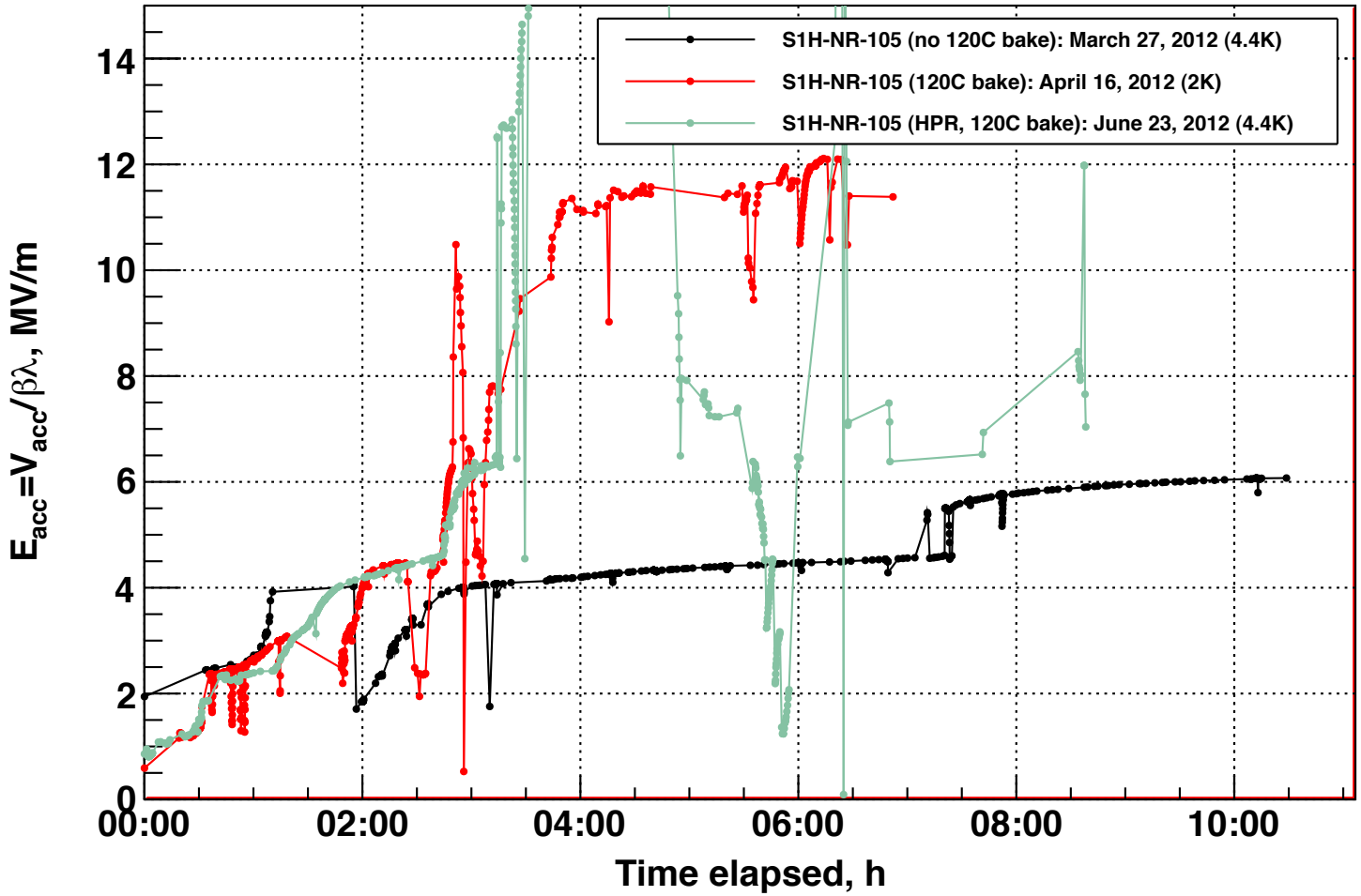
- 10 cavities received
- 7 cavities qualified
- 3 more to test



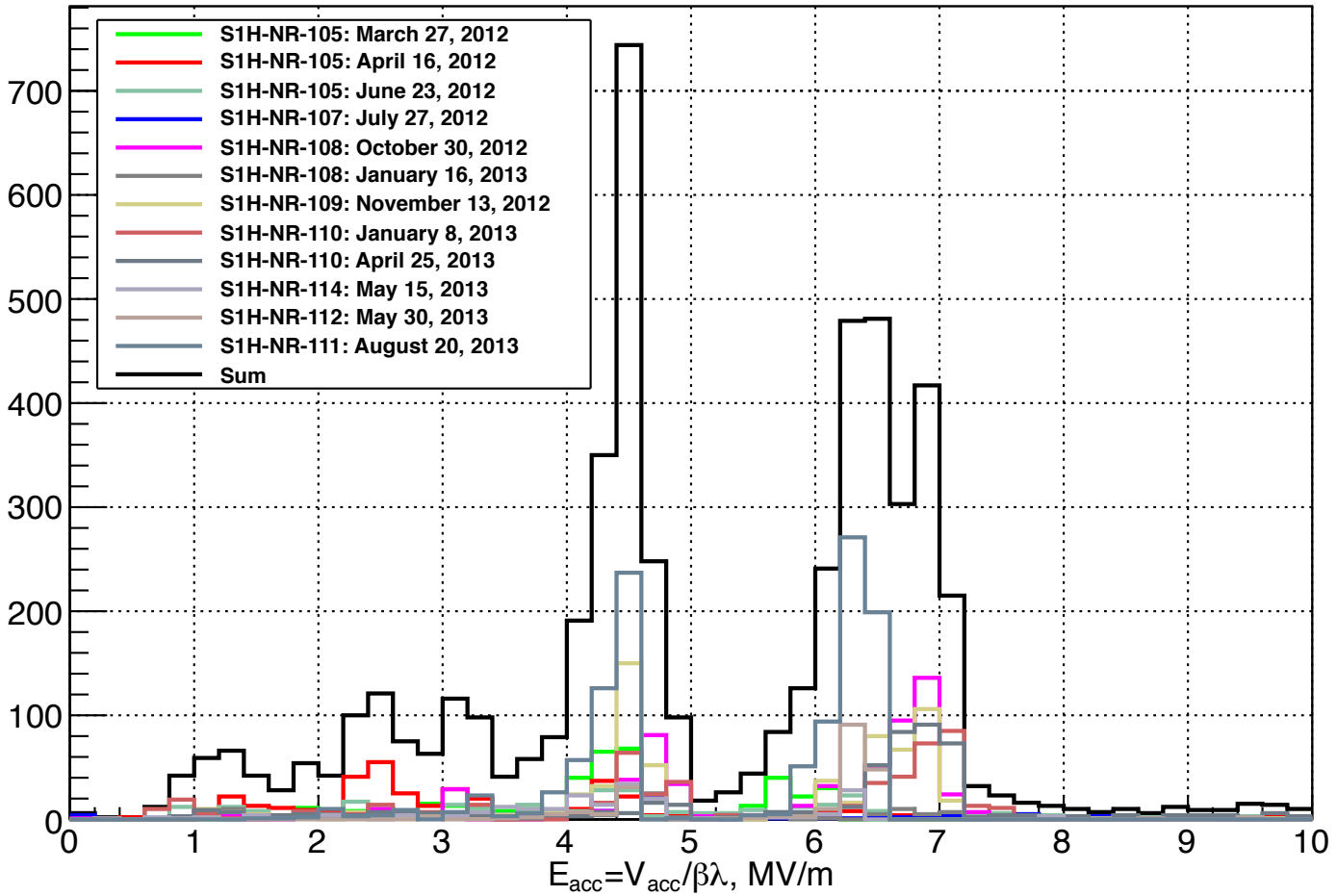
Residual Resistance



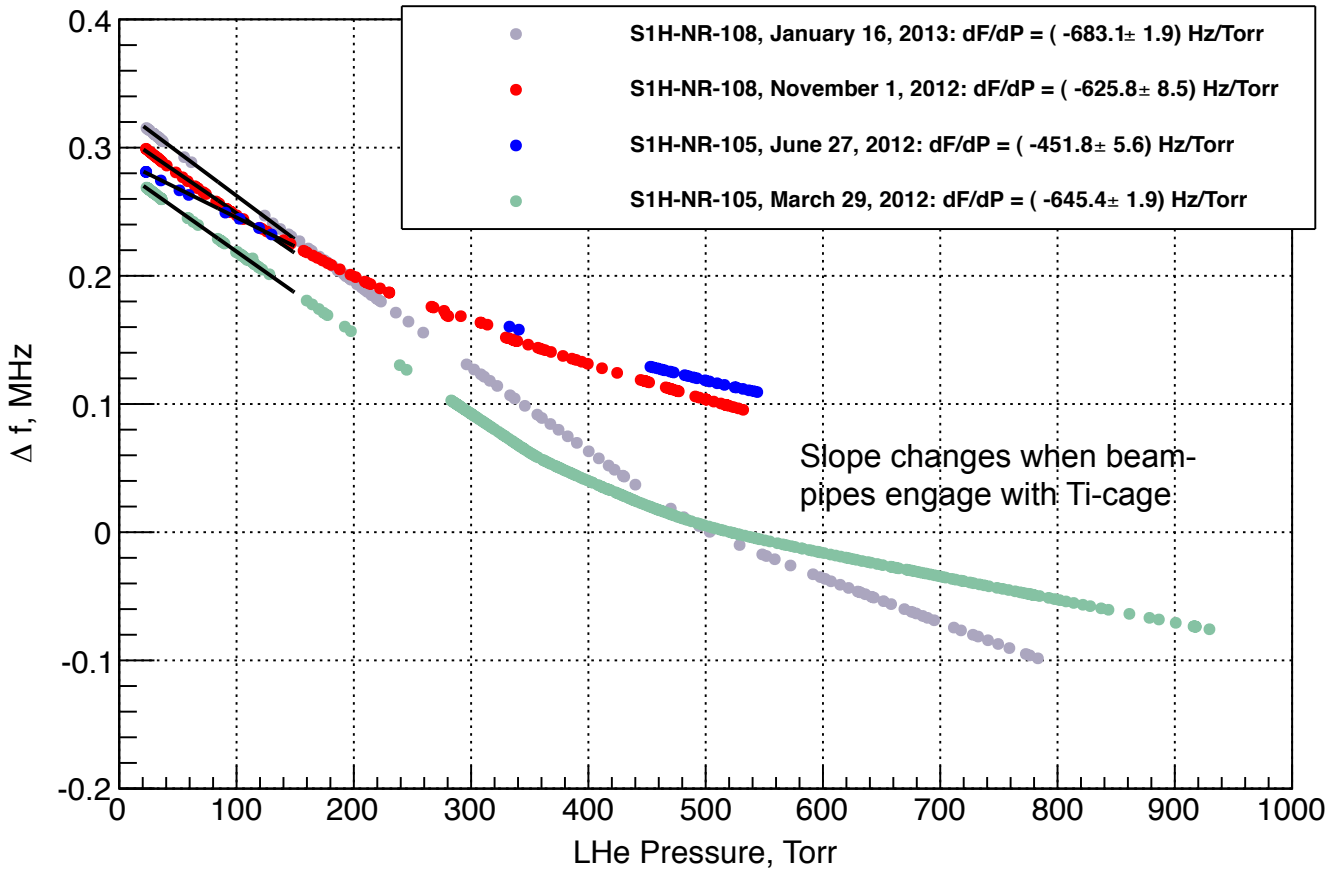
Multipacting Processing vs. 120C Bake



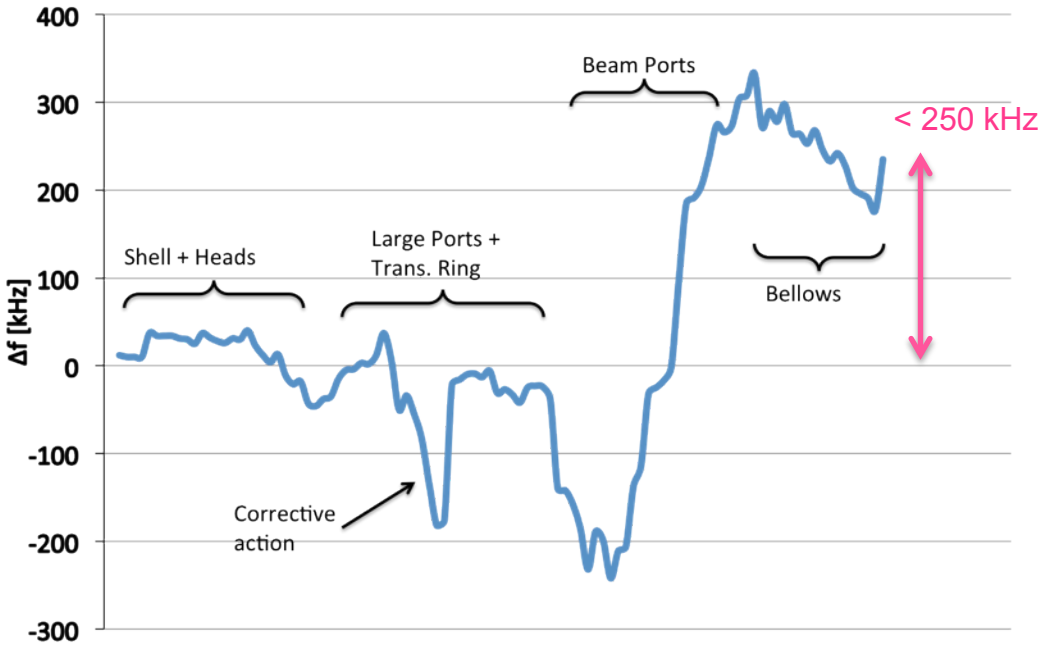
Multipacting Barriers

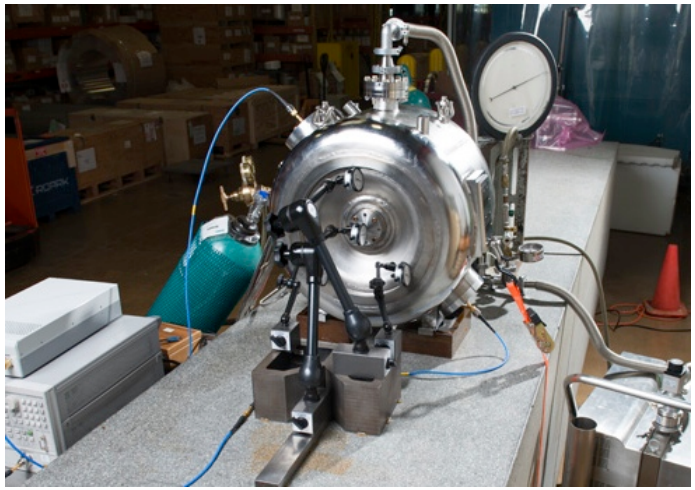


Sensitivity of Bare Cavity



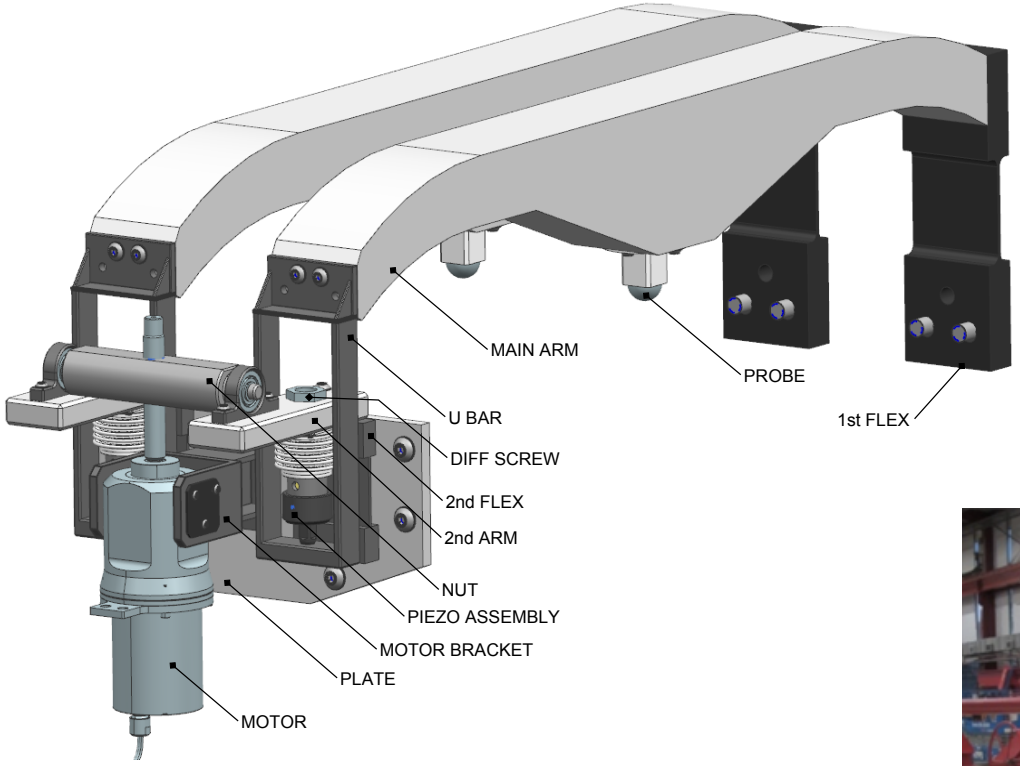
Jacketing – Shifts and Sensitivity

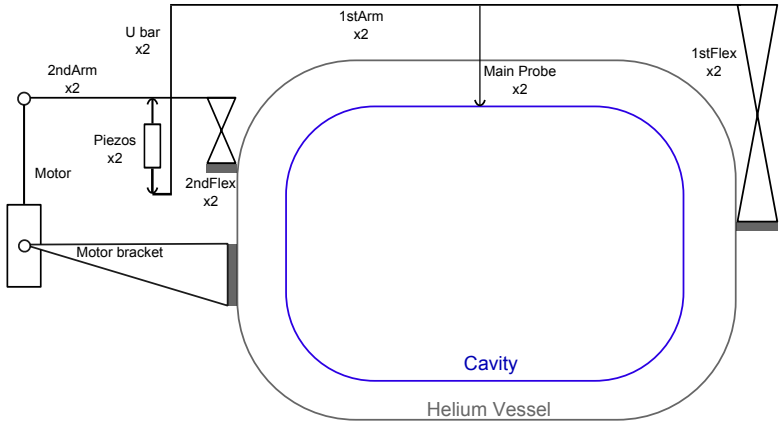




First Jacketed Tests
Measured df/dP in warm conditions:
+10 Hz/torr (free)
+4 Hz/torr (with dummy tuner)
Requirement is < 25 Hz/torr

The double-lever tuner





Coarse Range	135 kHz (0.25 mm)
Motor F_{MAX}	1250 N (1:6)
Fine Range	1 kHz (2 μm)

Summary and Outlook

- 10 Production SSR1 received (8 needed for 1st CM)
- EBW holes repaired, process improved
- Decision to modify flanges from ConFlat to Aluminum Seal
- 7 Cavities qualified for PXIE SSR1 Cryomodule
- First repaired cavity exceeded requirements
- First Jacketed cavity received, sensitivity meets requirements
- Cold tests of Jacketed cavity: end of 2013
- 2014 devoted to Testing remaining cavities, manufacturing tuner prototype, jacketing more cavities