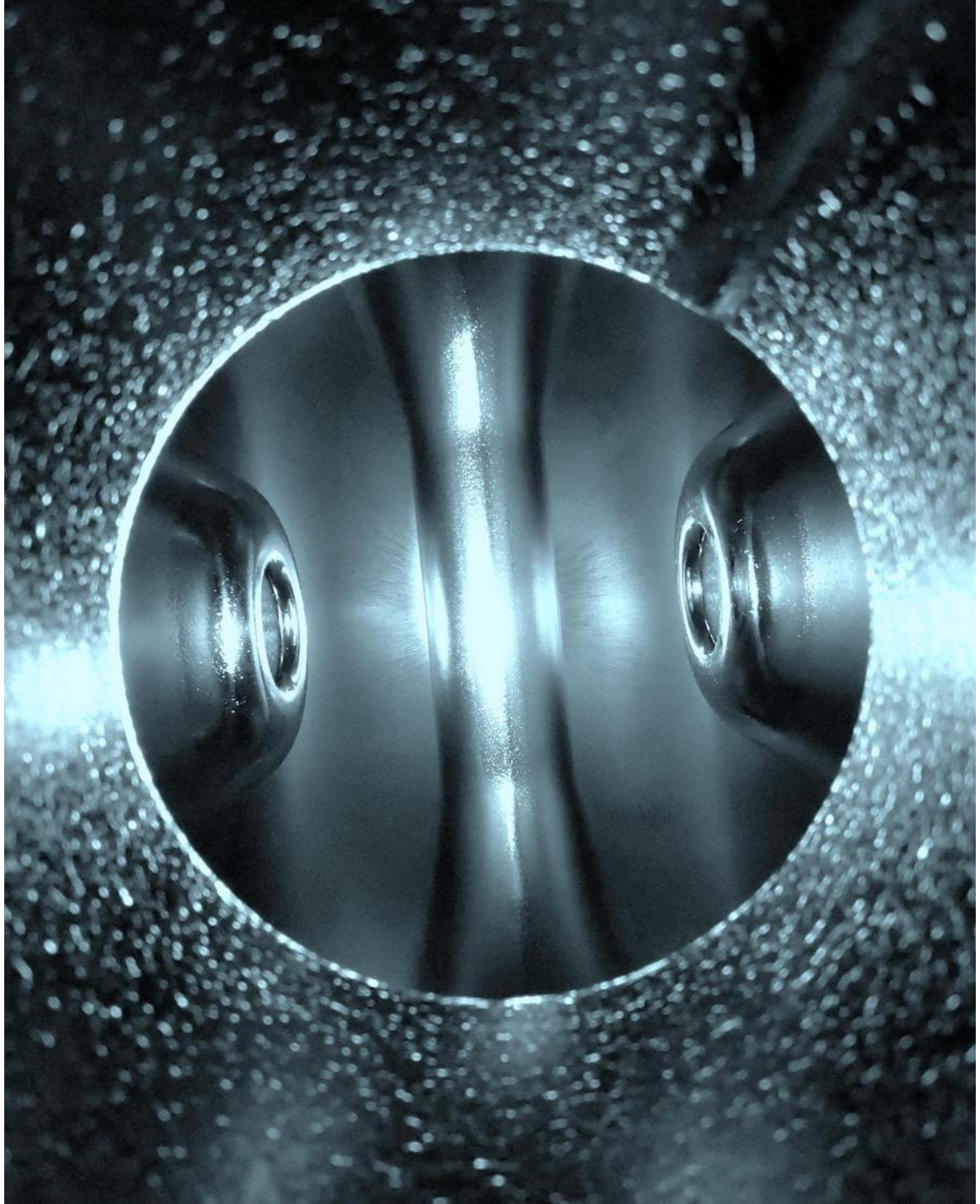
TRIUMF

Fabrication Experience with Balloon SSR at TRIUMF

R.E. Laxdal

TRIUMF

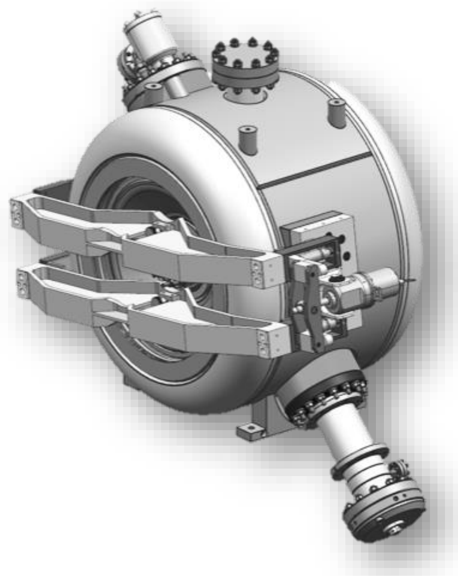
Feb. 5, 2020

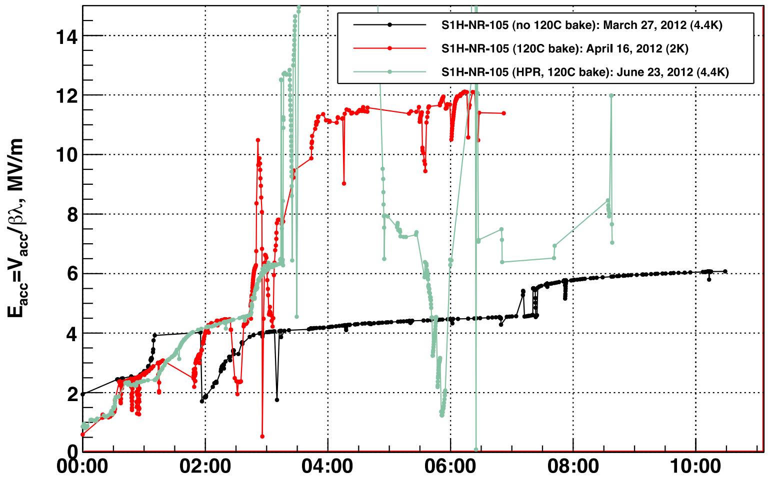


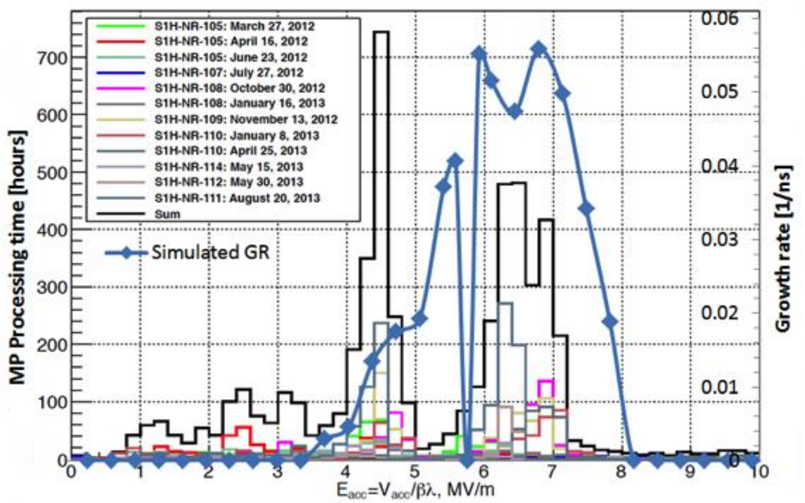
Discovery, accelerated

Multipacting in Single Spoke Resonator (SSR)

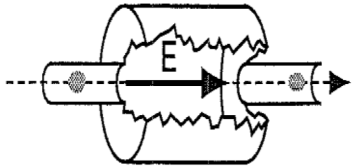
325MHz beta=0.22 SSR1   Leonardo Ristori, TTC2016



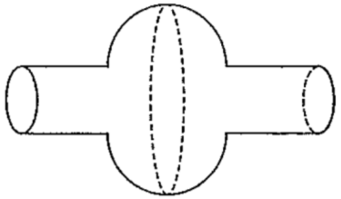




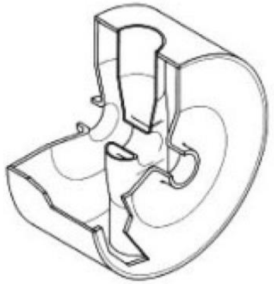
Pillbox



Elliptical



Spoke Cavity



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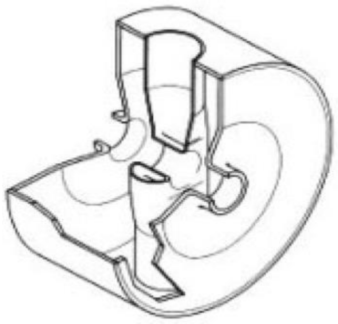
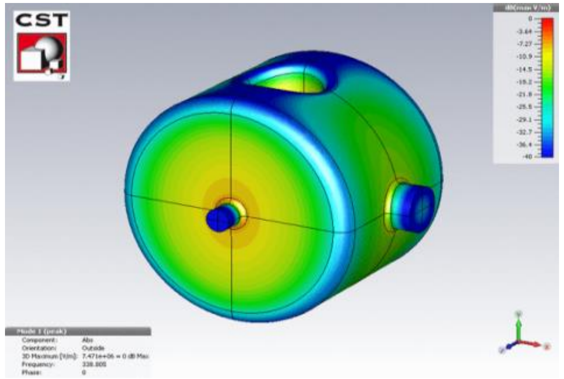
U. Klein, D. Proch, Proc. of the Conference on Future Possibilities for Electron Accelerators, N1-17 (1979).

Balloon Concept

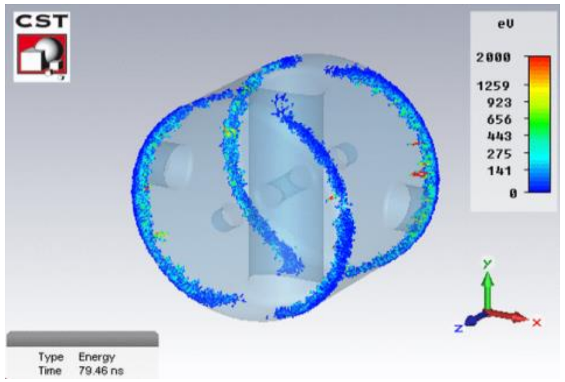
Traditional Spoke Cavity



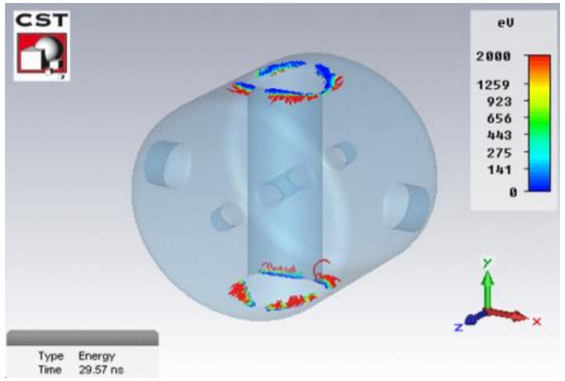
Pillbox + Spoke



Higher orders



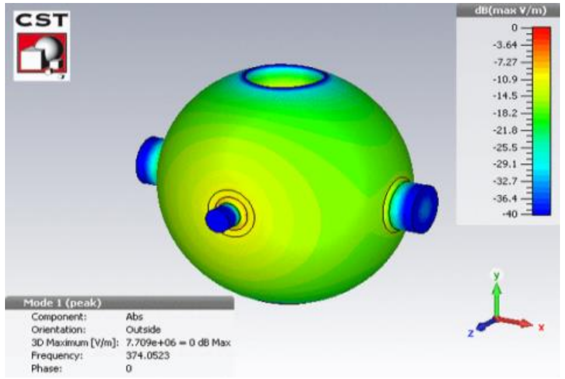
1st order

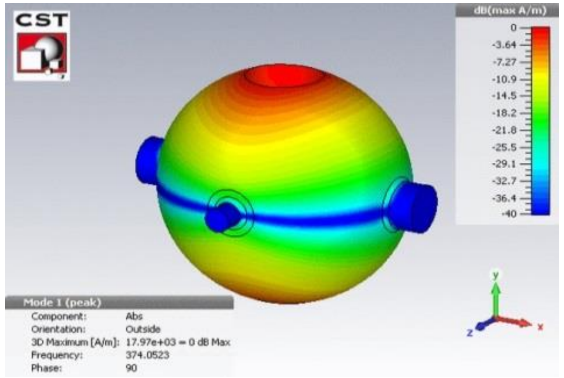


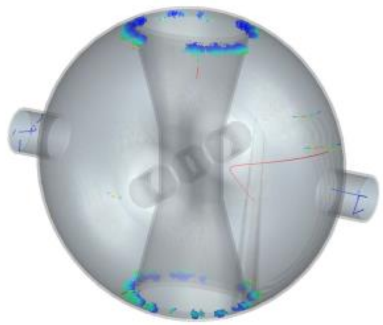
Multipacting areas are spoke bases for 1st order barrier, and rim for higher order ones.

Balloon shaped outer conductor (large radius) and local geometry of spoke bases (small radius) narrow these barriers and push them to lower gradient by changing local EM field. Z.Yao, et al, `Balloon variant of single spoke resonator', submitted for publication

Balloon

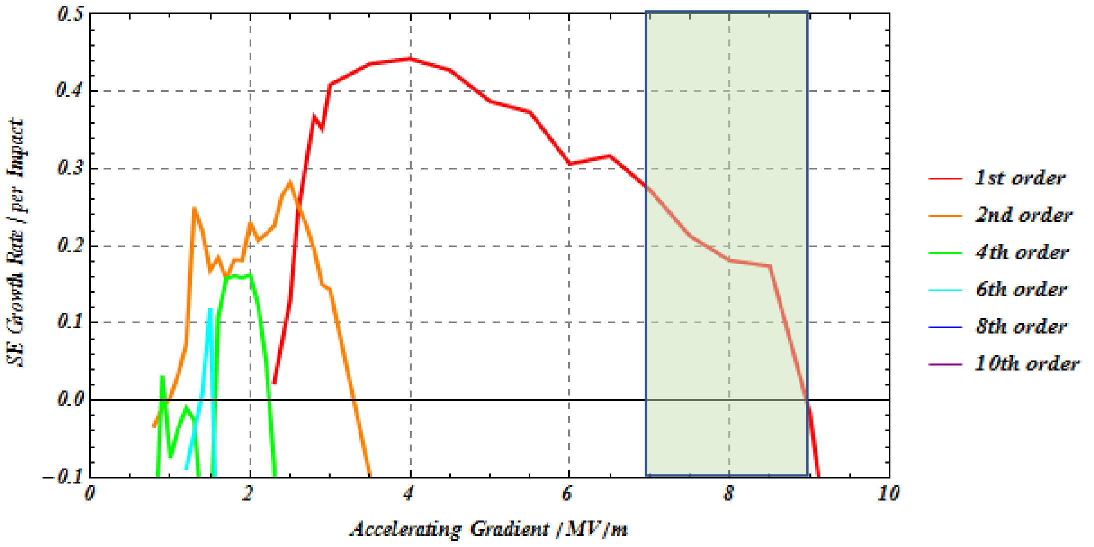


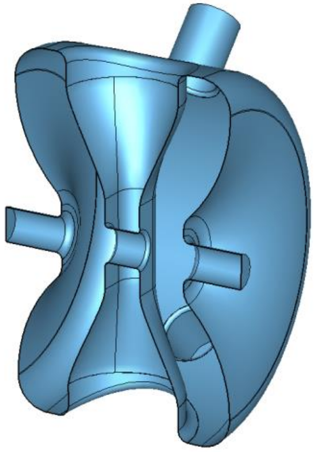




Balloon + Spoke

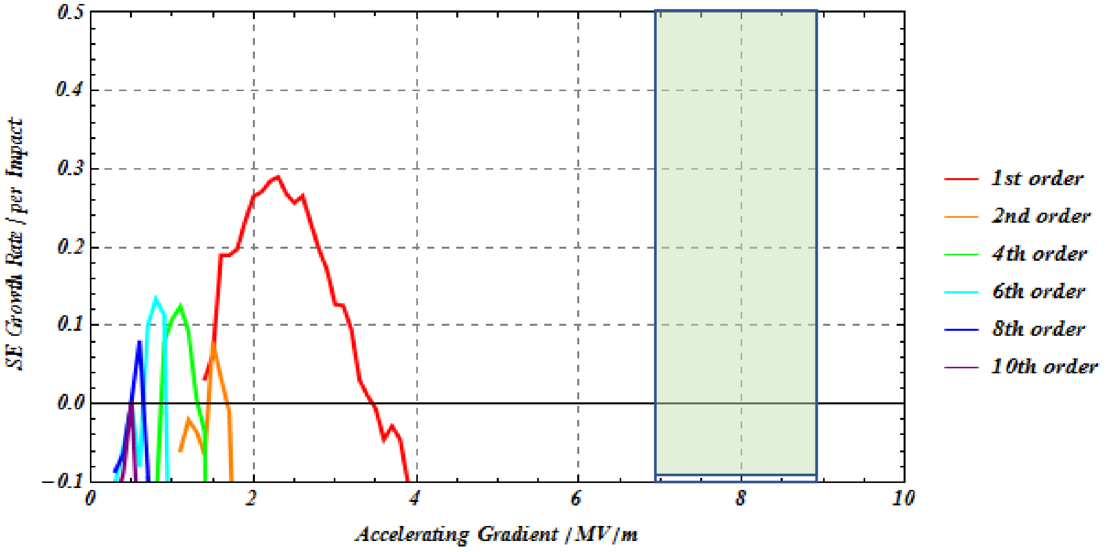
SSR - Traditional Design vs Balloon Design (325MHz, β=0.3)

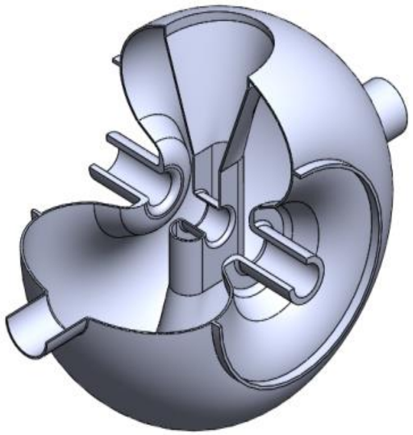




Traditional variant

- MP barriers are relatively strong and can extend to operating gradient





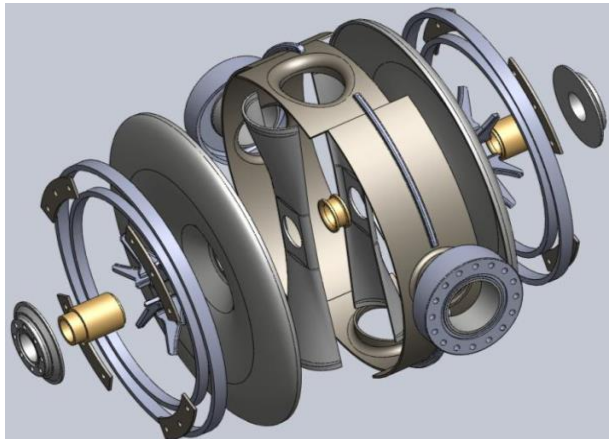
Balloon variant

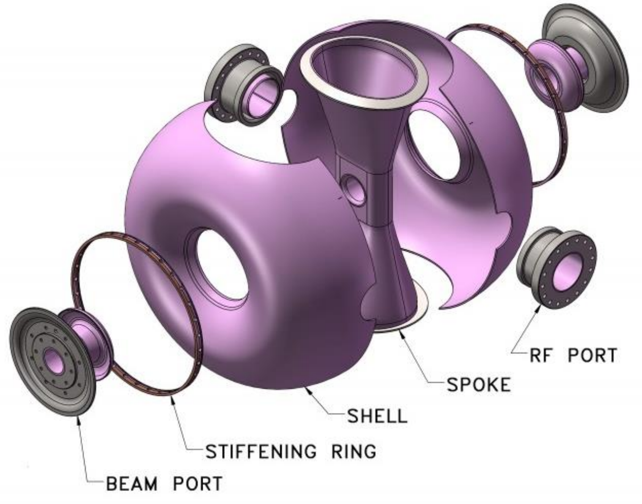
- MP barriers are pushed to low fields away from the operating gradient and reduced in severity

SSR Fabrication – Traditional vs balloon

Also

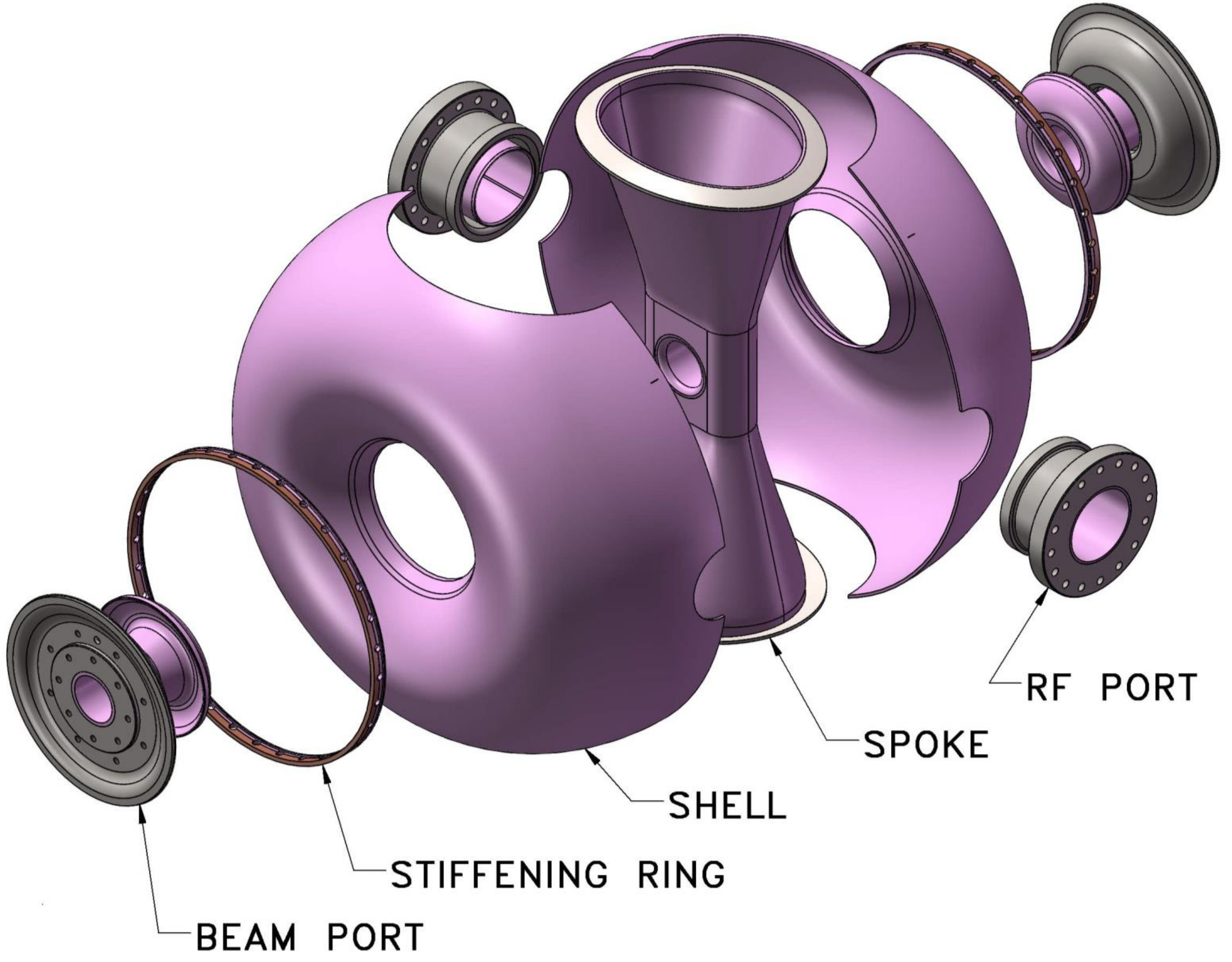
- The balloon cavity reduces the number of parts and EB welds as compared to traditional SSR cavity
  - The central spool of the traditional design is eliminated.
  - The balloon design is mechanically more stable (sphere vs drum). It requires fewer stiffeners so several welding steps are eliminated.





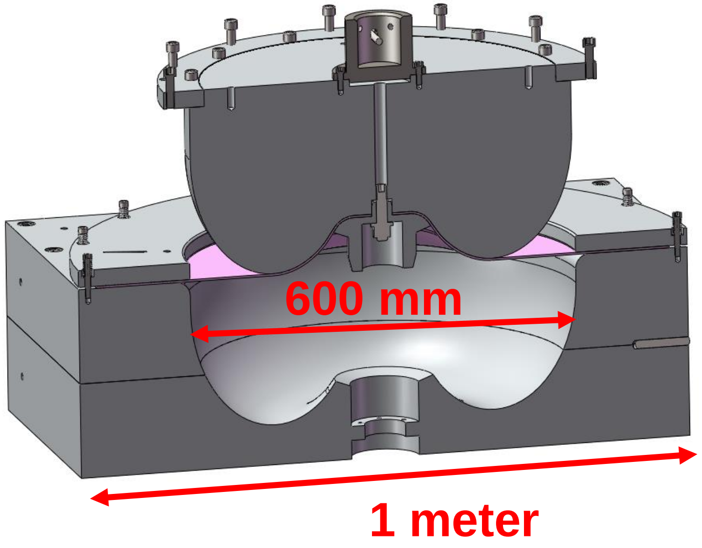
Bare Cavity Sub-Assemblies

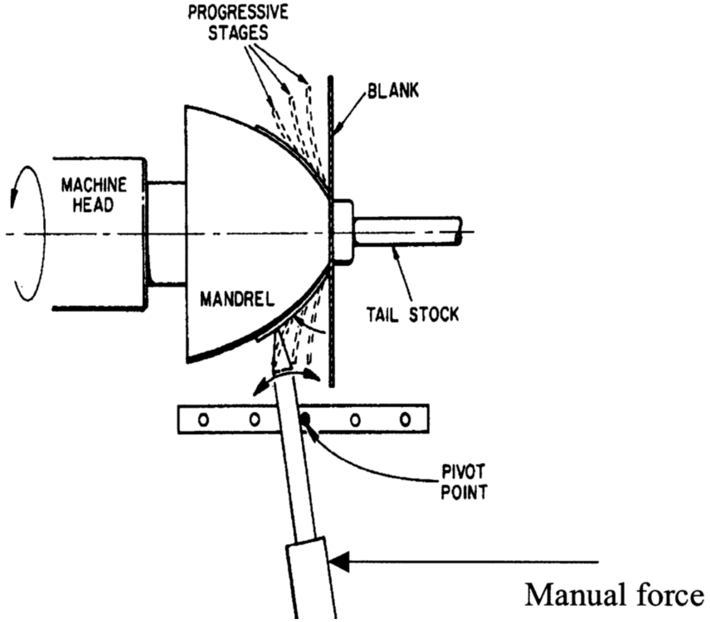
- TRIUMF commissioned to design and fabricate two prototypes at 325MHz beta=0.3
- Spokes formed by deep drawing with collar welded to spoke for easier welding to shells
- Helium jacket is made from SS so ports are made with Nb to SS Cu braze joints
- What about the shells?



Shell fabrication – forming vs spinning

- The shells would typically be produced by deep drawing - requires large expensive tooling – also time consuming
- TRIUMF chose to fabricate the shells with spinning
  - the raw sheet is fixed against a mandrel and rotated while the material is pressed against the die by a roller to shape the sheet to the profile of the mandrel.
  - Useful technique for fast prototyping as the tools are relatively inexpensive and straightforward
  - Tooling (case hardened mandrel and rollers) took ~3 weeks to design and manufacture
  - Tooling, testing and spinning of 4 shells cost ~10k$US and took ~6 weeks from start to completion
  - When spinning, niobium is prone to thinning – also some work-hardening (though much less than copper)



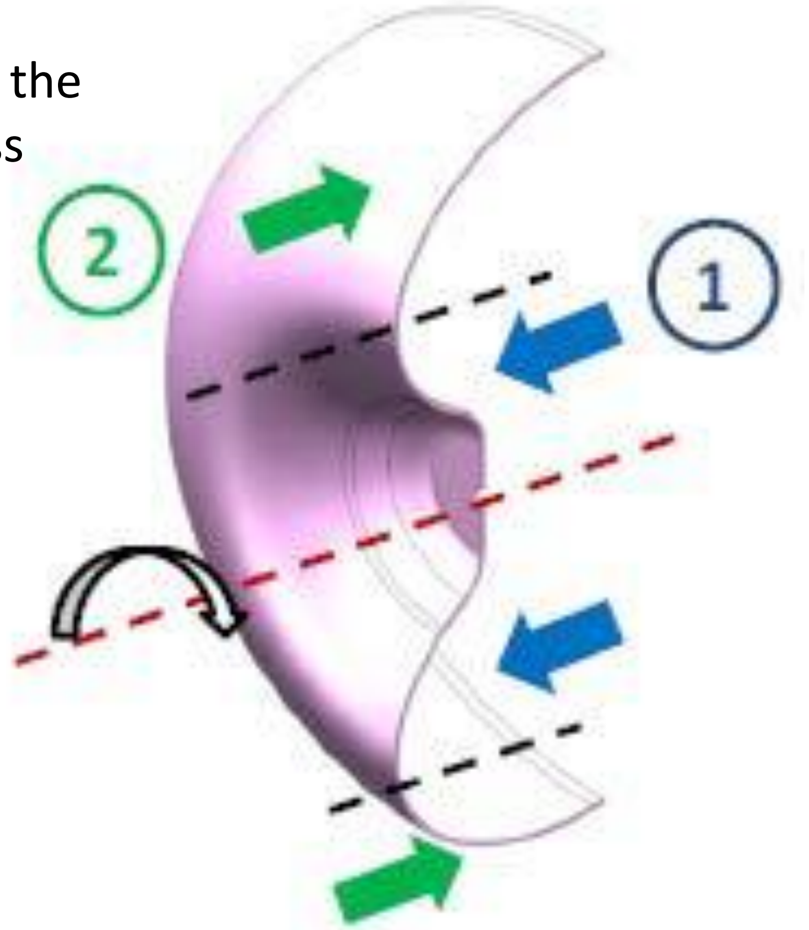


Spinning development

- The shells were spun at AMS Industries Ltd. of Vancouver – experienced company but not with Niobium
- Raw stock 3 x 890 x 890 RRR>300   12.5k$US per sheet – so want to reduce risk of failure
- Several preparatory steps were taken before the final Nb spinning was done.
- ✓ First a smaller hemisphere shape was spun from 2.8 mm Nb sheet to give the fabricator experience with Nb.

Testing the tooling with copper

- Next the final mandrel was proofed using Cu sheet.
- The shell is formed in two sequences: the inner part is pressed against the die to form the inner shape and then the part is reversed and the shell is pressed against the forming die to get the reverse bend.
- Initial Cu was selected with a hardness near to Niobium HV 40-60 – since the copper work hardens some staged annealing was done during the process



Testing the tooling with copper

✓ Results of spinning two Cu blanks – spun shells were tested for dimensional tolerances

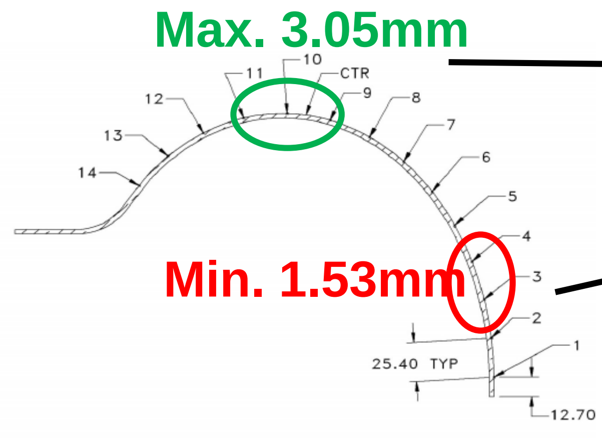
Niobium shells

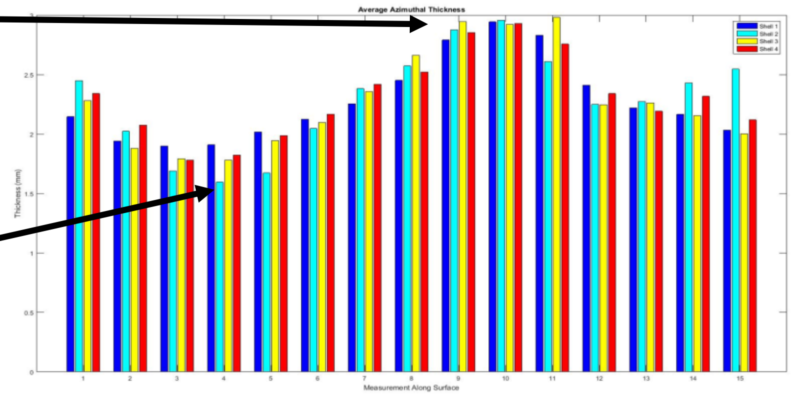
✓ Next the final Nb material was trimmed to size and four shells were spun.

Shell Thinning from Spinning

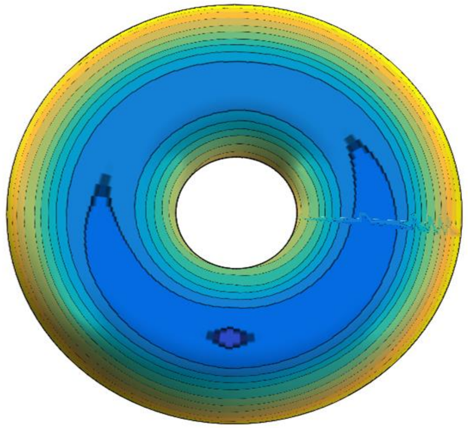
- Significant thinning was noticed on both Cu and Nb spun shells

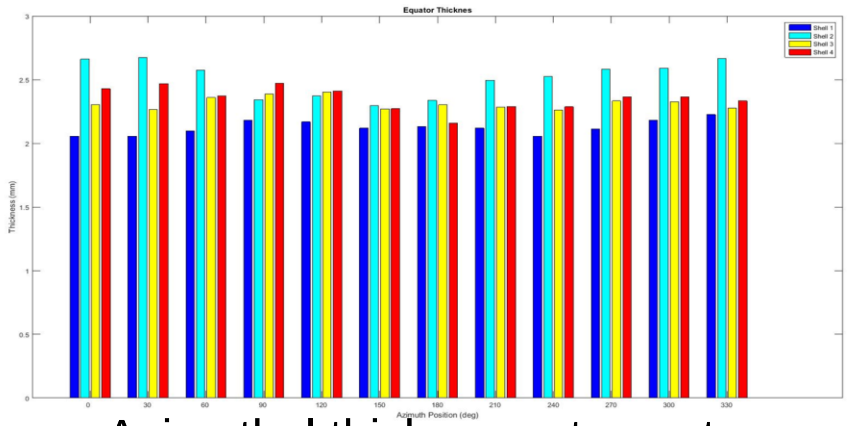
The spinning thinned the material in quite a reproducible way with thickness varying from 3 mm to 1.5 mm. A 3D mapping of the material thickness was made based on US measurements.





Radial profile of 4 shells



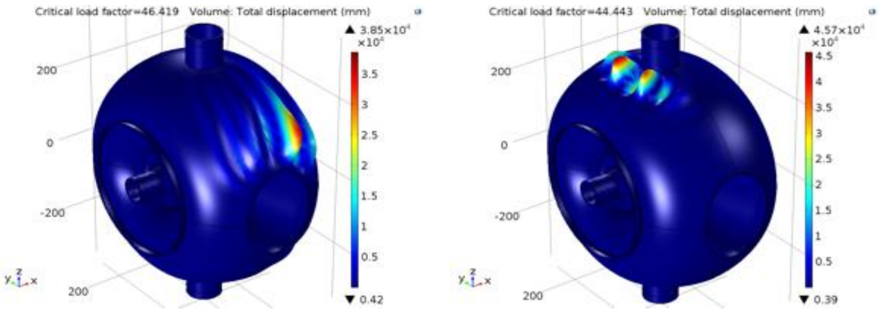


Azimuthal thickness at equator

Shell Thinning vs mechanical

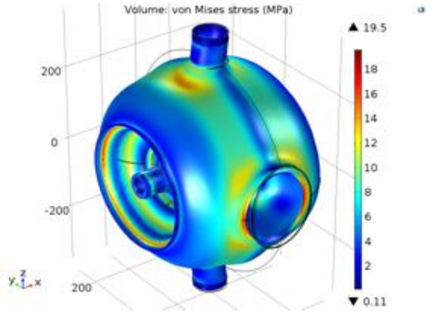
- Design complies with ASME guidelines
- The actual shell thickness was fed back into the mechanical simulations to ensure the cavities met the specification
- linear buckling analysis and pressure load analysis – ok
- Pressure sensitivity increases by a factor of 3

1. Linear buckling analysis



Critical load factors > 40

2. Pressure load analysis



Peak stress increases about 18%.

3. Pressure sensitivity check

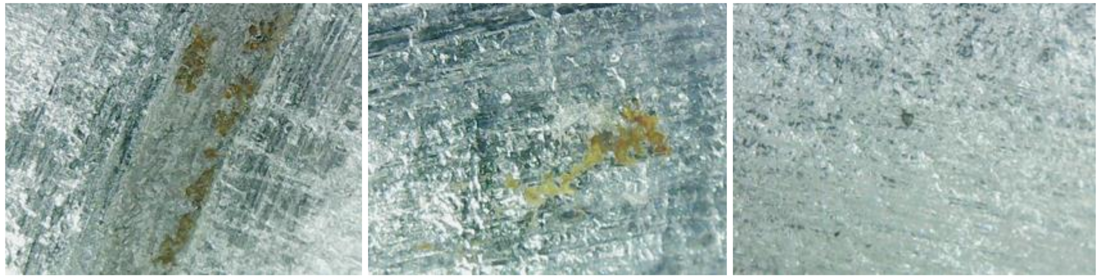
3mm thickness df/dp < ±2Hz/mbar → Real thickness df/dp < ±6Hz/mbar

Accepted by design specification

Inclusion Check

- Mechanical polishing completed at vendor after spinning to get rid of tool marks
- TRIUMF checks
  - Salt water soak
  - Nitric acid clean (X2)
  - Ultrasound
  - 10um BCP both sides
  - ✓ Salt water soak
  - Ultrasound

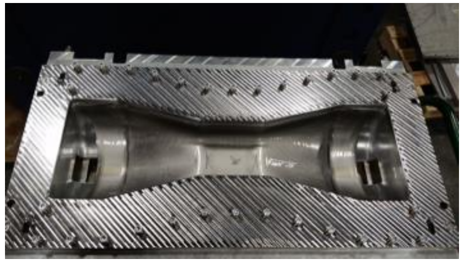
Rust spots

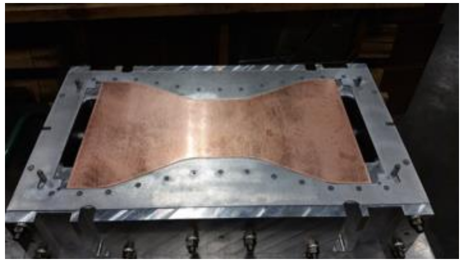
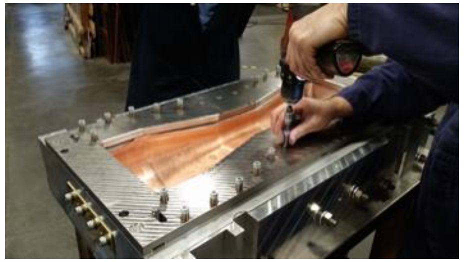


Post-BCP salted water soak

Spoke Forming

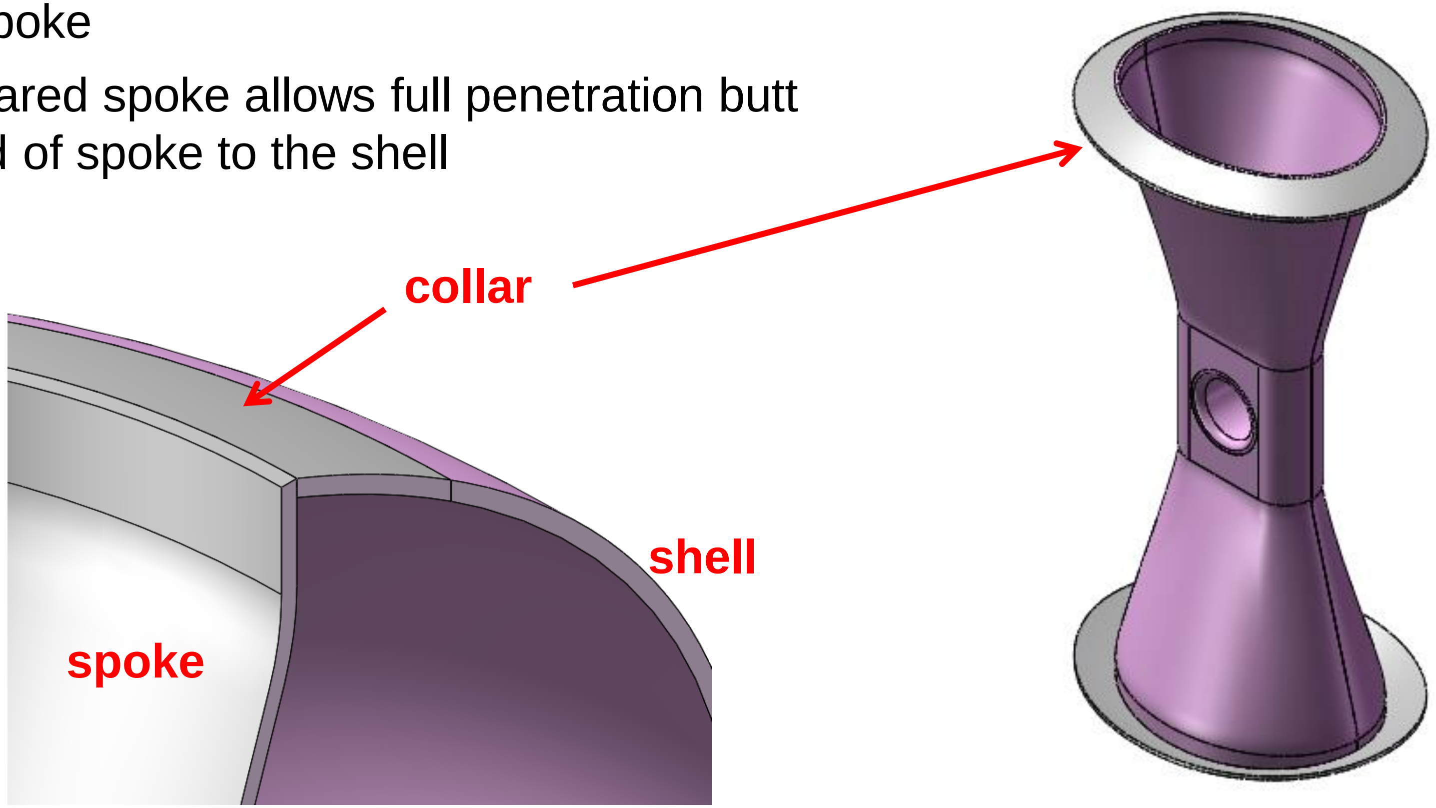
- Spoke forming for balloon prototype was done by traditional method of deep drawing
- Deep drawing was completed in TRIUMF shop
  - Die tested in copper first
  - Die shape was good. No modification was required.
  - Niobium half spokes were then punched and machined.



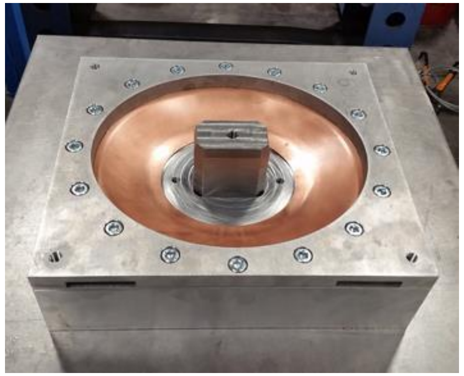
Collar is formed and welded to spoke

- Collar is formed in a die set then welded to spoke
- Collared spoke allows full penetration butt weld of spoke to the shell



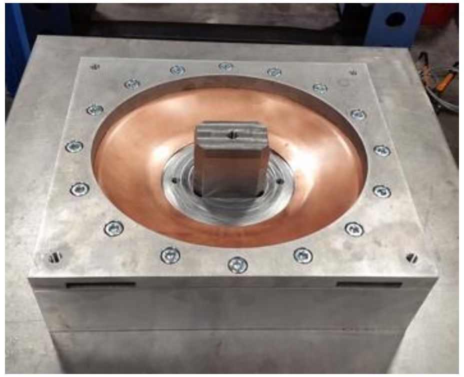
Collar forming

16



Other Parts

Collar forming



RF tubes, Beam tubes, SS flanges

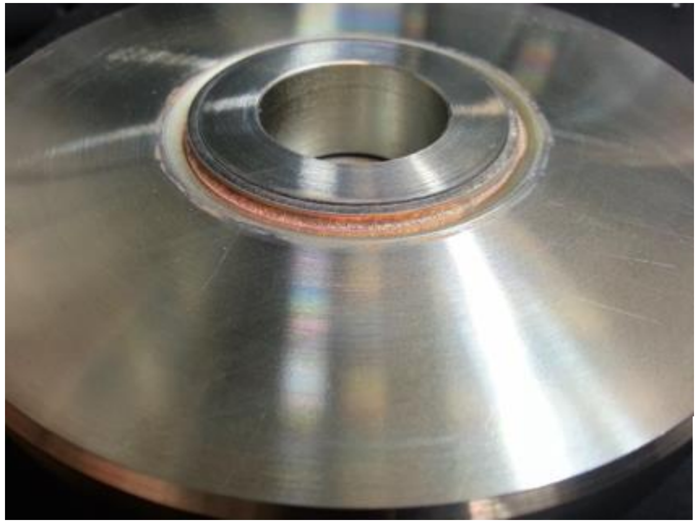
Nb-SS Brazing

Follow recipe from CERN, ATLAS and FNAL.

[1] J.P. Bacher, CERN/EF/RF 87-7.

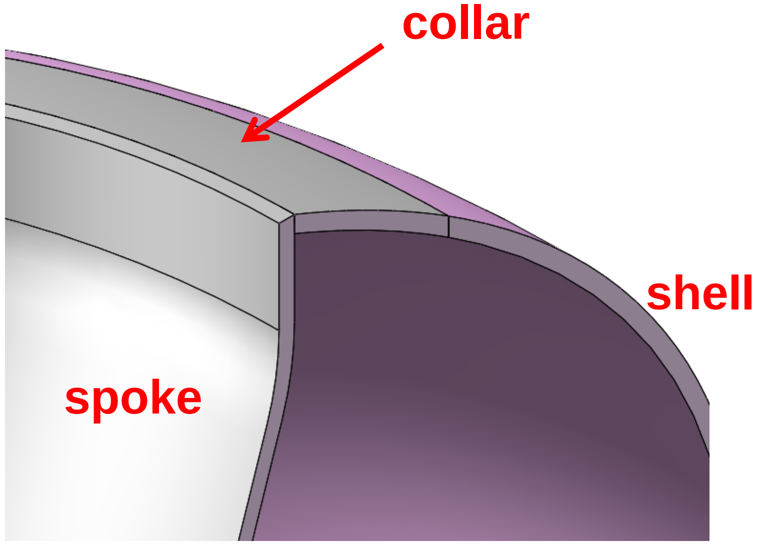
[2] J.D. Fuerst, TUP11, SRF2003.

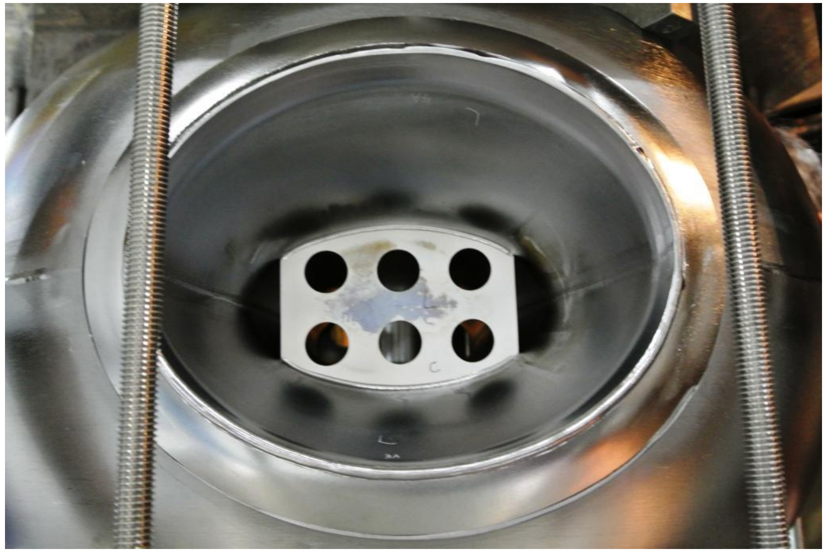
[3] L. Ristori, WEPPC058, IPAC2012.



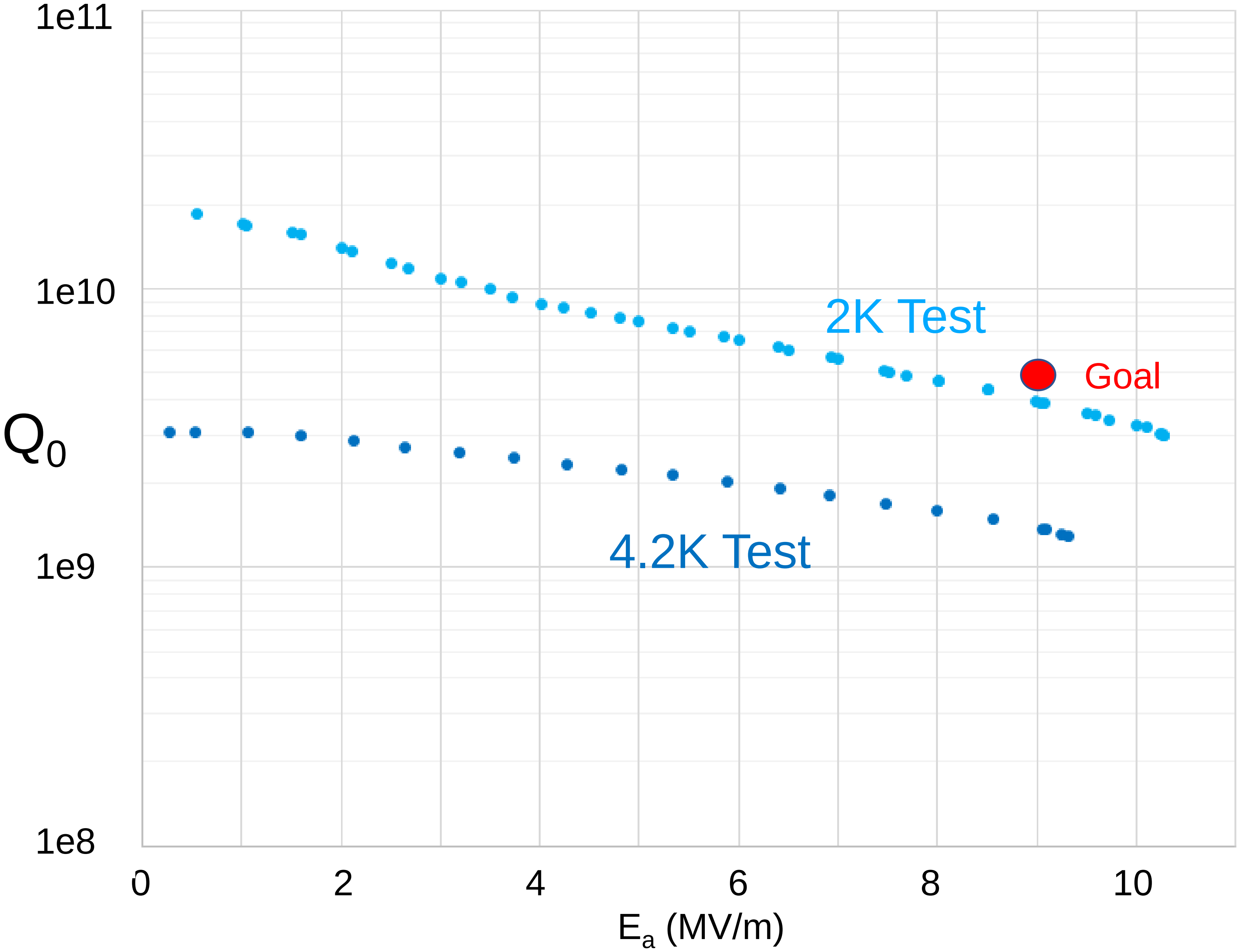
Final welds

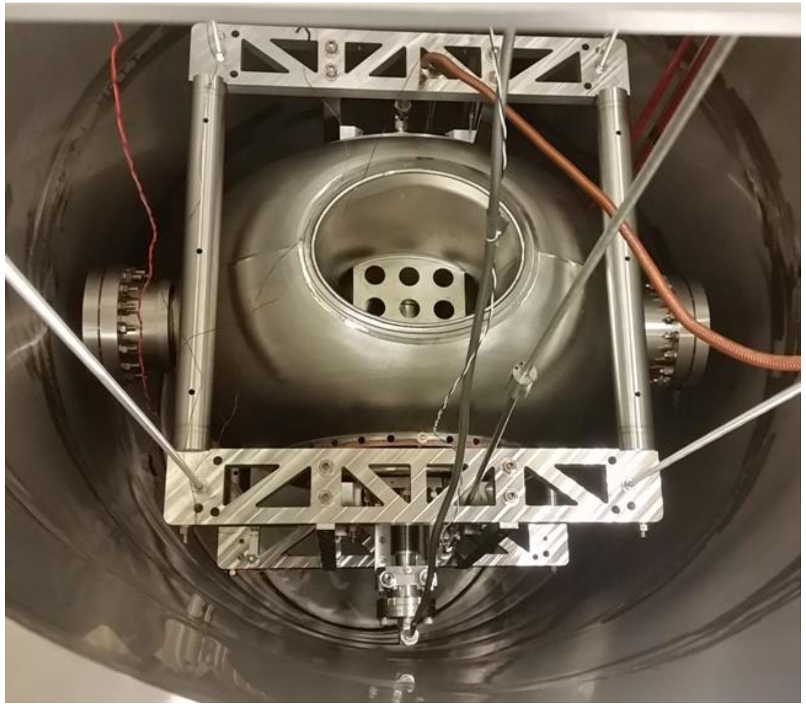
- The thinning of the shell made the final spoke/collar to shell welds challenging
- Required thinning the collar and hand fitting collar to shell





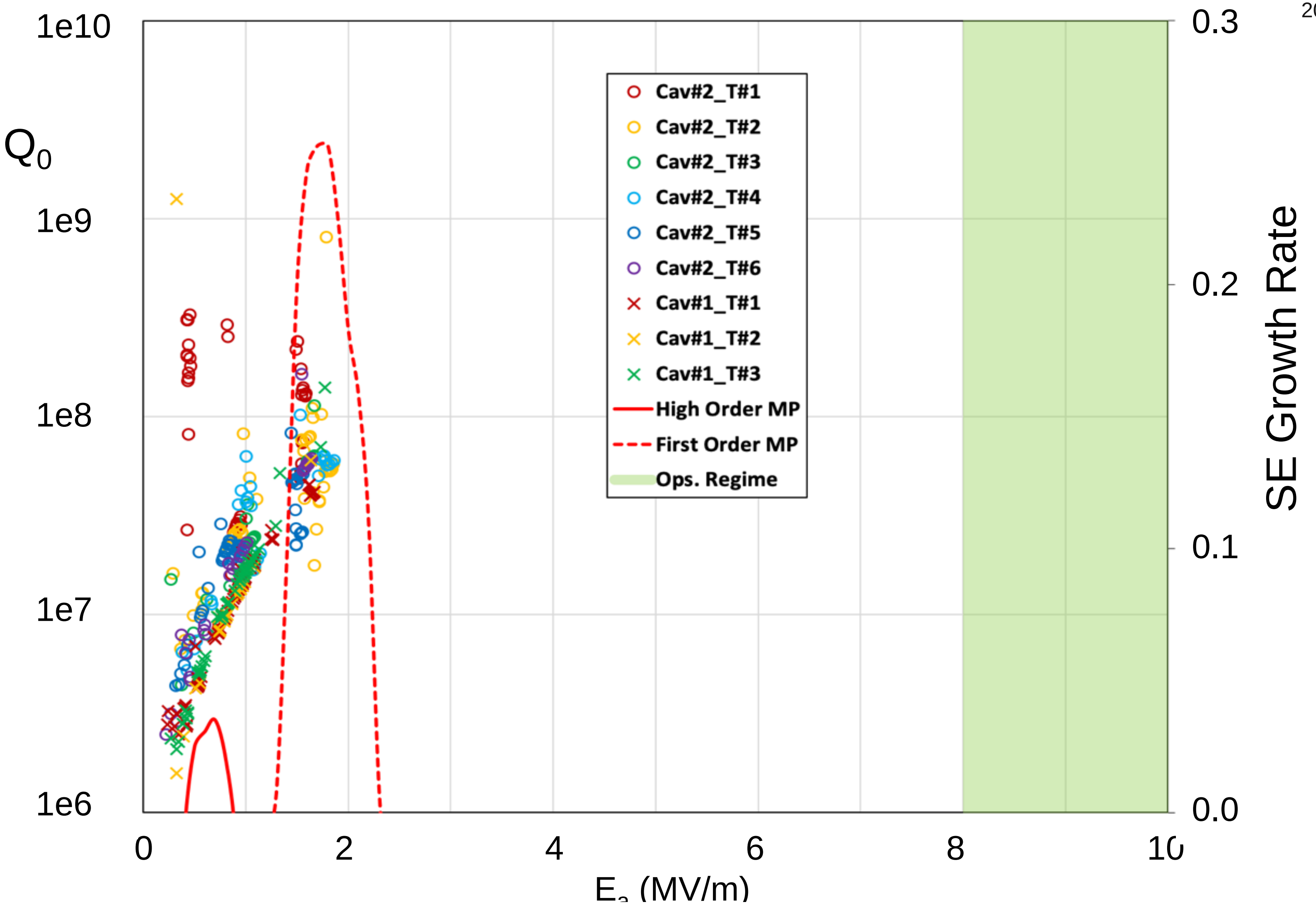
Unjacketed Cold test





Multipacting

- There is excellent agreement between MP simulations and cold test data
- No multipacting barriers near the operational gradient
- The barriers only exist between 0.2 MV/m and 1.8 MV/m.



TRIUMF

- The balloon variant of single spoke resonator is designed to mitigate problematic multipacting around operational field level.
- The first balloon SSR variant has been designed, fabricated and tested at TRIUMF meeting all the aims of the prototyping stage of the project
- Spinning of the shells has been successfully used for rapid, low cost prototyping

Discovery, accelerated

Acknowledgements

Thanks to:

- RISP
- Xu Ting, Jie Wei (FRIB)
- TRIUMF machine shop (machining and forming)
- Vector Aerospace (brazing),
- AMS Industries Ltd. (spinning)
- ROARK (EB welding)

Thank you
Merci

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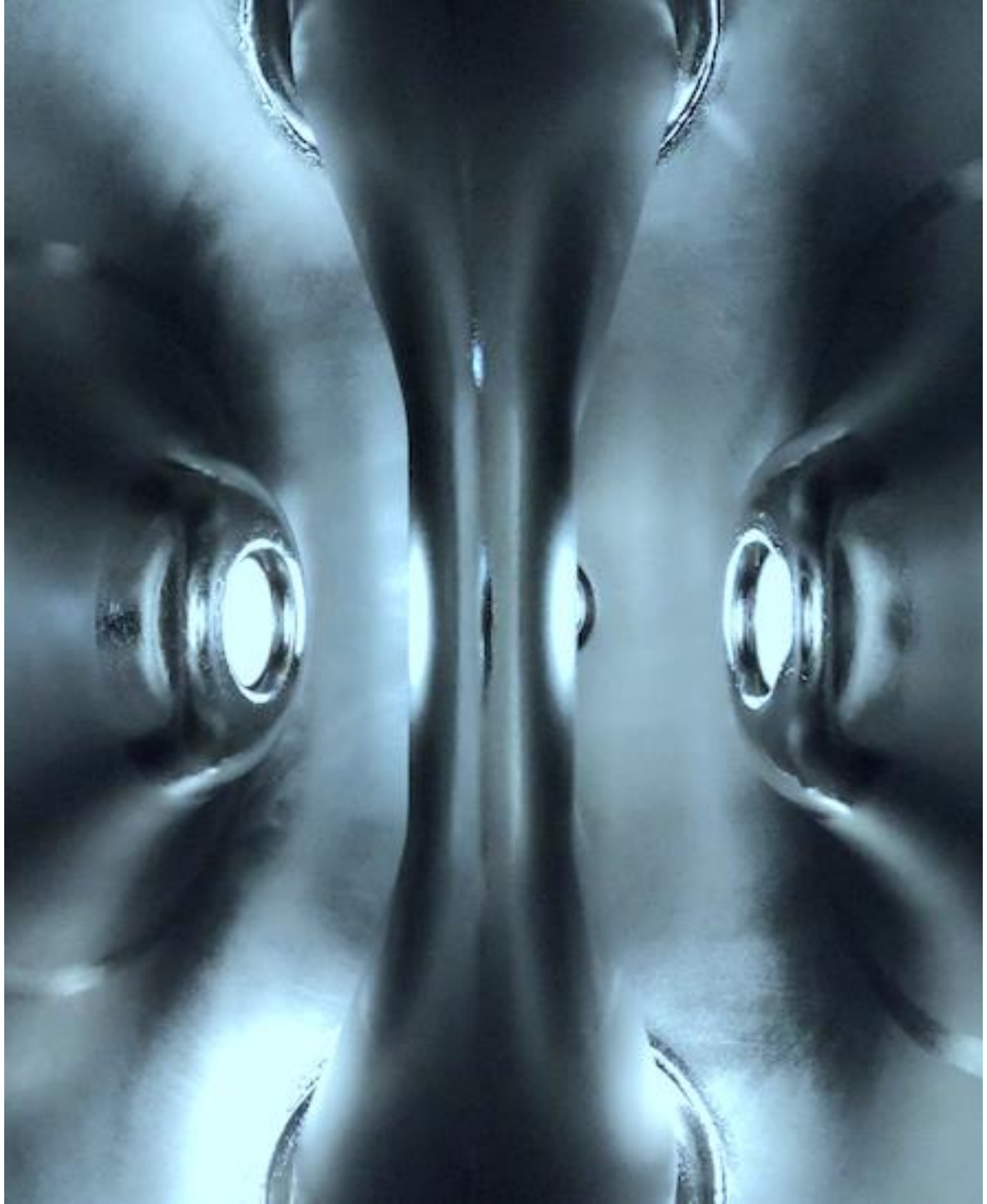
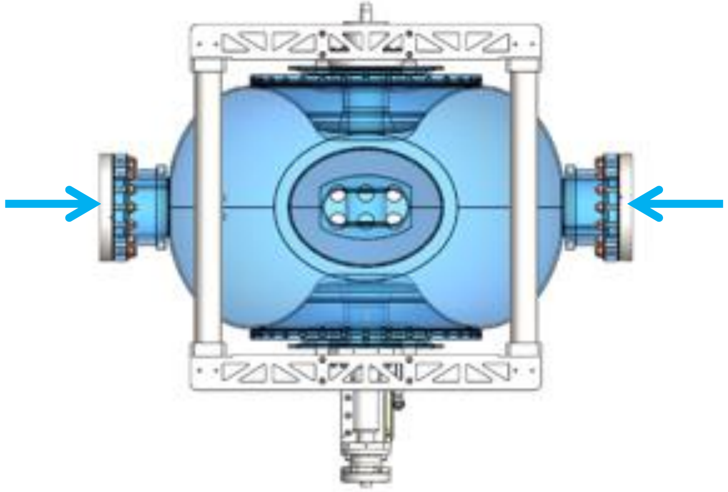


Discovery,
accelerated

Quench limitation

- Boroscope investigation
  - Evidence of bubble traces on shell near RF ports
  - Small geometry defects observed on the shell
  - Imperfect welds at the spoke collars

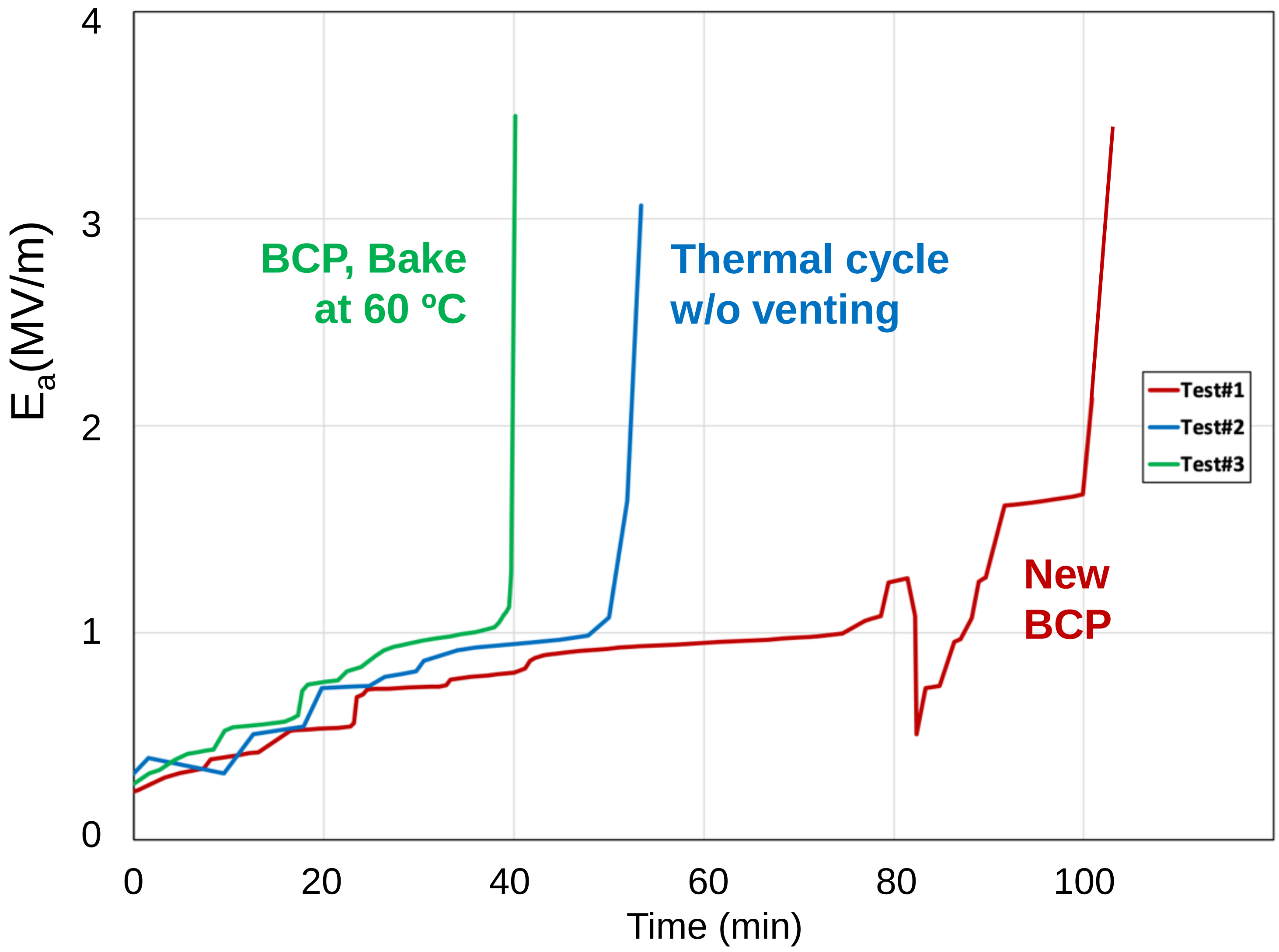


Jacketing at TRIUMF

- Measured warm frequency (324.6MHz), spring constant (10kN/mm), tuning sensitivity – within warm goals
- Cold frequency excellent
  - 4.3K – 324.978 MHz
  - 2.1K – 324.995 MHZ (within 5kHz!)
- df/dp = 15Hz/mbar
  - Due to uneven thinning of half shells

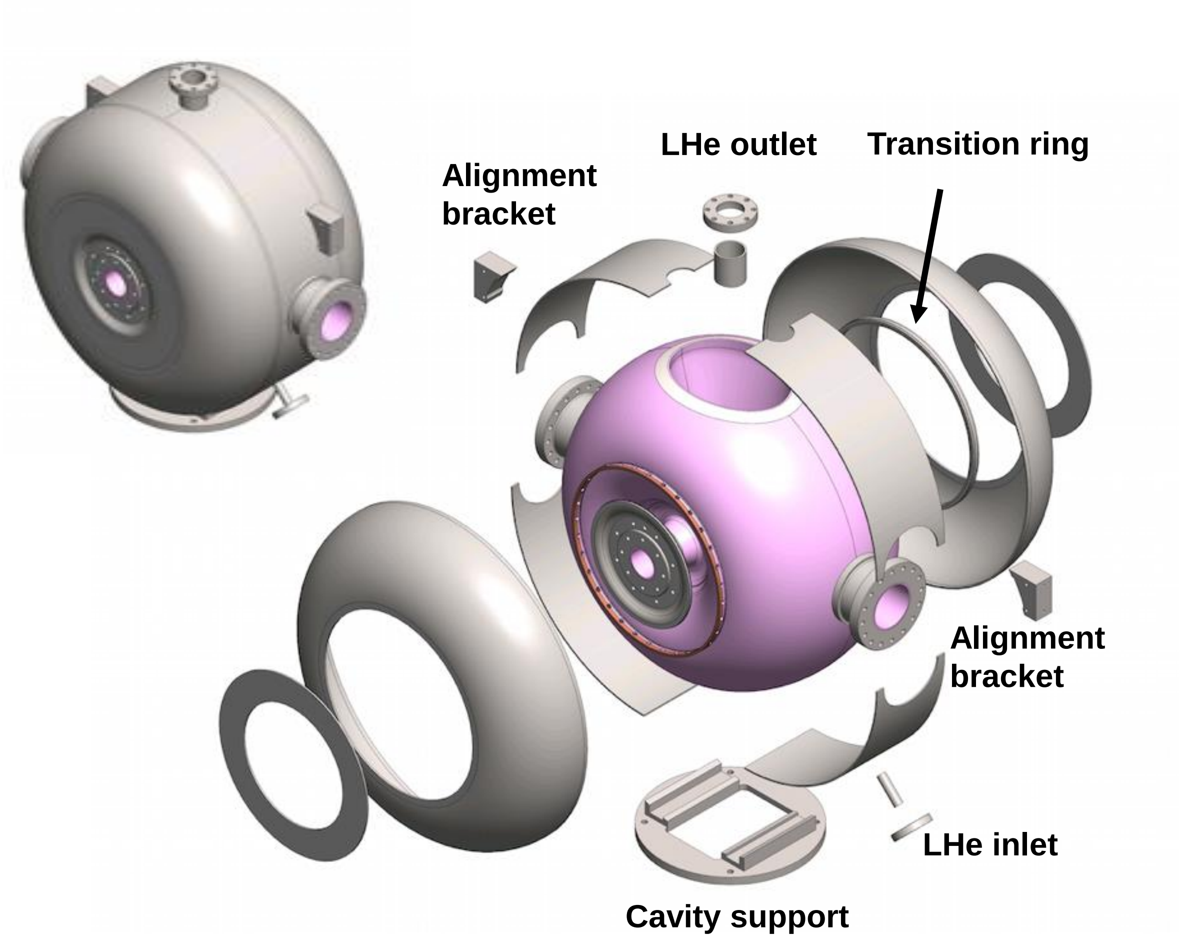
Multipacting conditioning time

- Conditioning time < 2 hours
- Baking before cooldown reduces MP conditioning time by ~50%
- Two recipes
  - 50~60 ºC for several hours
  - 120 ºC for 48 hours
- CW conditioning at over coupling and ~10 W RF power

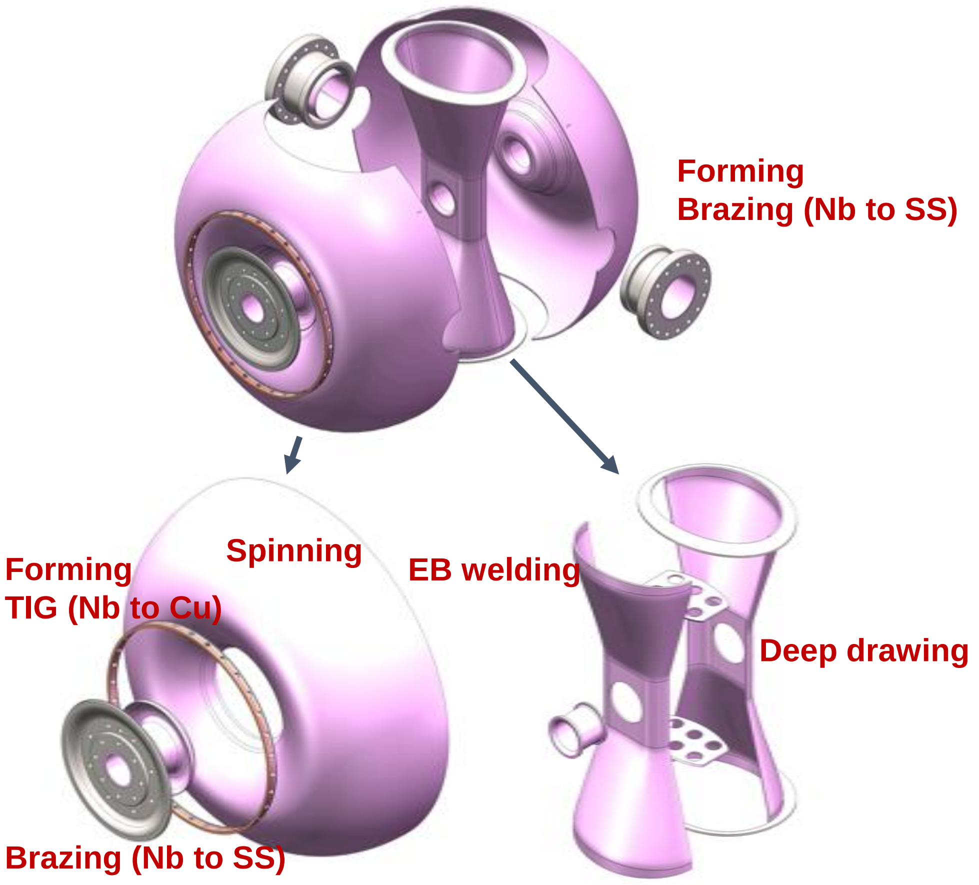


Engineering Design

Jacketed cavity

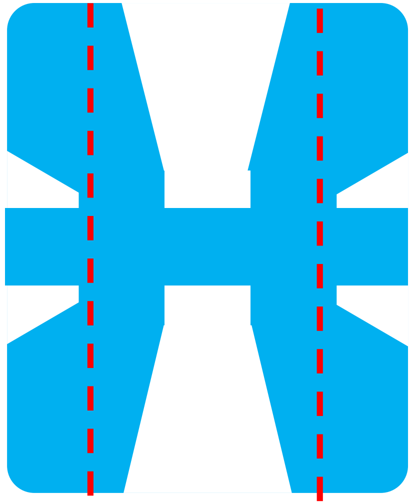


Bare cavity

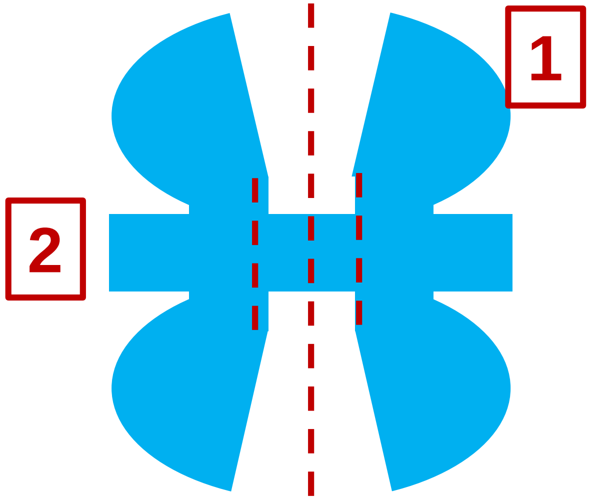


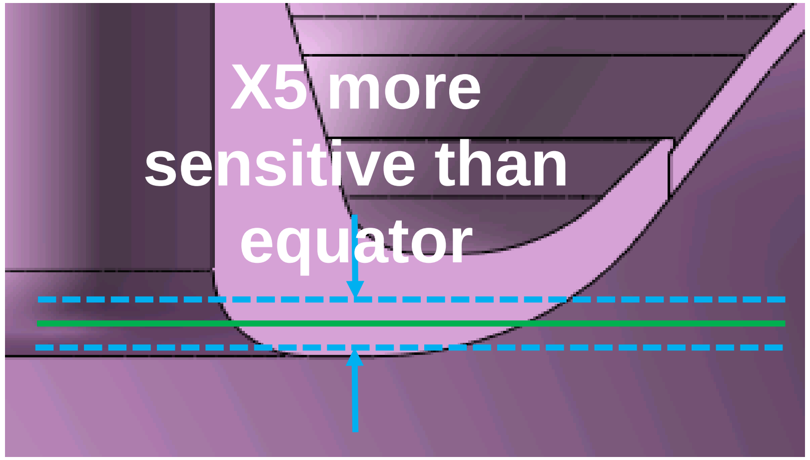
Frequency Control

Conventional

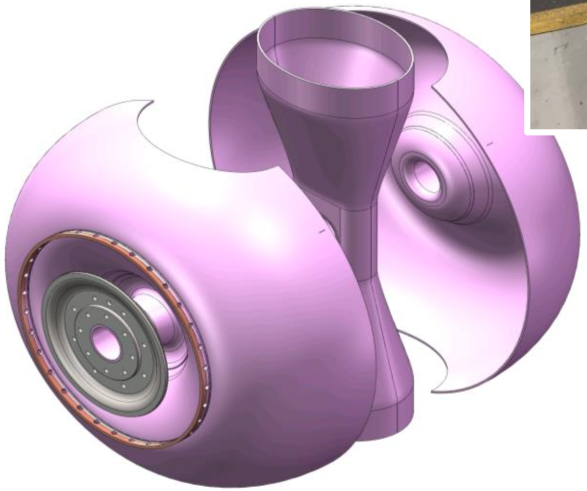


Balloon

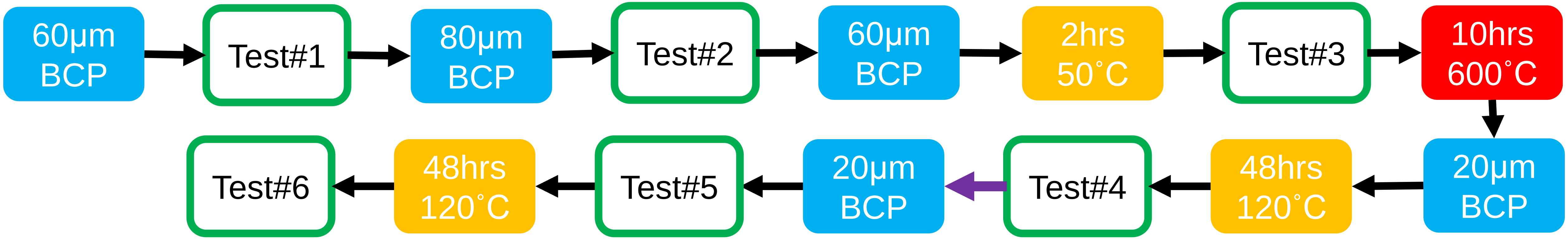


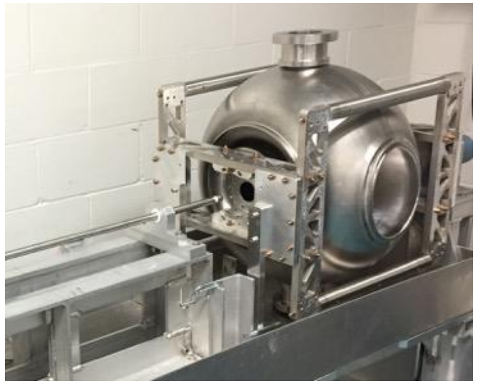


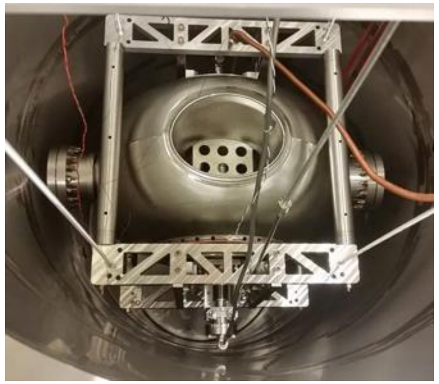
Trim grounded nose cone (not equator) to tune cavity

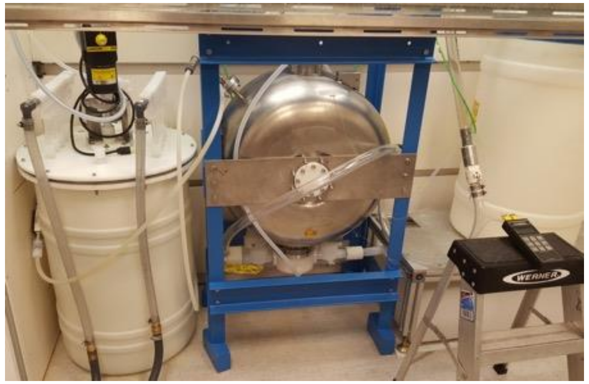


Cavity#2 Processing and Cryogenic Tests









Unjacketed Cold Test – R_{BCS} and R_0

- Total etching depth of 220 µm
- The base residual resistance is 5nΩ – due to background field (35mG) from new cryostat
- 2K Q-curve has a pronounced Q-slope in the medium field range due to the significant field dependence on residual.
- Cavity quench limits the cavity gradient at 10.3 MV/m, corresponding to a nominal peak magnetic field of 63 mT.
- Surface defects in the form of either geometry or inclusions are suspected.