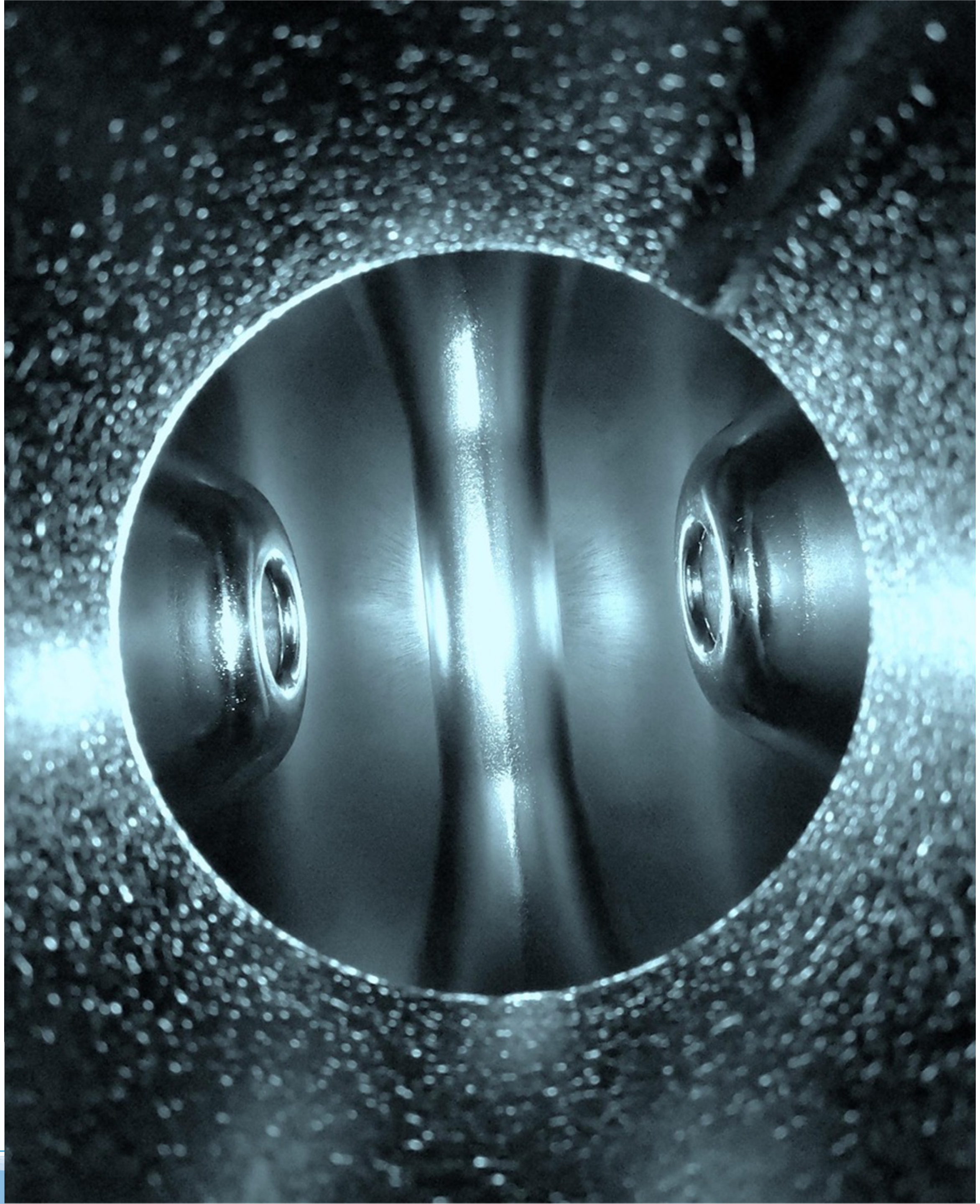
TRIUMF

Balloon Single Spoke Resonator - A New SSR Variant for Reduced Multipacting

R.E. Laxdal, Z. Yao

TRIUMF

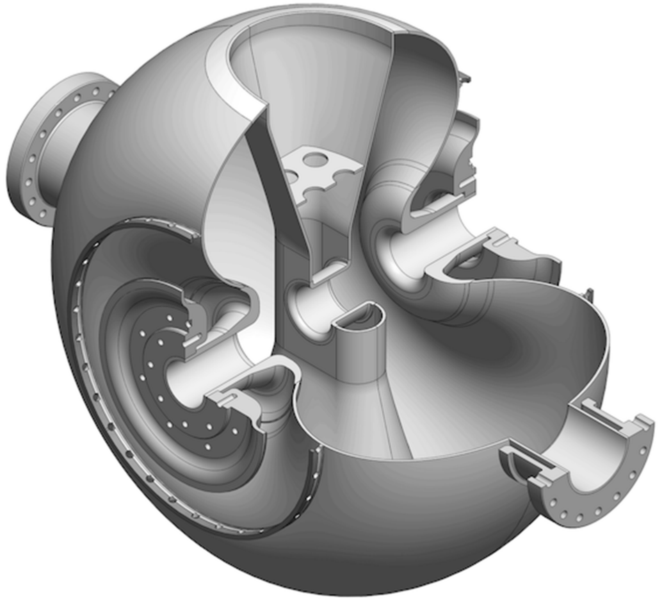
July 5, 2019

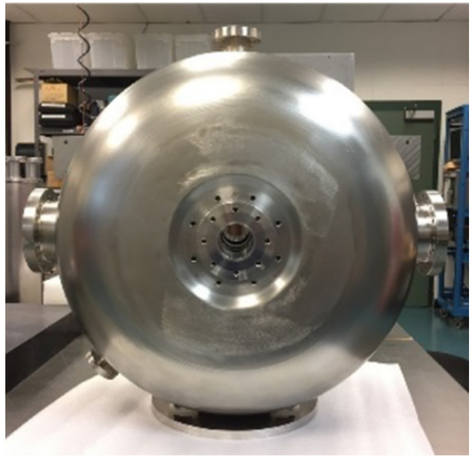


Discovery, accelerated

Outlines

- Balloon Concept
- RISP SSR1 prototype cavity
- Cavity Design
- Cavity Fabrication
- Cavity Processing
- Cold Tests and Results
- Summary

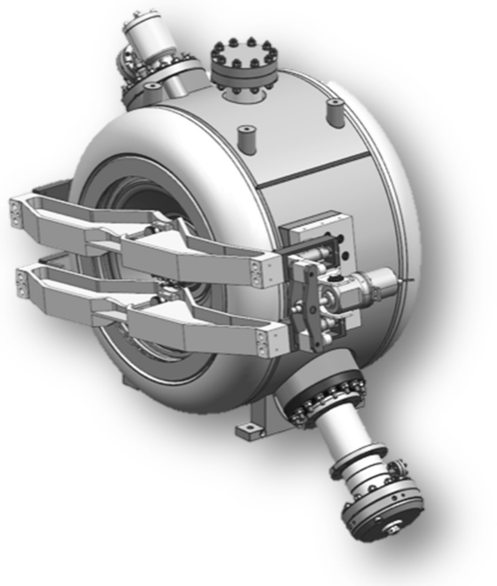


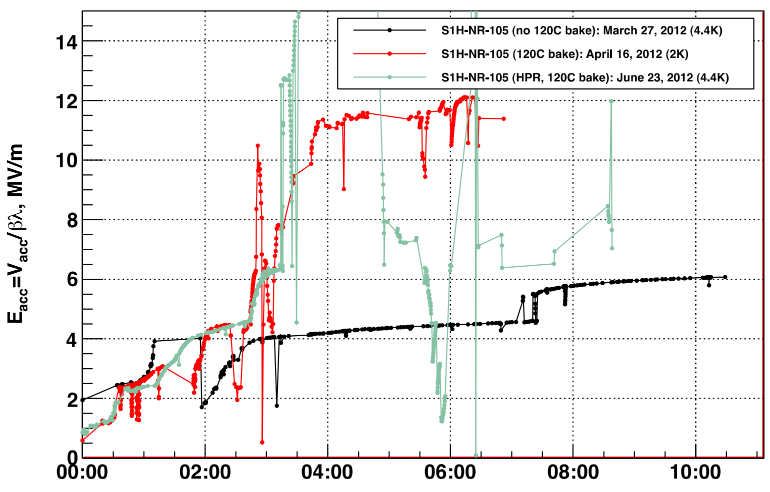


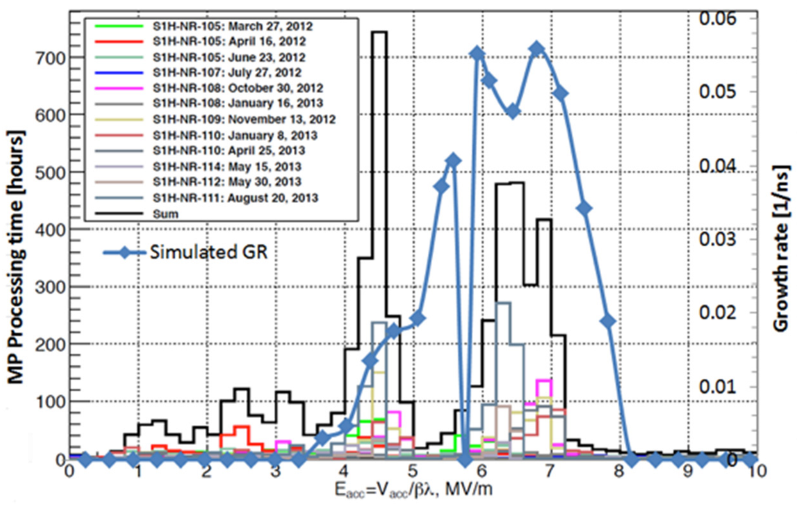
What is the Balloon Single Spoke Resonator?

Multipacting in Spoke Cavity

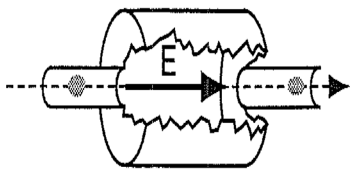
325MHz beta=0.22 SSR1 Leonardo Ristori, TTC2016



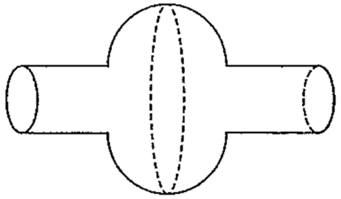




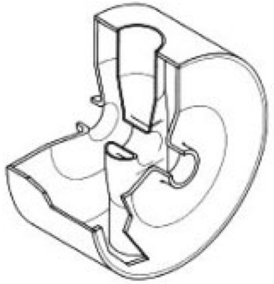
Pillbox



Elliptical



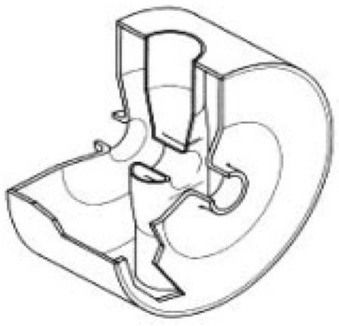
Spoke Cavity



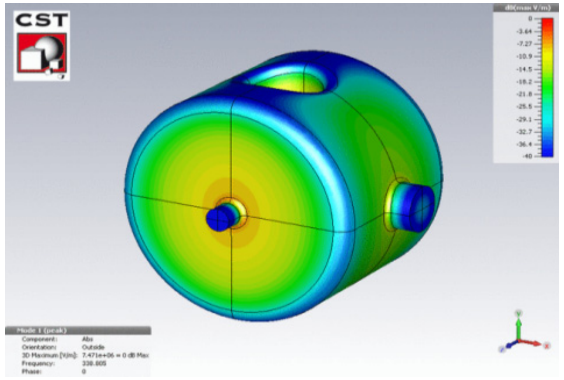
U. Klein, D. Proch, Proc. of the Conference on Future Possibilities for Electron Accelerators, N1-17 (1979).

Balloon Concept

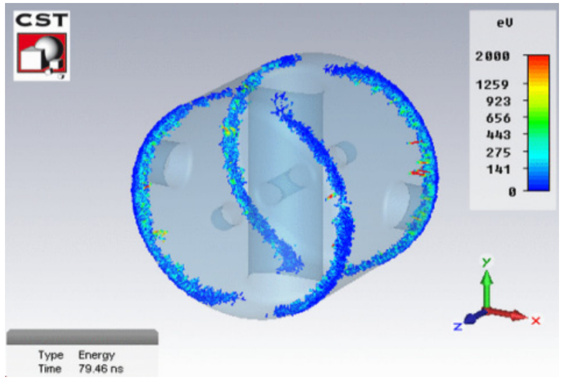
Traditional Spoke Cavity



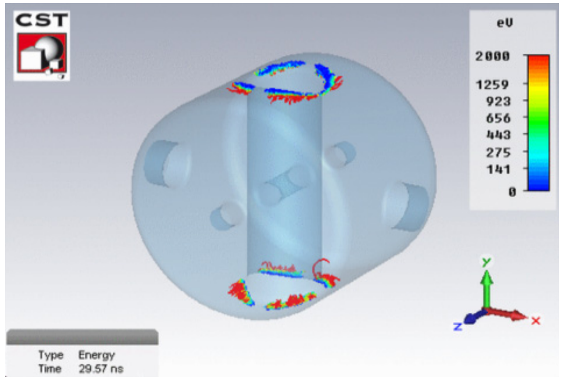
Pillbox + Spoke



Higher orders

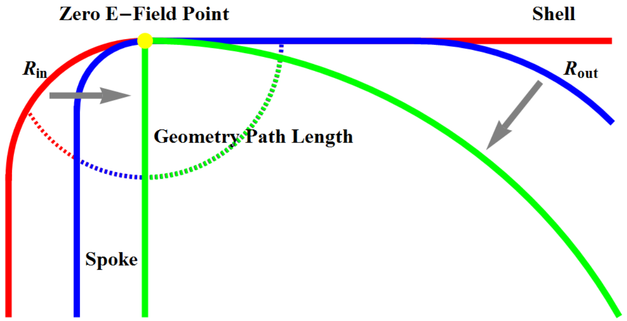


1st order



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.



Higher orders

$$\mathcal{E}_{impact} \propto n\left[\left(\frac{E_{local}}{E_{acc}}\right)^2\left(\frac{H_{local}}{E_{acc}}\right)^2\right]E_{acc}^4$$

1st order

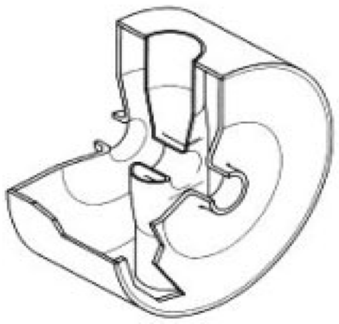
$$\mathcal{E}_{impact} \propto E^a H^b$$
$$1.5 < b/a < 2$$

Phenomenological theory

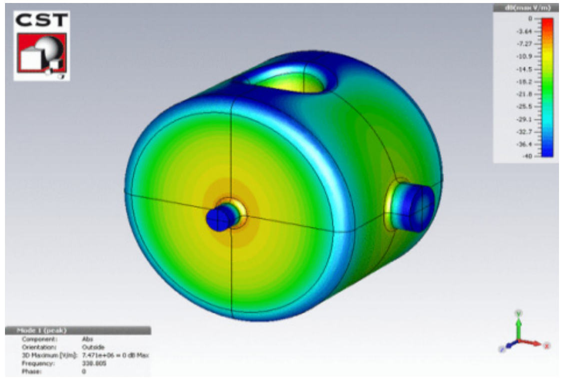
Z.Yao, et al, `Balloon variant of single spoke resonator', submitted for publication

Balloon Concept

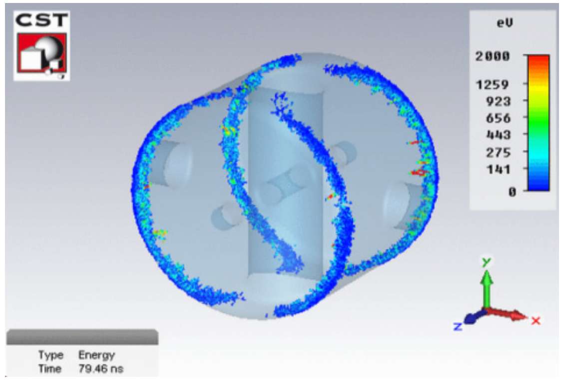
Traditional Spoke Cavity



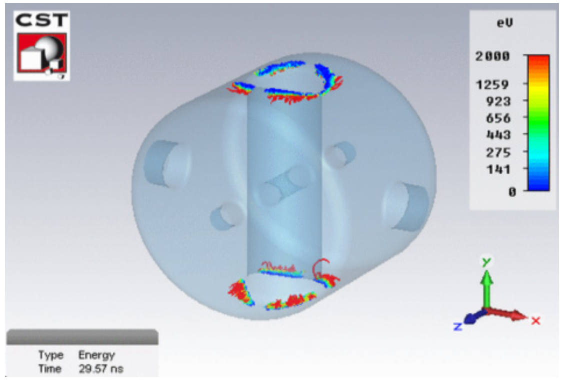
Pillbox + Spoke



Higher orders



1st order



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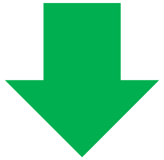
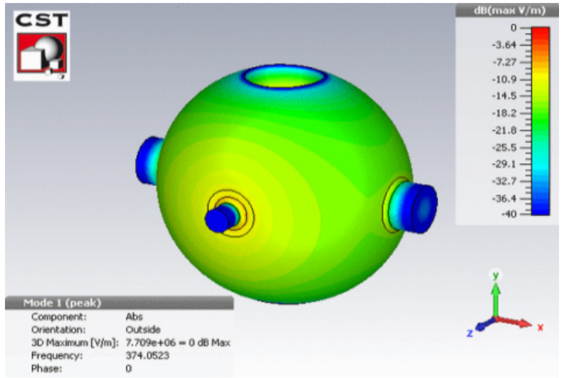
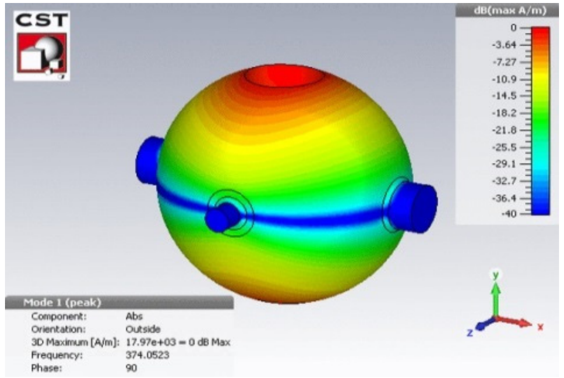
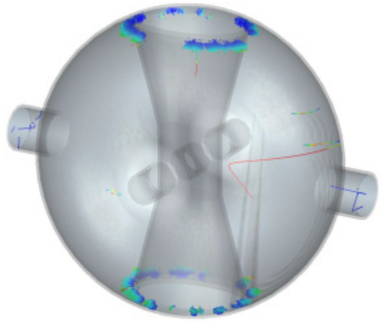


Balloon



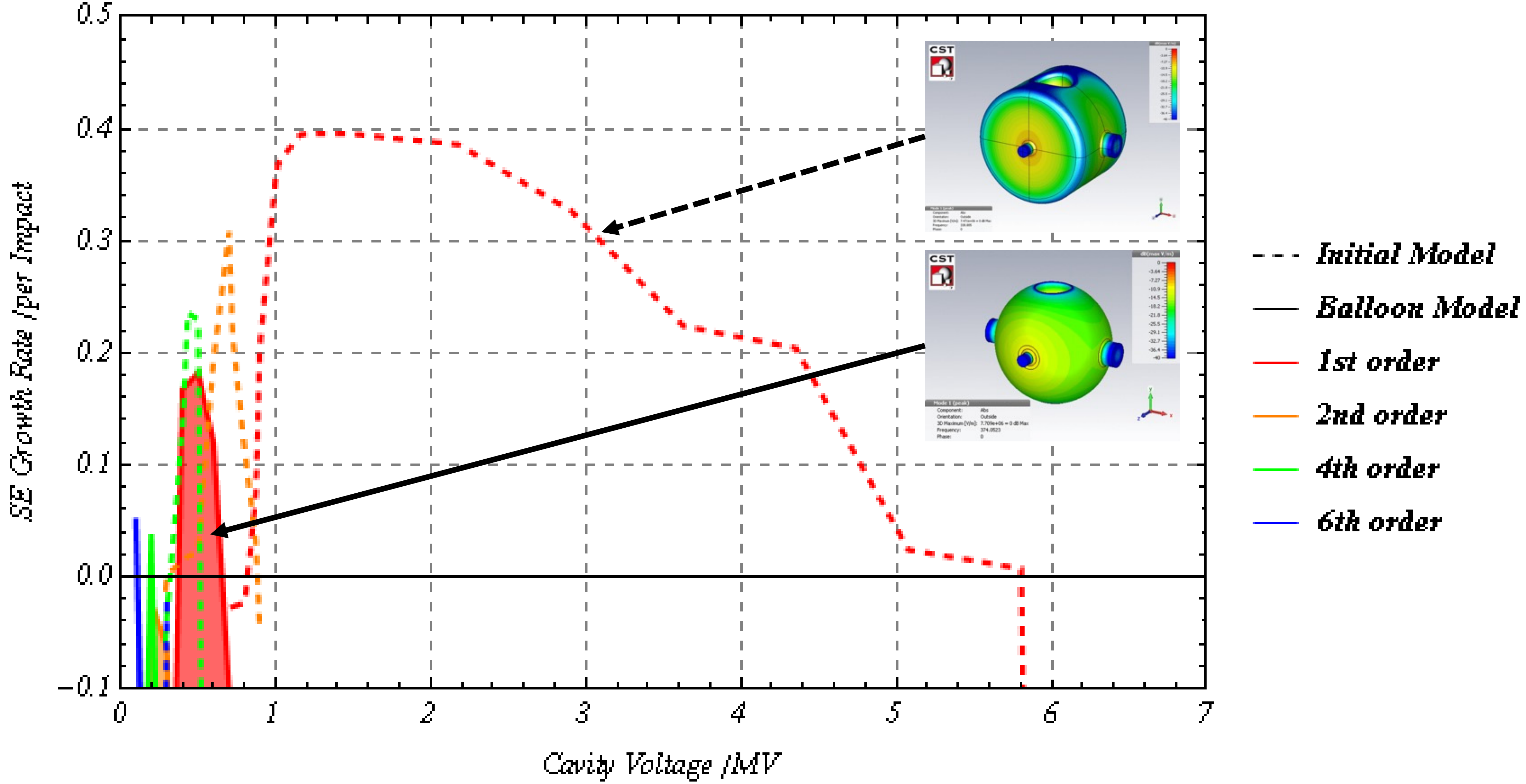




Balloon + Spoke

Z.Yao, et al, `Balloon variant of single spoke resonator', submitted for publication

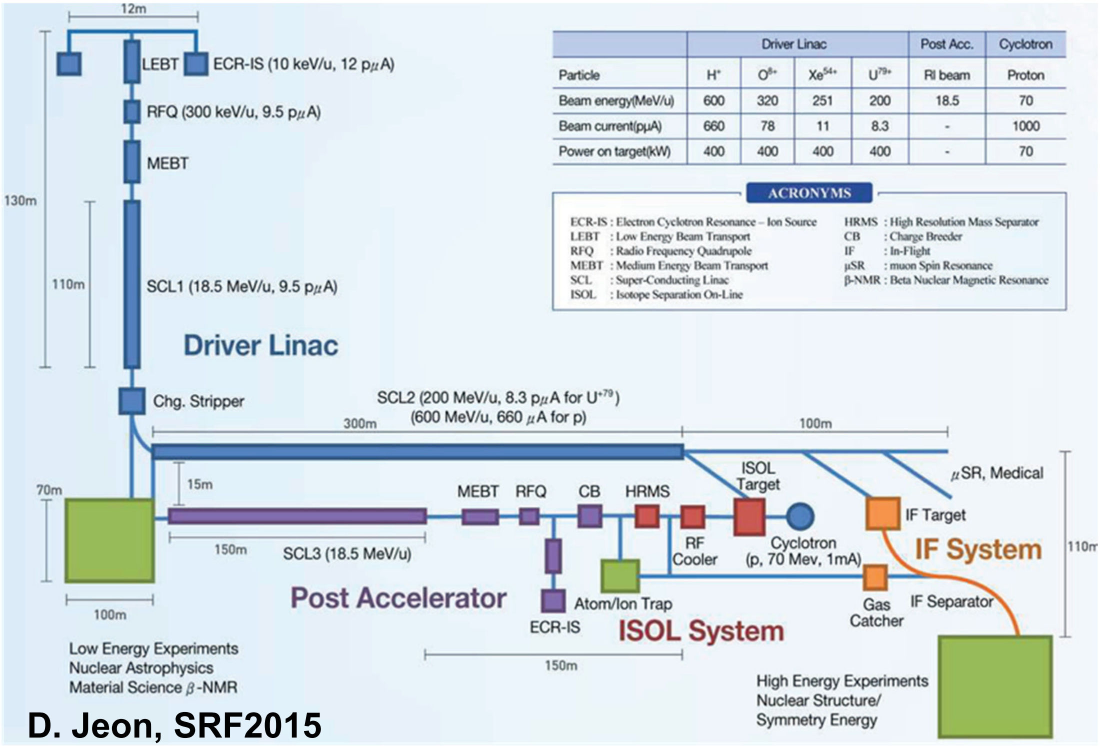
Comparing MP in Traditional SSR and Balloon SSR



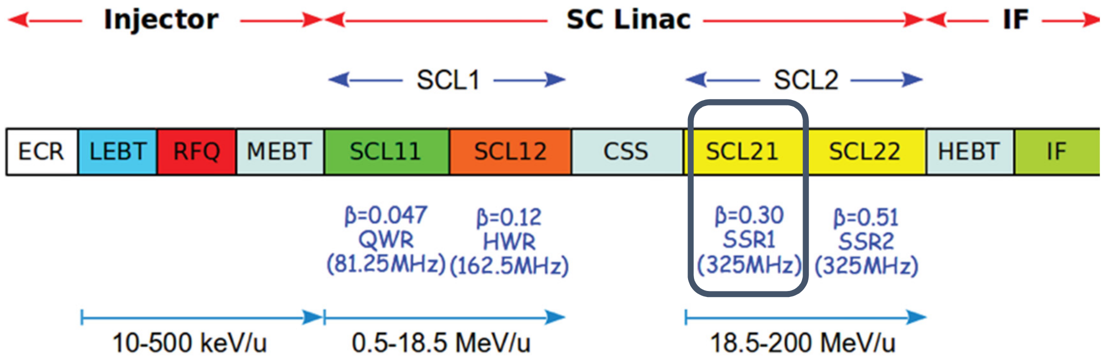
RISP SSR1 Cavity

MOFAB3 H.C. Jung

RISP SSR1 Cavity



D. Jeon, SRF2015



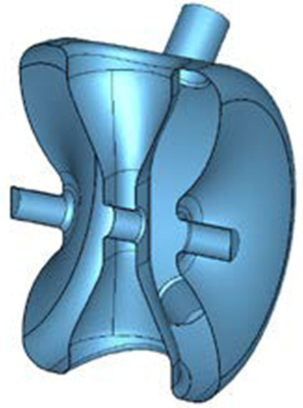
TRIUMF was commissioned to design, fabricate, and test balloon variant prototypes for RISP SSR1.

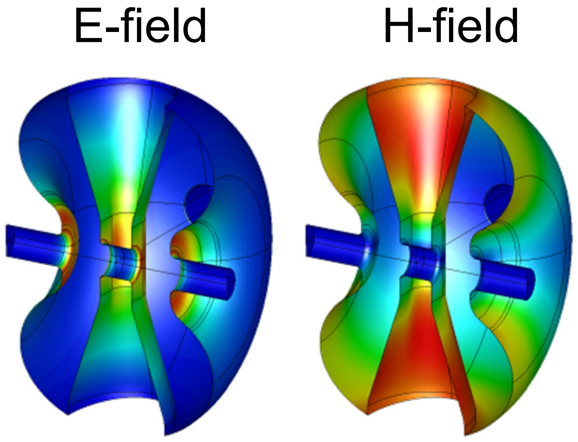
RISP SSR1 Specifications	
Operating frequency	325 MHz
Geometry β	0.30
Operating temperature	2K
Q_0	$>5X10^9$
E_{peak}	35 MV/m
V_{acc}	>2.5 MV
df/dp	<10 Hz/mbar
Frequency tuning range	±100 kHz
Q_{ext}	$8X10^6$
RF bandwidth	40 Hz
Beam aperture	50 mm
Pressure envelop at 300K	2 bar
Pressure envelop at 2K	5 bar

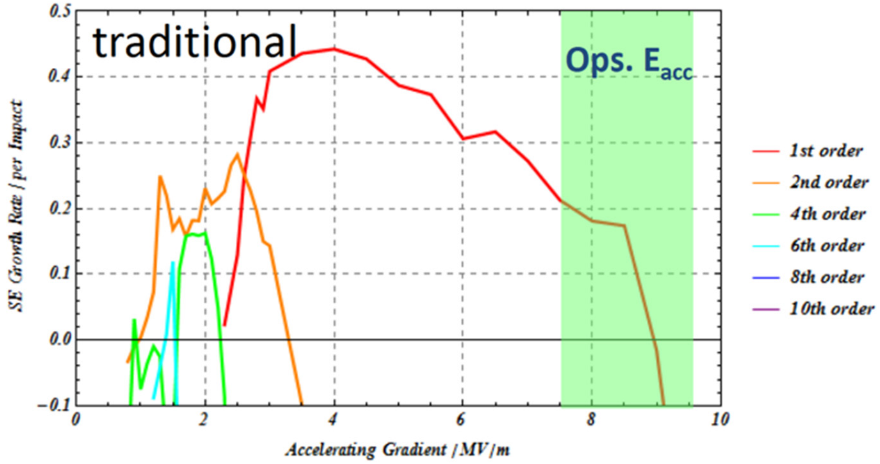
SSR1 Traditional Design vs Balloon Design

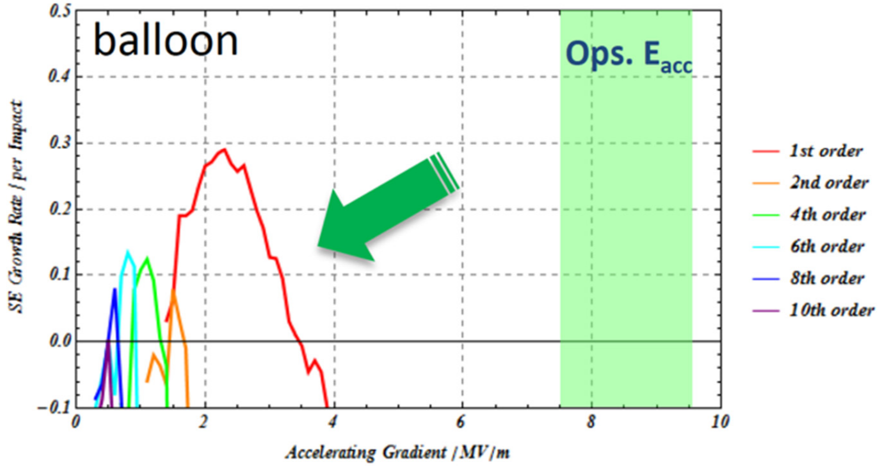
- TRIUMF redesigned SSR1 traditional design to balloon variant
- Very similar RF performance in terms of basic parameters with balloon having slightly higher Veff and lower B peak
- Main difference – MP barriers pushed to low fields away from operating gradient

SSR1 Design	Traditional (RISP)	Balloon (TRIUMF)
Frequency (MHz)	325	325
Geometry β	0.3	0.3
Geometry Factor (Ω)	93	93
R/Q (Ω)	229	233
Epeak/Eacc	3.96	3.84
Epeak (MV/m)	**35**	**35**
Bpeak/Eacc (mT/(MV/m))	**6.46**	**6.07**
Bpeak (mT)	57.1	55.3
Veff (MV)	2.45	2.52
Diameter (mm)	525	570





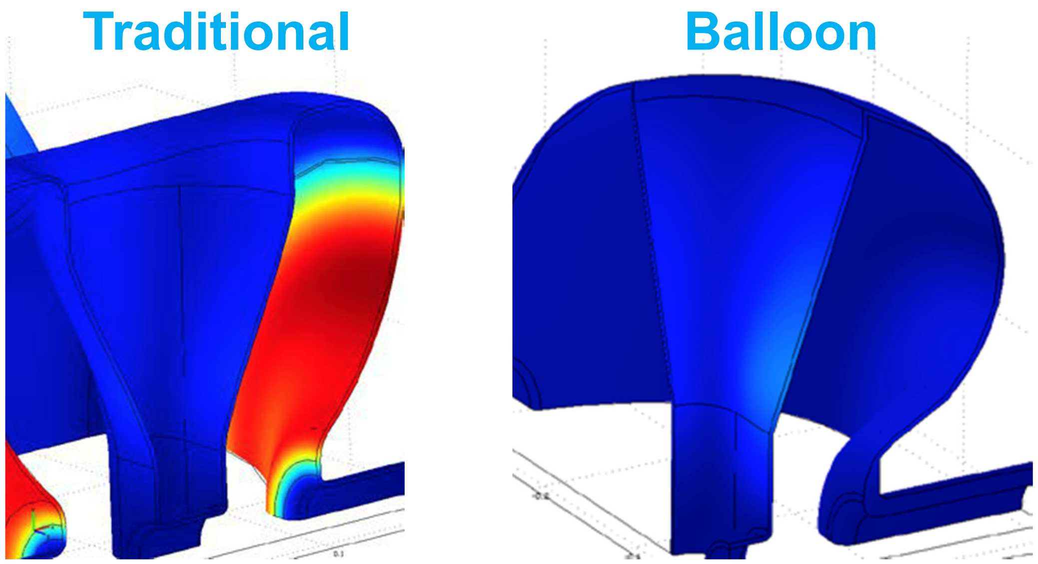




Mechanical Design - I

- The Bare Balloon cavity is inherently more rigid mechanically (sphere vs drum)
  - Lower natural df/dp - easier to minimize
  - Fewer stiffeners are required – cheaper fabrication costs

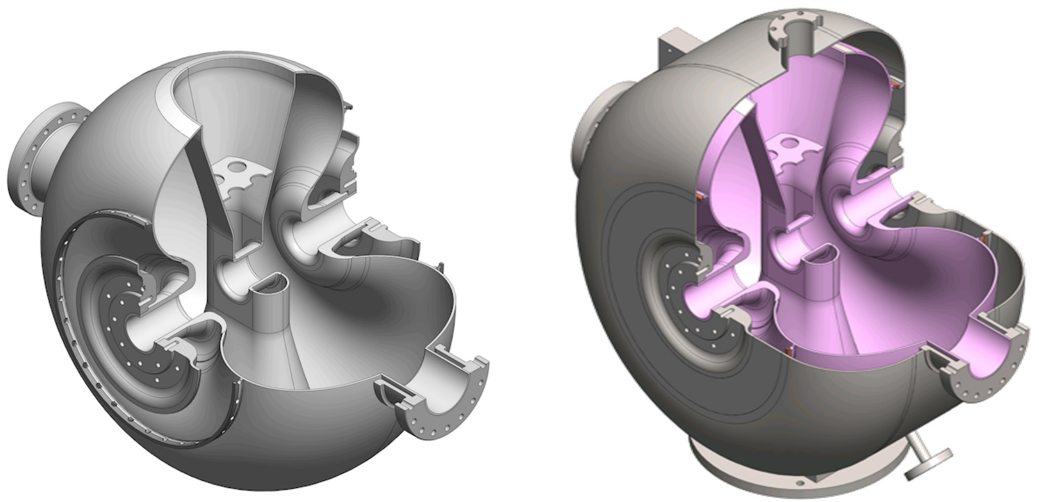
Parameters	Beam Pipes C.	Baseline	Balloon	Unit
Internal Stress @1bar pressure	Fixed	323	49	Mpa
	Free	150	99	
df/dp	Fixed	-145	-16.5	Hz/mbar
	Free	-1718	-1289	
LFD	Fixed	-4.5	-2.1	Hz/(MV/m)^2
Tuning	N/A	300	545	kHz/mm
	N/A	2.1	3.3	kN/mm
	N/A	67.3	85.5	MPa/mm



The deformations of both designs under 1bar external pressure load. The color ranges are shown in the same scale.

Mechanical Design - II

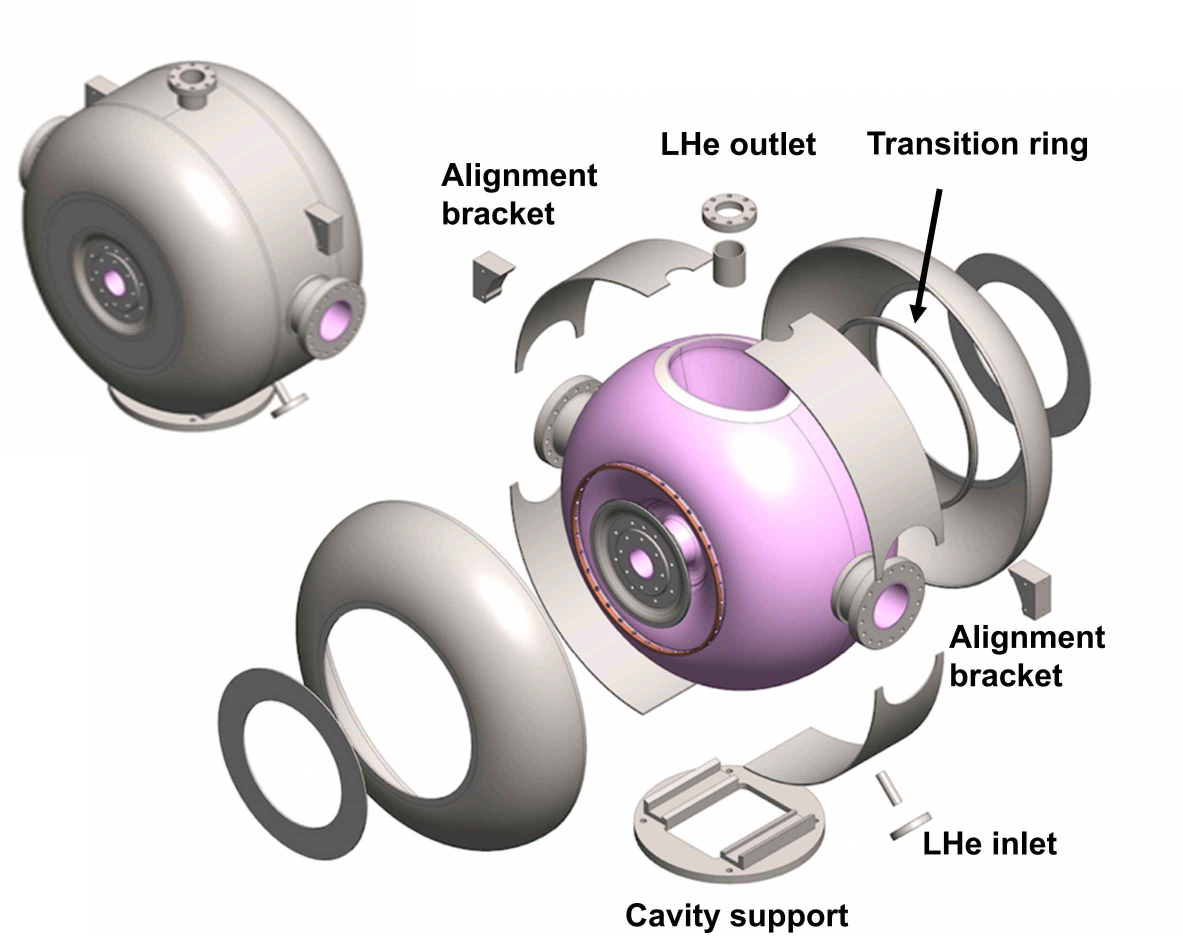
- Design complies with ASME guidelines
  - Only requires spoke reinforcing plates and two stiffener rings on shell
- To minimize pressure sensitivity
  - Ring stiffeners are attached to jacket on only one side
  - End shell geometry of helium jacket adds compensation



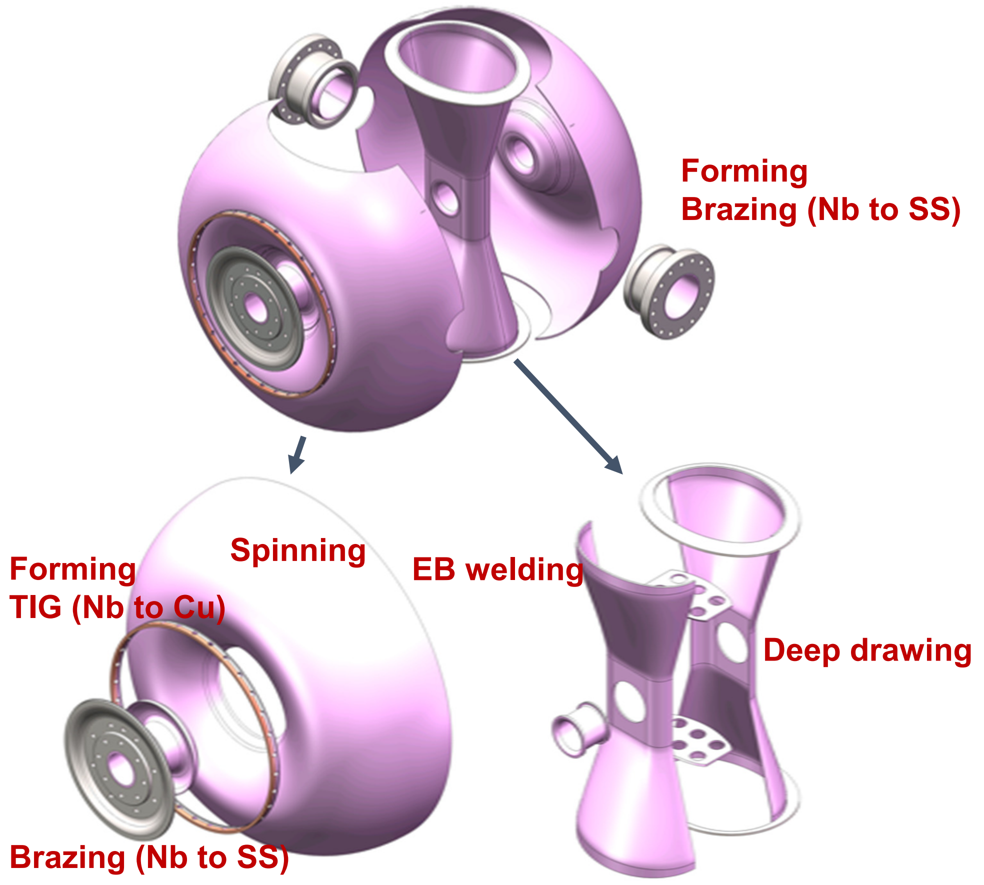
Parameters	Beam Tube	Value
df/dp /Hz/mbar	free fixed	-1.6 +1.5
LFD /Hz/(MV/m)^2	free fixed	-8.7 -1.4
Tuning sensitivity		467 kHz/mm 32.7 kHz/kN

Engineering Design

Jacketed cavity



Bare cavity

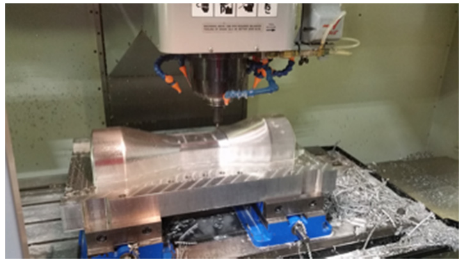


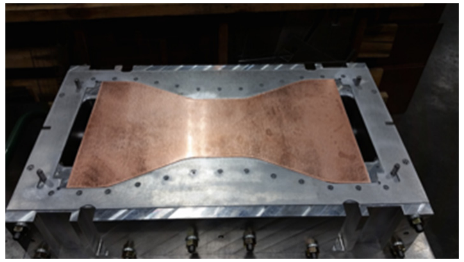
Shell subcomponent **Spoke subcomponent**

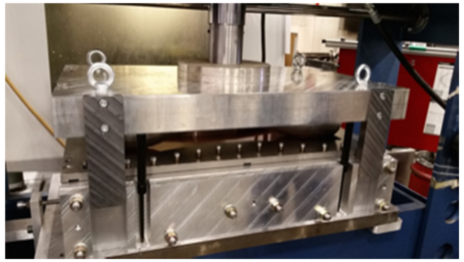
Cavity Fabrication

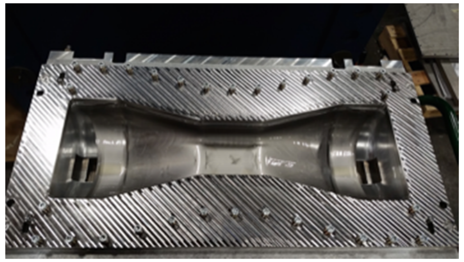
Spoke Forming

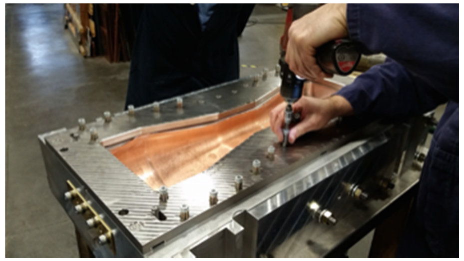
- Spoke forming die was developed and fabricated at TRIUMF.
- Deep drawing was completed in TRIUMF shop
  - Die tested in copper first
  - Die shape was good. No modification was required.
  - Niobium half spokes were then punched and machined.





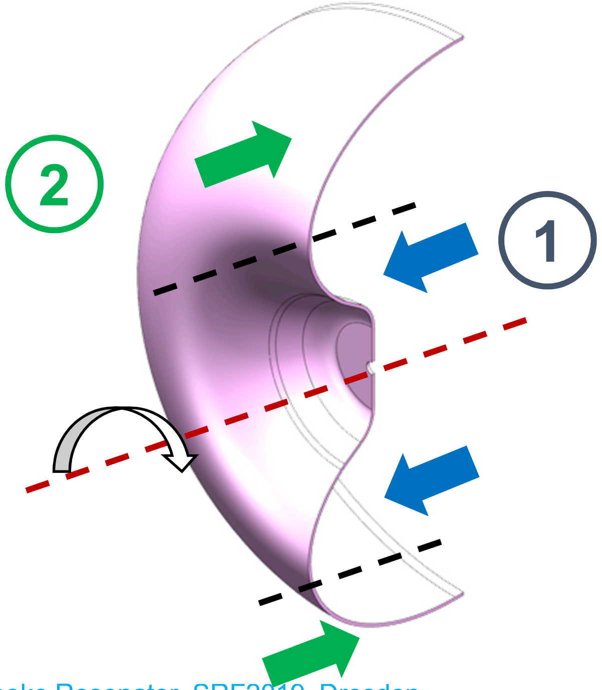






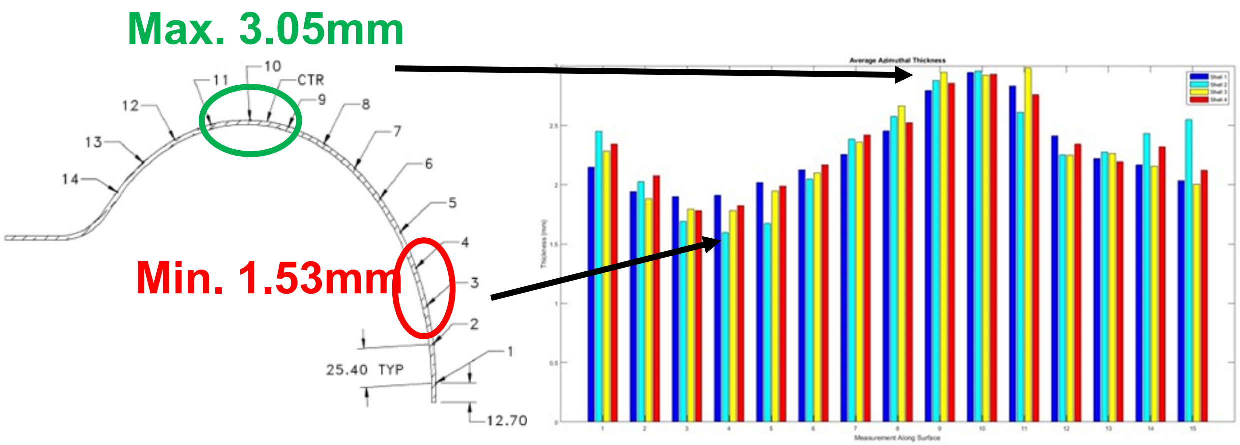
Shell Spinning

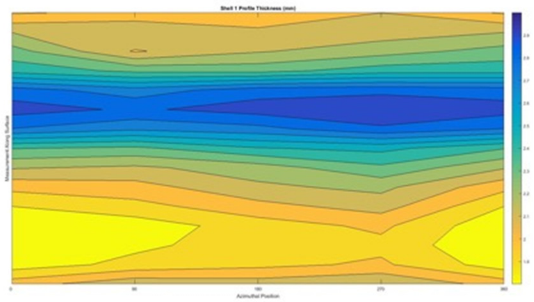
- Due to the size of the shell and hence the size of the required forming dies TRIUMF opted to form the shells by spinning
- 2-steps spinning for shell.
  1. Spin nose cone
  2. Spin outer shell
- Two Cu shells spun then moved to Nb shells.

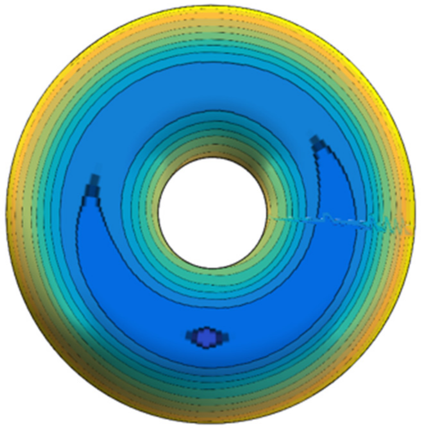


Shell Thinning

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

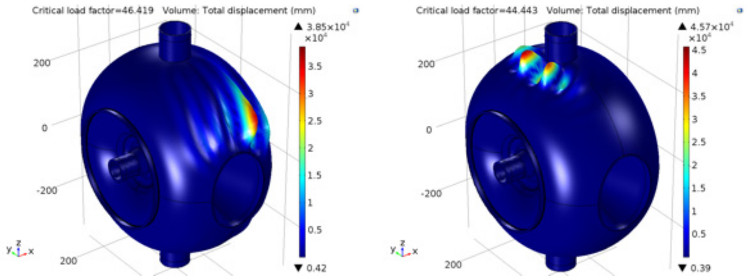






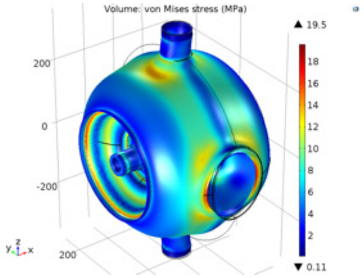
Analyze with real shell models

1. Linear buckling analysis



Critical load factors > 40

2. Pressure load analysis



Peak stress increases about 18%.

3. Pressure sensitivity check

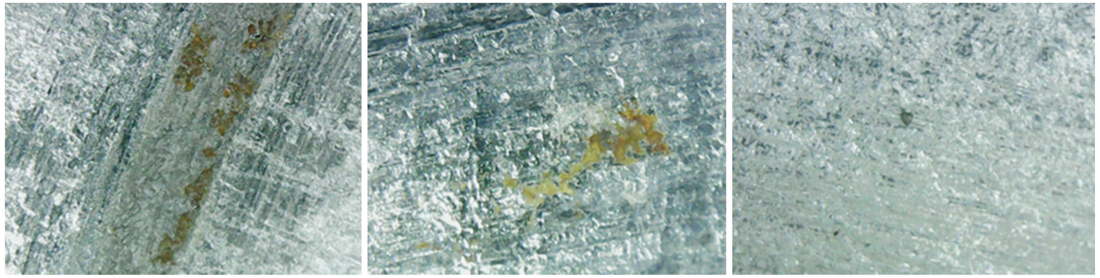
3mm thickness df/dp < ±2Hz/mbar → Real thickness df/dp < ±6Hz/mbar

Accepted by design specification

Inclusion Check

- Mechanical polishing completed at vendor
- TRIUMF checks
  - Salt water soak
  - Nitric acid clean (X2)
  - Ultrasound
  - 10um BCP both sides
  - Salt water soak
  - Ultrasound

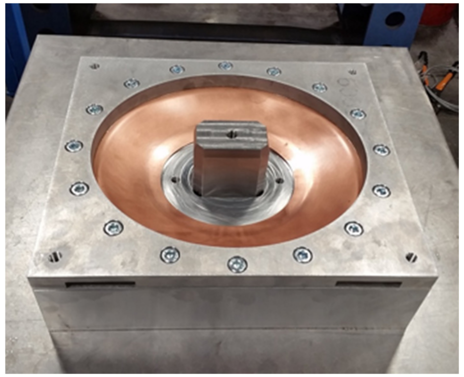
Rust spots



Post-BCP salted water soak

Other Parts

Collar forming



RF tubes, Beam tubes, SS flanges

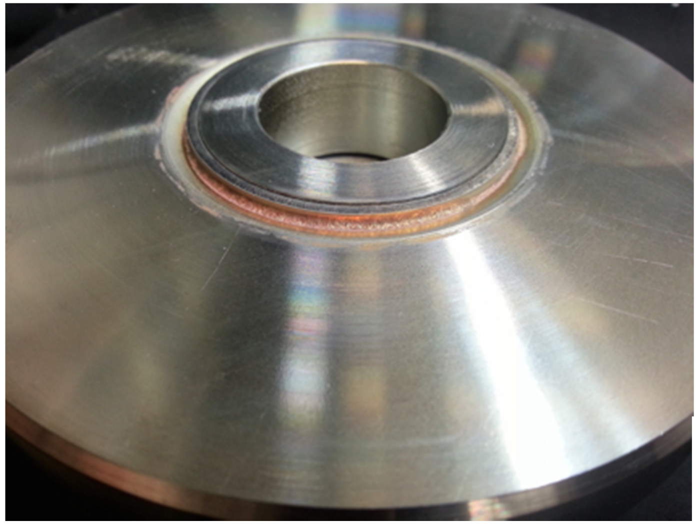
Nb-SS Brazing

Follow recipe from CERN, ATLAS and FNAL.

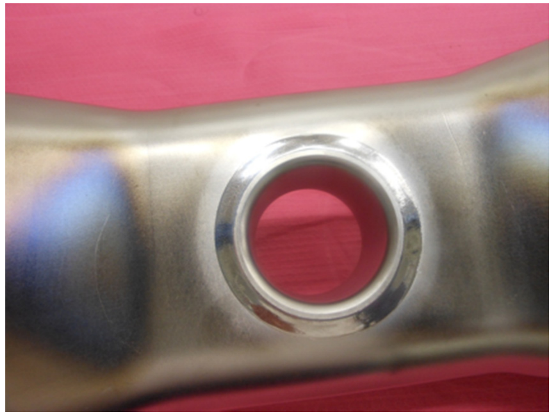
[1] J.P. Bacher, CERN/EF/RF 87-7.

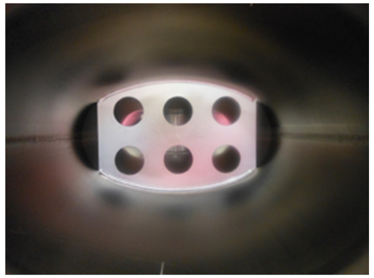
[2] J.D. Fuerst, TUP11, SRF2003.

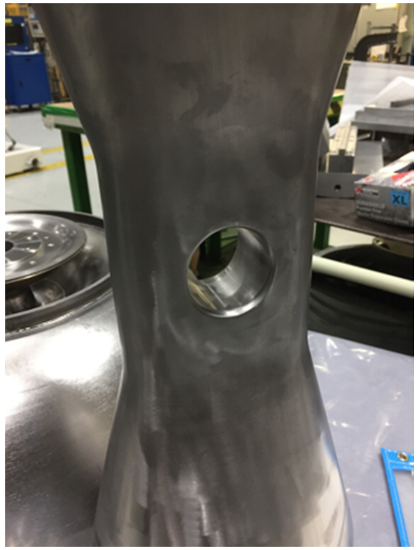
[3] L. Ristori, WEPPC058, IPAC2012.

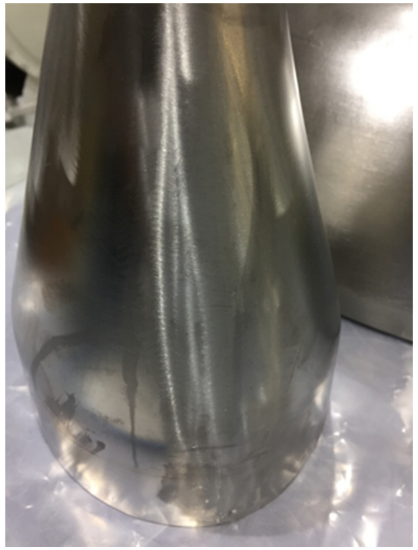


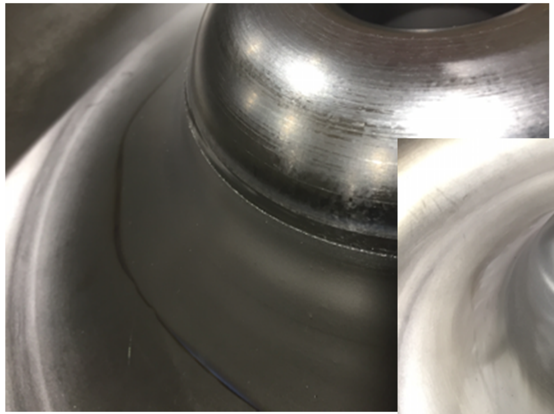
EB Welding

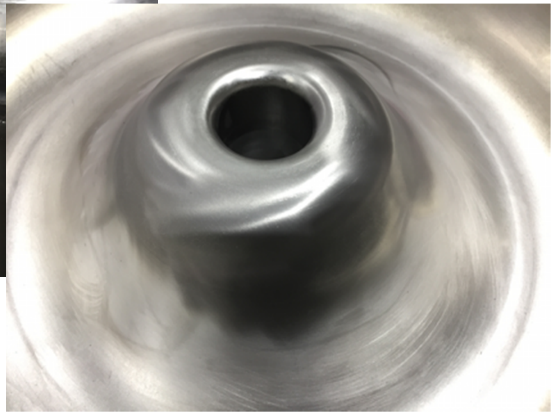






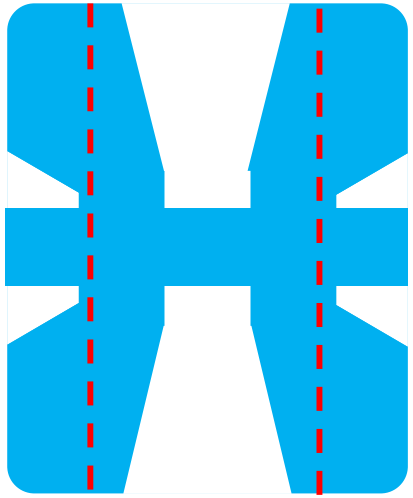




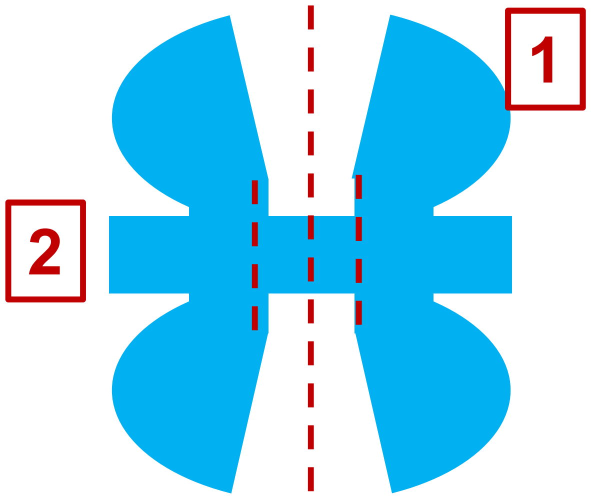


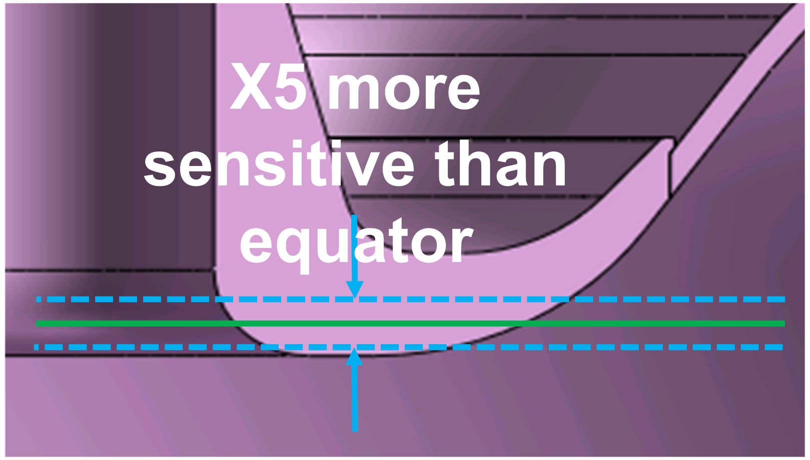
Frequency Control

Conventional



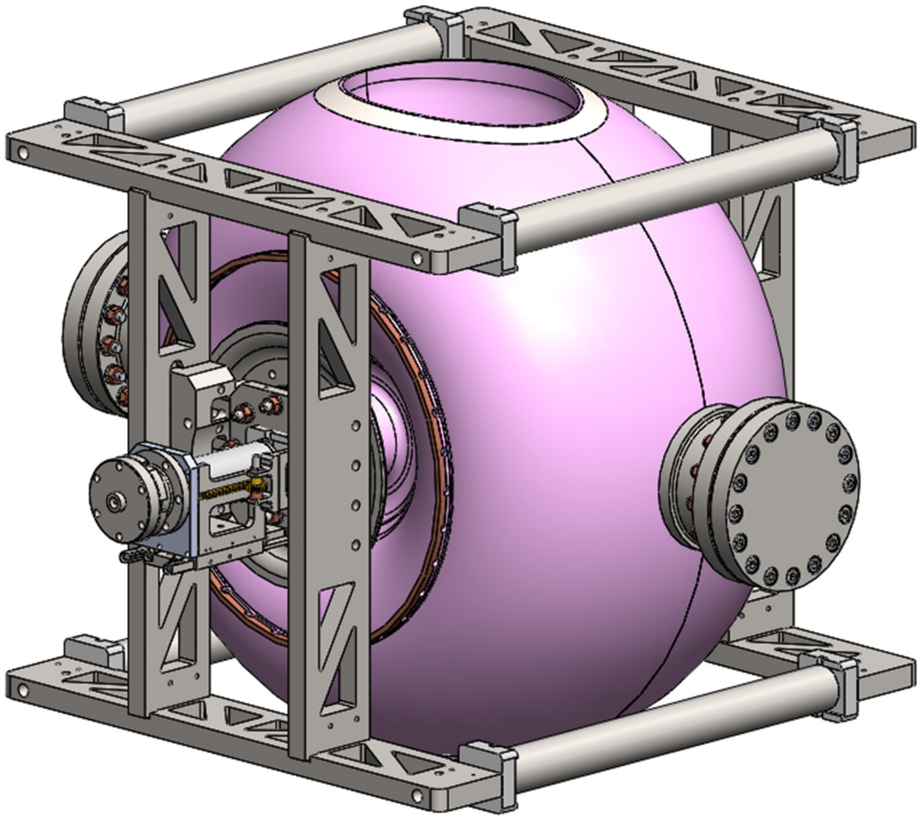
Balloon





Choose to trim grounded nose cone rather than equator

Unjacketed Cavity and Test Frame

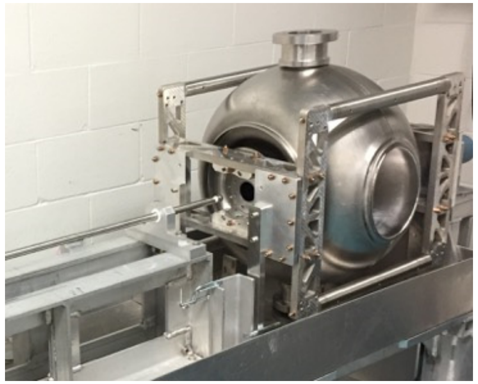
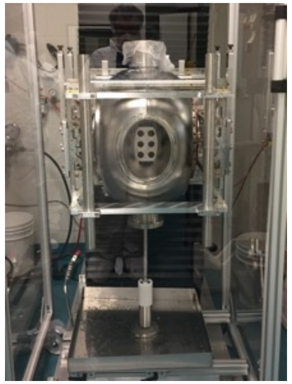


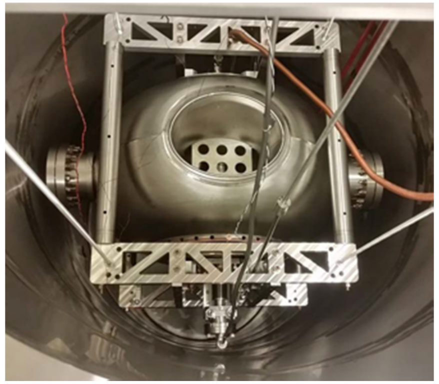
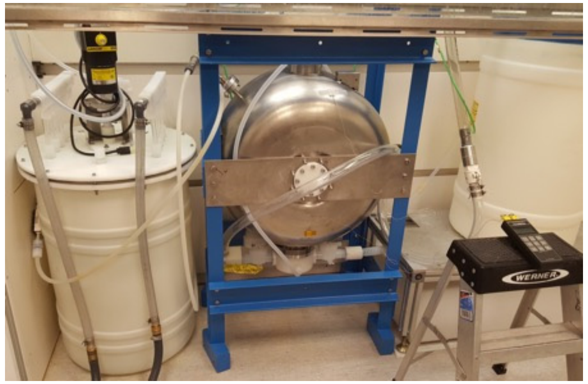
Cavity Processing and Cold Tests

Cavity#2 Processing and Cryogenic Tests

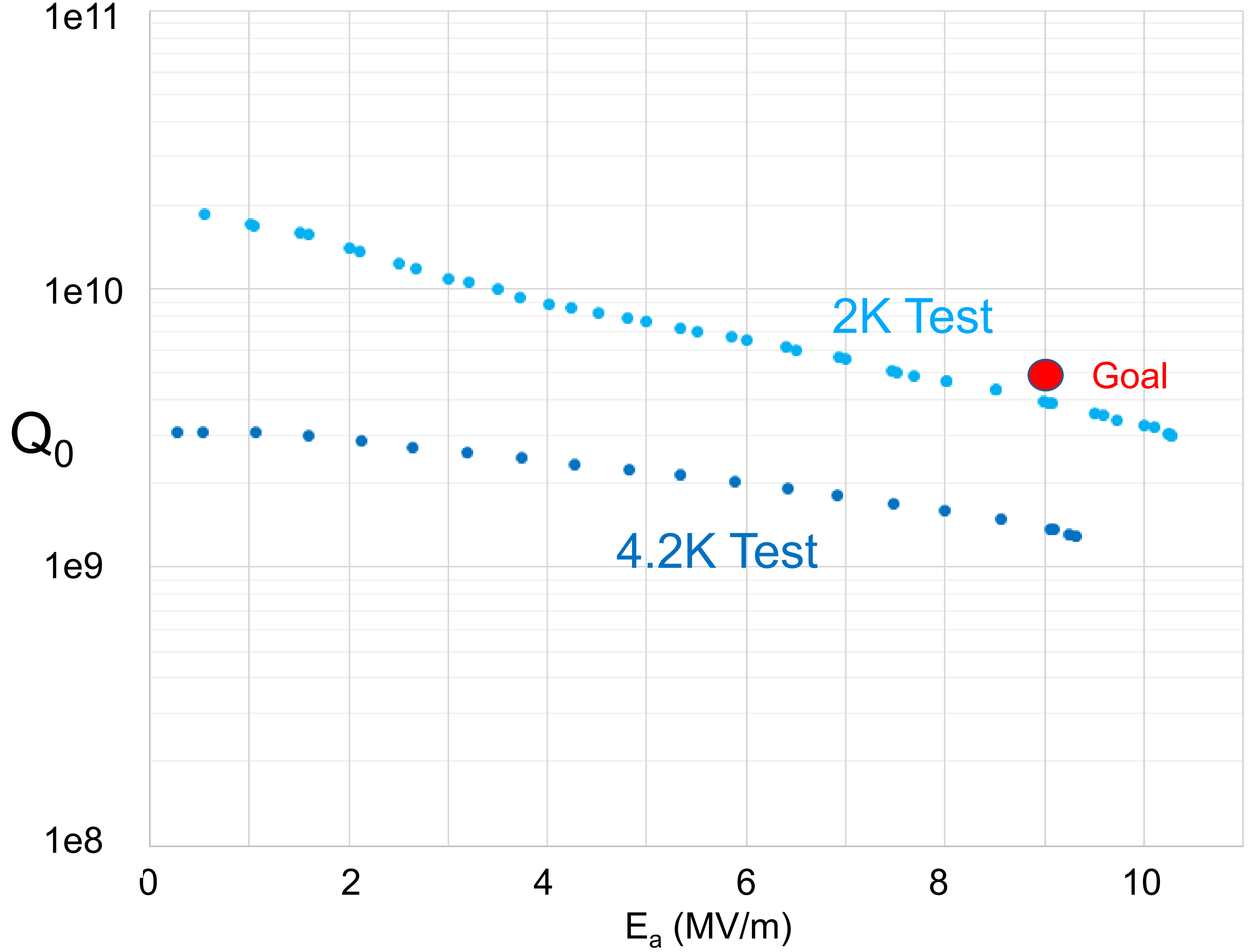
60µm BCP → Test#1 → 80µm BCP → Test#2 → 60µm BCP → 2hrs 50˚C → Test#3 → 10hrs 600˚C

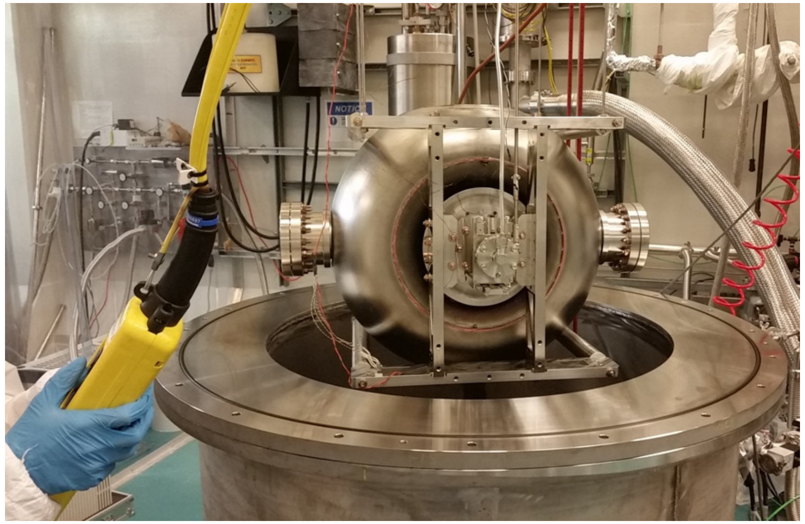
→ 20µm BCP → 48hrs 120˚C → Test#4 → 20µm BCP → Test#5 → 48hrs 120˚C → Test#6

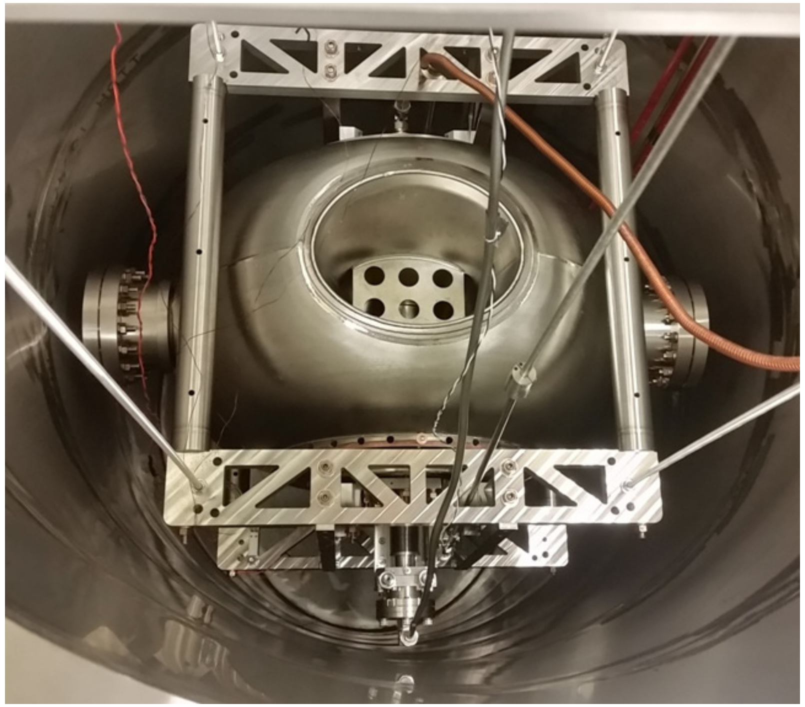



Unjacketed Cold test

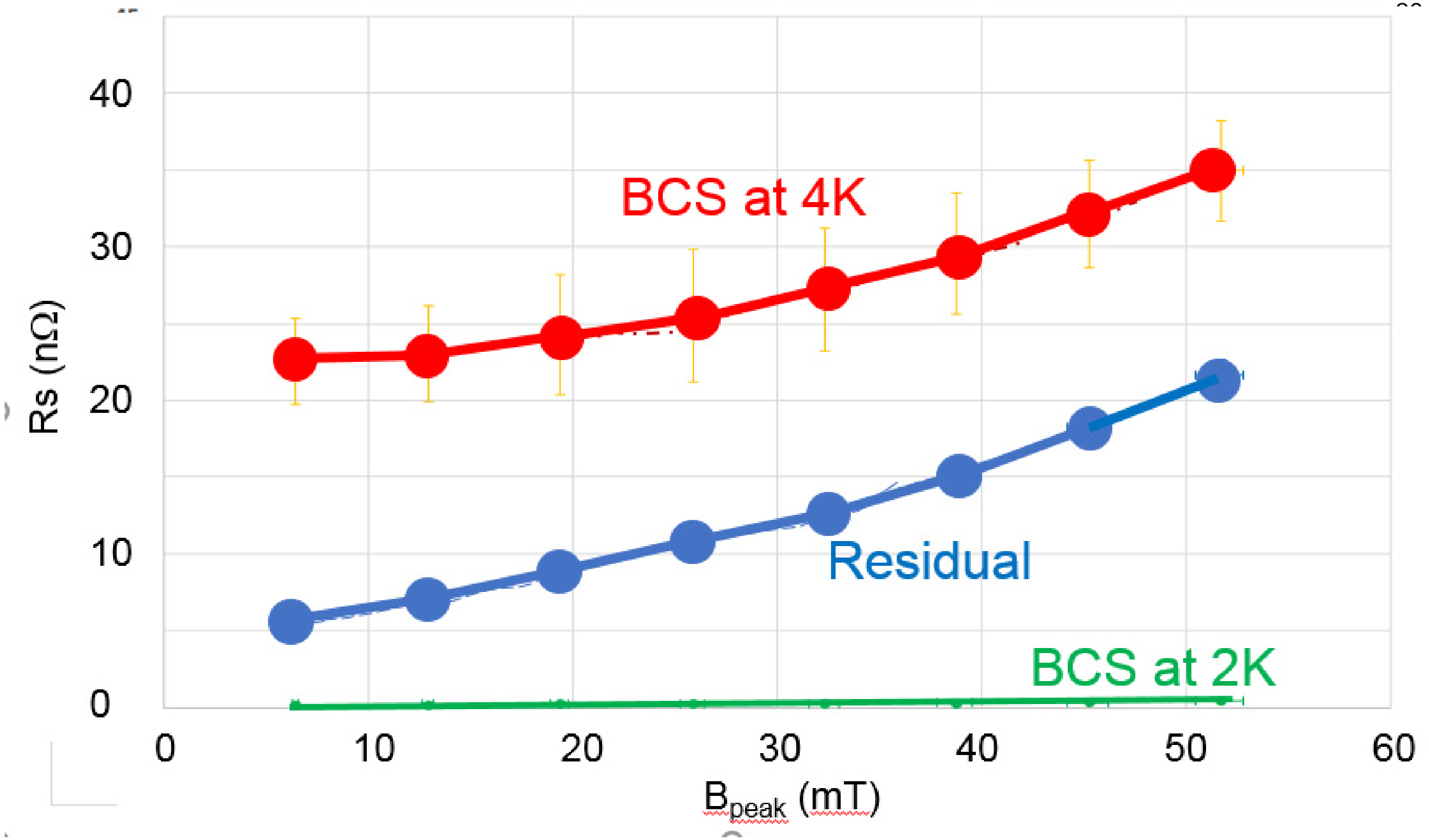






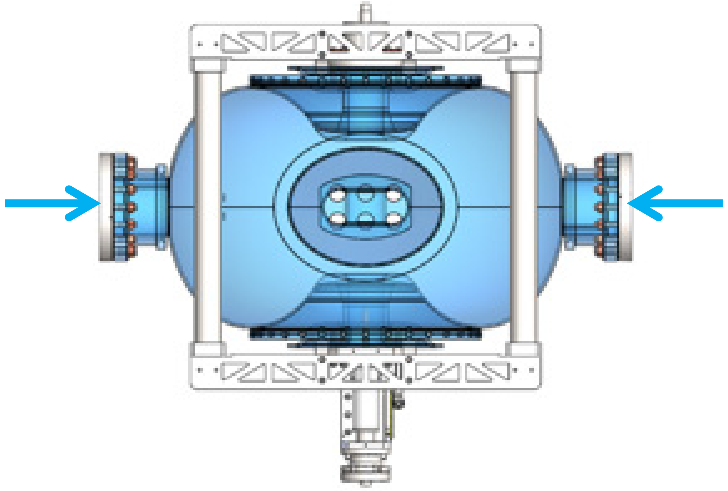
Unjacketed Cold Test – R_{BCS} and R_0

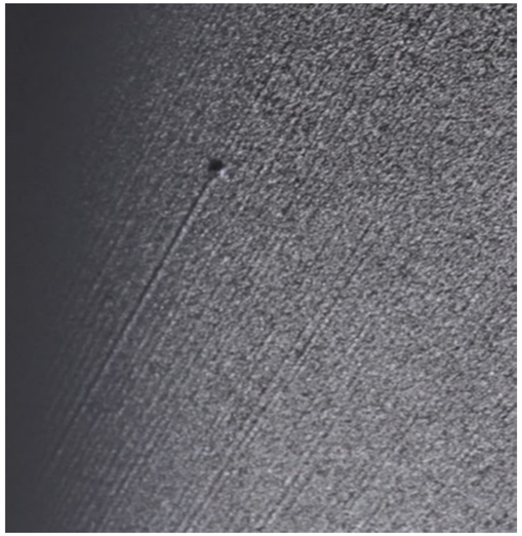
- Total etching depth of 220 µm
- The base residual resistance is 5nΩ – due to background field (35mG) from new cryostat
- 2K Q-curve has a pronounced Q-slope in the medium field range due to the significant field dependence on residual.
- Cavity quench limits the cavity gradient at 10.3 MV/m, corresponding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



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





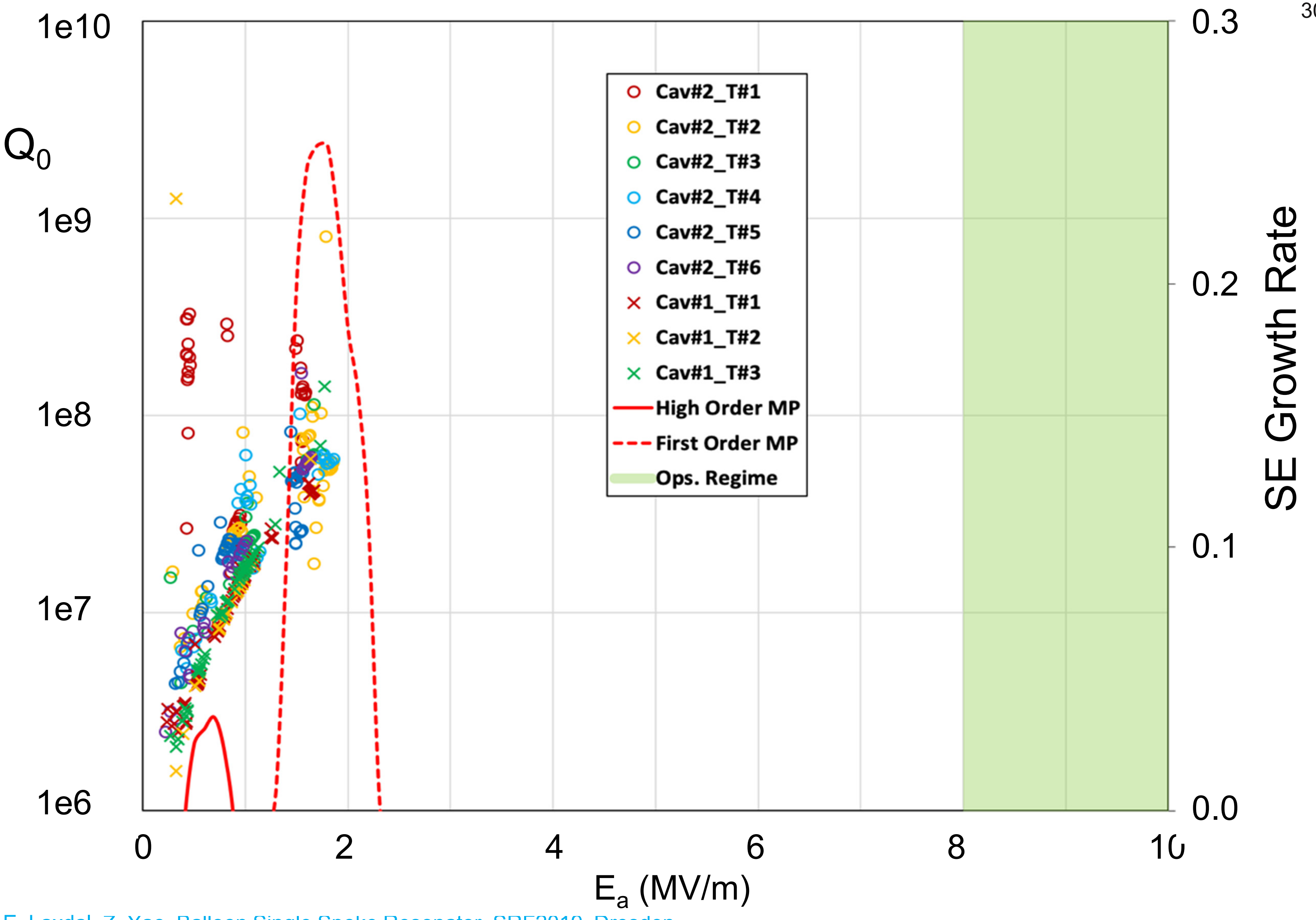
Jacketing at TRIUMF

- 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 behaviour

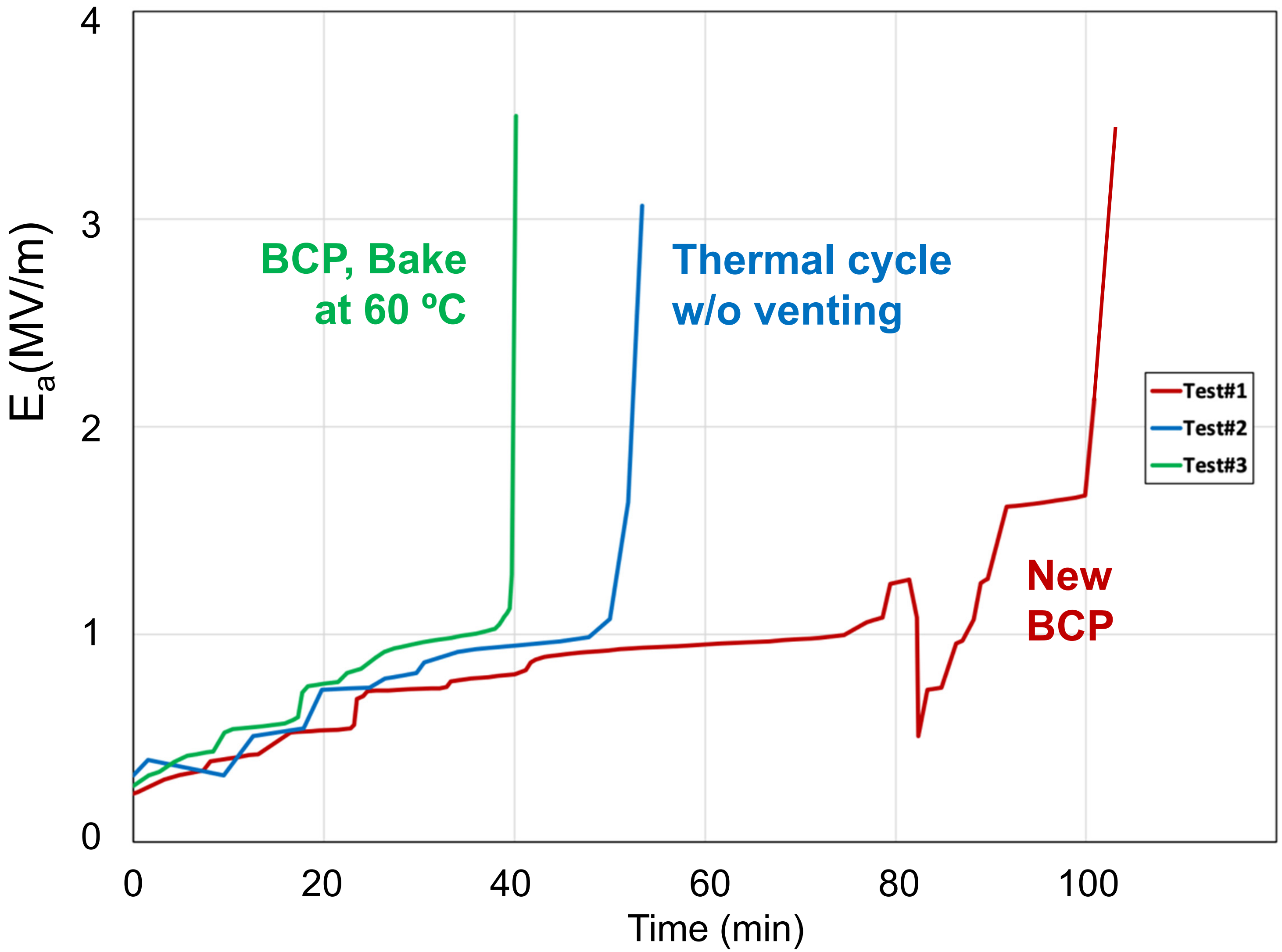
Multipacting

- 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.

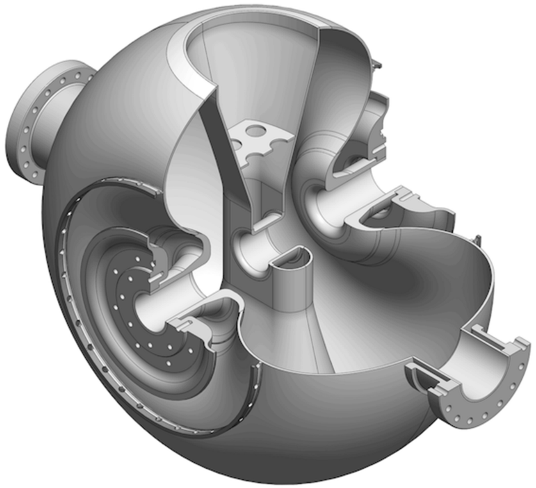


Multipacting conditioning time

- 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



- The balloon variant of single spoke resonator is proposed to mitigate problematic multipacting around operational field level.
- The first balloon SSR variant has been designed, fabricated and tested at TRIUMF.
- The cold tests demonstrate the principle of the balloon concept and achieved the design goals.
  - There are no multipacting barriers near the operational gradient and low levels are easily processed
  - Cavity geometry achieves high R/Q and G, and high V_{acc} with low B_{peak}
  - Fabrication is simplified with less welds and reinforcing ribs required
  - Mechanical design complies with ASME guidelines and minimizes pressure sensitivity for CW operation.



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

Thank you

Merci

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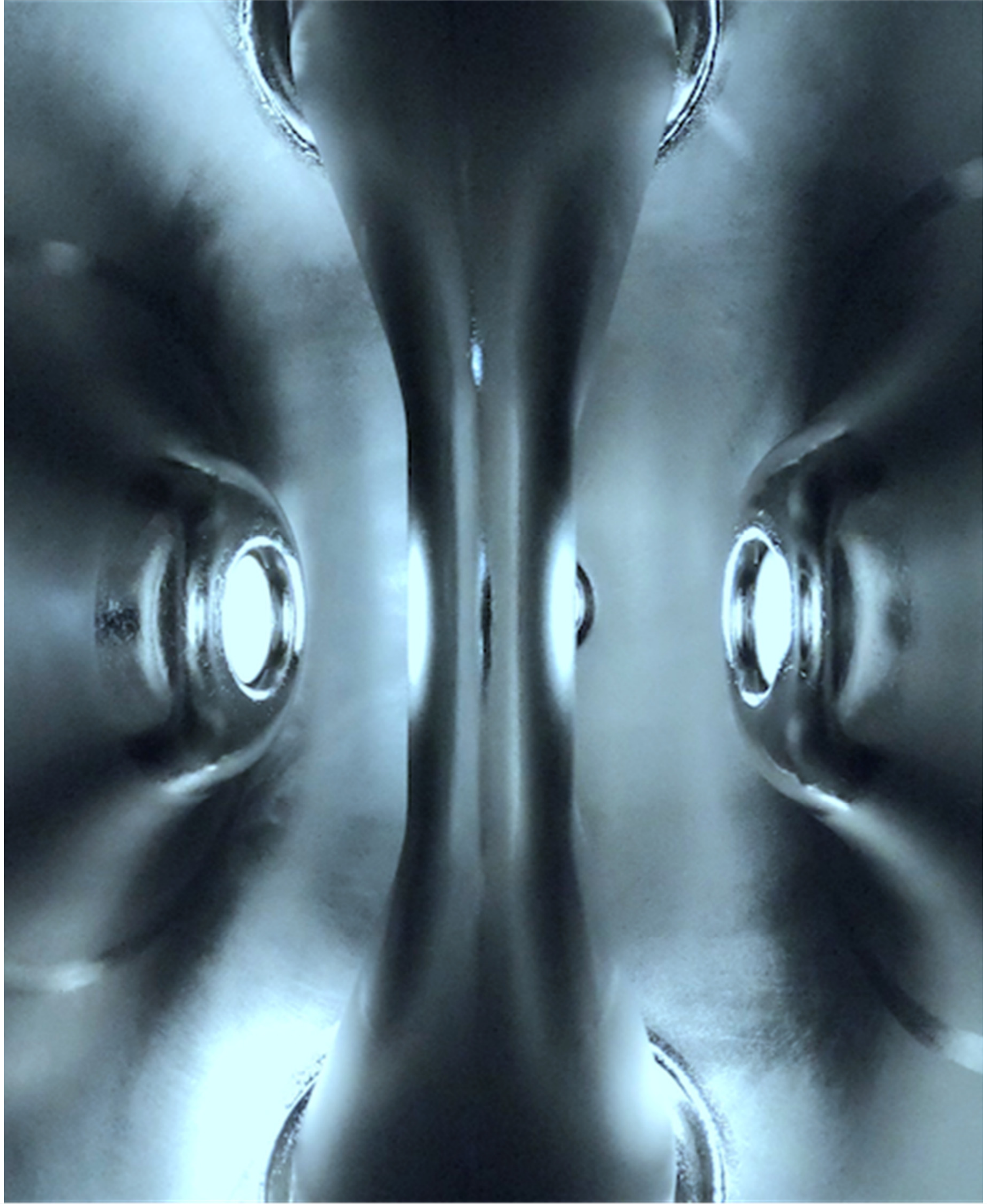

Discovery,
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