Development and testing of spoke cavities

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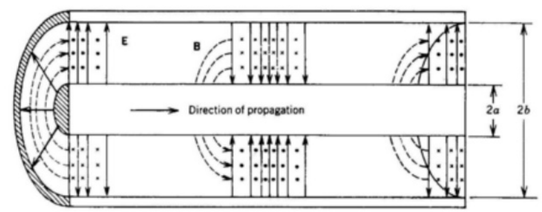
Outline

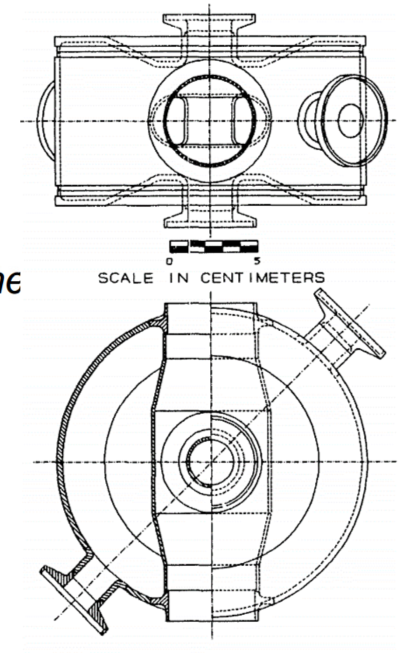
- Background
  - History of spoke cavity development
  - Projects that use or propose spoke cavities
- Design
- Fabrication
- Post processing
- Vertical test statistics

History of spoke cavity development

- Spoke cavity is a TEM-like resonator, where the length of the spoke is approximately half of the RF wavelength.



TEM propagating wave in a coaxial line



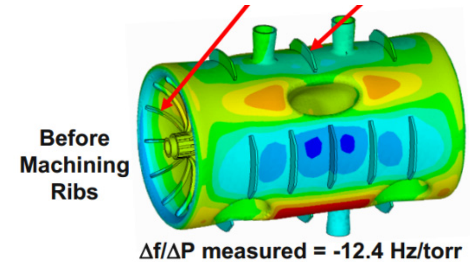
855 MHz, β_0=0.30, 2-gap spoke resonato

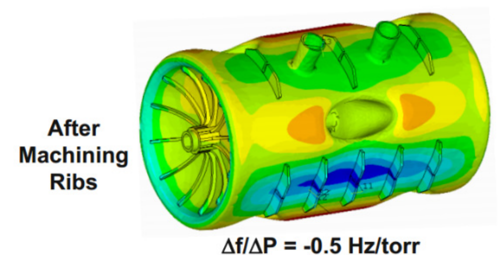
- The first single-spoke resonator (SSR) was proposed by J. Delayen at ANL in SRF1989, with f_0=855MHz and β_0=0.3.
  - The first VT test results was published in Linac1992, with Ea ~ 4.3MV/m (with L_{eff} defined as Ngap*β_0*λ/2), Ep ~ 25MV/m, and Bp ~ 56mT.
- The first multi-spoke cavity (345MHz, β_0=0.4) was developed at ANL in 2003, which adopted EP to pieces before final EBW

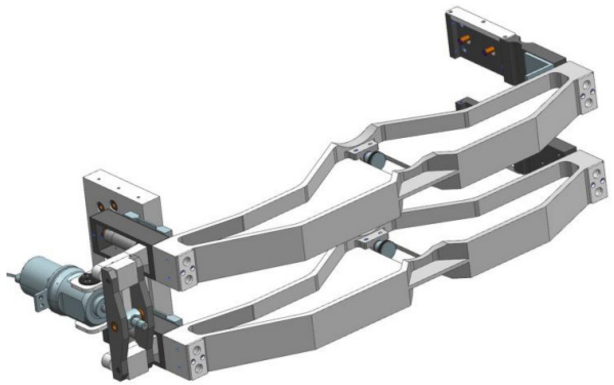
Reference [1-3]

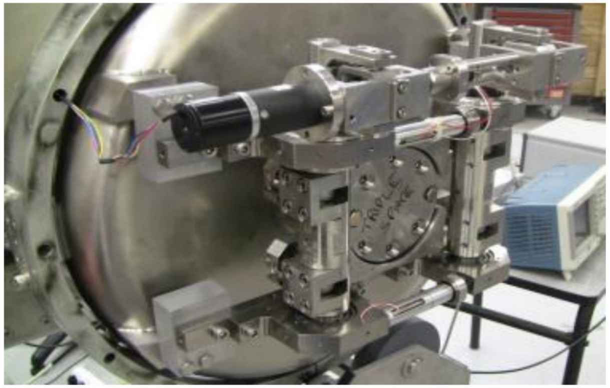
History of spoke cavity development (2)

- "Self-compensating" design was first applied to spoke cavities to reduce df/dp at ANL in 2005.
- β_0~0.14 SSR was developed at IHEP in 2012
- β_0~1 spoke was developed at ODU/JLab in 2013
- Ancillaries for spoke cavities have been well developed nowadays
- SSR have been commissioned with CW proton beam of 2mA at IHEP in 2017









Projects that choose spoke cavities

- 20 cavities in tunnel; 257 approved; 105 more as planned.

Project	Duty factor	Frequency [MHz]	β_0	# of spoke cavities	Status
PIP-II	CW	325	0.22/0.47	16/35 (12)	Pre-research
ESS	Pulsed	352	0.5	26	Construction
Raon	CW	325	0.3/0.53	69/150	Construction
LCS-JAEA	CW	325 (650)	1	dependent	Pre-research
CADS-injector I	CW	325	0.14	14	Operation
CADS-main linac	CW	325	0.24	6	Commissioning
CIADS	CW	325	0.42	54	Proposed

Reference [8,10,12-14]

Design target

- Resonance frequency f ← beam long. size&f
- Number of gaps N ← velocity acceptance
- Transient time factor ← velocity acceptance, beam optics
- Optimized beta β_0 ← beam optics
- Bore radius ← beam transv. size

Beam specifications

- E_{peak} / E_{acc}, B_{peak} / E_{acc}
- Ra/Q
- Geometry factor G
- Lorentz force detuning coefficient: ${}^{\Delta f}/_{E_{acc}^2}$
- He pressure sensitivity: df/dp

$$G \times {}^{R_a}/_{Q} = \frac{\left(T(\beta) \times \int_{-\infty}^{+\infty} |E(z)| dz\right)^2}{{}^{1}/_{2} \iint |H|^2 dA}$$

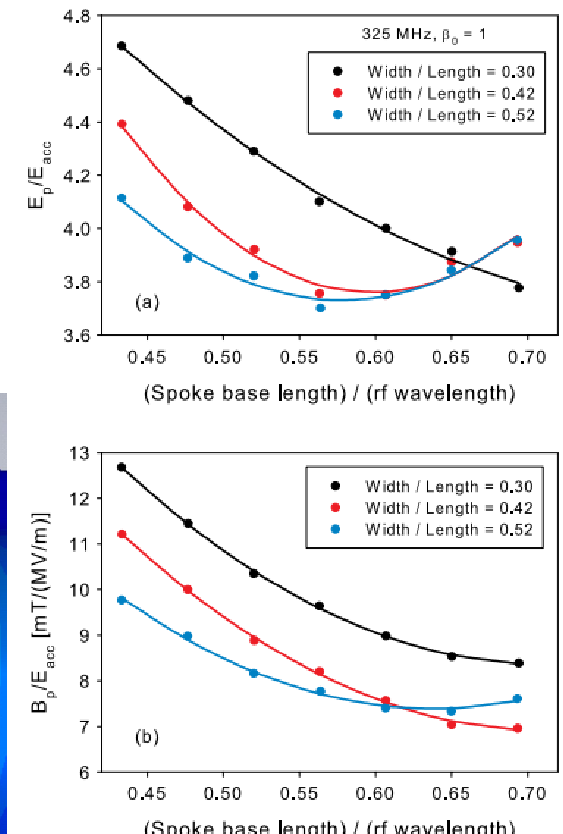
Technological choices

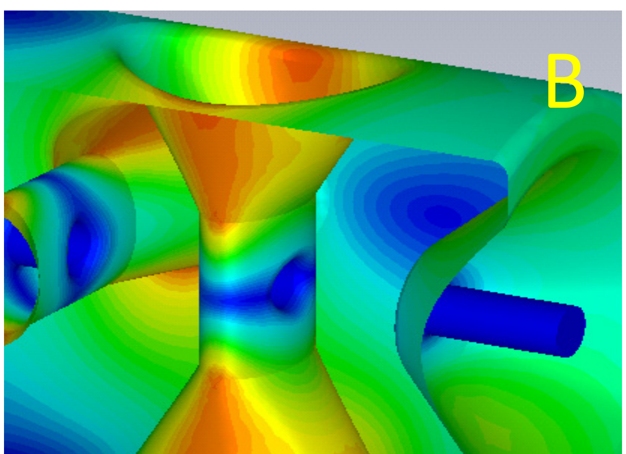
Outline

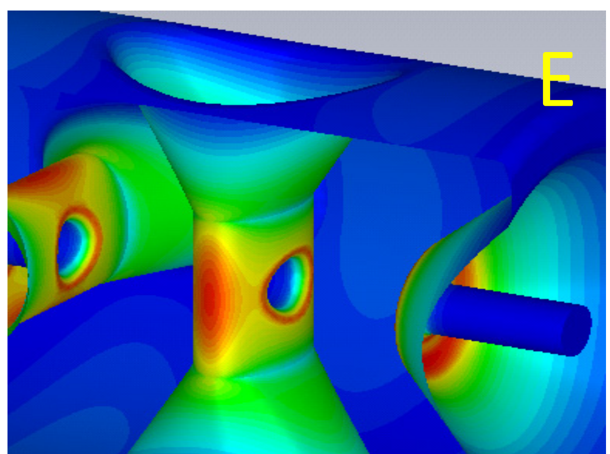
- Background
- Design
  - Design target
  - RF optimization
  - Multipacting analysis
  - Mechanical analysis
- Fabrication
- Post processing
- Vertical test statistics

RF optimization

- Surface field is minimized by distributing field to larger area:
  - Base of spoke and end-cover: magnetic field
  - Central part of spoke: electric field
  - Typical Bp/Ep is 2~2.3 $^{mT}/_{(^{MV}/_{m})}$, and E_p/E_a~3.3 or B_p/E_a ~ 7 is achievable for β>0.2



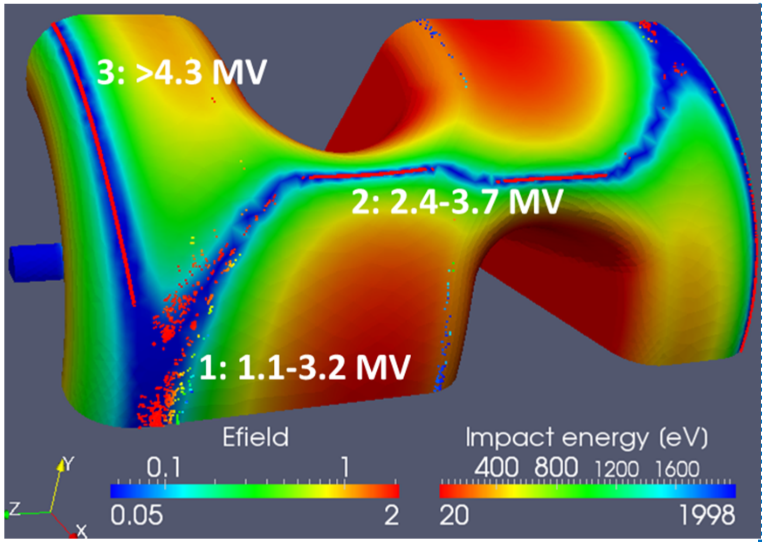


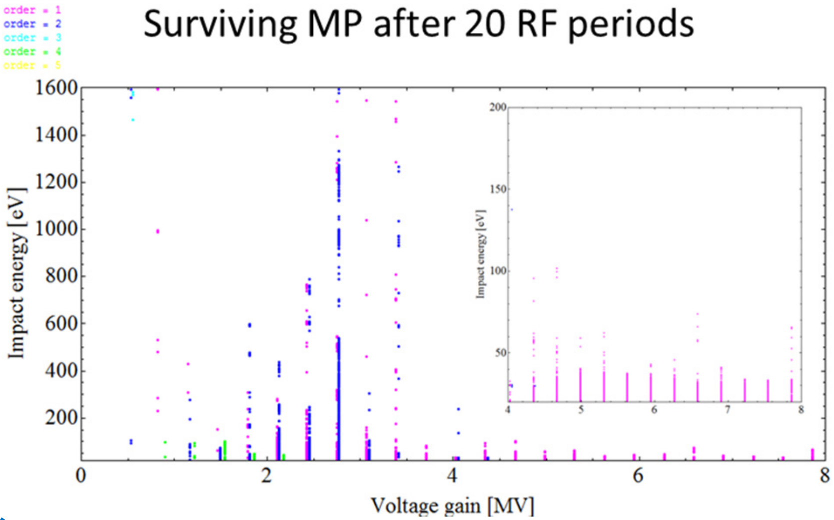


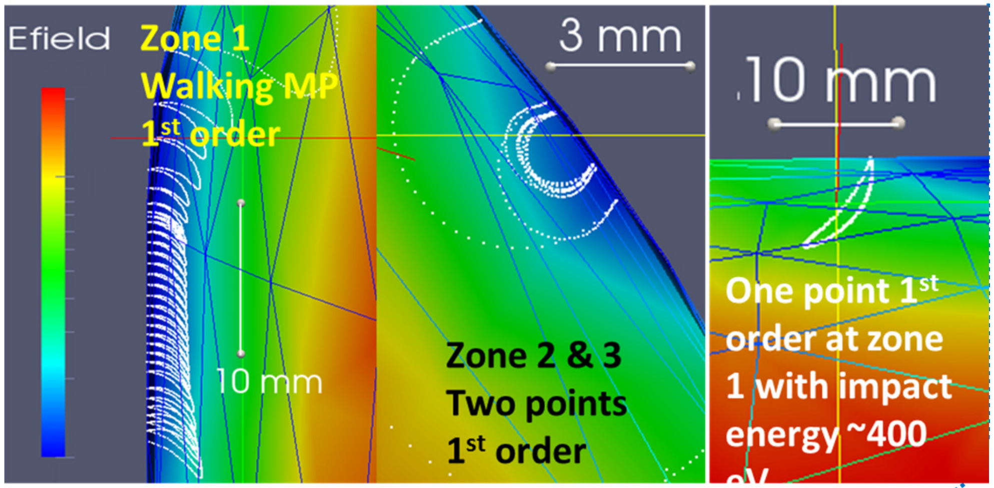
Reference [15]

Multipacting analysis

- Stable MP could be eliminated by larger blending radius
- MP has never been a show-stopper in the testing of spoke cavities



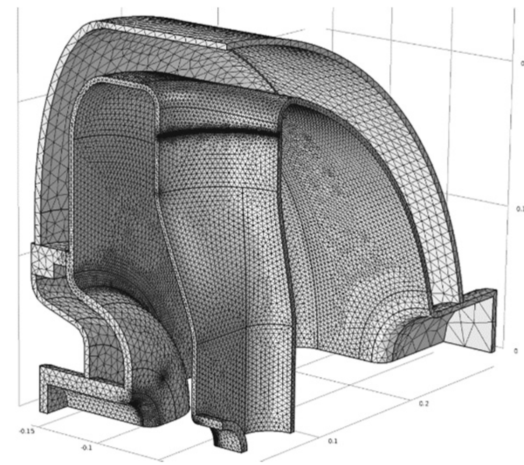




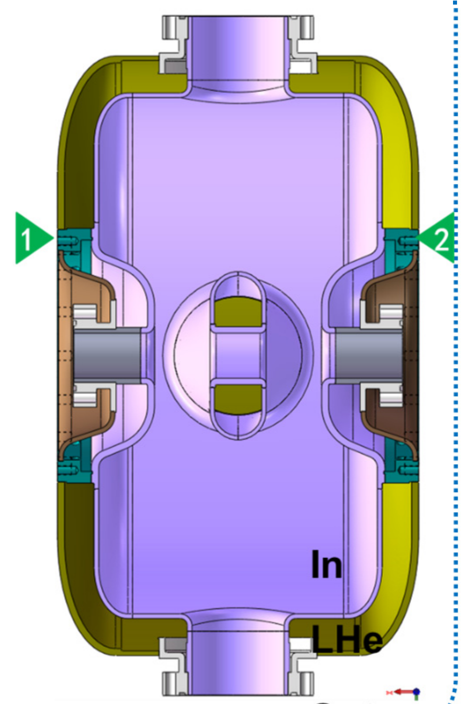
Reference [16]

Mechanical analysis

- Stress and buckling analysis:
  - Pressure vessel code, e.g. ASME-BVPC-VIII.Div2.Part5
  - Typical allowable stress for Nb is ~50MPa at RT

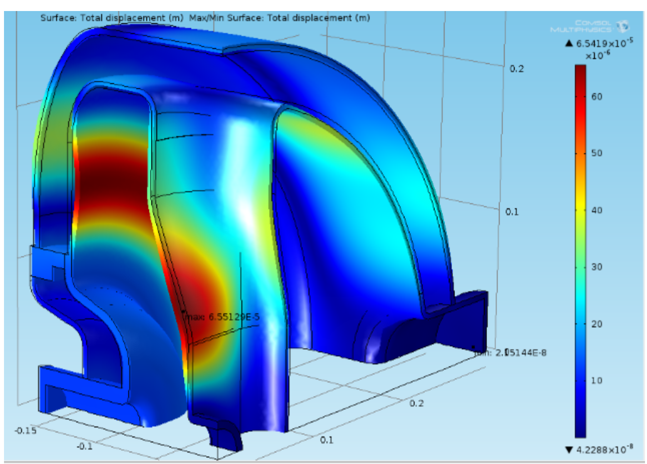


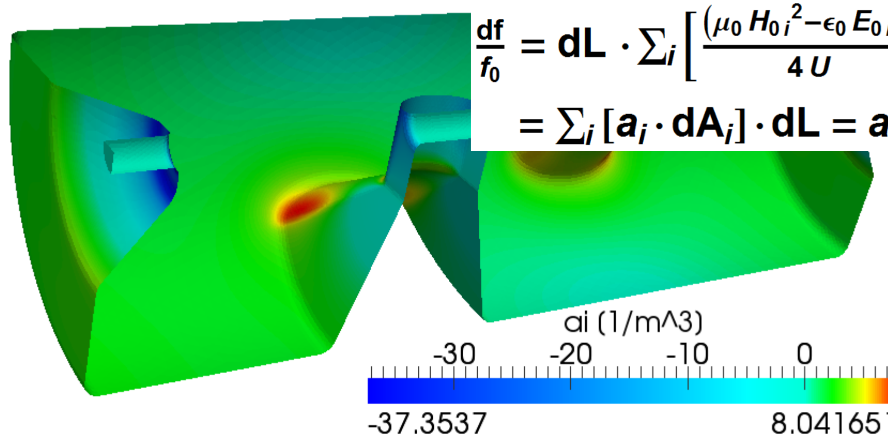
	Boundary	In	LHe	Out	T
Tuning	Pull/Push	1 bar	1 bar	1 bar	RT
Cavity-string leak check	Free	Vacuum	1 bar	1 bar	RT
Cool down/ Operation	Free+pull	Vacuum	0.03-2 bar	Vacuum	4K/2K



Mechanical analysis (2)

- Reducing LFD
- Vibration of the spoke
- Reducing df/dp
  - Makes cavity body stronger
  - Stiffening ribs to control distortion as needed
  - Connect cavity to He vessel to cancel unwanted distortion





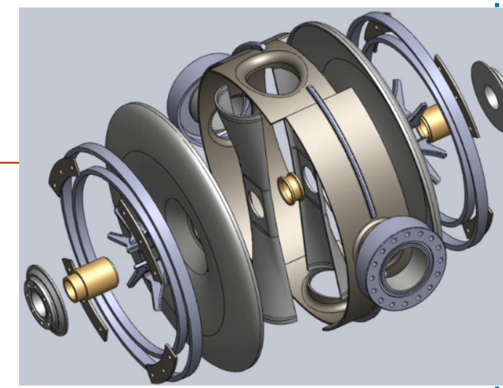
$$\frac{\mathbf{df}}{f_0} = \mathbf{dL} \cdot \sum_i \left[\frac{\left(\mu_0 H_{0\,i}^{\,2} - \epsilon_0 E_{0\,i}^{\,2}\right)}{4\,U} \cdot \mathbf{dA}_i \right]$$

$$= \sum_i \left[a_i \cdot \mathbf{dA}_i \right] \cdot \mathbf{dL} = a \cdot \mathbf{dL}$$

Outline

- Background
- Design
- Fabrication
  - Fabrication sequence
  - Surface quality control
  - Shape control
  - Frequency control
- Post processing
- Vertical test statistics

Fabrication of the spoke cavity



LHe vessel ← Vertical test

Design → Fabrication → Post processing → String assembly

Material

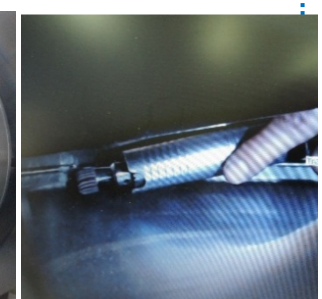
Certification from vendor
Eye inspection

Technology

- Deep drawing
- Annealing
- Machining
- EDM
- Frequency tuning
- Grinding
- EBW

Quality control

- Defect inspect and grinding before final EBW
- Shape control
- Frequency control



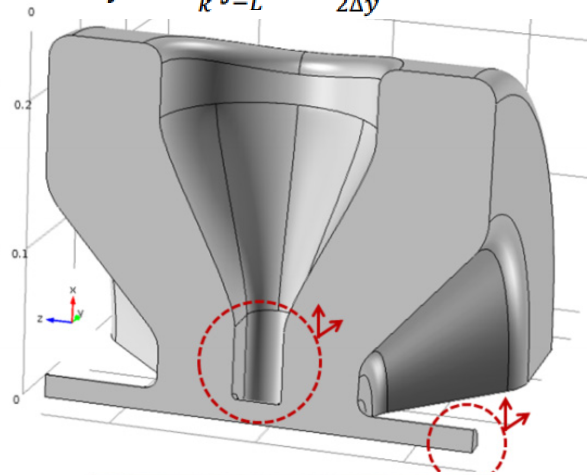
Surface quality control

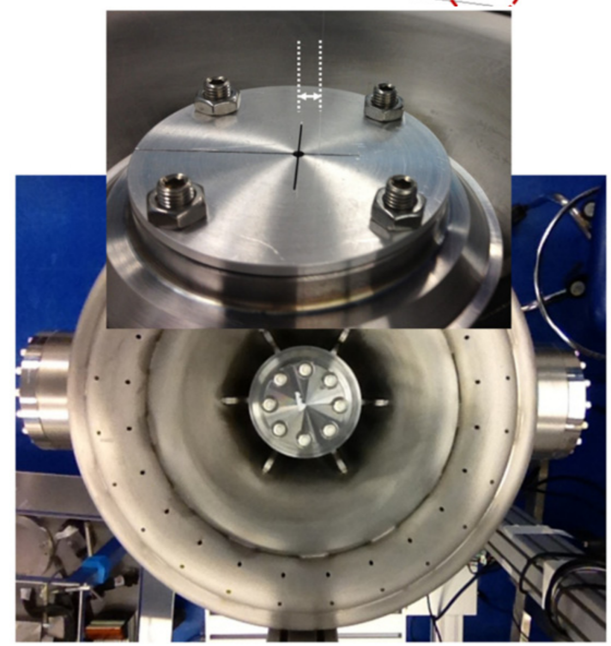
- Before final EBW it is the last chance to get easy access to the cavity inner surface
- Defect, e.g. pits in diameter 0.1mm, could be addressed by eye inspection. Sometimes magnifier or very light BCP helps to find defects.

Shape control

$$\Delta Px.c = \frac{j}{k}\int_{-L}^{L}\frac{(Ez^{+\Delta x} - Ez^{-\Delta x})}{2\Delta x}e^{j\frac{k}{\beta}z}\,dz$$

$$\Delta Py.c = \frac{j}{k}\int_{-L}^{L}\frac{(Ez^{+\Delta y} - Ez^{-\Delta y})}{2\Delta y}e^{j\frac{k}{\beta}z}\,dz$$



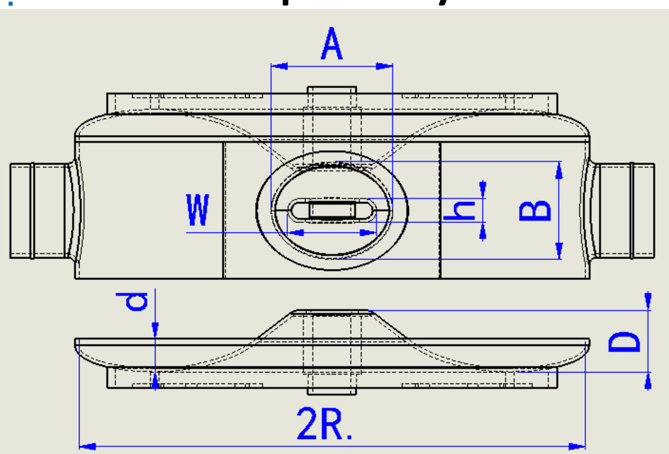


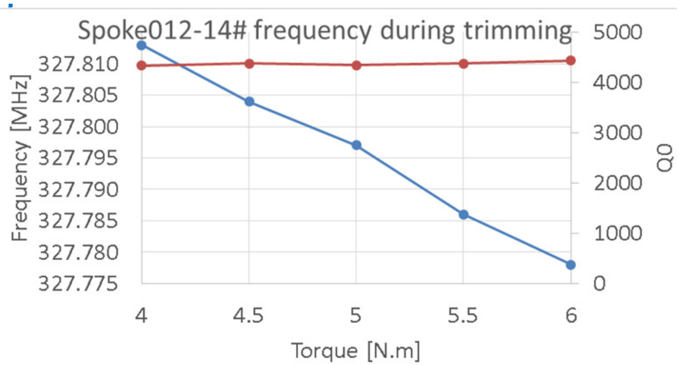
- Transverse displacement of beam pipe or spoke may introduce transverse kick.
  - FNAL measured the trans. kick by bead-pull, and confirmed 0.7mm of displacement introduce ~1.1mrad beam deviation, which is within the ability of the 10mrad corrector
- Longitudinal error had no significant effect on either field flatness or transverse kick, due to the very strong coupling between gaps

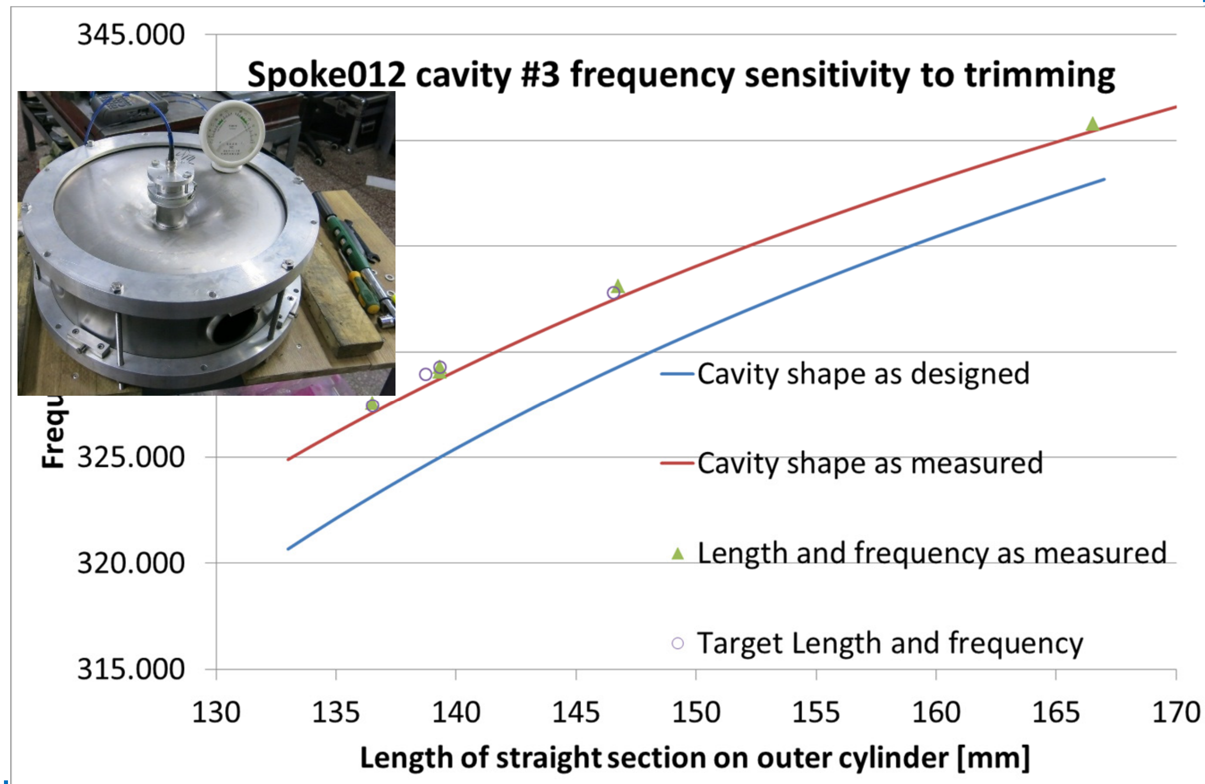
Reference [17]

Frequency control

- Frequency tuning is typically done by stacking parts together before EBW, and trim the cylindrical part after frequency measurement.

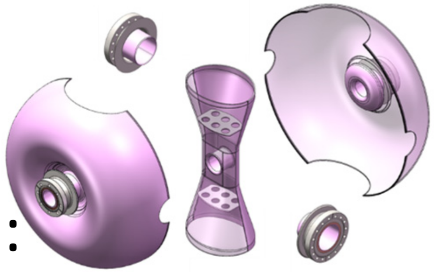




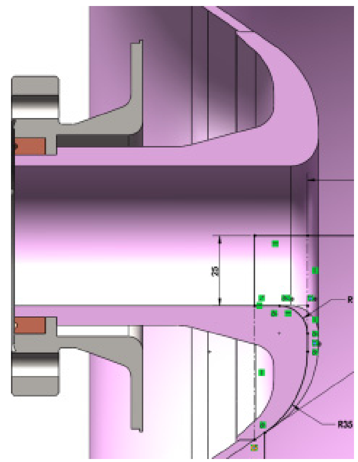


Reference [18]

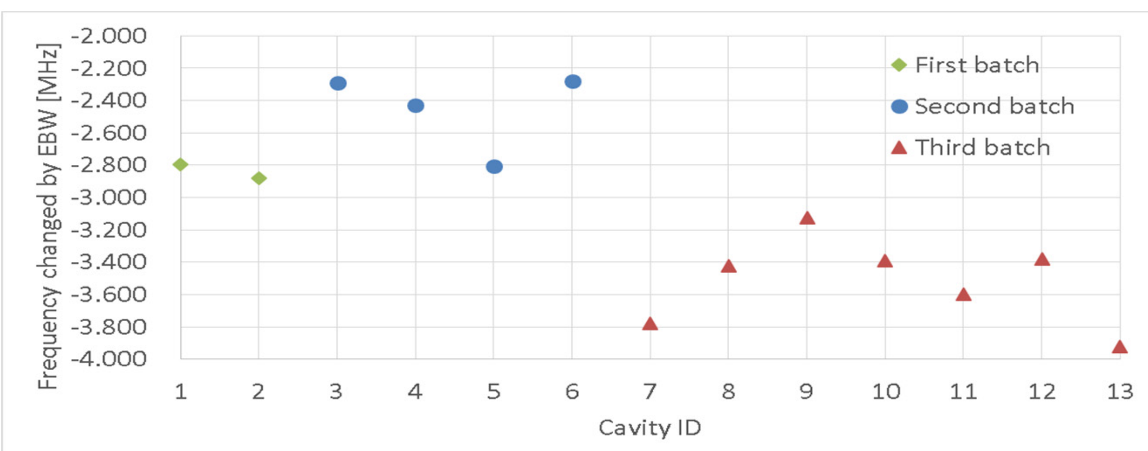
Frequency control (2)

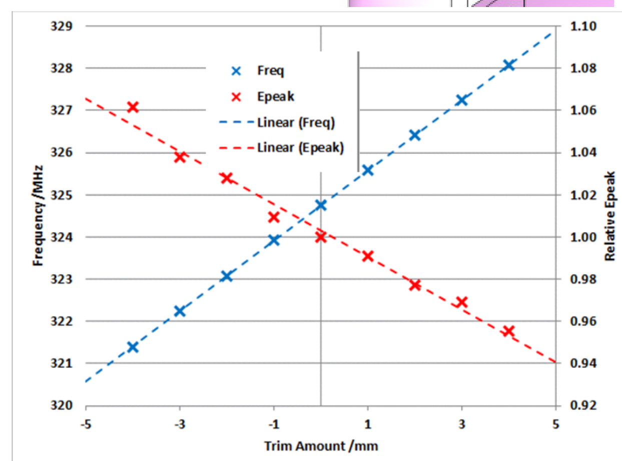


- Other idea on frequency trimming (RISP SSR1):
  - End-cone is made of ingot Nb
  - The end-cove is trimmed after stacked frequency measurement



- Frequency change other than EBW shrinkage: distortion of end-cover induced by EBW has to be well understood and controlled





Reference [19]

Outline

- Background
- Design
- Fabrication
- Post processing
  - BCP, part EP
  - HPR
  - Clean assembly
- Vertical test statistics

Post processing (etching)

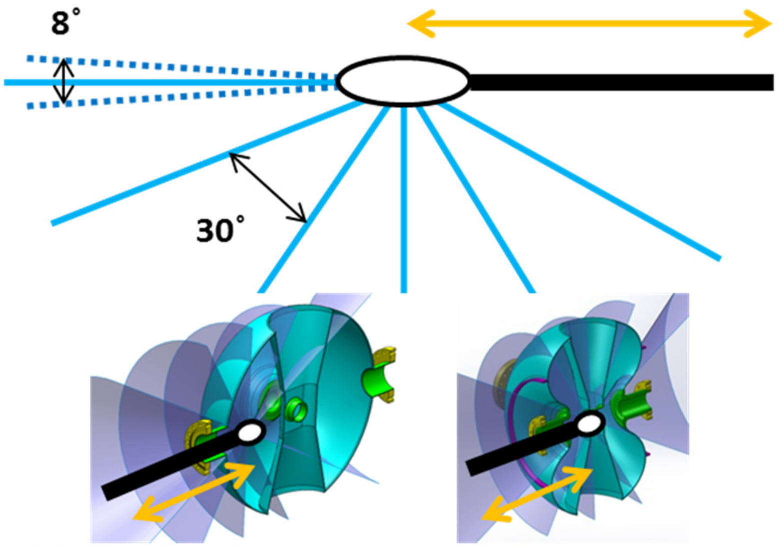
- Standard treatment as elliptical cavities

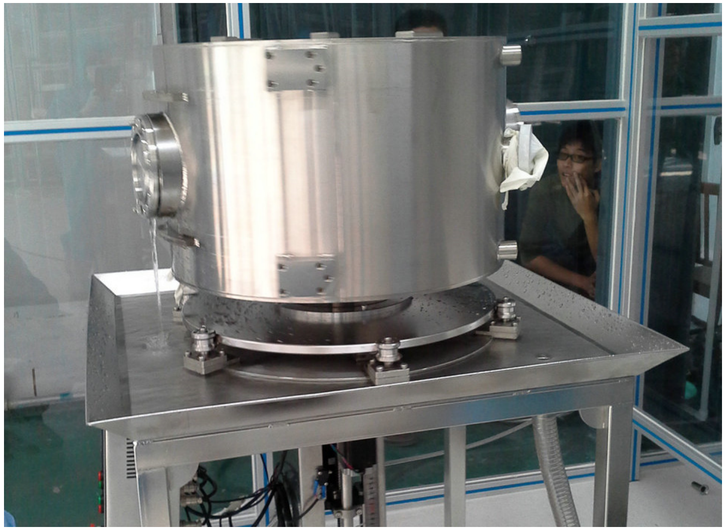
Ultrasonic
↓
BCP120-200 um
↓
600-800C for hrs
↓
Flash BCP
↓
HPR
↓
120C 48hr
↓
Vertical test
↓
Vessel weld
↓
(high baking)
↓
(light BCP)
↓
HPR
↓
String assembly

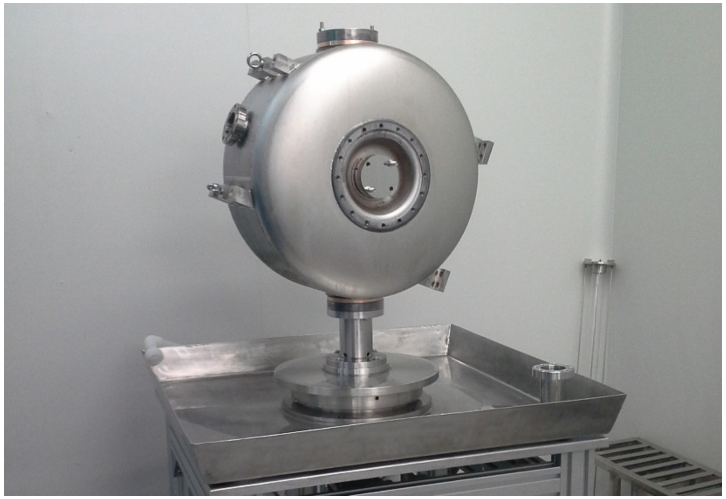
Reference [8,20]

HPR

- HPR is typically through all available ports.
- Coverage to inner surface could be checked with CAD software.

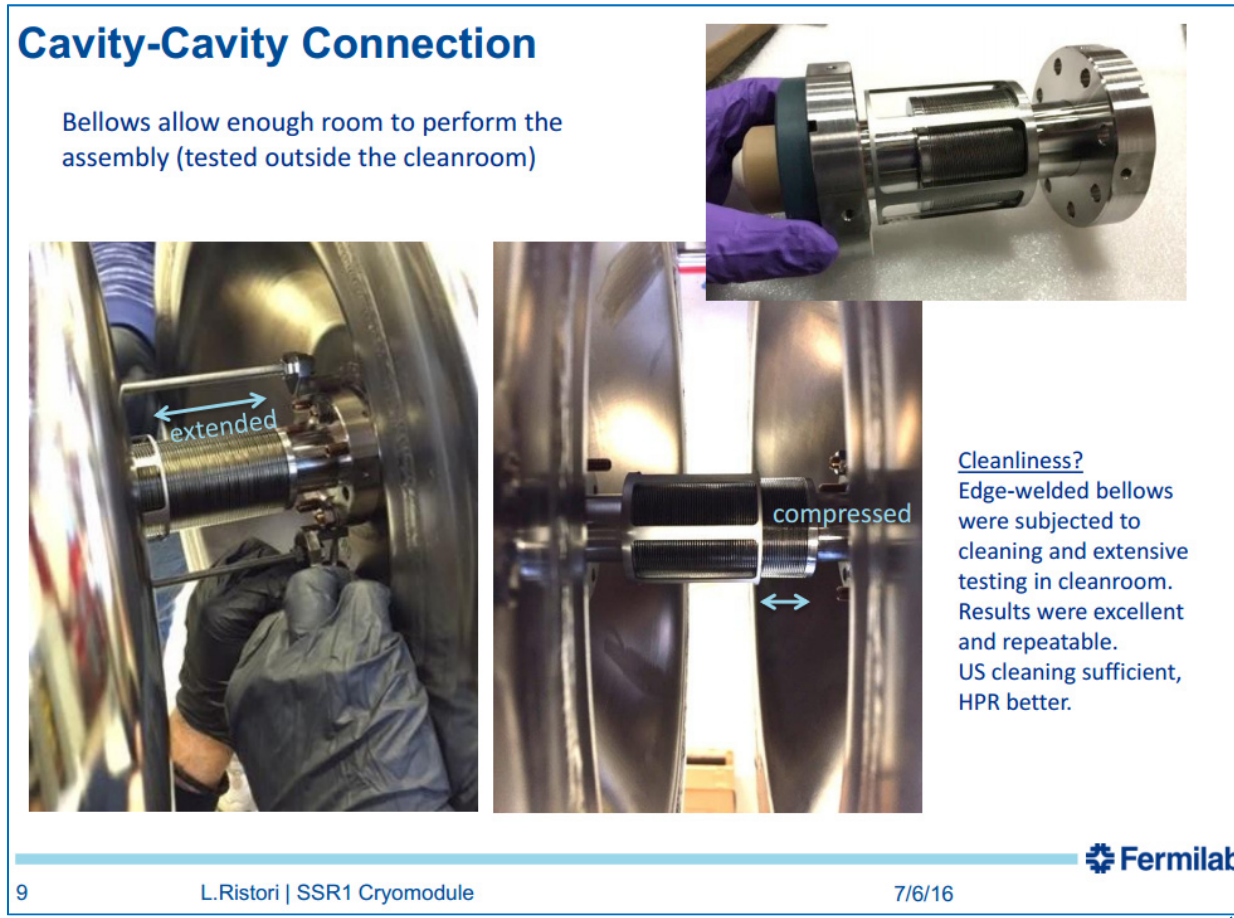






Clean assembly

- Cavity or string assembly is performed in ISO4 cleanroom.
- Edge-welded bellows are used for PIP-II to save space in between spoke cavities



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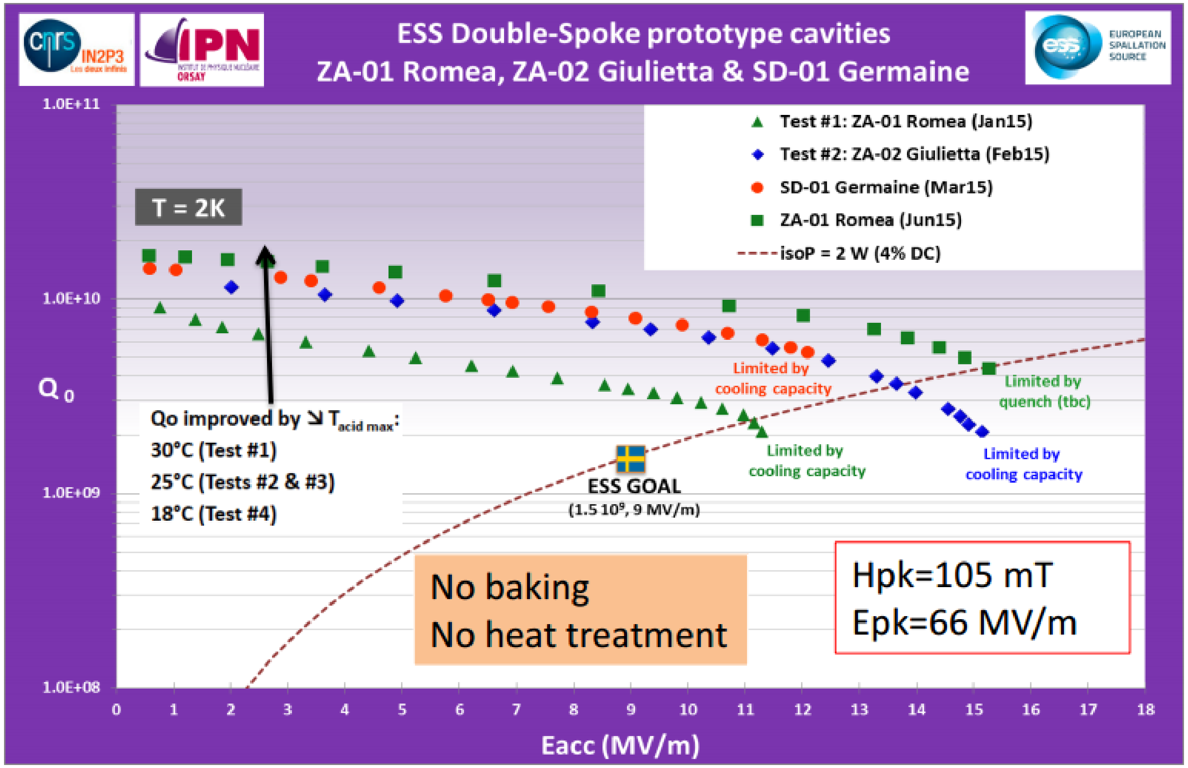
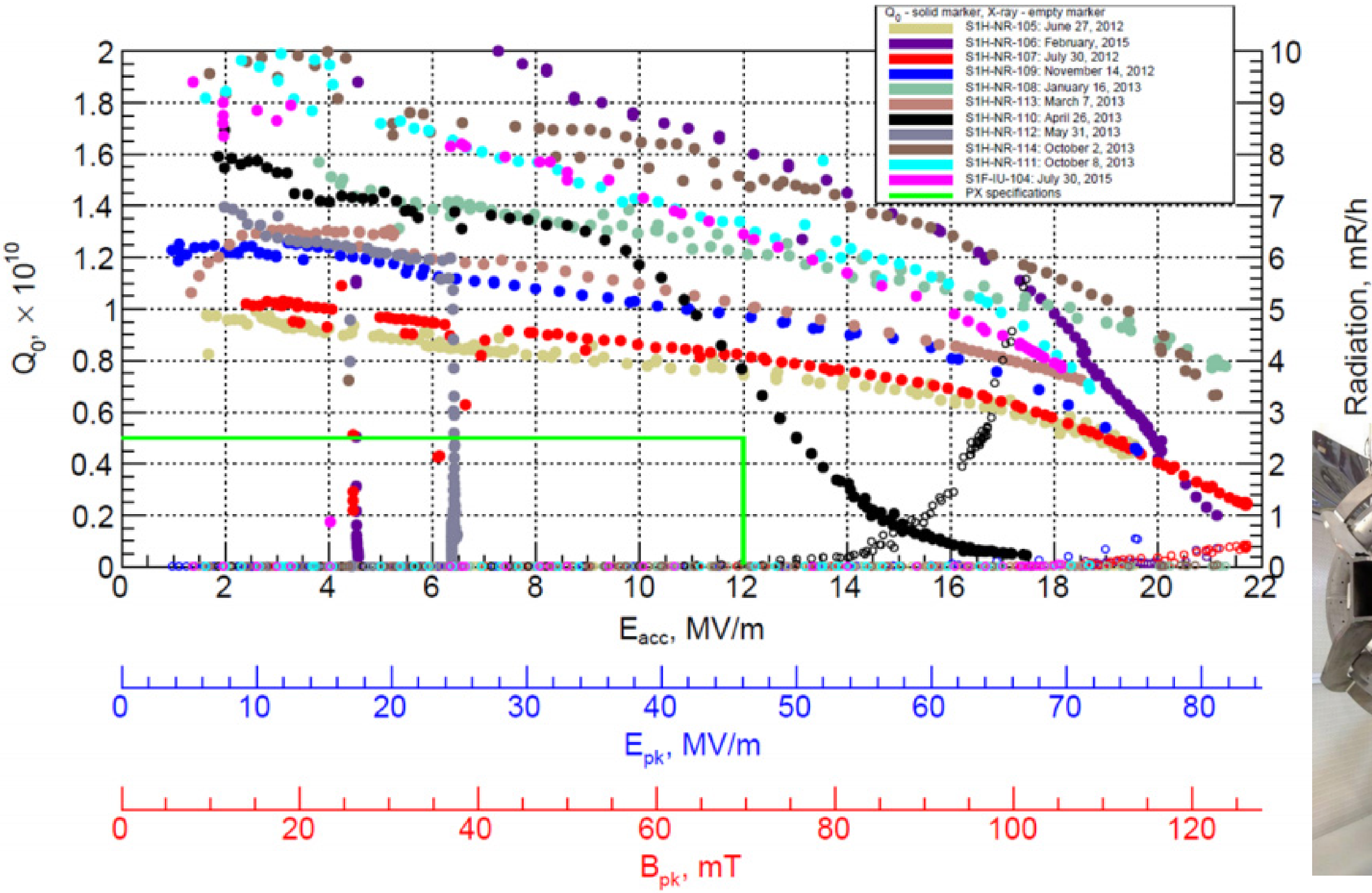
ESS prototype cavity VT results

➔ Spoke cavity exceeding ESS requirements in vertical test on both Eacc and Qo



- Eacc_max=15.3 MV/m achieved with "Romea"
- Several MP barriers but easily processed.
- Qo > 1.6 10^{10}
- Strong FE at max gradient
- Limitation is the cooling capacity (unstable conditions, cavity in vertical position)

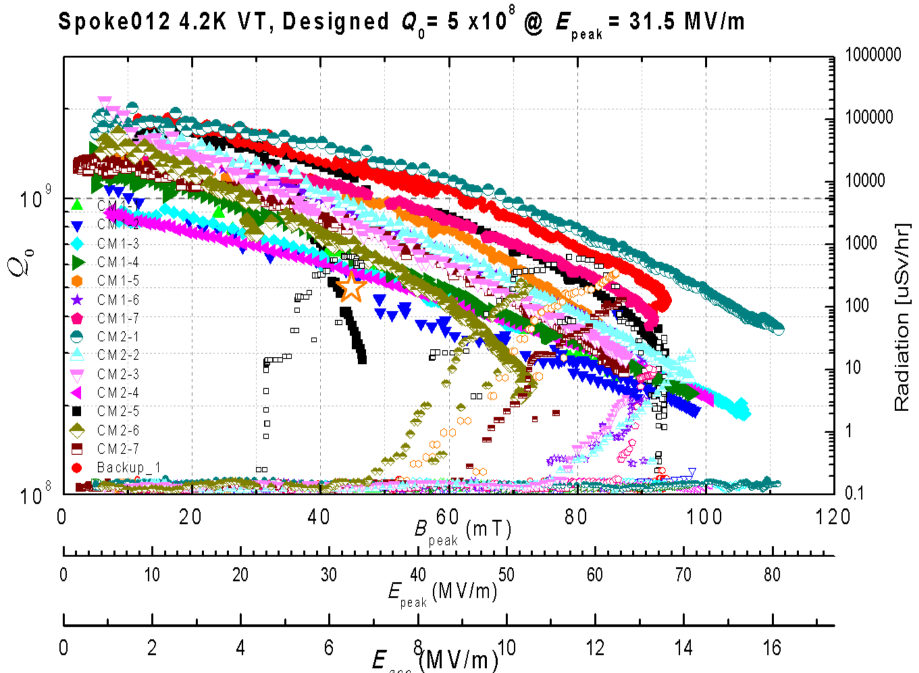
PIP-II prototype cavity VT results

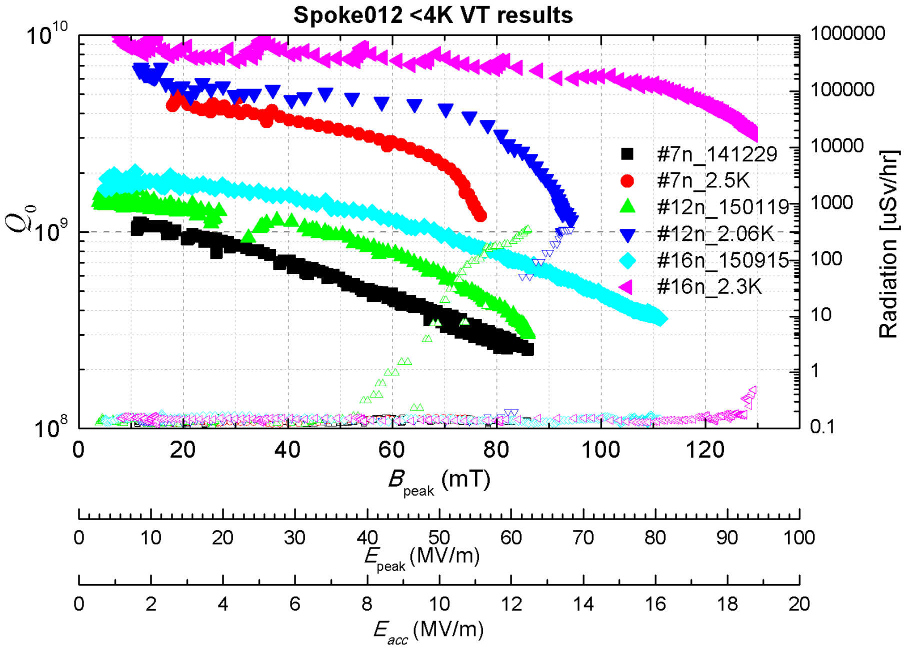


Reference [9]

CADS-injector I spoke012 VT results

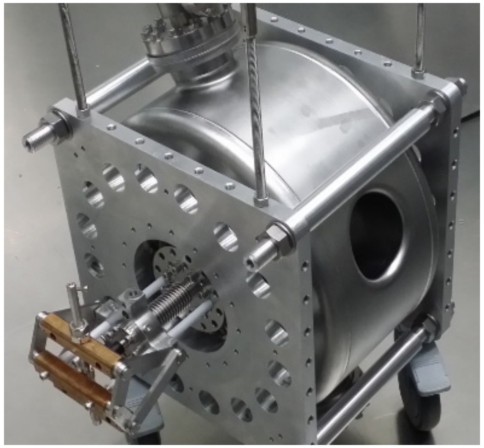
- MP conditioned in 1 hour with variable coupler
- Eacc increased by 2 MV/m with better cooling
- 120C baking increases Q_0 by about 50-100%
- At 2K, Q0 is 6 times higher, Bp~125mT achieved.

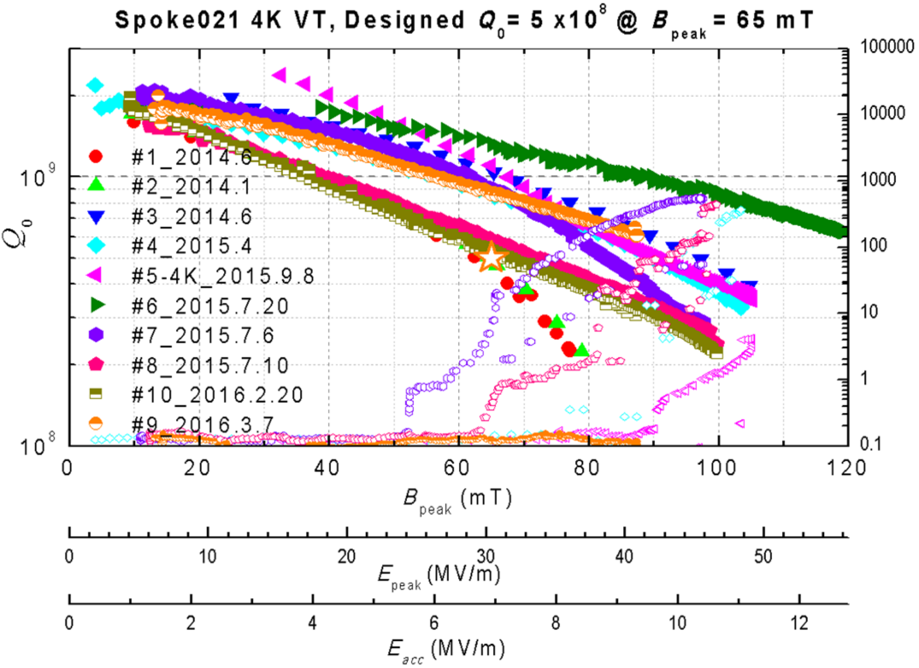


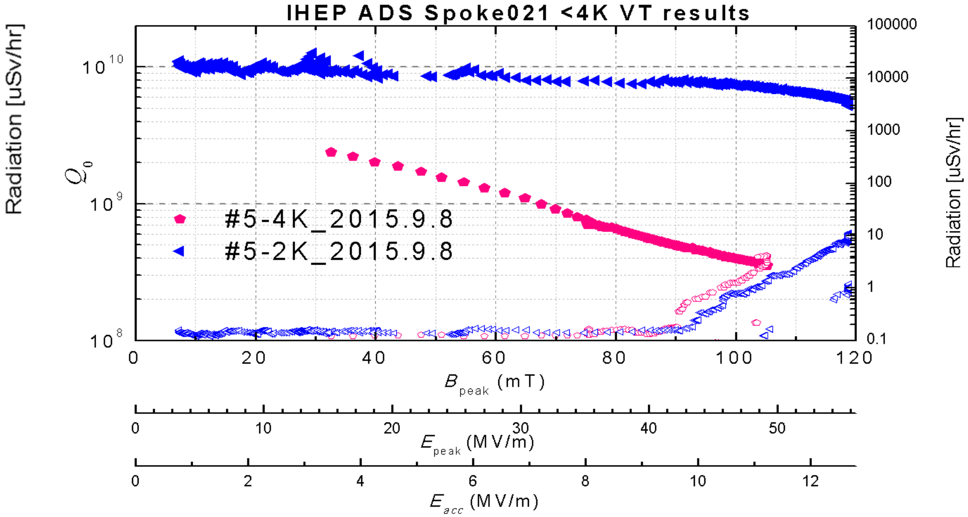


CADS-main linca Spoke021 VT results

- MP conditioned in 1 hour
- Design target consistently exceeded
- Bp of 120mT and Rres of 7nΩ achieved at 2K

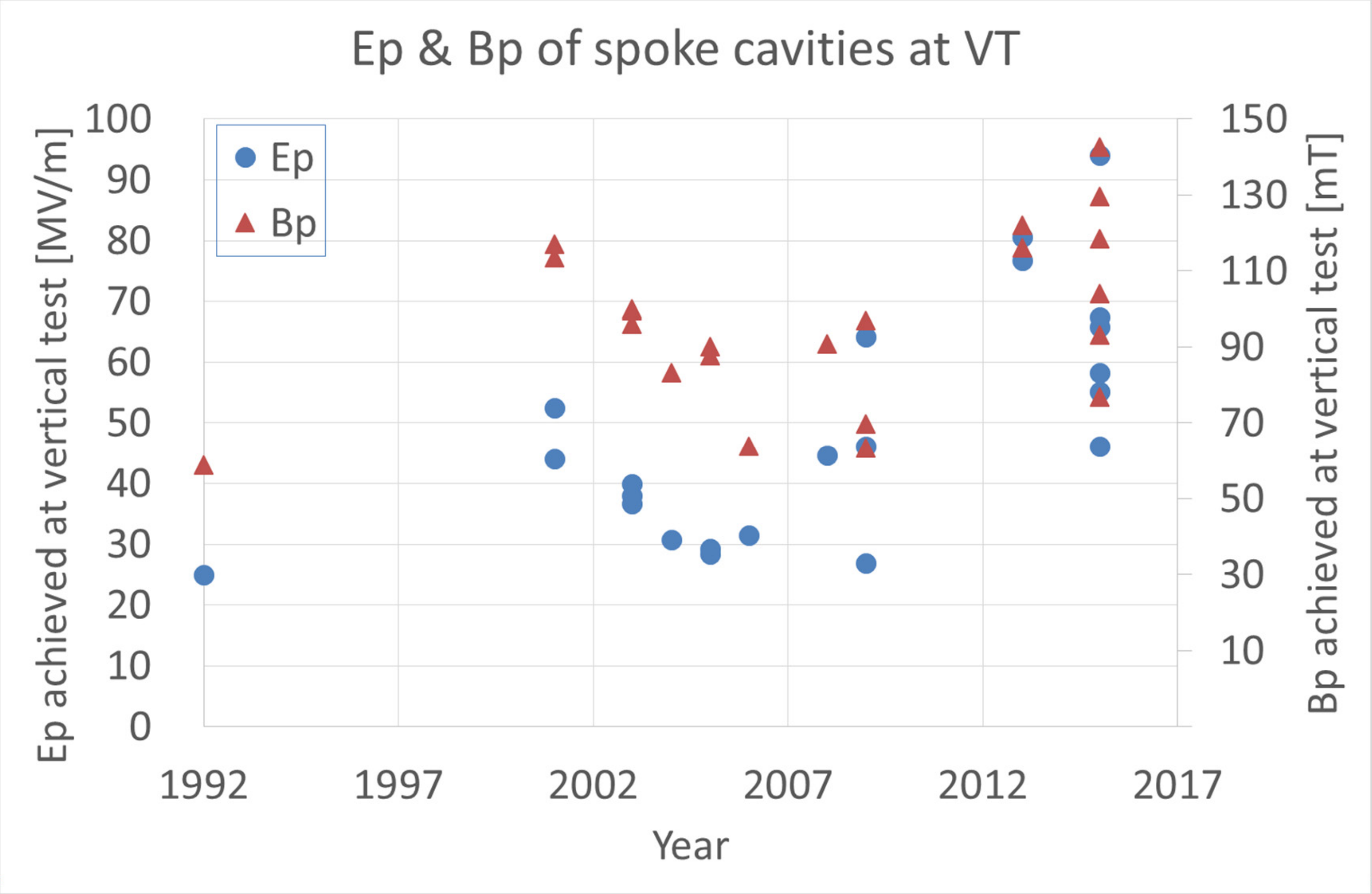






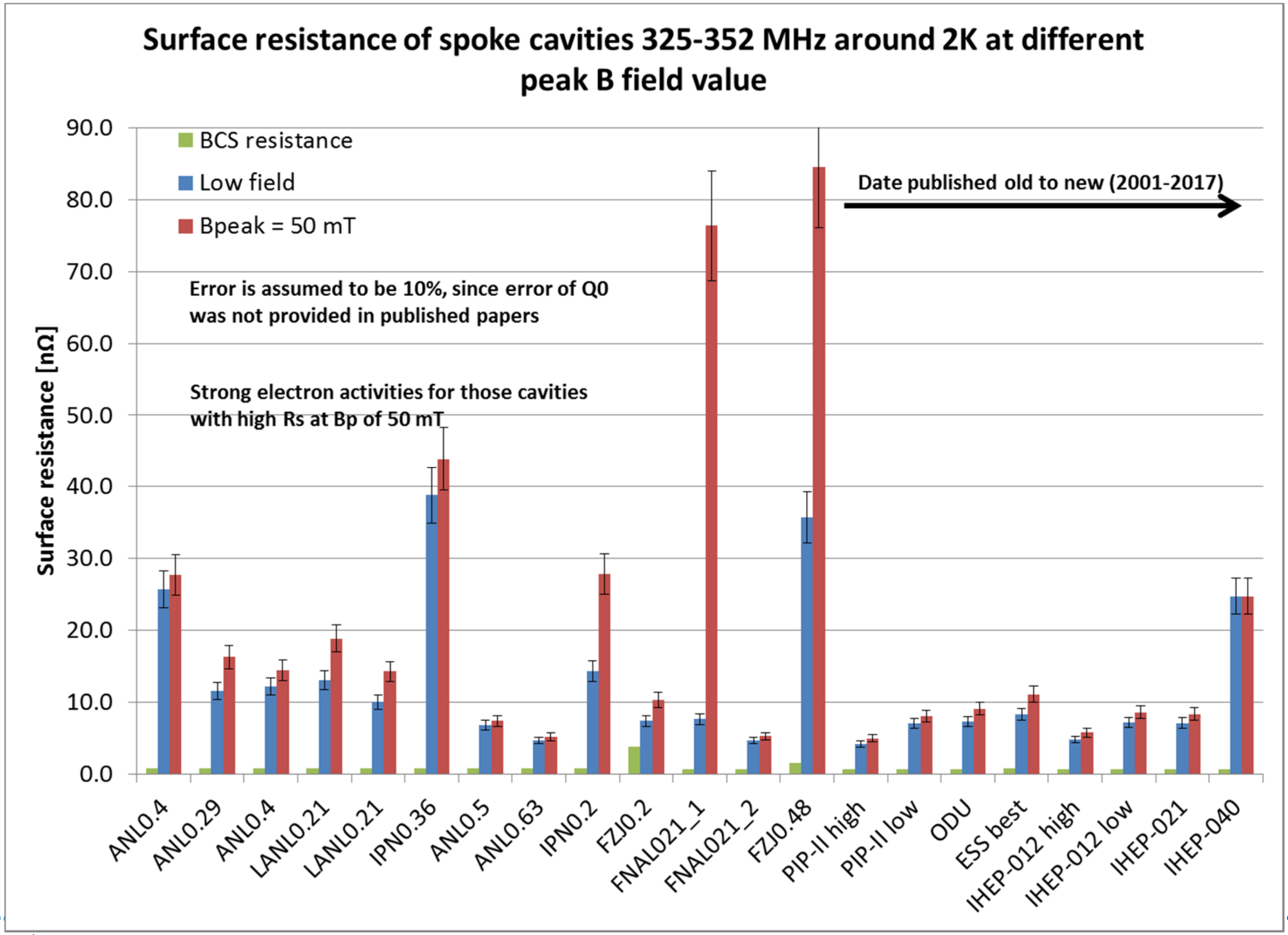
State of art performance

- Bp>80mT & Ep>60MV/m is routinely achievable at VT



What Rs to expect for spoke cav?

- Rres < 10nΩ should be safe enough



Thanks for your attention!

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