Project X & PXIE

Fermi National Accelerator Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

Status of SSR1 Cavity

Outline

- SSR1 Requirements and EM design
- SSR1 Mechanical design
  - Safety requirements (ASME)
  - Finite Element analyses
  - He pressure sensitivity reduction
- Tuner design
  - Requirements, geometry, analyses on main joint, maintenance
- Status of activities
  - Final welding shifts
  - Videoscope inspections
  - Inelastic tuning
  - Development of brazed rings at ANL
  - Manufacturing Issues
  - Contribution from IUAC New Delhi
  - Cold tests of first production cavity

S1H-NR-105
The first production SSR1

SSR1 overview

- Single Spoke Resonators have been developed at Fermilab in the last few years
- 3 bare cavities tested in VTS and 1 jacketed prototype tested in HTS
- We are receiving an order of 10 resonators from US vendors, 8 needed for the PXIE cryomodule

Parameter	Value
Beam-pipe and cavity diameter	30 mm, 492 mm
β_G , β_{Opt}	0.215, 0.22
RF structure	CW, 1 mA
Bandwidth, Loaded BW	90 Hz, 43 Hz
He temperature and pressure	2 K, 20 torr
Expected He pressure var.	± .25 torr
E_{acc} , Gain/cavity	10 MV/m , 2 MeV
Q_0 at E_{acc}	> $.5x10^9$
Max Surf Magn Field, nom.	60 mT
Max Surf Electric Field, nom.	39 mV/m
P rating (warm and cold)	2 bar, 4 bar
df/dp (jacketed)	0 ± 10 Hz/torr
K_{cav} and tuning sensitivity	< 30 kN/mm, 540 kHz/mm


1st prototype
Zanon

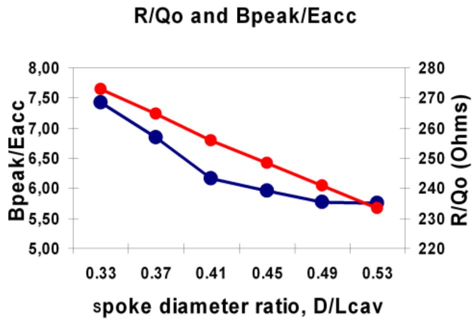

1st prototype
Jacketed at FNAL

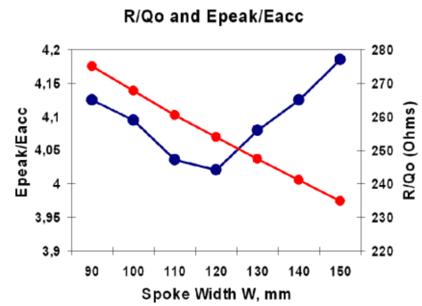

1st production cavity
(Roark-Niowave)

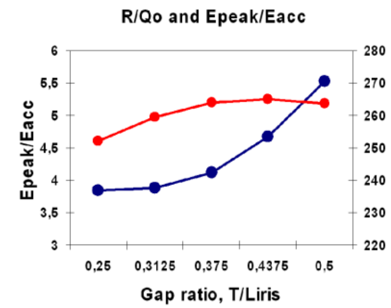

VTS


Spoke Cavity
Test Cryostat

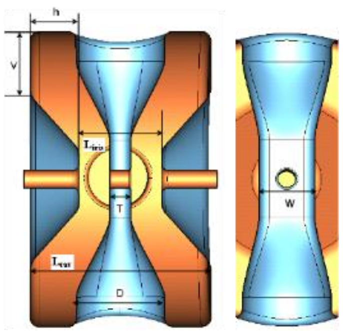
RF design of SSR1

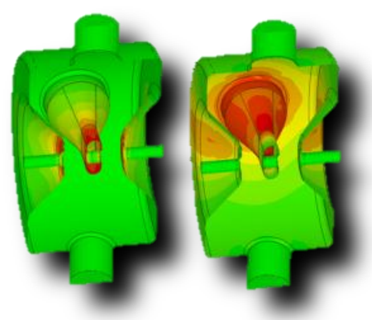






- The dimensions were varied in MWS to optimize the RF design.

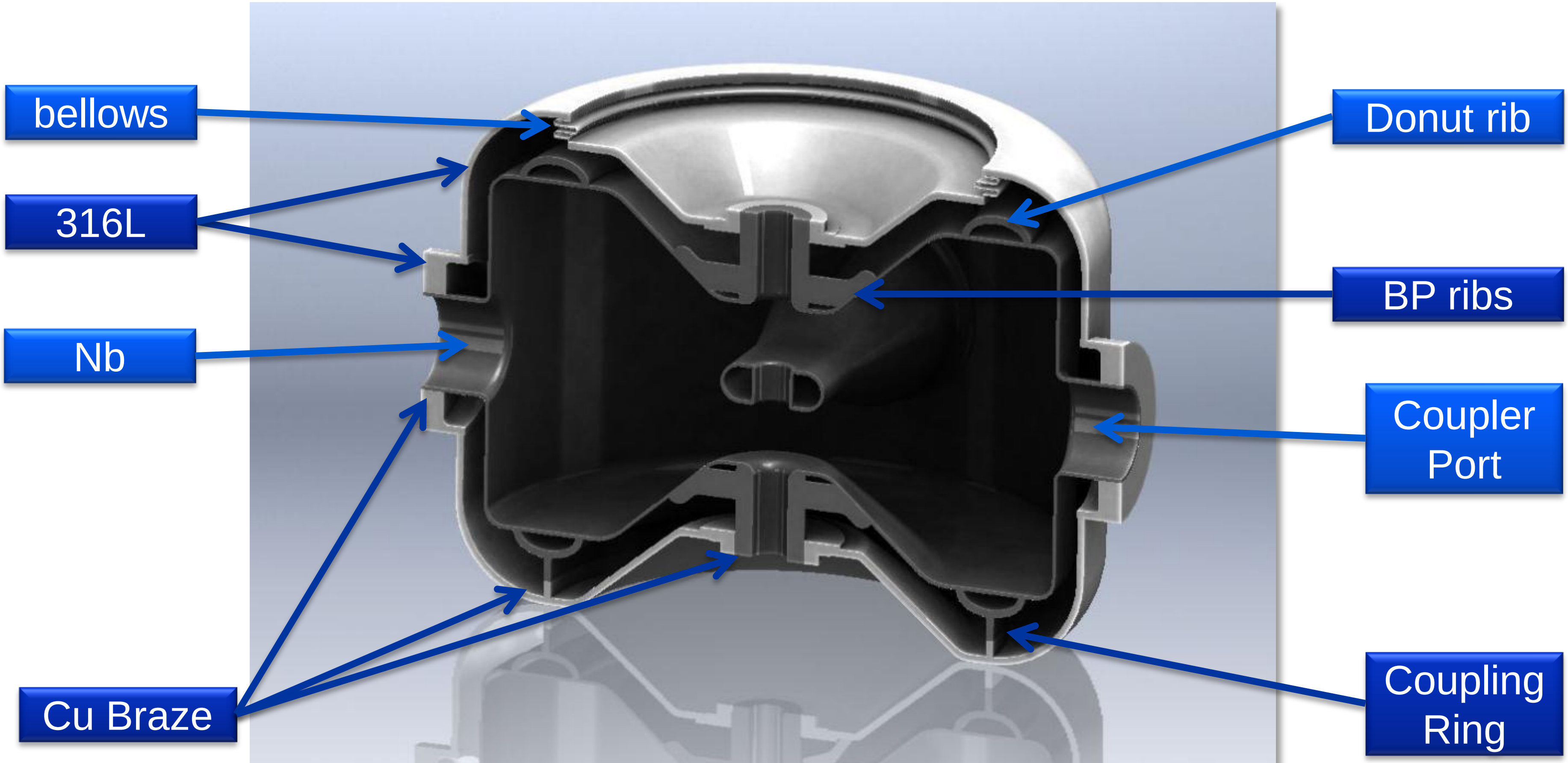




- Surface electric (left) and magnetic (right) fields in SSR1.
- The field strength increases as the color changes from green to yellow to red.

RF design parameters	
Epeak/Eacc	3.84
Bpeak/Eacc	5.81 mT/(MV/m)
Leff (2*βλ/2)	198.5 mm
G	84 Ω
R/Q	242 Ω

Mechanical Design overview



2010 ASME Boiler and Pressure Code VIII Division 2 – Part 5

We must comply with the ASME Boiler and Pressure vessel code.

Division 1 vs. Division 2 of Chapter VIII.

Division 2 allows utilizing complex shapes without limitations in principle, it generally results also in thinner walls of the vessels. We decided to follow this approach for the production cavities.

The ***Design-by-Analysis methodology*** utilizes the results from *finite element analysis* to assure:

1. Protection against plastic collapse

avoid unbounded displacement in each cross-section of the structure due to the plastic hinge

- Elastic stress analysis method
- Elastic-plastic stress analysis method

2. Protection against collapse from buckling

buckling is characterized by a sudden failure of a structural member subjected to high compressive stress, where the actual compressive stress at the point of failure is less than the ultimate compressive stresses that the material is capable of withstanding.

- Elastic stress analysis (Linear buckling)

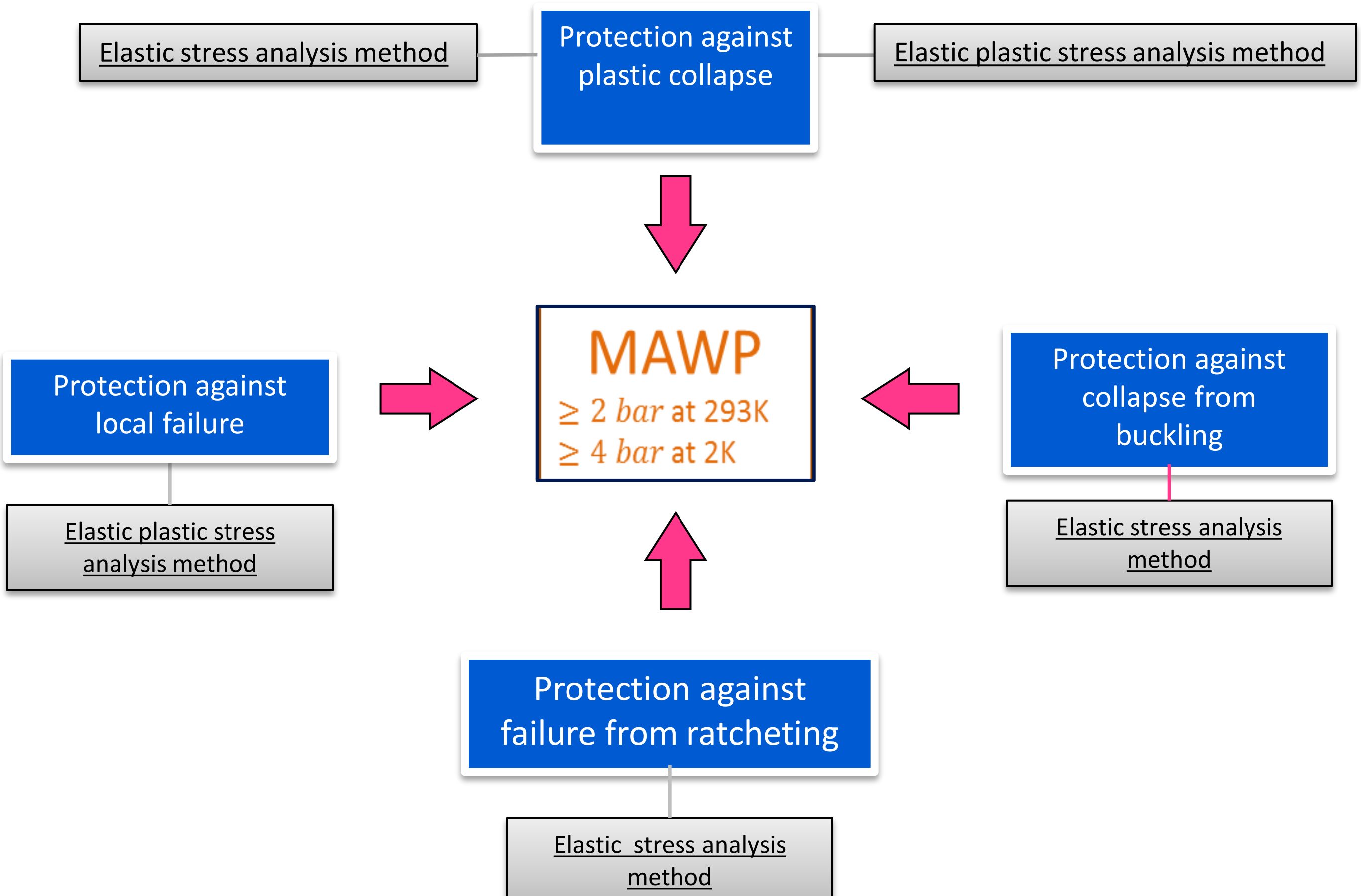
3. Protection against failure from cyclic loading

- Elastic ratcheting analysis method

4. Protection against local failure (i.e. joints)

- Elastic-plastic analysis under the achieved MAWP

Design-by-Analysis goals



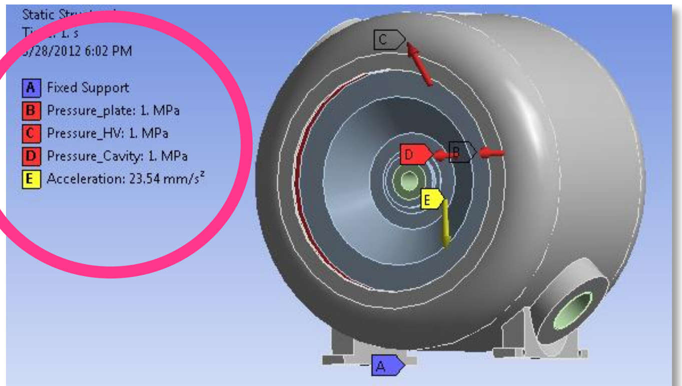
Example: Protection against plastic collapse
Elastic plastic stress analysis - @ 293K

(Donato Passarelli)

Elastic plastic material property @ T=293K

Load combination applied: 2.4(P+D)

Refined mesh




```
TIME OF LAST SOLUTION . . . . . . . . . . .0.53500E-01
   TIME AT START OF THE LOAD STEP . . . .  0.0000
   TIME AT END OF THE LOAD STEP . . . . .  1.0000
NOTE: FOR CONVERGING SOLUTIONS, ADDITIONAL EQUILIBRIUM ITERATIONS MAY BE
      ADDED IN THE RESTART (NEQIT COMMAND) USING THE RESTART FILE
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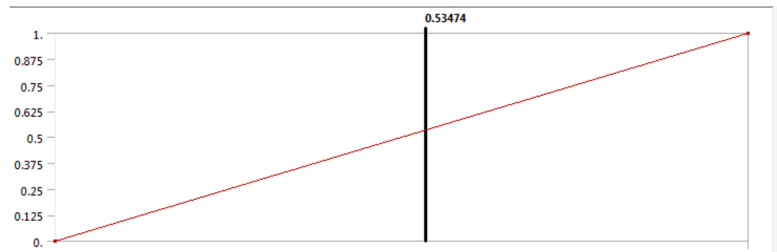
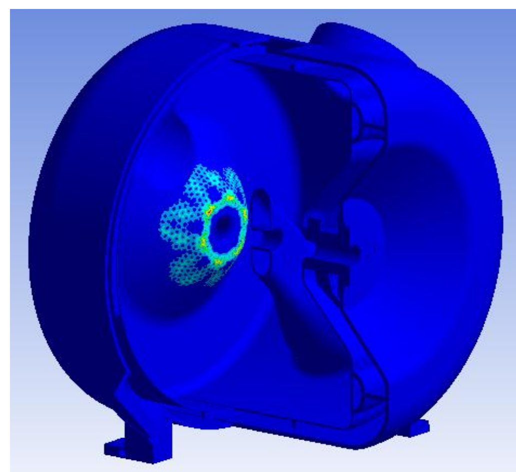


	Steps	Time [s]	Pressure [MPa]
1	1	0.	0.
2	1	1.	1.
*			

Pressure of last solution………5.35bar

$$MAWP_{RT} = \frac{5.35}{2.4} = 2.23bar\ (32.3\ psi)$$



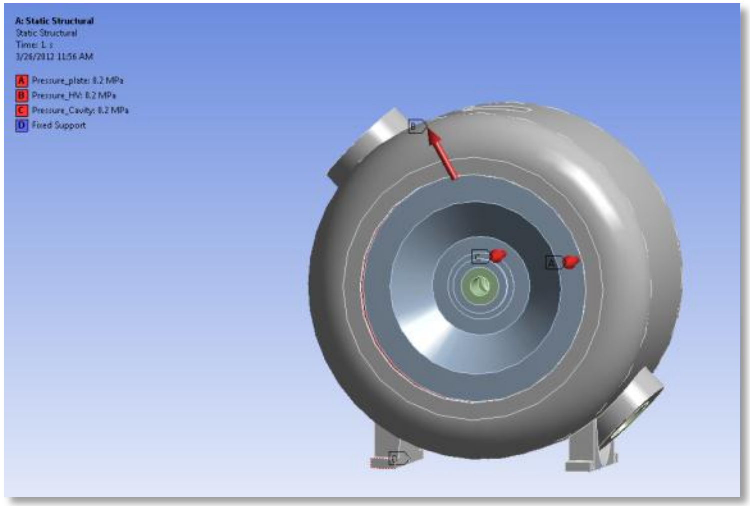
The elastic plastic stress analysis at 293K shows that the plastic collapse occurs on the *area of the Endwall* (bellows side), connected to the *Daisy ribs*, under a pressure of 5.35 bar (77.6 psi)

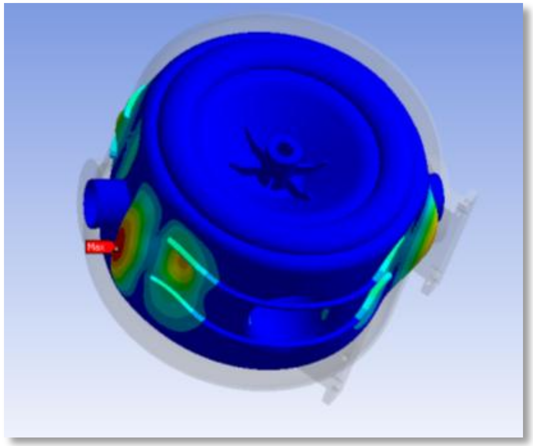
Example: Protection against collapse from Buckling
Linear Buckling analysis - @ 293K (Donato Passarelli)

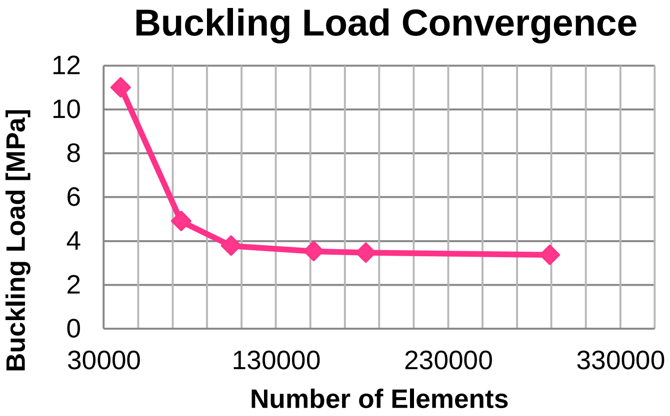
Material properties @ T=293 K
The *cavity* is the component with the *lowest* buckling load

- Buckling pressure **33.6 bar**
- Capacity reduction factor for cylinders under external pressure $\beta = 0.8$
- Design factor $\varphi = \frac{2}{\beta} = 2.5$

$$MAWP_{RT} = \frac{33.6}{2.5} \cong \mathbf{13}\ bar\ (188.5\ psi)$$







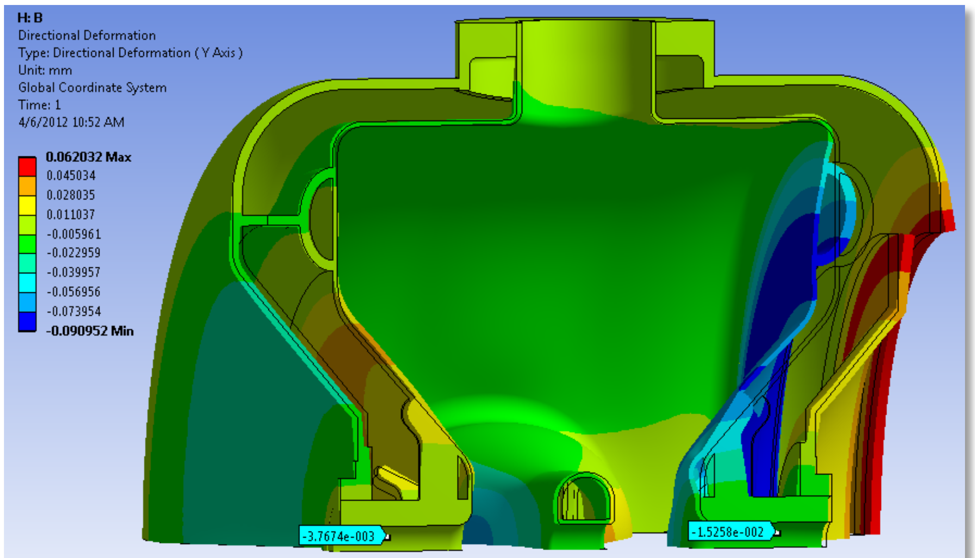
He pressure sensitivity

- History
  - SSR1 designed for pulsed operation had df/dP= -150 Hz/torr
  - CW operation required minimizing df/dP
  - Cavities were already designed and orders placed
  - Several options were investigated to reduce this sensitivity at the helium vessel and tuner level
- Options for reducing df/dP
  - Increasing stiffness of tuner
  - Increasing bellows diameter
  - Utilizing two bellows
  - Coupling one or both cavity end-walls to the helium vessel
- Adjustment after jacketing
  - The possibility of adjusting df/dP after the cavities are jacketed is very important due to the uncertainties in the analyses and the manufacturing variations
  - E.g. If BP deformations depend strongly on tuner stiffness, one can adjust df/dp by “changing” the tuner stiffness

SSR1 jacketed cavity: Pressure Sensitivity

(Donato Passarelli)

- Adopted the solution with a bellows (of appropriate diameter) on the tuner side and a coupling ring on the opposite side



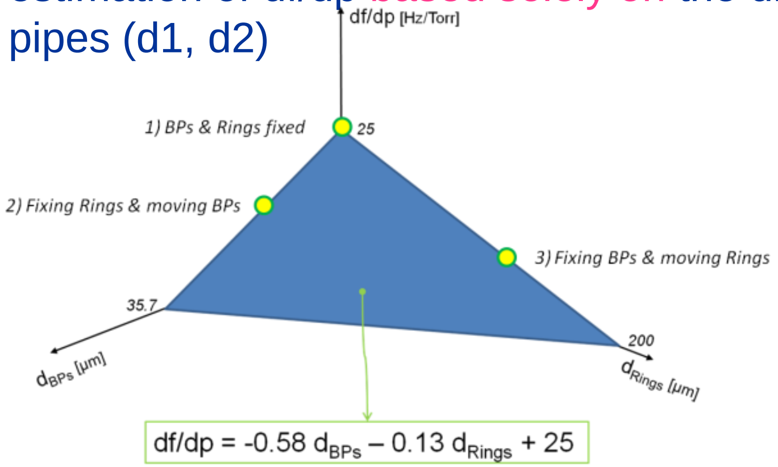
- Figure shows deformations for a cavity under vacuum and Helium at 1 atm
- Beam pipes deform only few µm inward
- df/dP < 10 Hz/torr
- Deformations in high E and B regions balance out resulting in a small frequency shift

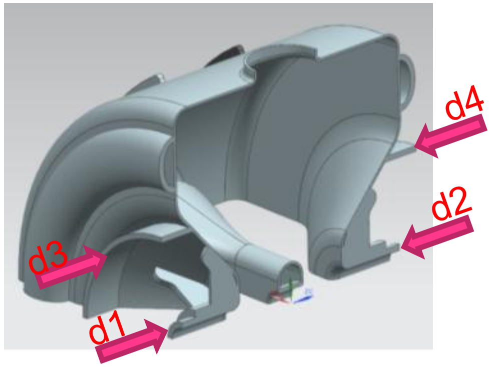
df/dP = **-2 Hz/Torr** without Tuner effect (by Ansys, Comsol and equation)
df/dP ≈ **6 Hz/Torr** with Tuner “infinitely” rigid
The actual case will fall within these limits

Mechanical analyses for df/dP estimation

(Donato Passarelli)

- The cavity is constrained to the helium vessel in several locations (e.g. d1, d2, d3, d4,..)
- After a first series of RF-mechanical coupled analyses, we can perform mechanical only analysis to predict df/dP.
- The computation time is reduced considerably, basic codes can be used, more licenses available, more users capable of launching such simulations.
- Example: In a specific case of SSR1 with two coupling rings, only 3 RF simulations (3 points of the plane) were needed to define the mathematical relation to have an estimation of df/dp based solely on the displacements on Rings (d3, d4) and beam pipes (d1, d2)

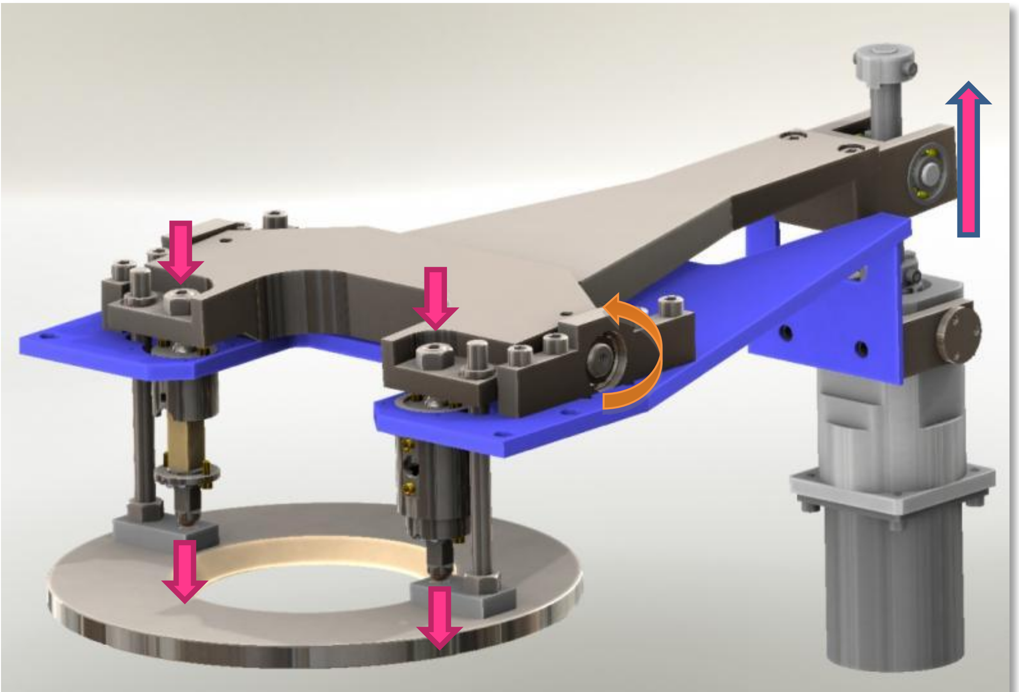




SSR Tuner Design

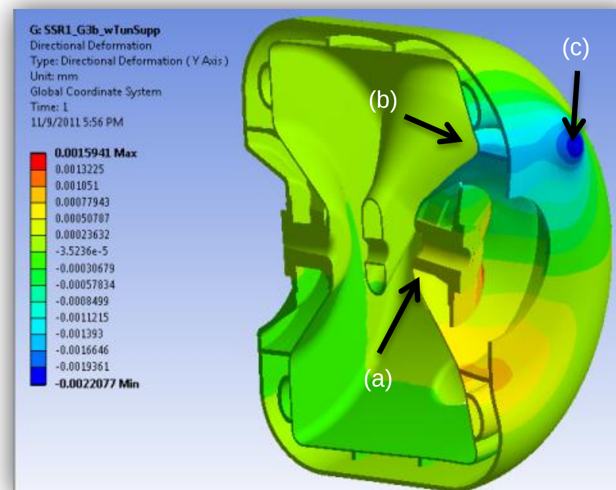
Spoke Tuning System Requirements	value	unit
Cavity and Mechanical system specs		
Cavity end-wall spring constant	30000.00	N/mm
Cavity elastic sensitivity at end-wall	540.00	kHz/mm
Frequency range necessary for operation	**135.00**	kHz
Stroke at BP	**0.25**	mm
Max force at BP	**7500.00**	N
Mech advantage Beampipe/Motor	0.17	
Mech advantage Beampipe/Piezo	0.50	
Elastic efficiency Beampipe/Motor	0.25	
Elastic efficiency Beampipe/Piezo	0.25	
Transmission coefficient from Motor (mech adv x el effic)	0.04	
Transmission coefficient from Piezo (mech adv x el effic)	0.13	
Piezoelectric actuators specs (Fine tuning)		
Max force	3750.00	N
Frequency range	1.00	kHz
Stroke at BP	1.85	um
Stroke cold	14.81	um
Motor assembly specs (Coarse tuning)		
Max Force at Nut pushing (safety operation)	non-issue	N
Max Force at Nut pulling (normal operation)	1250.00	N
Stroke	6.00	mm
Frequency resolution	0.02	kHz
Axial resolution at Nut	888.89	nm
Lifetime linear travel of Nut	1500.00	mm

Prototype tuner ?



- Two piezo actuators “in series” with slow tuner arms (pivot with 5:1 mech. advantage).
- The piezoelectric actuators are buried between the cavity beam pipe and the solenoid adjacent the cavity, impossible to service them.
- The life expectancy of piezoelectric actuators is reduced in presence of radiation

- If we introduce a tuner similar to the lever prototype, the cavity deforms in an unwanted way.
- The G3 vessel is more flexible than the prototype



When subject to an arbitrary tuning force, the beam pipe area appears to rotate (a) more than translate.
Also, the end-wall shape is distorted (b) due to the reactions on the vessel wall (c)

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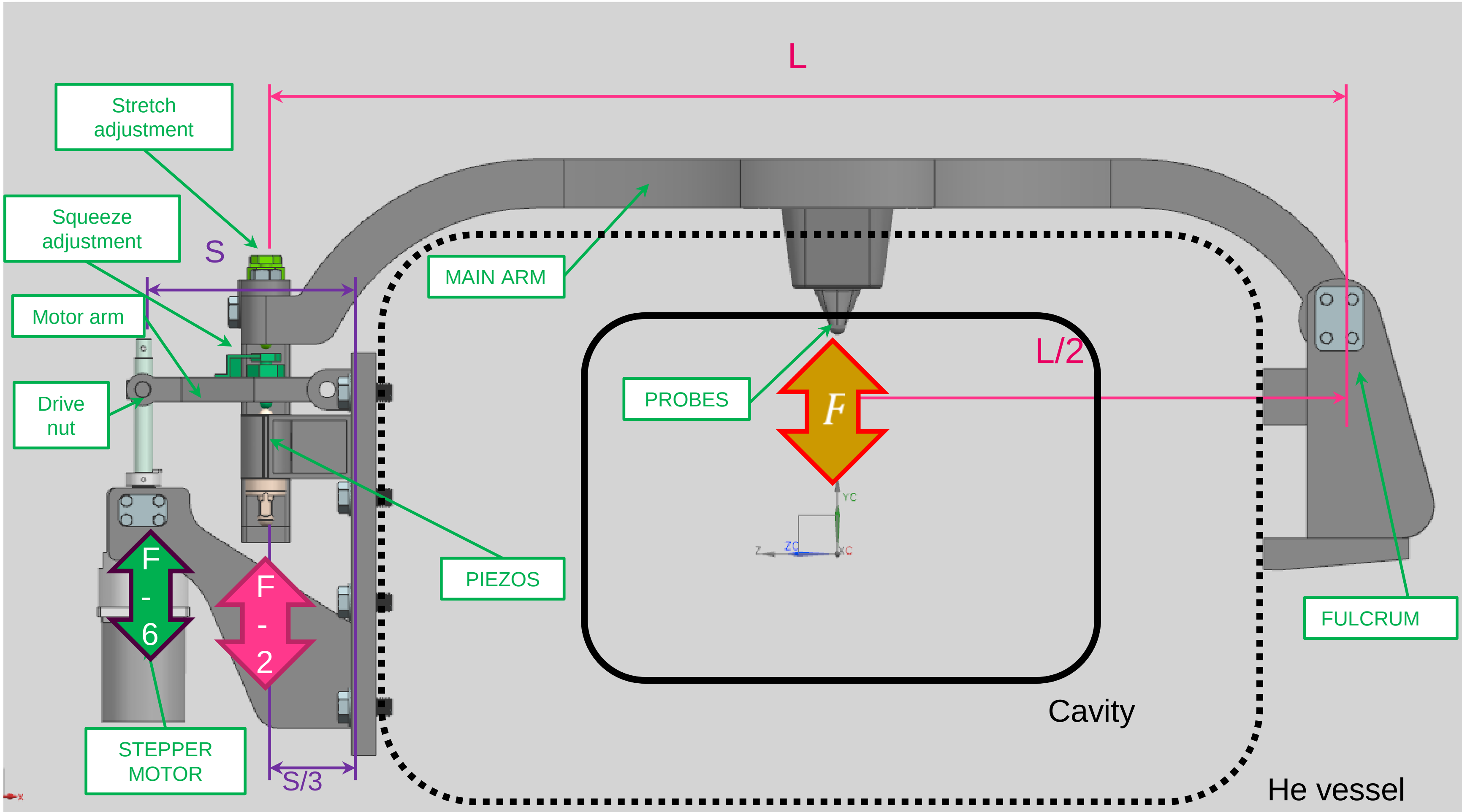
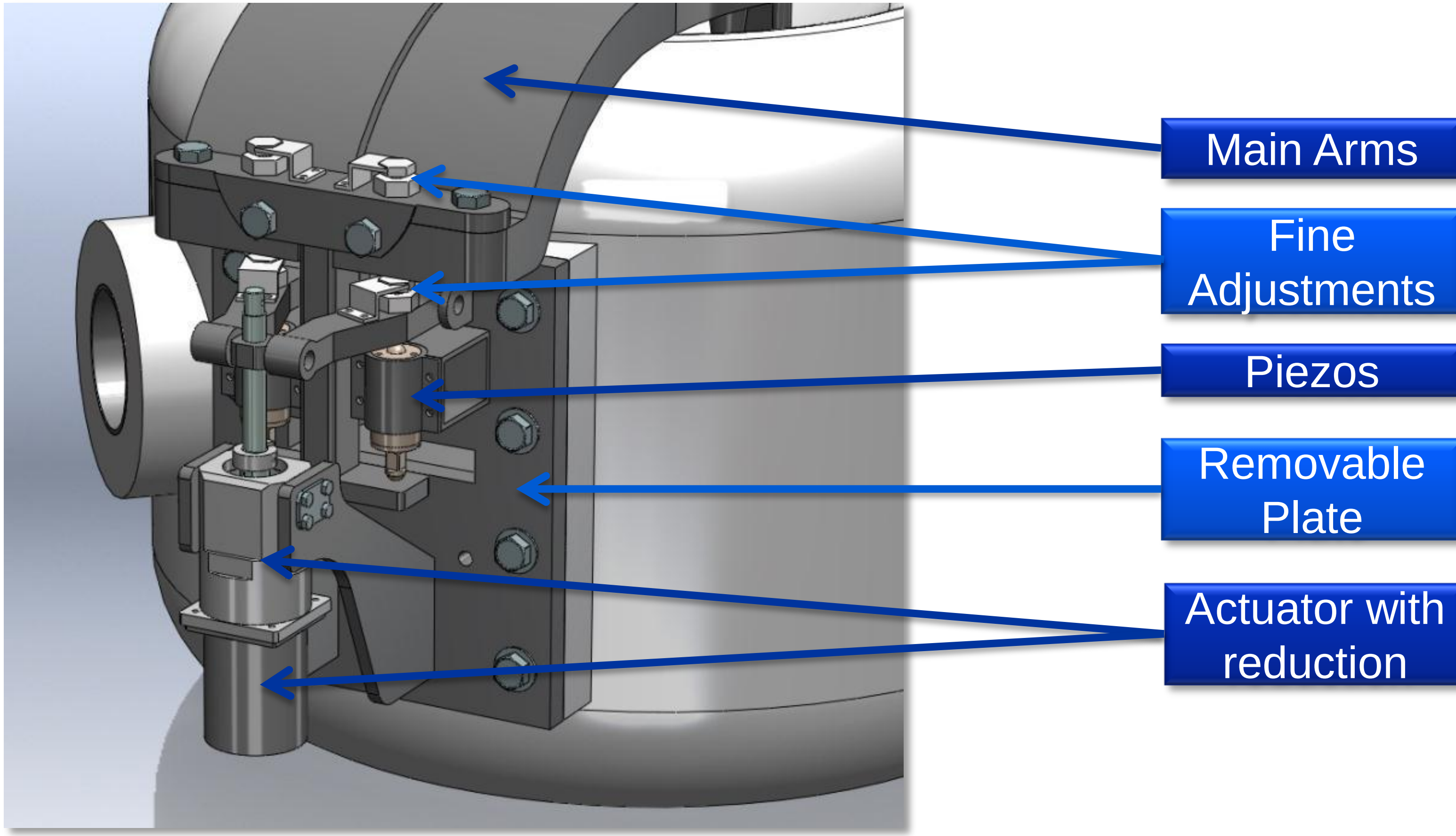
SSR Tuner scheme

(Donato Passarelli)



SSR Tuner details

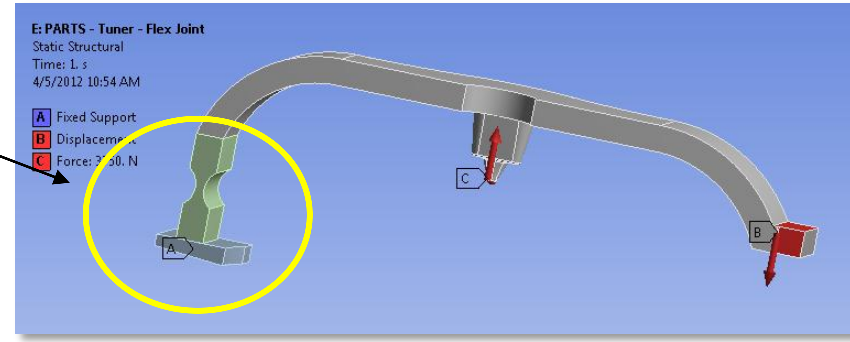
(Donato Passarelli)

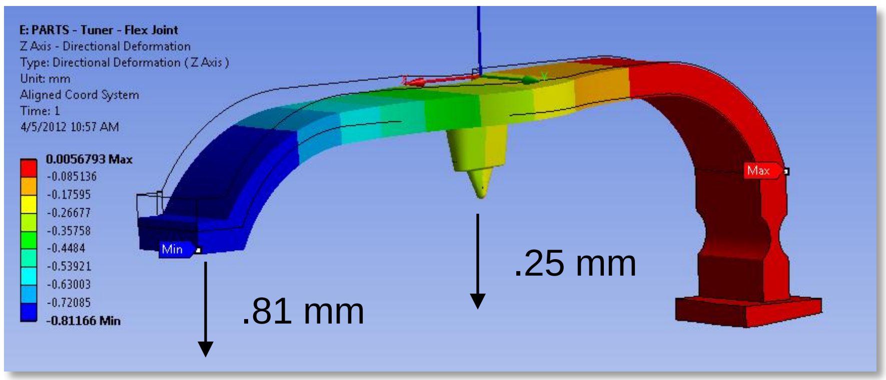


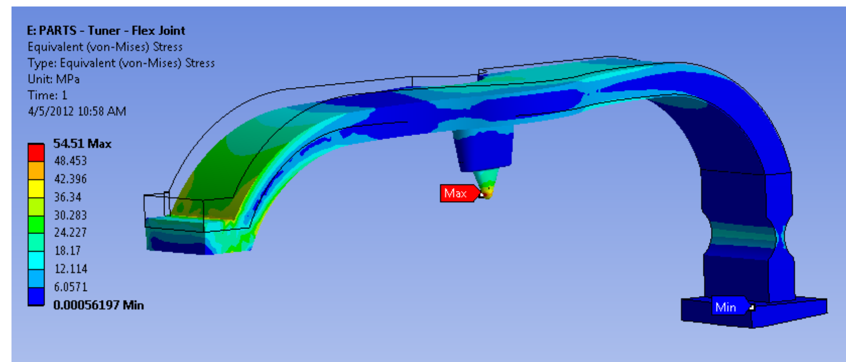
Studies on flexible joint

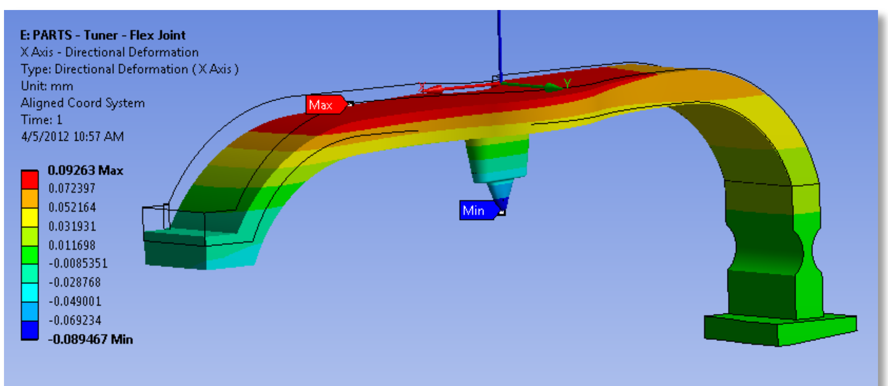
(Margherita Merio)

- Alternative to bearing joint





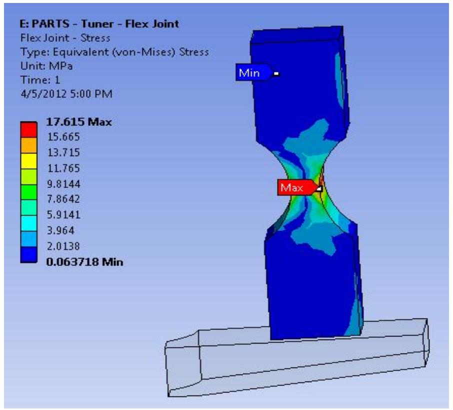


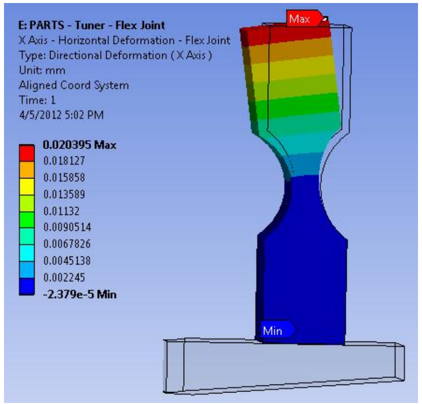


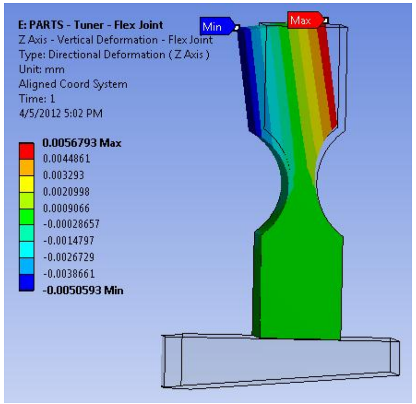
Z Axis Displacement @ BP [mm]	X Axis Displacement @ BP [mm]	Max Stress [MPa]
-0.25485	-0.0813	54

Studies on flexible joint

(Margherita Merio)







Initial Design	
Elastic Efficiency	0.697
Transmission Coeff	0.31
Force Required [N]	-2669

Flexible Joint	
Elastic Efficiency	0.707
Transmission Coeff	0.32
Force Required [N]	-2678

- When using the flexible joint a (slightly) higher force is required to obtain the desired displacement, one can minimize it at the cost of higher stresses in the joint.
- Main purpose is to reduce relative movement in the joints whenever possible and mitigate hysteresis phenomena when tuning the cavity.

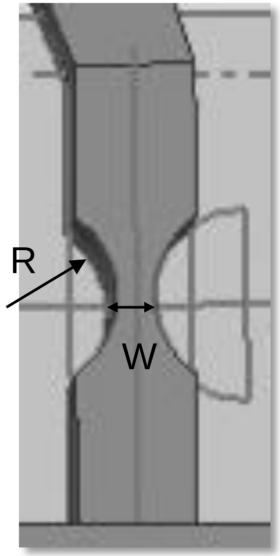
Studies on flexible joint

(Margherita Merio)

It is possible to modify two parameters in the joint design:

- Radius of the notch
- Width of the narrow section

Radius	Width	Force @ Displacement	VERTICAL - BP Displacement	X Axis - BP Displacement	Horizontal Deformation - Flex Joint	Stress @ Joint	Stress @ BP	Elastic Efficiency
mm	mm	N	mm	mm	mm	MPa	MPa	
20	2	2686	-0.2501	-0.0694	0.0241	18	54	0.7034
20	4	2714	-0.2456	-0.0784	0.0205	18	54	0.6909
40	2	2684	-0.2504	-0.0686	0.0244	14	54	0.7043
40	4	2707	-0.2468	-0.0761	0.0214	15	54	0.6942



This shows that the elastic efficiency (EBPP) can be improved by making the narrow section smaller.

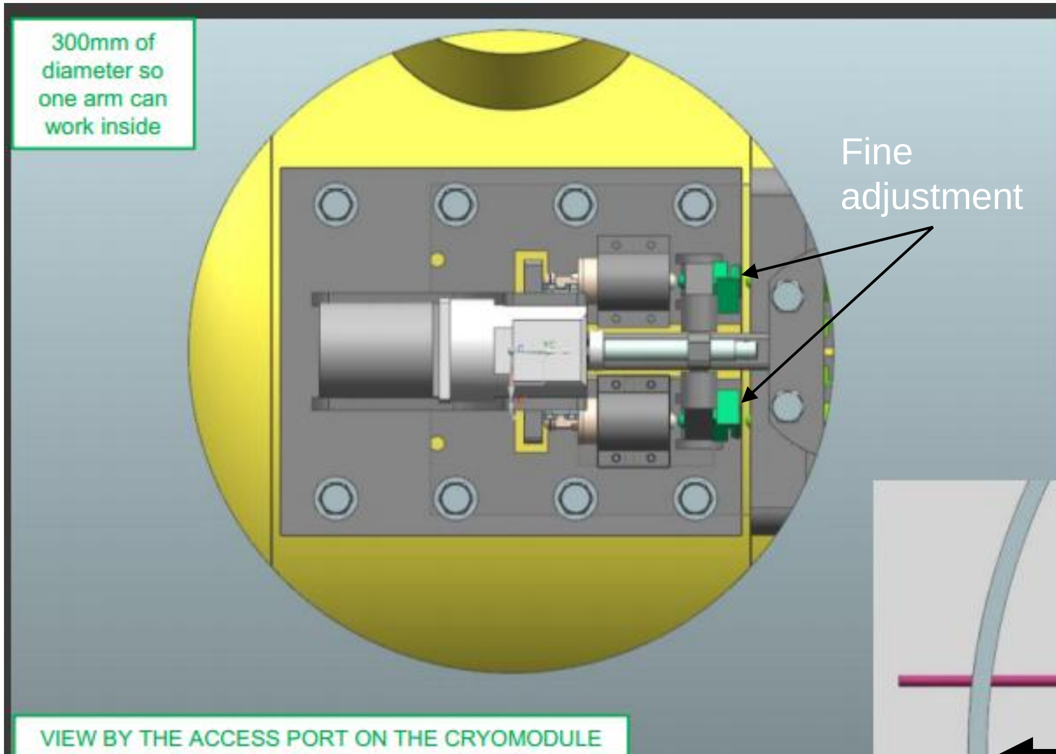
Choosing a smaller radius and reducing the width of the narrow section reduces the maximum stresses

After these considerations, the proposed design for the joint is the following:

Radius	Width	Force @ Displacement	VERTICAL - BP Displacement	X Axis - BP Displacement	Horizontal Deformation - Flex Joint	Stress @ Joint	Stress @ BP	Elastic Efficiency
Mm	mm	N	mm	mm	mm	MPa	MPa	
18	1	2678	-0.2512	-0.0667	0.0252	18	54	0.707

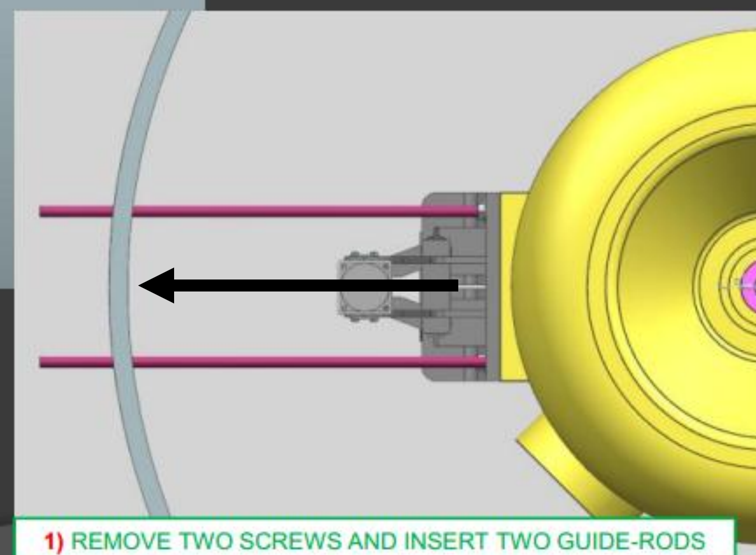
Tuner maintenance

(Donato Passarelli)



Fine adjustment screws allow relieving loads in case of failure under load.

Motor, piezos, motor arms and main plate can be removed in one piece (cartridge approach).

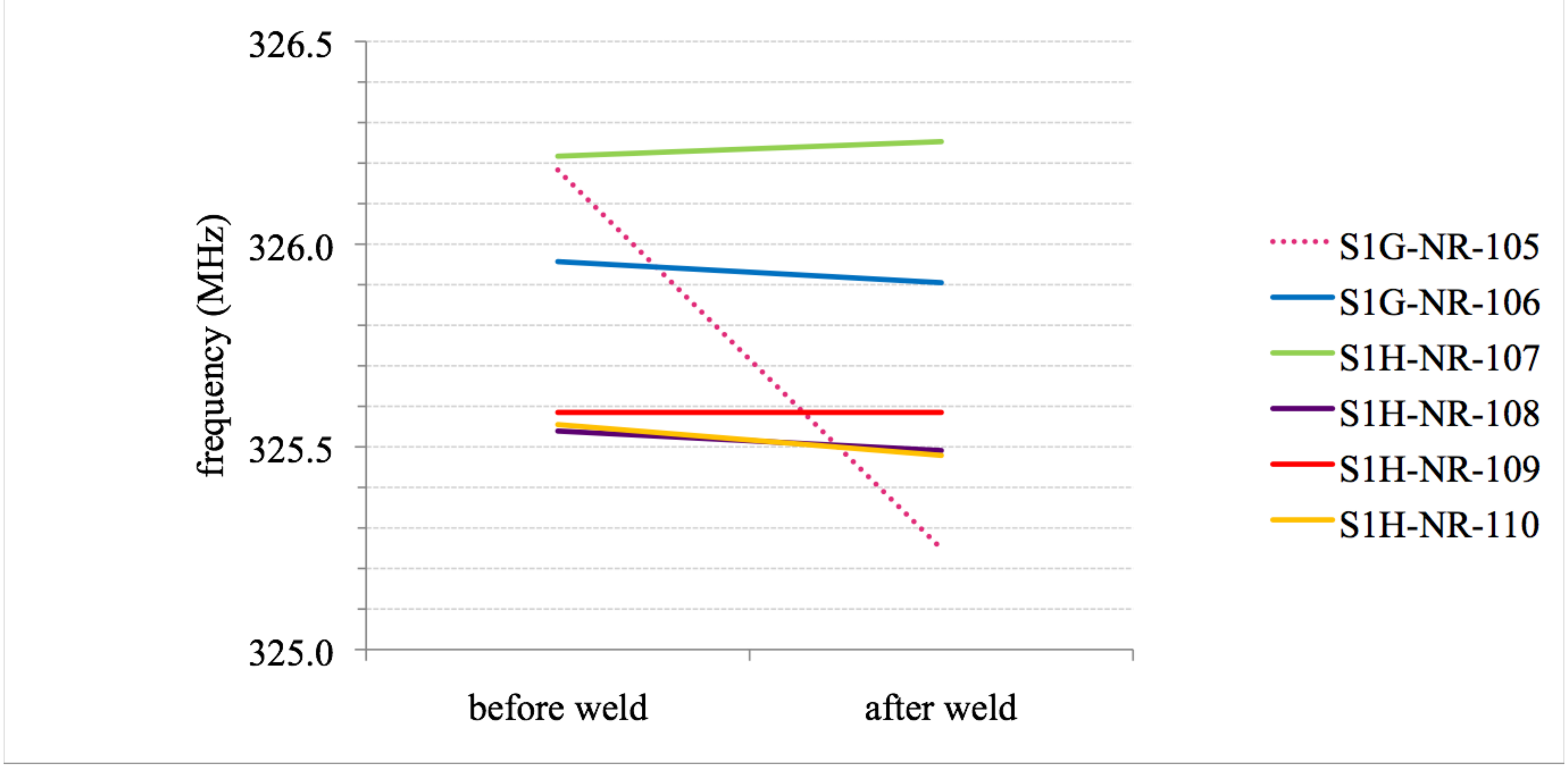


Status of activities

- Received 6 cavities of 10
  - Performed incoming inspections (Visual, CMM, leak check, RF)
- First cavity (S105) was processed and cold tested, now undergoing a 120' C bake and will be re-tested next week
- Second cavity (S106) is currently being processed

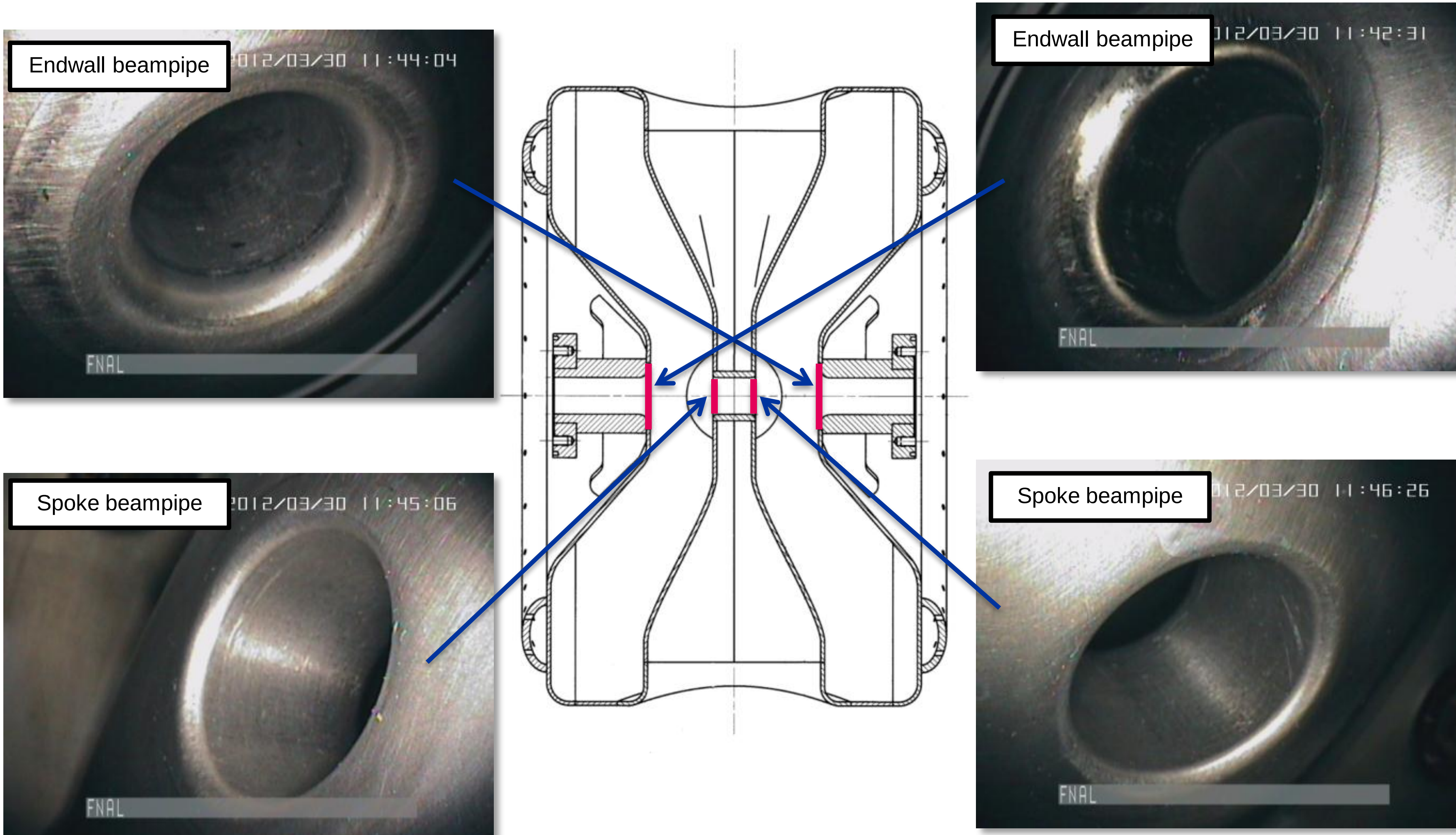
	Forming	sub-assy EBW	Trim	final EBW	Delivery to FNAL	QC	Bulk BCP	Bake	RF tune	Light BCP	VTS	Jacketing	BCP	HTS
S1 ZN 101					11-May-07									
S1 RK 102					31-Jul-08							Oxidized at Roark	at AES	
S1 IU 103														
S1 IU 104														
S1 NR 105					9-Mar-11		ANL				23-Mar-12			
S1 NR 106				hole	24-Oct-11		ANL							
S1 NR 107					4-Nov-11									
S1 NR 108					4-Nov-11									
S1 NR 109					19-Dec-11									
S1 NR 110					19-Dec-11									
S1 NR 111				hole	1-May-12									
S1 NR 112				on hold	1-Jun-12									
S1 NR 113		hole in collar		on hold	1-Jun-12									
S1 NR 114		hole in collar		on hold	1-Jun-12									
S1 RK 115	holding													

Shifts due to final welding



- Cavities so far showed negligible shifts (E and B areas compensate?)
- Large shift of #105 due to repeated welds on one side

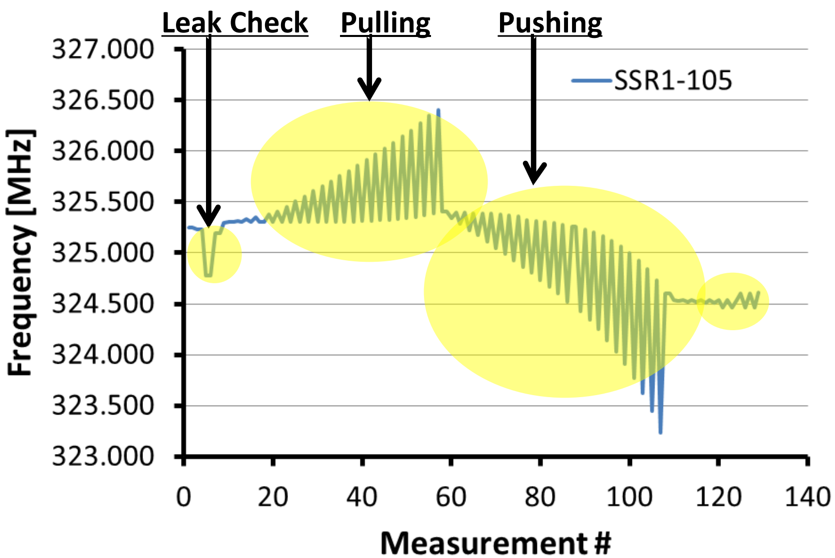
Videoscope inspections

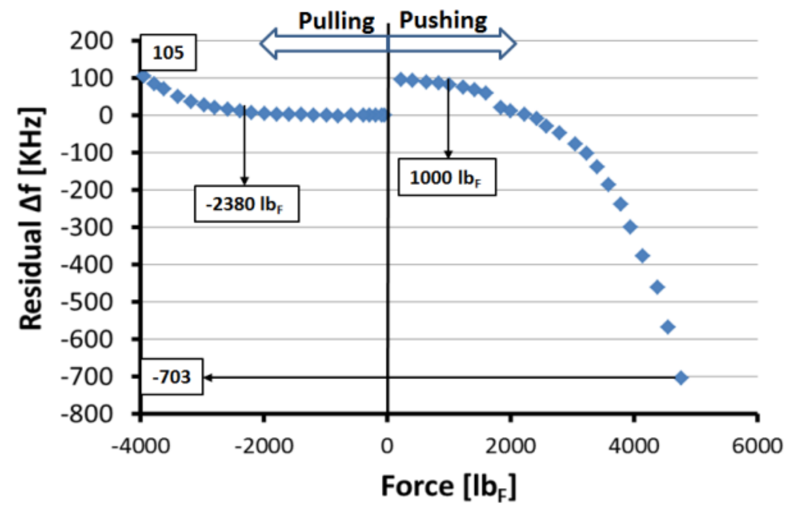


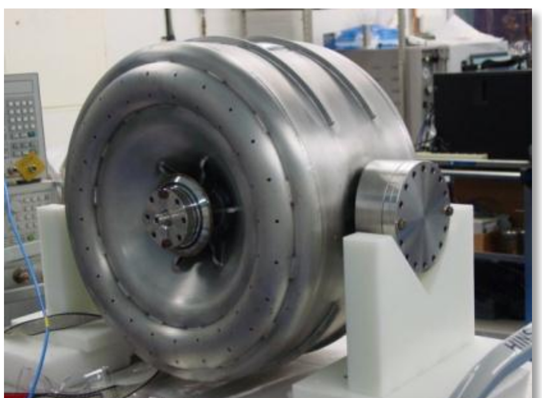
Project X & PXIE

Inelastic tuning

(T. Khabiboulline, M. Hassan)







Measured df/dL=584.6 Hz/μm
Simulated df/dL=540.0 Hz/μm

Measured dF/dL=18 KN/mm
Simulated dF/dL=23 KN/mm

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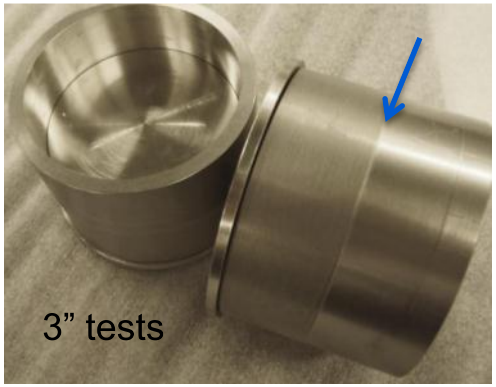
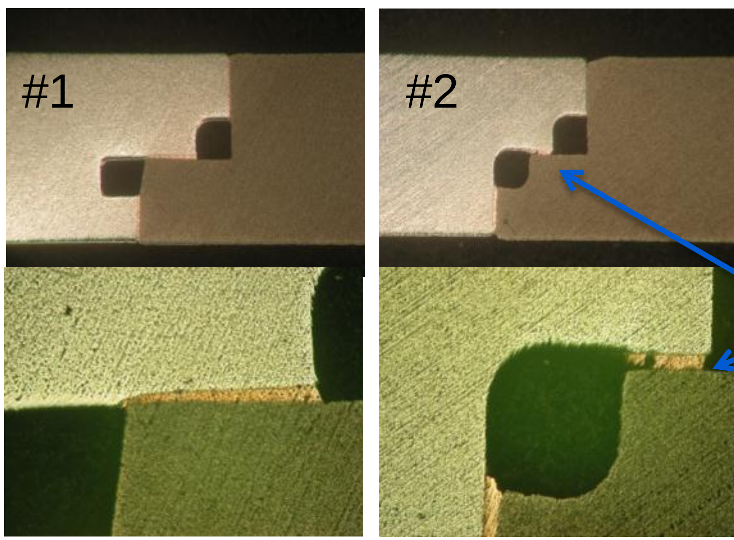
Brazed Coupling rings

(ANL William Toter)



At ANL the development of the brazed coupling ring is in progress with good initial results.
Soon will produce the actual rings to be EBW on cavities

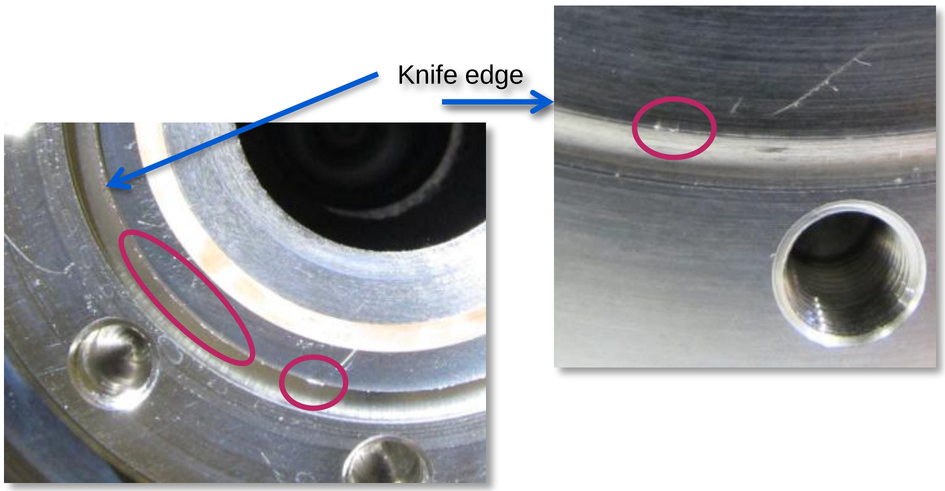
Two different joint designs investigated



- Chose option #2 for ease of machining but <u>increased length of vertical joint</u>
- Proceeded to 10” tests
- Tensile tests, thermal cycling and leak checks in progress

Issues

- Weld blow-throughs
  - Occurrence is 4 events in 191 minutes of welds (T = 47 min)
  - Currently on hold, improvements made on process and now measuring occurrence
  - 3 repairs made, first repaired cavity is undergoing processing and will be tested in the next weeks
- Knife edge damages
  - Cavity S105 was leak tight on arrival
  - After processing, one beam pipe flange had a leak
  - Successfull refinishing of knife edge allowed seal and cold tests
  - Cefix copper gaskets is an option we have in hand if necessary



Collaboration with IUAC (India)

4 completed end-walls

EP of shell

EP of end wall

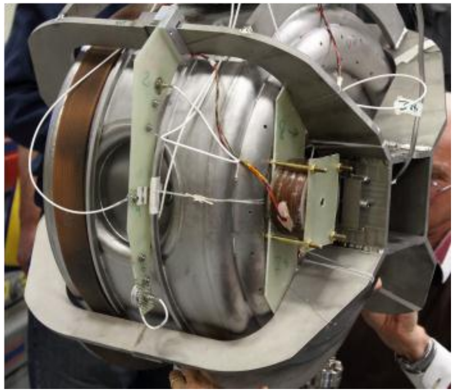
- IUAC in New Delhi is working on the development of two SSR1 resonators.
- Niobium provided by FNAL.
- Parts receive EP prior to assembly

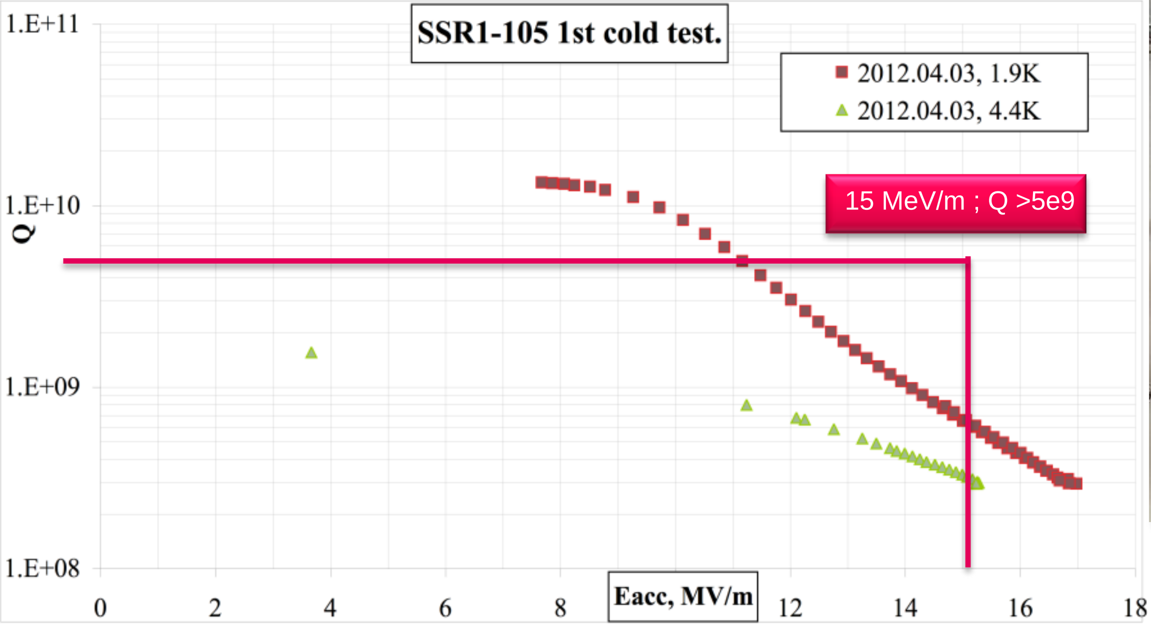
Abhishek Rai, P.N.Prakash, J.Sacharias, K.K.Mistri

Cold Tests of S105

(T. Khabiboulline, Y. Pischalnikov, et al)

- Design gradient achieved
- Design Q not achieved, possibly H_2O
- Usual multipacting behavior
- Hours (days) of processing
- 120' C bake in progress
- Will test again next week





Conclusions

- The mechanical design of the helium vessel of SSR1 was recently improved to address the sensitivity to helium pressure variations.
- All required safety analyses are near completion (MAWP: 2 bar warm, 4 bar cold)
- The conceptual designs of helium vessel and tuner are complete, now working on details.
- Development of brazed transition at ANL is progressing well and near completion.
- Received 6 cavities (ordered 10, need 8 in the PXIE CM)
- Performed first cold tests on S105, will test again after 120’ C bake
- IUAC is fabricating S103 and S104