Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

SRF Development for PIP-II
With focus on 325 MHz Spoke Resonators
(for the common aspects with crab cavities)

Leonardo Ristori
HL-LHC Crab Cavity Cryomodule Review
Cern - 11 November 2015

Proton Improvement Plan II (PIP-II) mission

❑ Particle Physics Project Prioritization Panel (P5) Science Drivers:

- Use the Higgs Boson as a New Tool for Discovery
- Pursue the Physics Associated with Neutrino Mass
- Identify the New Physics of Dark Matter
- Understand Cosmic Acceleration : Dark Energy and Inflation
- Explore the Unknown : New Particles, Interactions, and Physical Principles

❑ Proton Improvement Plan II (PIP-II):

The PIP-II goal is to support long-term physics research goals by providing increased beam power to neutrino experiments, while providing a platform for the future.

Proton Improvement Plan II (PIP-II) mission and strategy

- Increase Main Injector power

  from 700 kW (NOvA) to >1 MW (LBNF)
  in the energy range 60 – 120 GeV
- Increase Booster power from 80 to 160 kW
  - 8 GeV program: SBNE, …

⇒ Roadmap for CD-3 in FY19/20

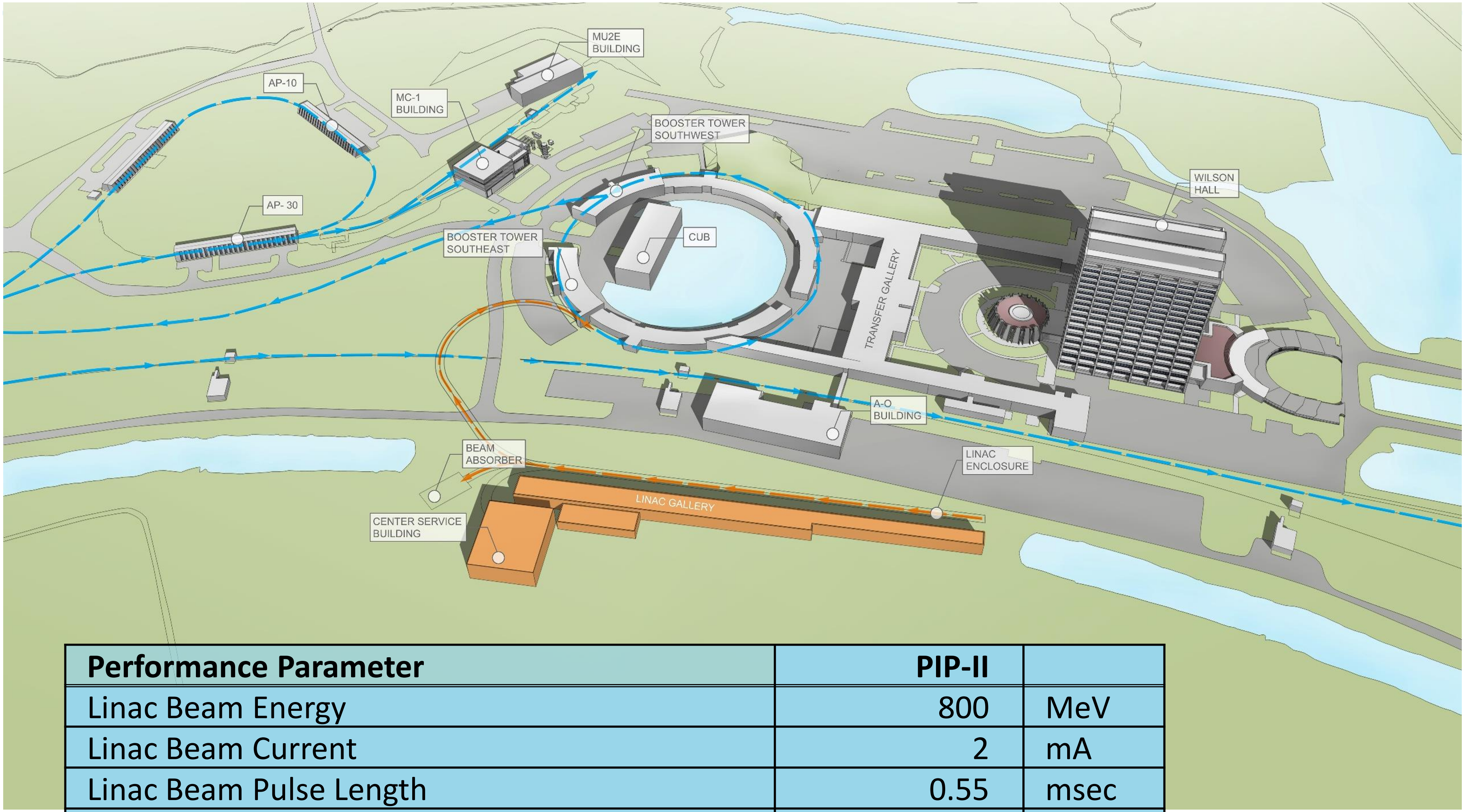
⇒ Construction phase is 5 years: 2019-23

⇒ Goal is 1 MW in 2024

The diamond of PIP-II is a state-of-the-art SRF Linac

Diamonds are beautiful but difficult to make

PIP II SC Linac Requirements

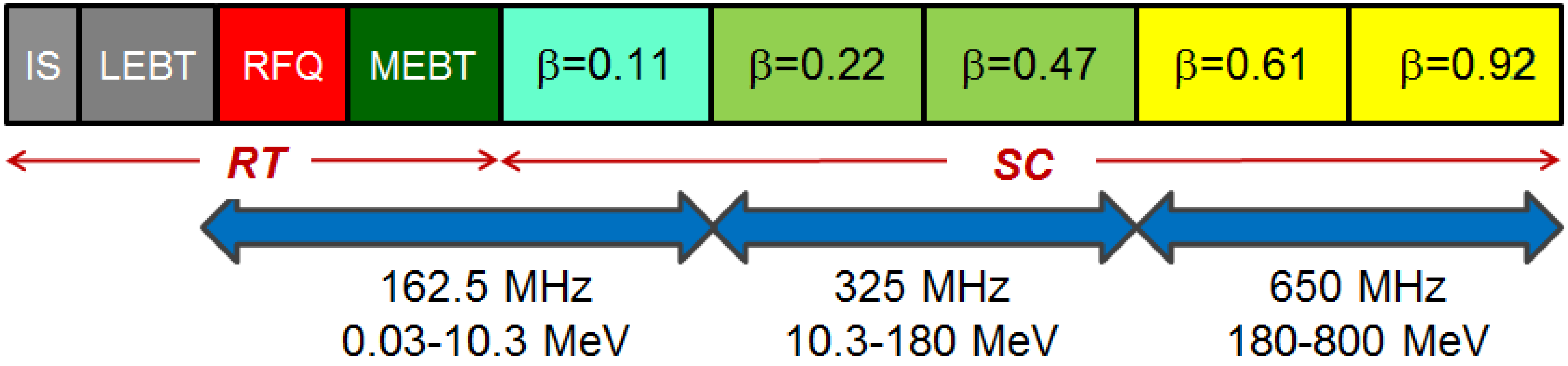


Performance Parameter	PIP-II	
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.55	msec
Linac Pulse Repetition Rate	20	Hz
Linac Beam Power to Booster	18	kW

The Linac Reference Design

- The reference design is ready:
- Frequency choice: sub-harmonics of 1.3 GHz
  - 162.5 MHz, 325 MHz and 650 MHz;
- RF cavity types and betas:
  - one section of 162.5 MHz HWR type, β = 0.11 cavity,
  - two sections of 325 MHz spoke-cavity type, SSR1 and SSR2 with β = 0.22 and β = 0.47; and
  - two sections of elliptical 650 MHz cavities with β = 0.61 and β = 0.92;
- Break points are optimized in order to minimize the number of the cavities;
- CM concept:
  - separate CMs,
  - solenoids for HWR and SSR,
  - no focusing elements for elliptical.
- Operating regimes – both pulsed and CW;
- No HOM dampers.

The Linac Reference Design



IS | LEBT | RFQ | MEBT | β=0.11 | β=0.22 | β=0.47 | β=0.61 | β=0.92

RT ⟷ SC

162.5 MHz
0.03-10.3 MeV

325 MHz
10.3-180 MeV

650 MHz
180-800 MeV

Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_g=0.61)	650	185-500	33/22/11	5-cell elliptical, doublet*
HB 650 (β_g=0.92)	650	500-800	24/8/4	5-cell elliptical, doublet*

*Warm doublets external to cryomodules

All components CW-capable

The Linac Reference Design

Name	beta	Freq (MHz)	Type of cavity	B_{peak} (mT)	E_{peak} (MV/m)	E_{acc} (MV/m)	Gain (MeV)
HWR	0.11	162.5	Half wave resonator	48.3	44.9	9.7	2.0
SSR1	0.22	325	Single-spoke resonator	58.1	38.4	10	2.0
SSR2	0.47	325	Single-spoke resonator	64.5	40	11.4	5.0
LB650	0.61	650	Elliptic 5-cell	72	38.5	15.9	11.9
HB650	0.92	650	Elliptic 5-cell	72	38.3	17.8	19.9

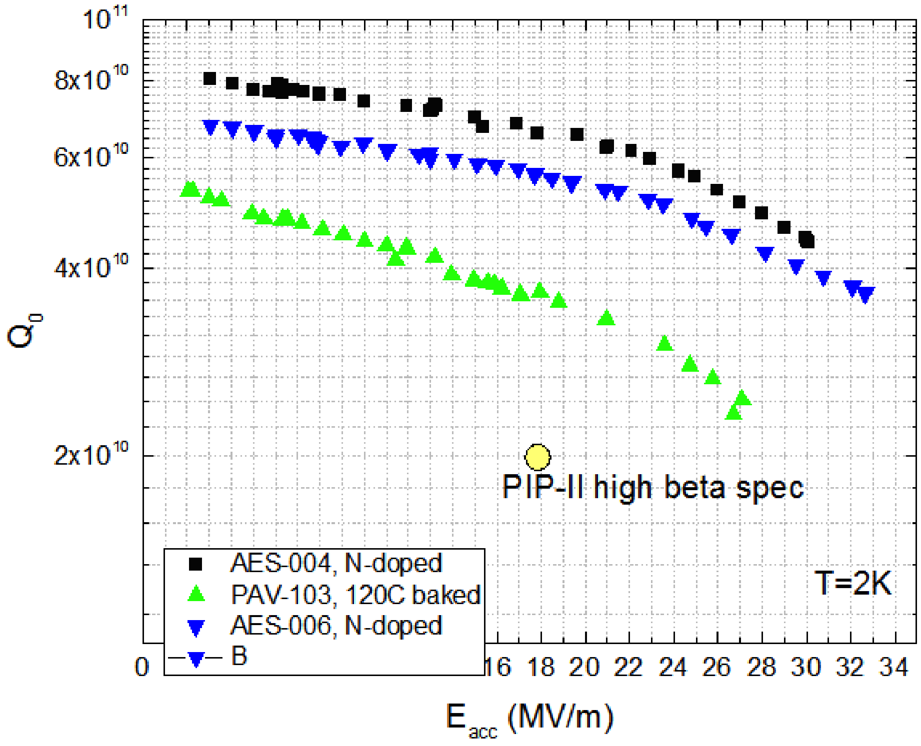
The main challenges and technical risks

- Future CW operation → cryo-losses → high Q_0 is desired;
- Low beam loading → narrow bandwidth;
  - Pulsed regime → Lorentz Force Detune (LFD);
  - CW regime → microphonics;
- High-Order Modes → “to damp, or not to damp?”

- High-Q0 program was initiated and is running successfully;
- Resonance Control program is underway in order to mitigate both microphonics and LFD;
- “Passive” mitigation of the cavity detune – improvement of cavity mechanical properties is underway;
- Detailed HOM analysis is performed.

High Q0 R&D program

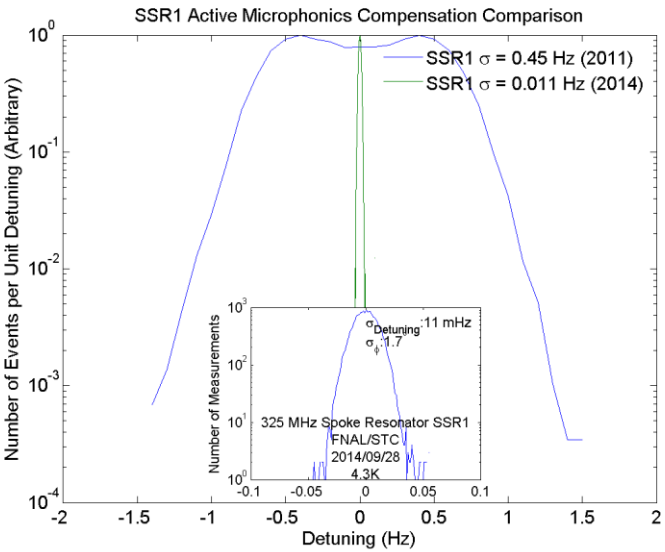
- Results – highlights – 120C bake versus N doping
  Q~ 7e10 at 2K, 17 MV/m – world record at this frequency!
- Applying N doping to 650 MHz (beta=0.9) leads to double Q compared to 120C bake (standard surface treatment ILC/XFEL)

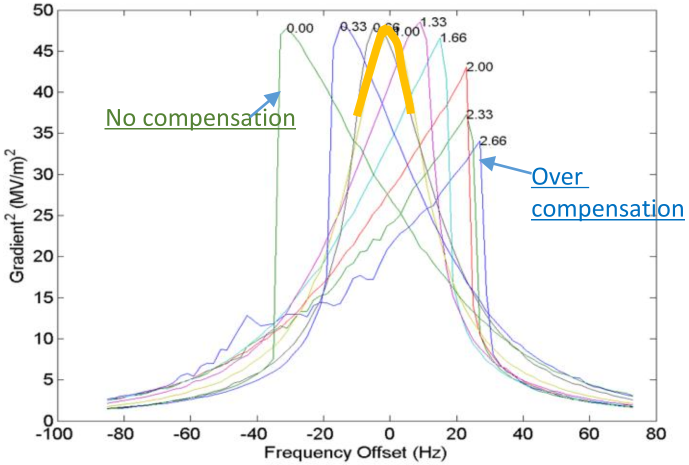


A. Grasselino, MOYGB2, IPAC15, Richmond; **MOBA06, MOPB029, MOPB091**

Resonance Control R&D program

- Piezo feedback has successfully stabilized the resonance with high precision in CW to negligible levels (11 mHz RMS)
- Ponderomotive instability has been successfully mitigated using piezo feedforward tied to the square of the gradient during both CW and pulsed operation
- Adaptive feedforward has successfully suppressed detuning from deterministic sources of detuning
- Techniques for fully characterizing the tuner-cavity-waveguide system automatically have been developed and used successfully





No compensation

Over compensation

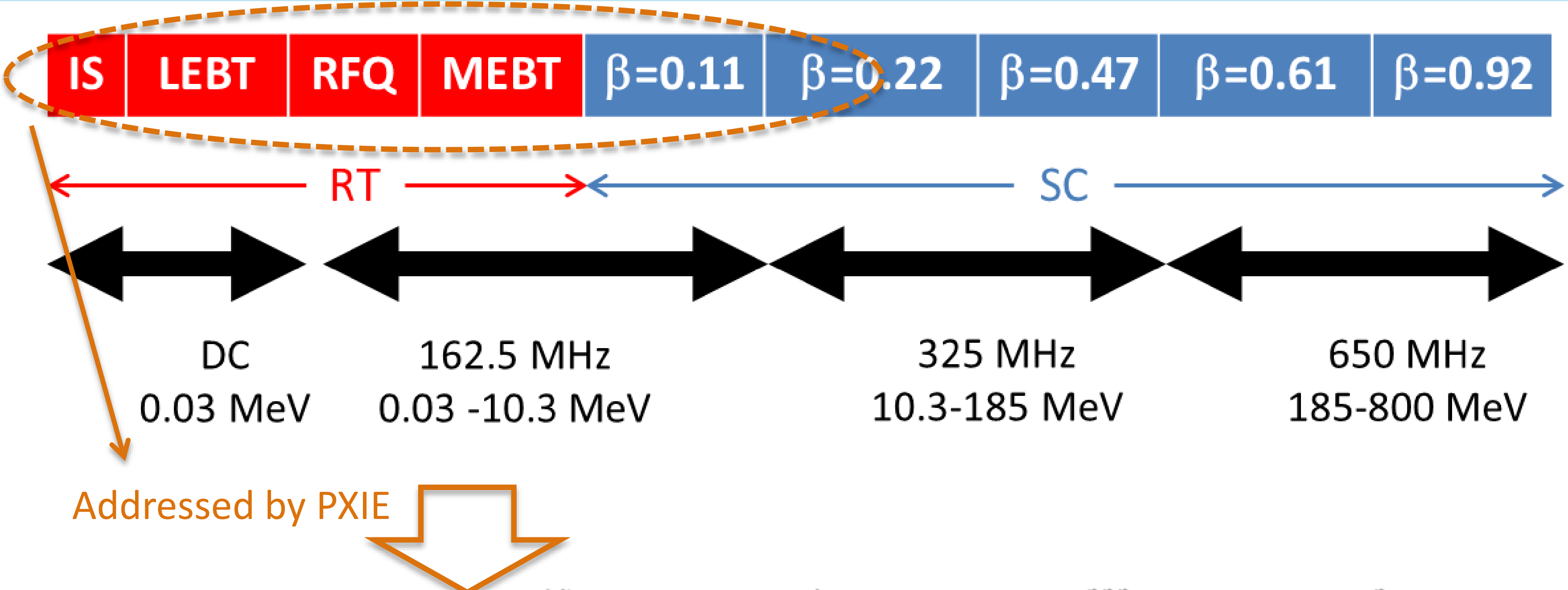
Poster TUPB095
"Resonance Control for Narrow Bandwidth SRF Cavities“

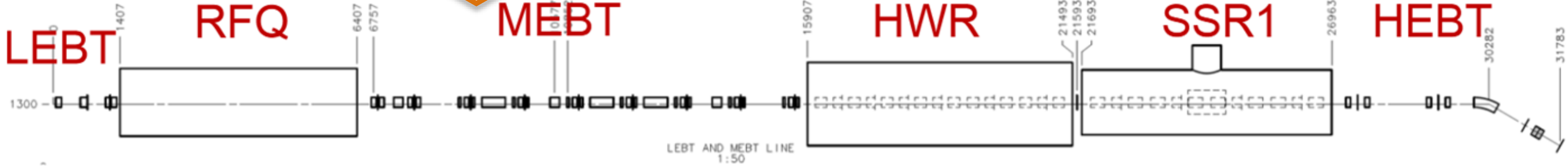
(W. Schappert, Yu. Pischalnikov, J. Holzbauer)

General design approach

- Most components (couplers, tuners, etc.) should be of the same or similar type;
- Cryomodules should be preferably of the same type and contain mostly the same parts;
- Two types of CMs are to be prototyped,
  - spoke-cavity CM for SSR1 and
  - elliptical cavity CM for HB 650.
- Other CMs will be developed basing on the lessons learned for these CMs.

PXIE: R&D program for PIP-II front end





30 keV H-, 5 mA from 1 µs to DC

2.1 MeV, CW 4-vane, 4- module. Designed and manufactured at LBNL.

~10 m, with bunch-by-bunch selection. Magnets are being made by BARC, India.

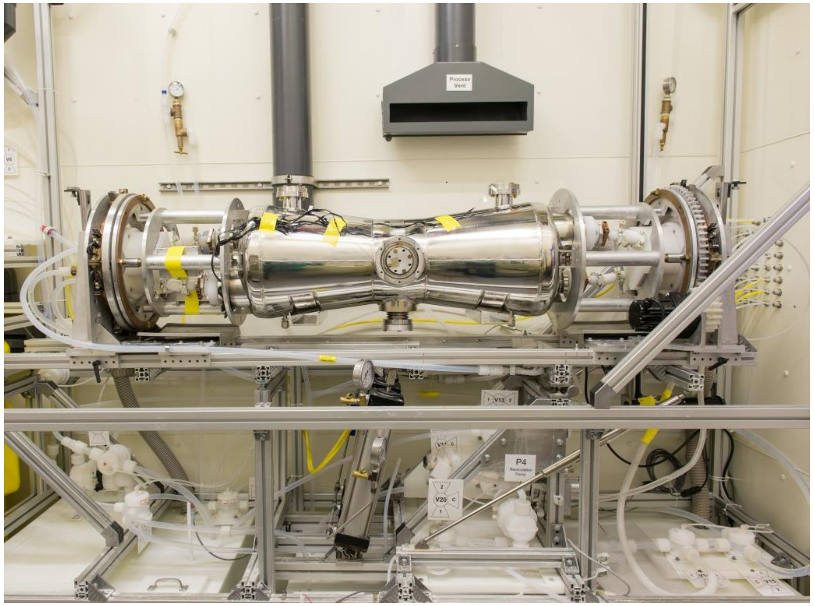
162.5 MHz, 10 MeV. Designed and being manufactured at ANL.

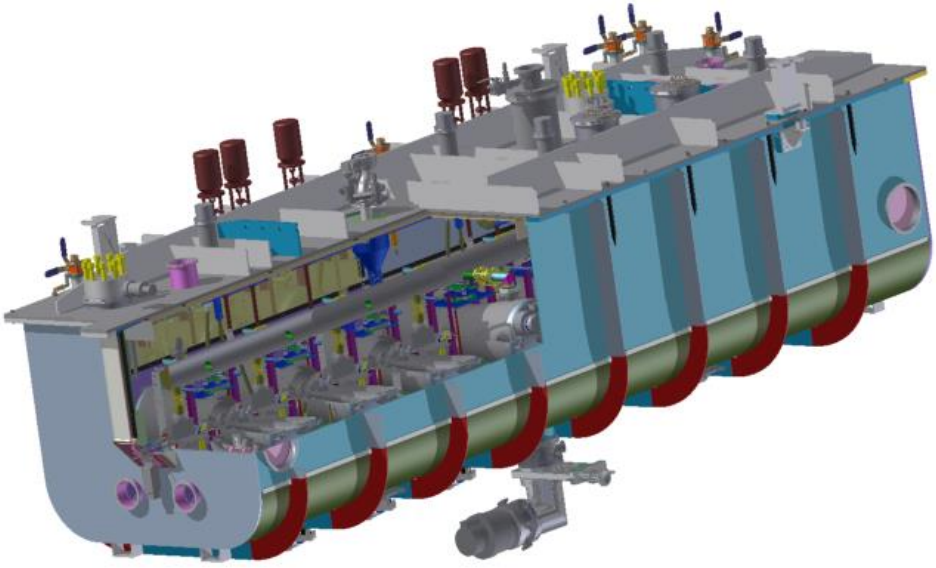
325 MHz, 25 MeV.

Diagnostics and 2 mA CW, 25 MeV dump.

Status of development of critical components. HWR (ANL)

- 2 HWRs were tested with very high performance:
  - residual resistance is <2.7 nOhm at 15 MV/ m accelerating field (E_{peak}=70 MV/m, B_{peak}=75 mT and voltage = 3.2 MV with the cavity length=0.206m)
  - No X-rays observed up to 70 MV/m E_{peak}





Z. Conway, WEBA05 SRF2015 – Whistler Canada
"Achieving high peak fields and low residual resistance in half-wave cavities"

Status of development of critical components, 650 MHz

650 MHz section:

Currently Available Cavities:

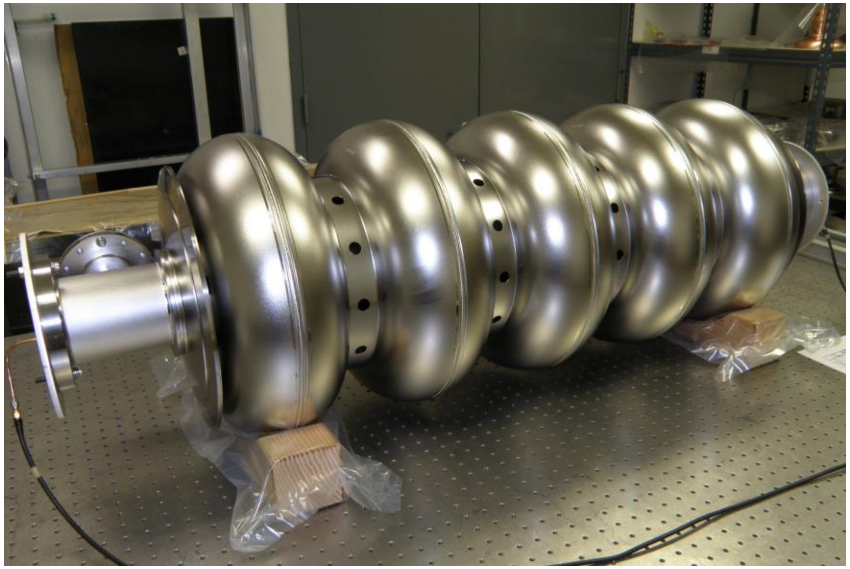
<u>1-Cell 650 MHz*</u>

1. B9AS-AES-001
2. B9AS-AES-002
3. B9AS-AES-003
4. B9AS-AES-004
5. B9AS-AES-005
6. B9AS-AES-006

<u>5-Cell 650 MHz</u>

1. B9A-AES-007
2. B9A-AES-008
3. B9A-AES-009
4. B9A-AES-010

*VTS Tested



Expected Cavities:

<u>1-Cell 650 MHz</u>

Pavac, Inc.

Three are delivered and VTS-tested

Two to be delivered in the end of 2015.

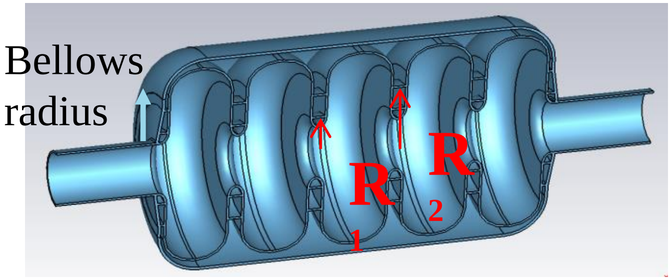
<u>5-Cell 650 MHz</u>

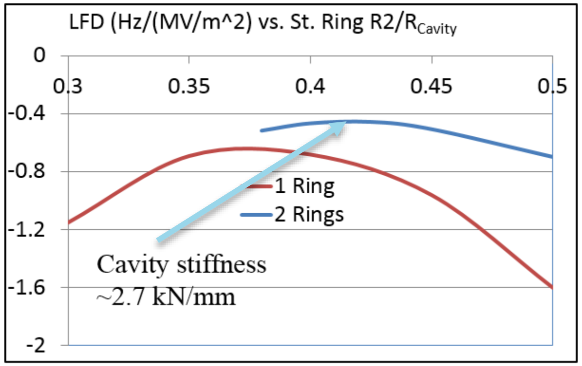
Pavac, Inc.

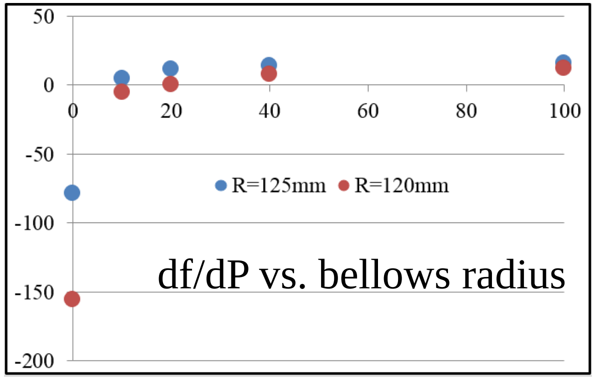
Five to be delivered in 2015.

Status of development of critical components, 650 MHz

Low-Beta Cavity

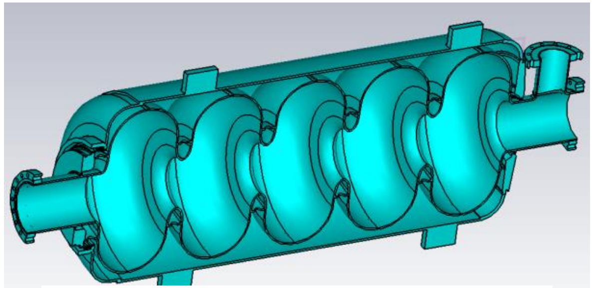


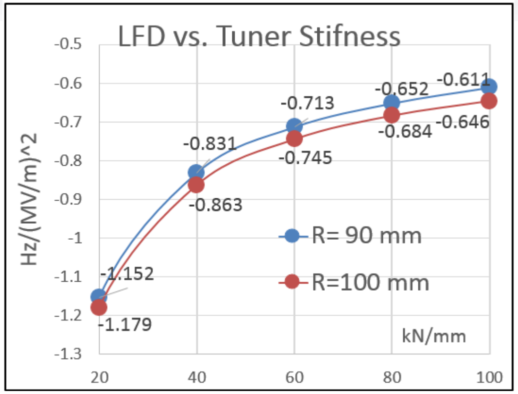


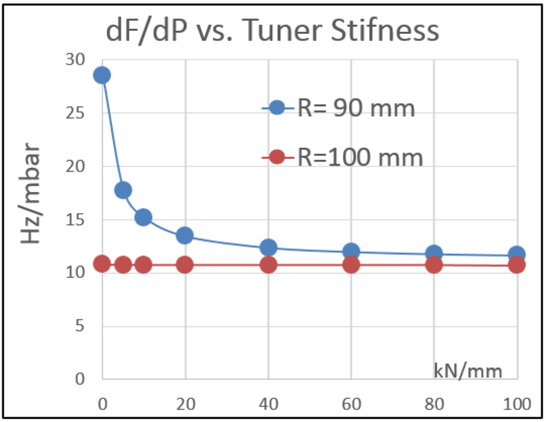


Poster THPB014

High-Beta Cavity



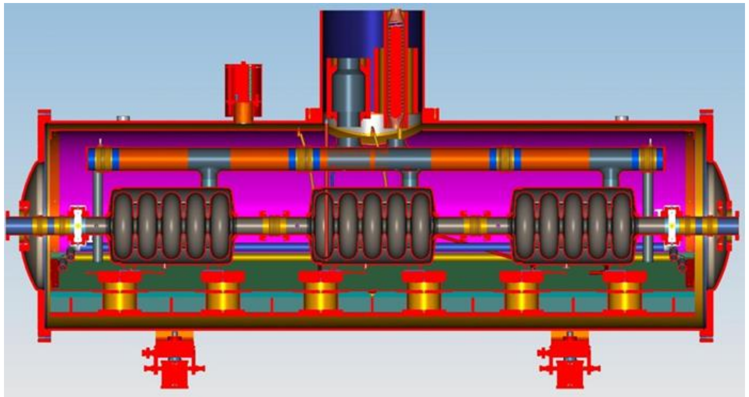




Status of development of critical components, 650 MHz CMs

Low-Beta Cryomodule

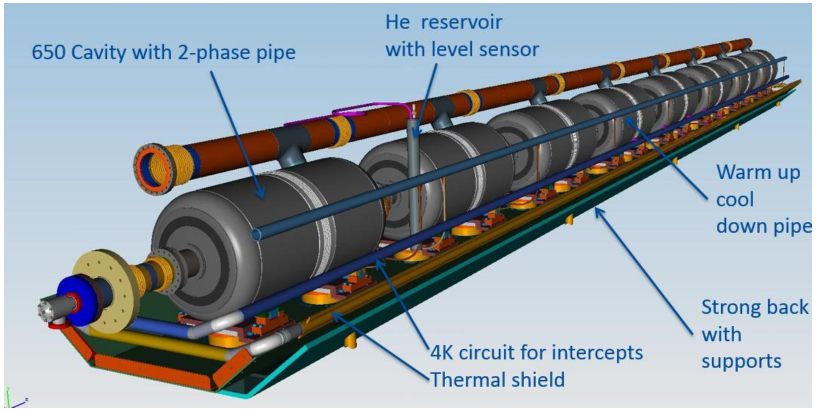
- 11 total cryomodules
- 3 cavities each (650 MHz, 5-cell)
- 33 total cavities
- No magnets internal to the cryomodule
- Approximate length = 3.9 m



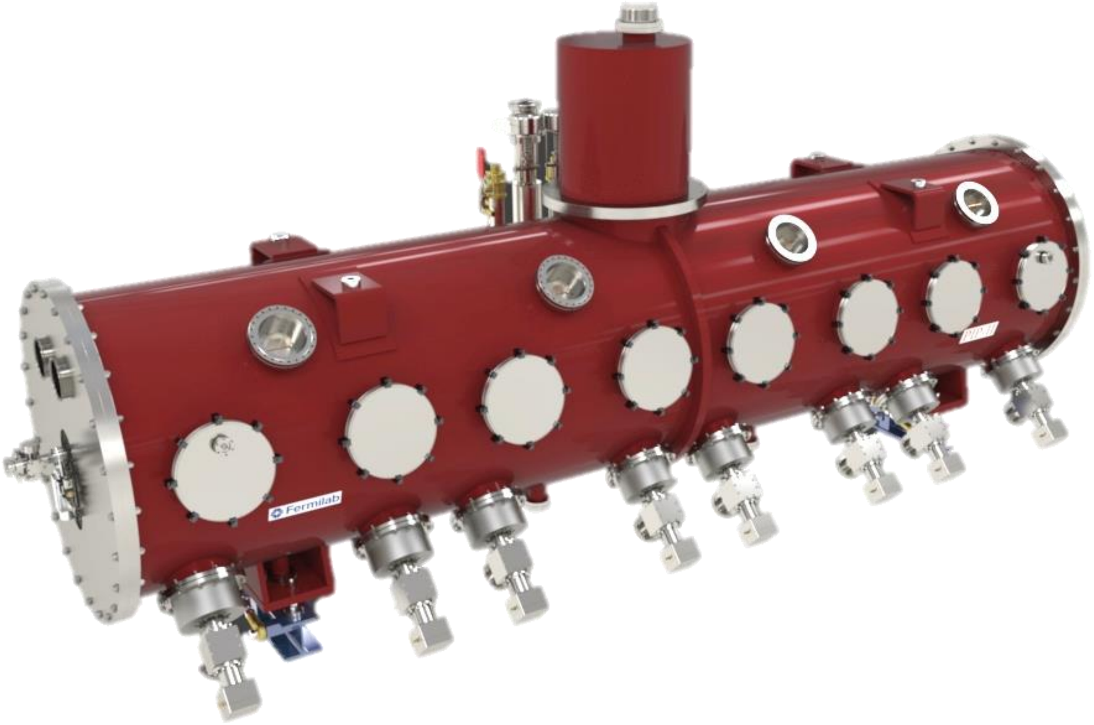
- Many design features common with the current SSR1 cryomodule design
- Coupler port locations are fixed with respect to the vacuum vessel
- Support system not subject to thermal distortions during cooldown
- To date, unproven

High-Beta Cryomodule

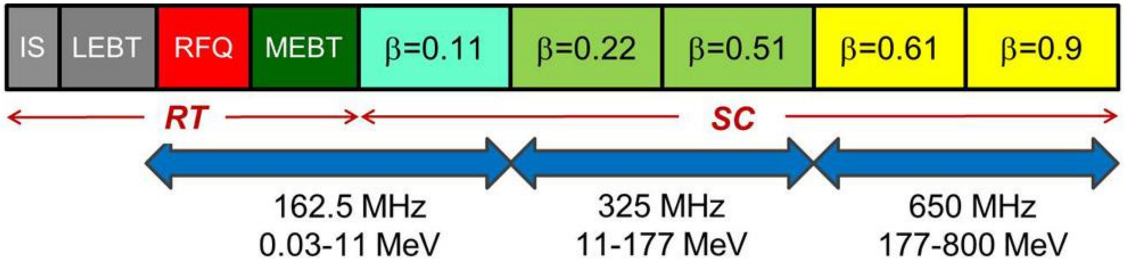
- 4 total cryomodules
- 6 cavities each (650 MHz, 5-cell)
- 24 total cavities
- No magnets internal to the cryomodule
- Approximate length = 9.5 m



SSR1 Cryomodule for PIP-II



Two **SSR1 cryomodules** will be part of the 800 MeV linear accelerator complex that Fermilab is planning to build in the framework of the Proton Improvement Plan-II (PIPII) project. The cavity string assembly of this cryomodule which constitutes the beam-line volume, contains *eight superconducting Single Spoke Resonators type 1 (SSR1)* with cold-end input couplers and four solenoids.



IS	LEBT	RFQ	MEBT	β=0.11	β=0.22	β=0.51	β=0.61	β=0.9

← RT → ← SC →

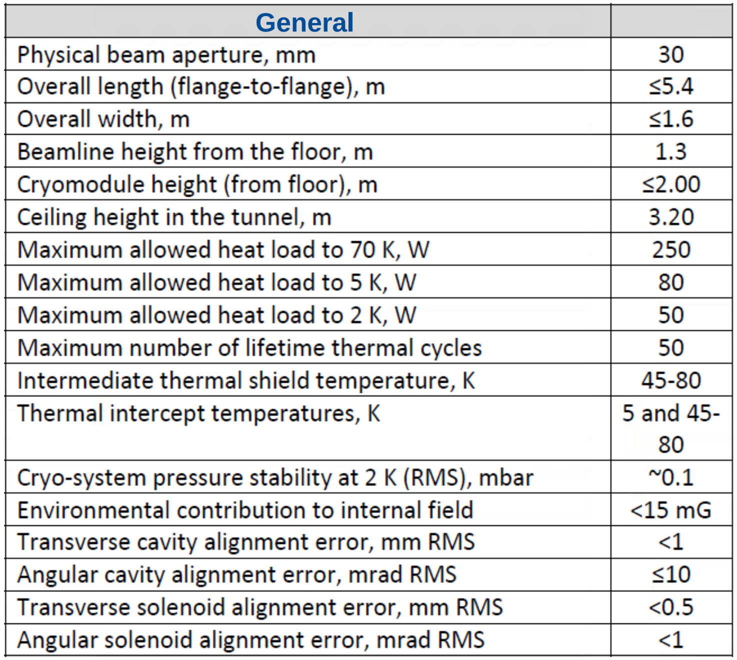
162.5 MHz
0.03-11 MeV

325 MHz
11-177 MeV

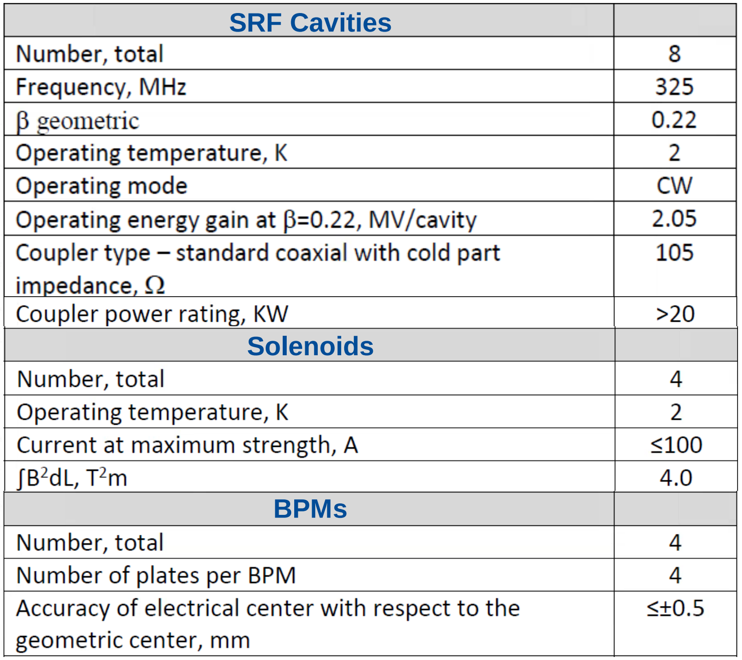
650 MHz
177-800 MeV

SSR1 Cryomodule: Functional Requirements Specification

This engineering document *"325 MHz SSR1 CRYOMODULE, FRS, ED0001316"* (available in Teamcenter) addresses the functional requirements of the PIP-II SSR1 cryomodule. It includes physical size limitations, cryogenic system requirements and operating temperature, instrumentation, cavity and lens sequence and alignment requirements, magnet current leads, and interfaces to interconnecting equipment and adjacent modules.



General	
Physical beam aperture, mm	30
Overall length (flange-to-flange), m	≤5.4
Overall width, m	≤1.6
Beamline height from the floor, m	1.3
Cryomodule height (from floor), m	≤2.00
Ceiling height in the tunnel, m	3.20
Maximum allowed heat load to 70 K, W	250
Maximum allowed heat load to 5 K, W	80
Maximum allowed heat load to 2 K, W	50
Maximum number of lifetime thermal cycles	50
Intermediate thermal shield temperature, K	45-80
Thermal intercept temperatures, K	5 and 45-80
Cryo-system pressure stability at 2 K (RMS), mbar	~0.1
Environmental contribution to internal field	<15 mG
Transverse cavity alignment error, mm RMS	<1
Angular cavity alignment error, mrad RMS	≤10
Transverse solenoid alignment error, mm RMS	<0.5
Angular solenoid alignment error, mrad RMS	<1



SRF Cavities	
Number, total	8
Frequency, MHz	325
β geometric	0.22
Operating temperature, K	2
Operating mode	CW
Operating energy gain at β=0.22, MV/cavity	2.05
Coupler type – standard coaxial with cold part impedance, Ω	105
Coupler power rating, KW	>20
Solenoids	
Number, total	4
Operating temperature, K	2
Current at maximum strength, A	≤100
$\int B^2 dL$, T^2m	4.0
BPMs	
Number, total	4
Number of plates per BPM	4
Accuracy of electrical center with respect to the geometric center, mm	≤±0.5

Prototype SSR1 Cryomodule for PXIE

A prototype cryomodule is under design and development to achieve the goals of:

- *Validate design concepts* of new spoke cavity cryomodule
  - Room temperature strongback
  - Individual support posts to control axial motion
  - Conduction cooled magnet current leads
  - Single-window coaxial input coupler
  - Integral beam instrumentation
  - Determine the practicality of tuner access ports
  - Estimate heat loads
- *Gain experience* with the required alignment tolerances and check alignment stability during cooldown.
- *Minimize risk ahead of full PIP-II design* and production effort by gaining experience with strings of spoke cavities, solenoids, and beam instrumentation, e.g. cleanroom operations, final assembly in the vacuum vessel, shipping and handling, etc.

SSR1 Cryomodule Heat Load Estimates

SSR1 Cryomodule Heat Load Estimates

T. Nicol -February 9, 2012

SSR1	**Each unit**			**Mult**	**Total**		
8 cavities, 4 solenoids	**80 K**	**4.5 K**	**2 K**		**70 K**	**4.5 K**	**2 K**
Input coupler static	5.36	2.82	0.50	8	42.88	22.56	4.00
Input coupler dynamic	0.00	0.00	0.25	8	0.00	0.00	2.00
Cavity dynamic load	0.00	0.00	1.78	8	0.00	0.00	14.24
Support post	2.76	0.36	0.05	12	33.12	4.32	0.60
Conduction lead assembly	36.80	13.20	1.24	4	147.20	52.80	4.96
MLI (total 70 K + 2 K)	30.54	0.00	1.42	1	30.54	0.00	1.42
Cold to warm transition	0.72	0.08	0.01	2	1.44	0.16	0.02
Total					**255.2**	**79.8**	**27.2**

Notes:

1. Cavity dynamic loads from Nikolai Solyak, February 2012.

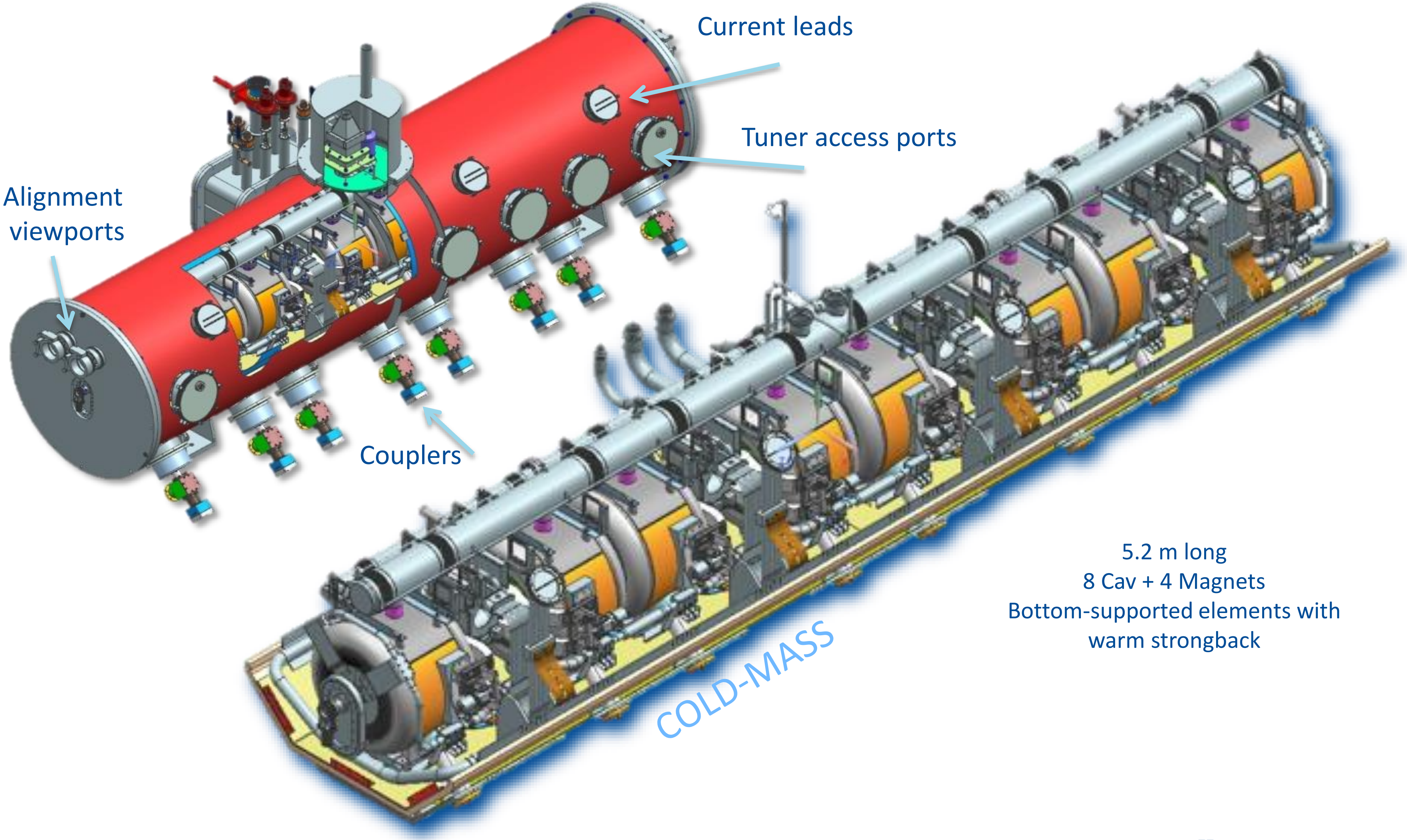
2. Input coupler static loads from S. Kazakov, February 2012, no copper plating on outer conductor, intercepts at 15 K and 125 K.

3. Current lead heat loads assume 2 coils at 50 A, 1 coil at 200 A.

SSR1 Cryomodule

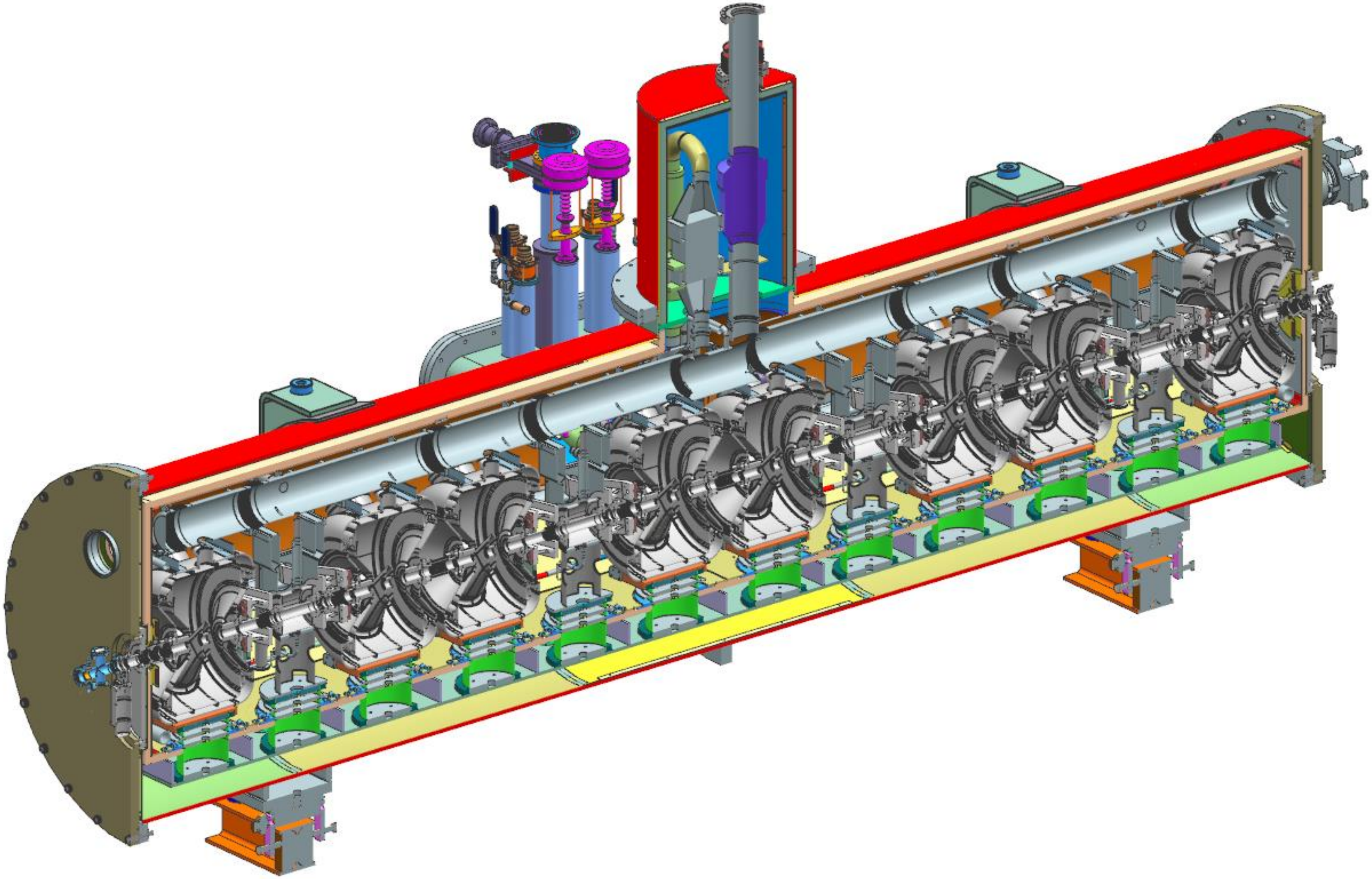
L. Ristori, T. Nicol, Y. Orlov, D. Passarelli, M. Parise

http://accelconf.web.cern.ch/AccelConf/PAC2013/papers/thpma09.pdf



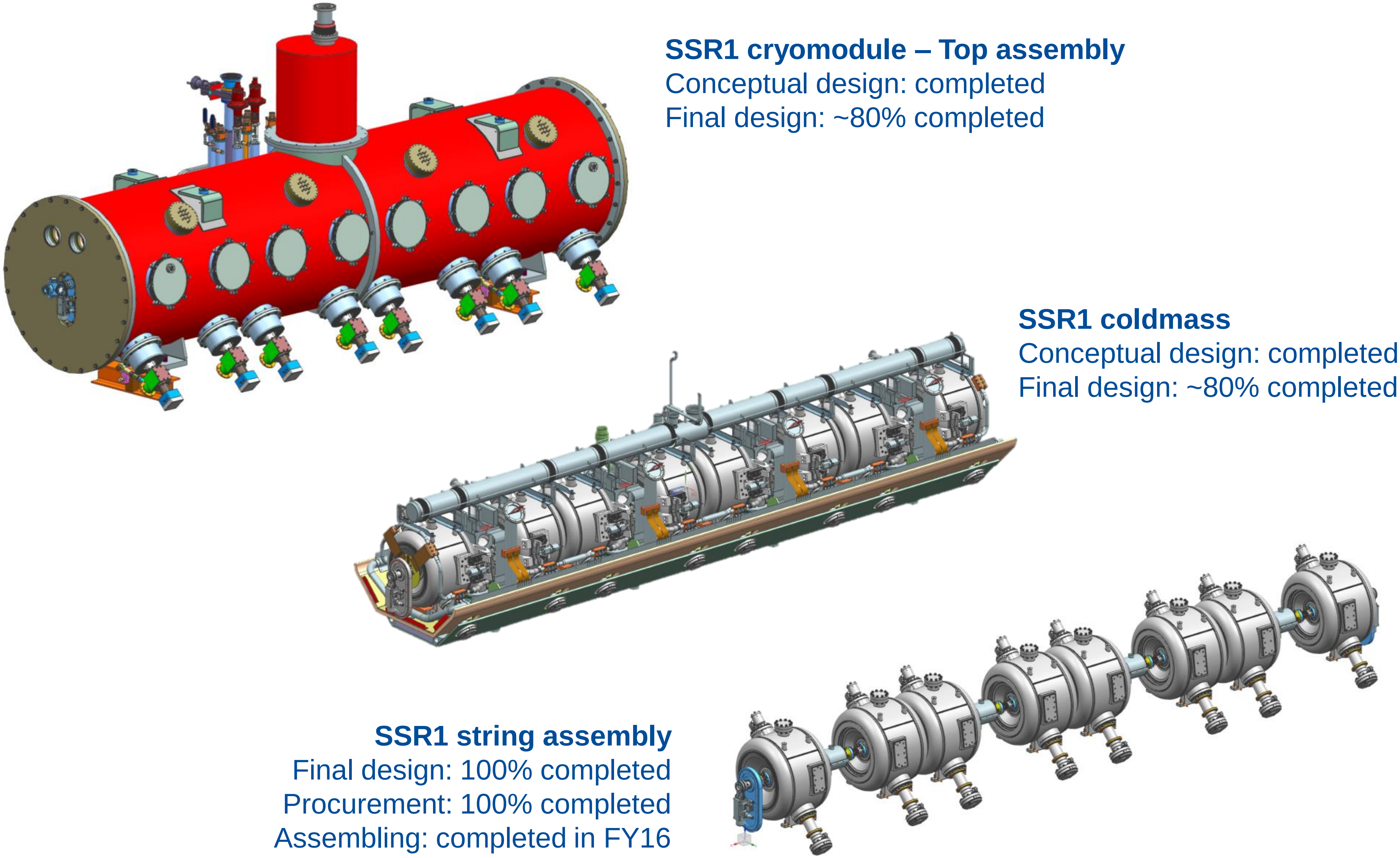
5.2 m long
8 Cav + 4 Magnets
Bottom-supported elements with
warm strongback

Cutview of the prototype SSR1 cryomodule



SSR1 Cryomodule Design for PXIE, T. Nicol et al., Proceedings of PAC2013, Pasadena, CA USA

Design of the prototype SSR1 Cryomodule



SSR1 cryomodule – Top assembly
Conceptual design: completed
Final design: ~80% completed

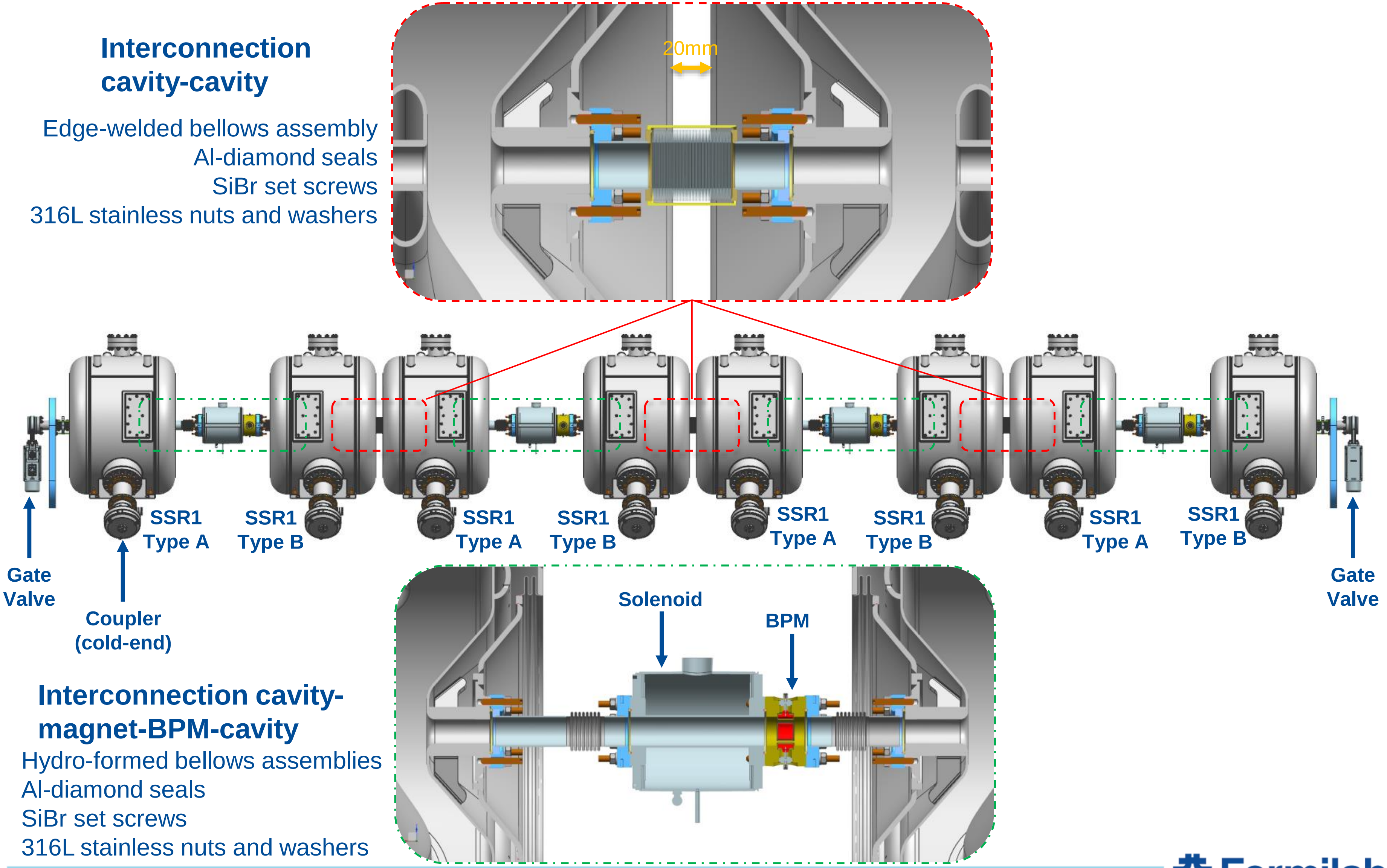
SSR1 coldmass
Conceptual design: completed
Final design: ~80% completed

SSR1 string assembly
Final design: 100% completed
Procurement: 100% completed
Assembling: completed in FY16

SSR1 String Assembly: design features

Interconnection cavity-cavity

Edge-welded bellows assembly
Al-diamond seals
SiBr set screws
316L stainless nuts and washers



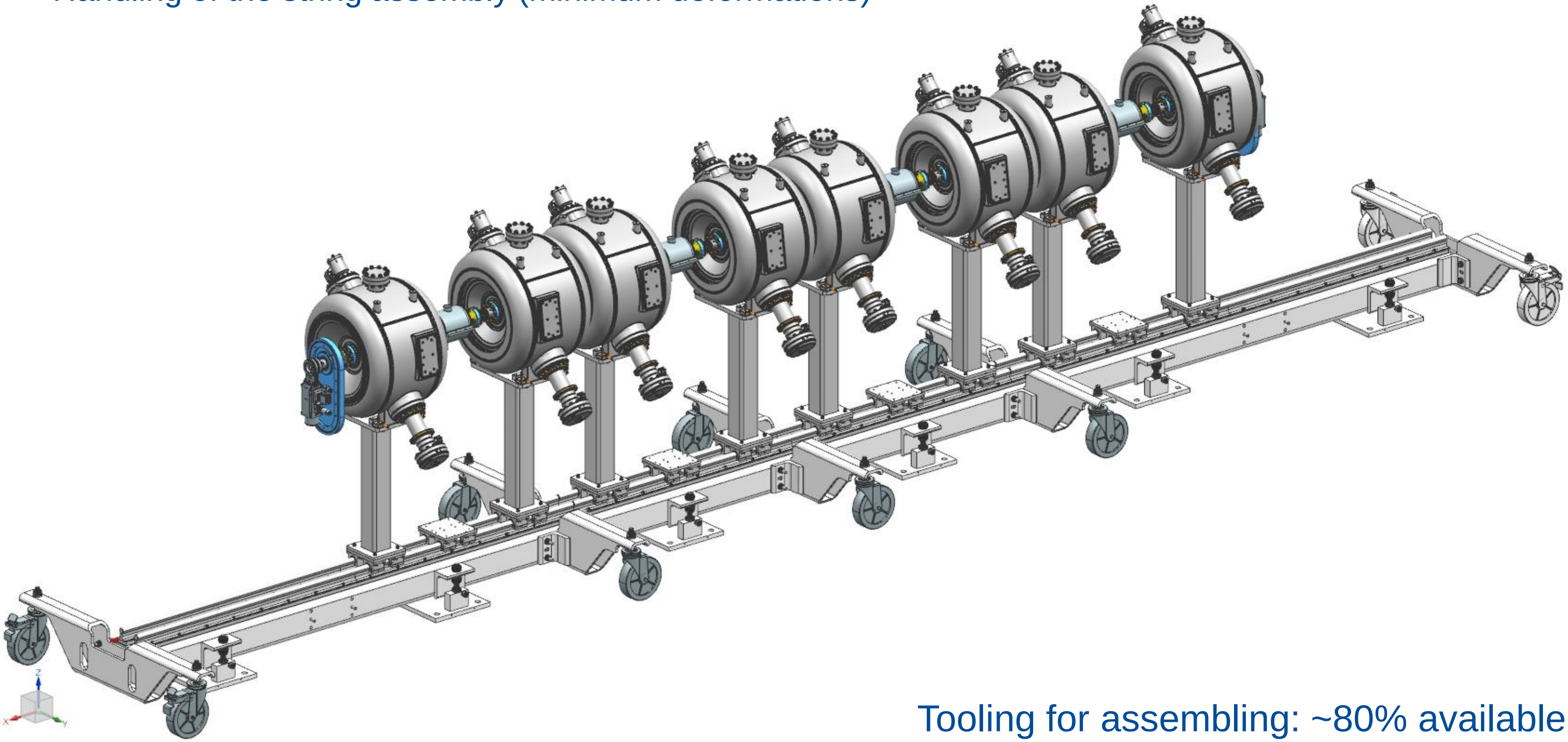
Interconnection cavity-magnet-BPM-cavity

Hydro-formed bellows assemblies
Al-diamond seals
SiBr set screws
316L stainless nuts and washers

SSR1 String Assembly in cleanroom

Key aspects:

- All cavities qualified bare and then jacketed with power coupler before string assembly
- Particle-free assembly in cleanroom class 10 (ISO 4)
- Alignment of cavities (electric axis) and magnets (magnetic axis) with a datum.
- Handling of the string assembly (minimum deformations)



Tooling for assembling: ~80% available

SSR1 Cavities: requirements

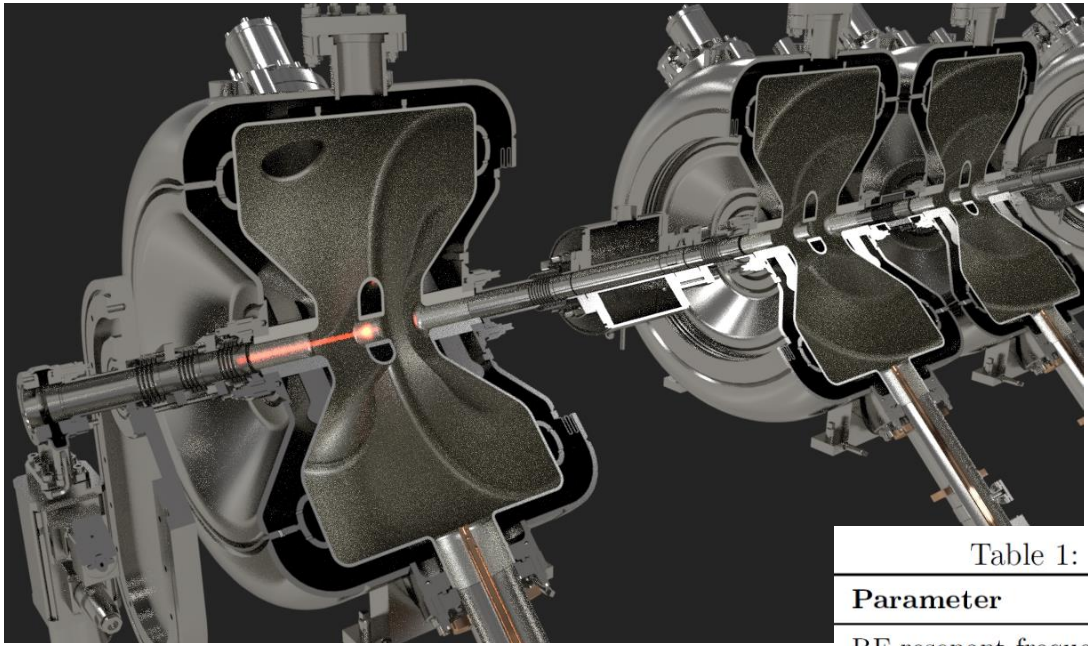
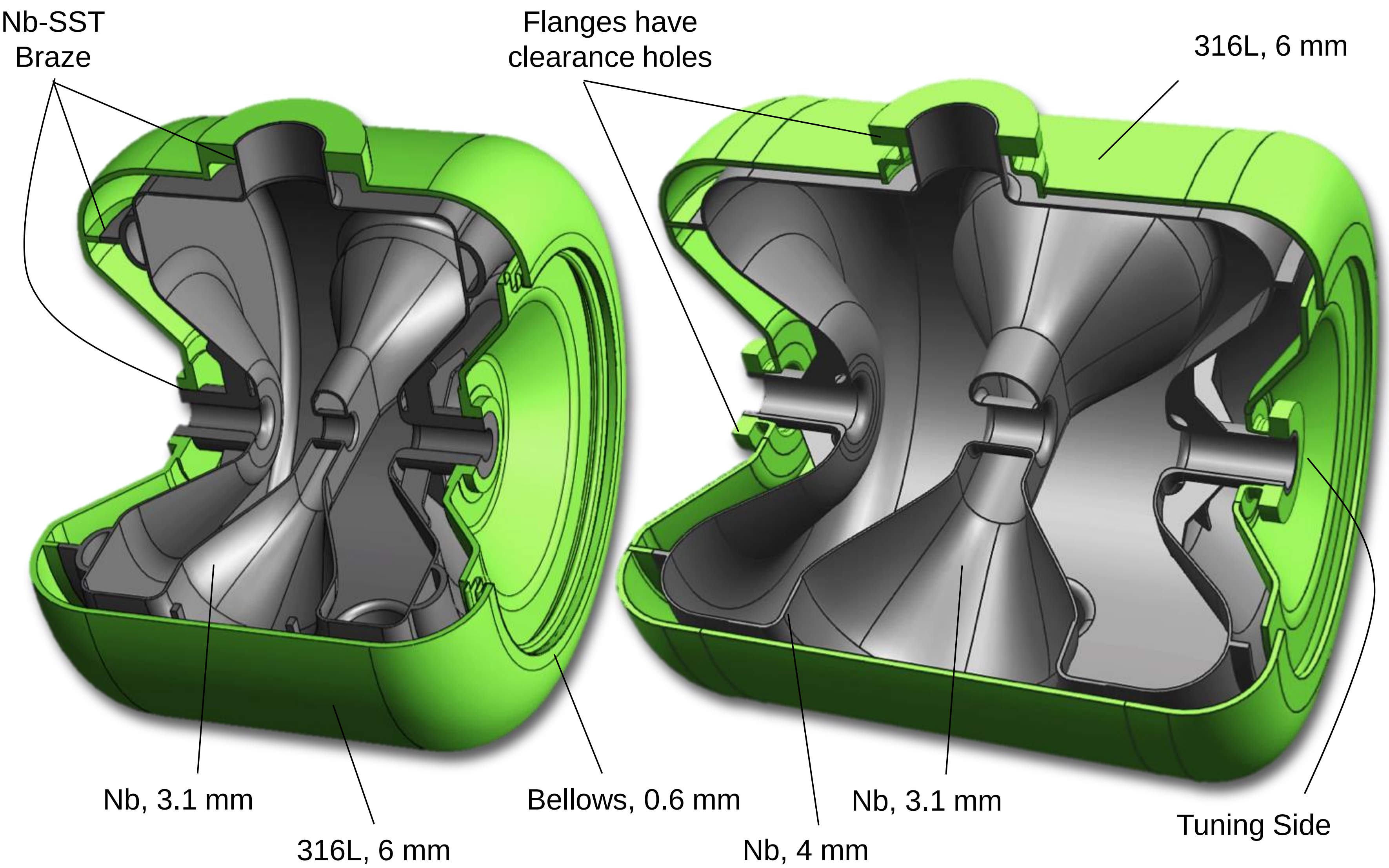


Table 1: Cavity operational and test requirements

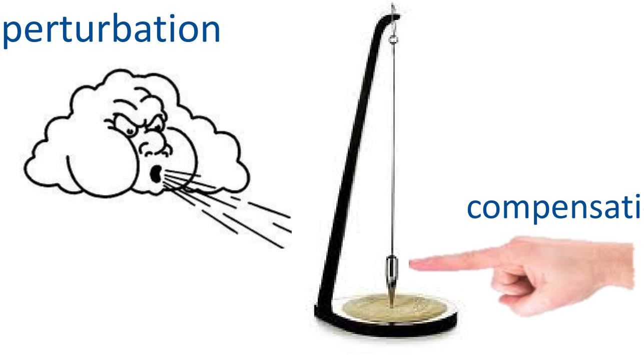
Parameter	Value
RF resonant frequency	325 MHz
Bandwidth	±20 Hz
Operating accelerating gradient (E_{acc})	12 MV/m
Quality factor (Q_0) at E_{acc}	$> 5 \cdot 10^9$
Operating gain per cavity	2 MeV
Maximum power dissipation at 2 K	5 W
Sensitivity to He pressure fluctuations	$<$ 25 Hz/Torr
Field flatness	±10%
Operating temperature	$1.8 \div 2.1$ K
Operating pressure	$16 \div 41$ mbar (differential)
Maximum allowable working pressure	2 bar at 293 K, 4 bar at 2 K
RF power input per cavity	6 kW (CW, operating)
Max Leak Rate (room temp)	$< 10^{-10}$ atm · cc/s

SSR1 and SSR2 – a closer look..



Active and Passive control for SRF cavities

Active only:
Constant compensation even without large perturbations

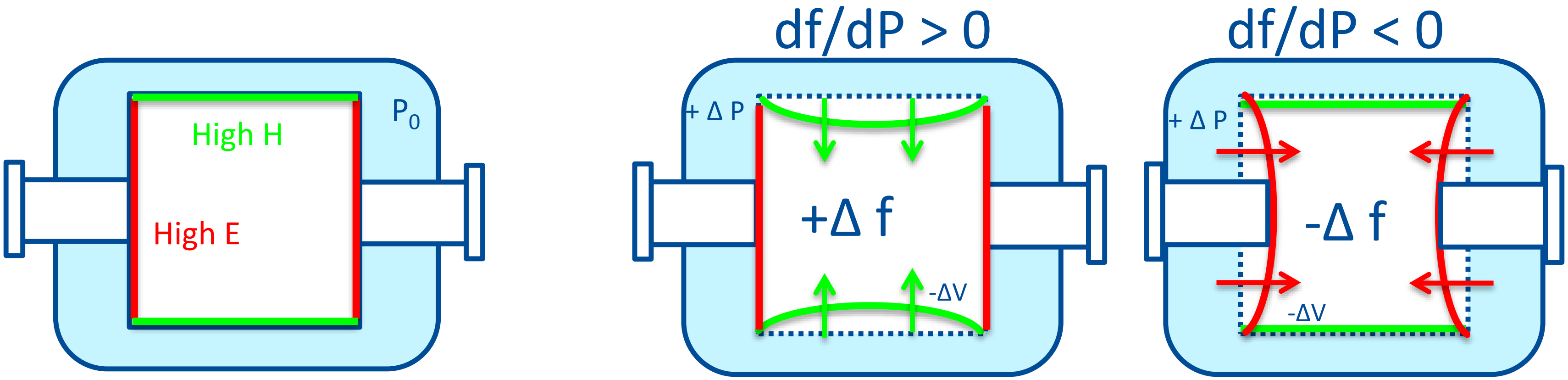


Passive + Active:
Compensation only during large perturbations

- Active controls
  - Compensating the effects of perturbations
- Passive controls (Environment)
  - Reducing perturbations
- Passive controls (Cavity Design)
  - Reducing sensitivity of cavity to perturbations (LFD, Mechanical Resonances, df/dP)

Passive Control: Sensitivity to He bath pressure (df/dP)

- Cavity walls deform proportionally to the increment of pressure in the liquid Helium.
- Changes in the cavity RF volume produce frequency shifts that can be positive or negative depending on the shape of deformation
- Slater's rule:
  - $\Delta f = k \int (\varepsilon_0 E^2 - \mu_0 H^2) dV$

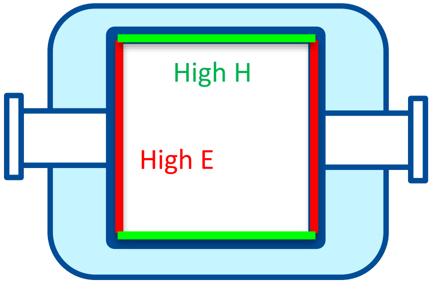


Minimizing He pressure sensitivity

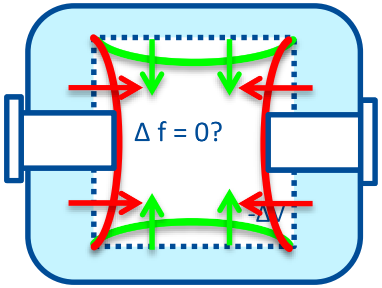
Options for reducing df/dP

- Reduce deformations of cavity walls
  - This approach is widely utilized and easy to implement (increase cavity wall thickness, increase number/size of stiffeners)
  - Drawback is a general increase in cavity stiffness and in most cases an increase in tuning resistance (dF/df)
  - Sometimes impractical to achieve df/dP=0

- Balance deformations of cavity walls
  - This method is less intuitive and requires a systematic approach
  - The specific behavior of the cavity needs to be understood
  - Opportunity to achieve df/dP=0
  - Keep tuning resistance under control

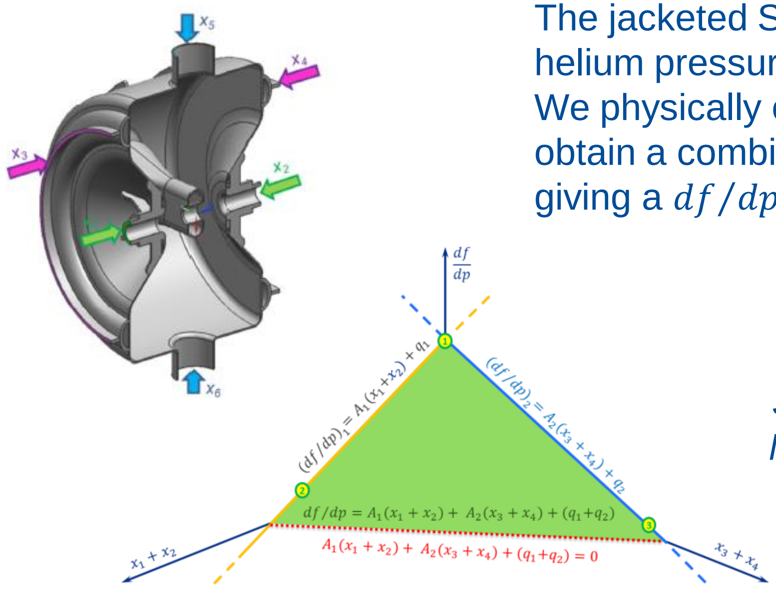


Reduce deformations by Increasing K_{cav}



Balance deformations

SSR1 Cavities: pressure sensitivity

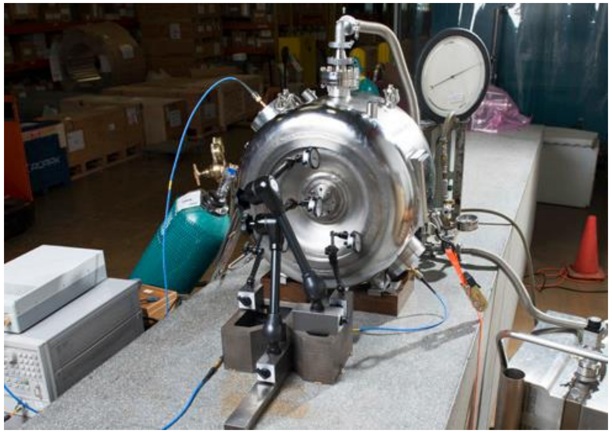


The jacketed SSR1 cavities were designed to have very low sensitivity to helium pressure fluctuations (microphonics).
We physically coupled the Nb cavity and the helium vessel such that we obtain a combination of cavity walls deformations $(x_1 + x_2)$ and $(x_3 + x_4)$ giving a $df/dp = 0$.

Self-compensated system --> Passive compensation
No active control to mitigate the pressure fluctuations

PIP-II requirements: -25 ≤ df/dp ≤ 25 Hz/Torr

	df/dp [Hz/Torr]	S106	S107	S108	S109	S110	S111	S112	S113	S114
Measured	Bare cavity (with transition ring)	-564	-561	-553.5	-555.1	-568.8	-525.8	-524.6	-544.7	-557.2
	With He Vessel (without Tuner)	8	8	-1.2	5.4	7.9	2.7	9.0	6.3	10
	Fully integrated	4*	4	0*	2*	4*	2*	5*	3*	5*

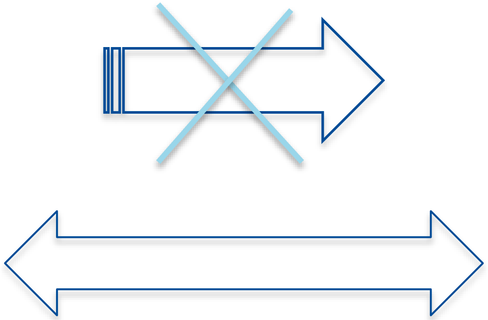


* Not measured yet (best guess)

SSR1 Cavities: design features

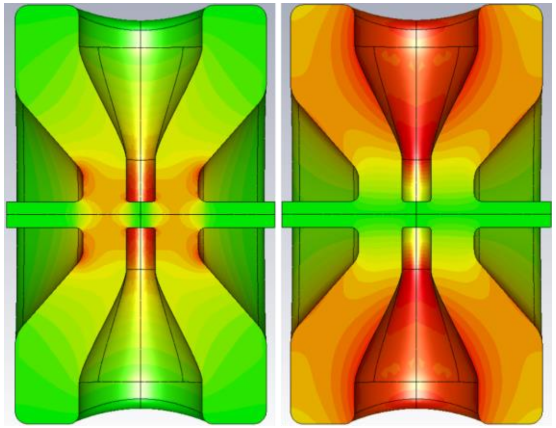
Electromagnetic Design

- Shape optimization
- Multipacting analysis
- Higher order modes
- Kick analysis
- Multipole effect
- Pressure Sensitivity
- Lorentz force detuning

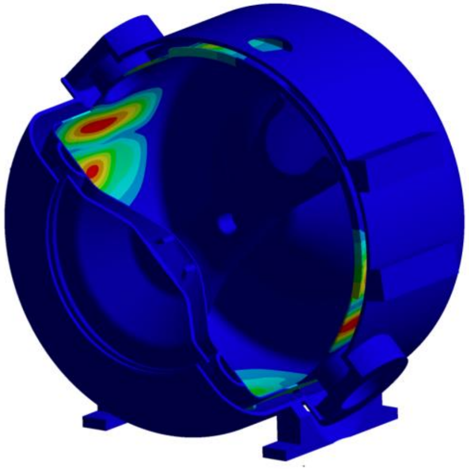


Mechanical Design

- Niobium shell design
- Vessel design
- Shape optimization
- Pressure Rating
- Stiffening and detuning
- Modal analysis
- Tuner Design

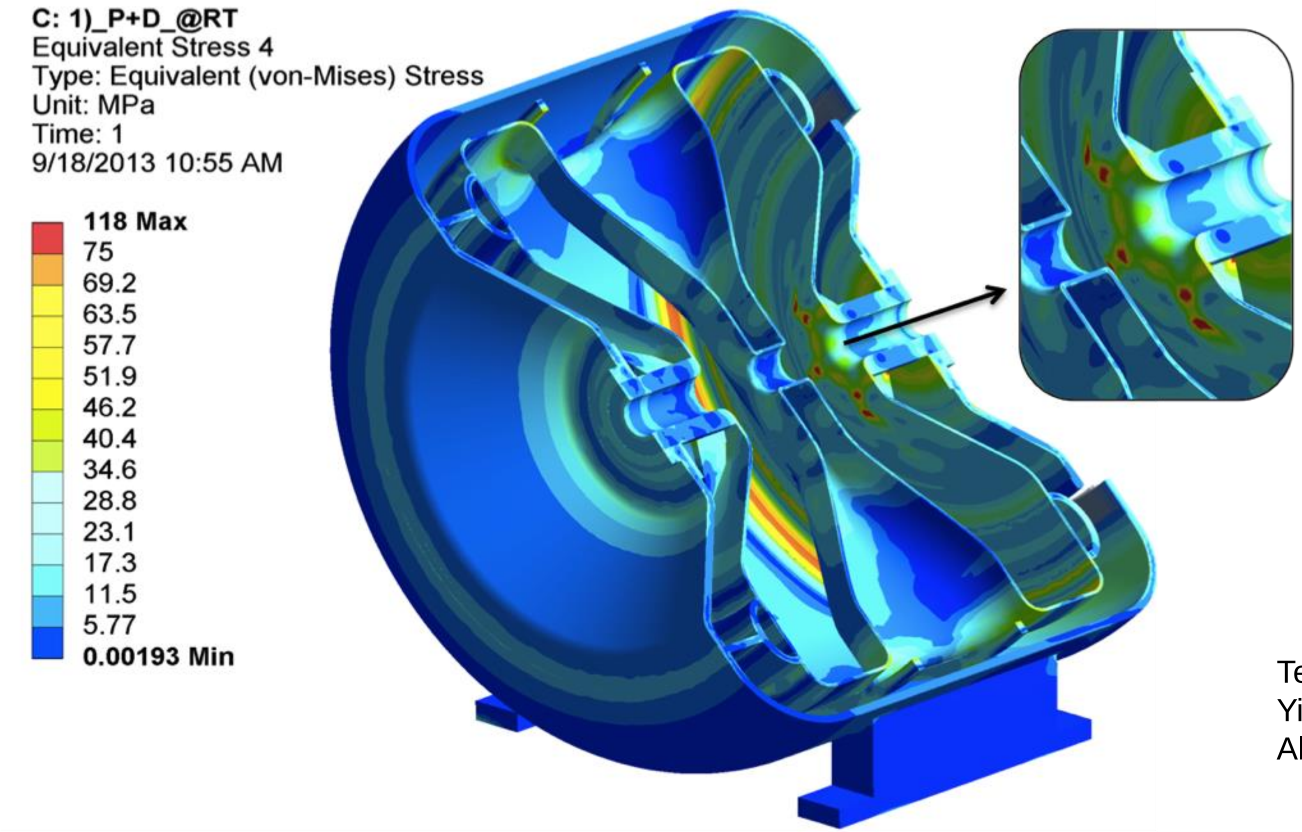


The parallel approach in performing RF/Mech analyses benefits the final design…



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

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

We must comply with the ASME Boiler and Pressure vessel code and determine the pressure rating of each SRF resonator

Division 1 vs. Division 2 of Chapter VIII:

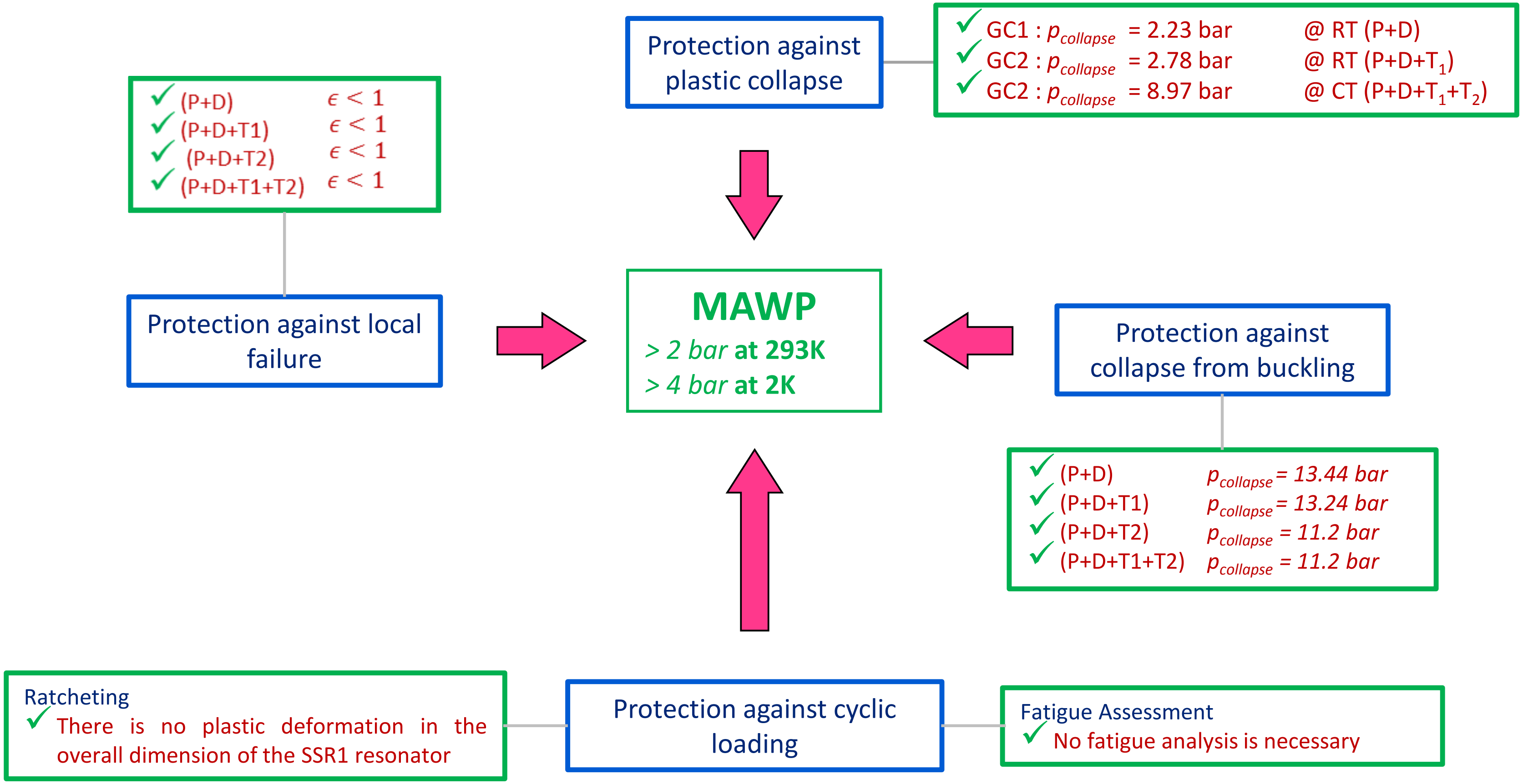
Division 2 allows utilizing complex shapes without limitations in principle, it generally results also in thinner walls of the vessels. We decided to follow this approach for the production cavities.

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 <u>less</u> 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

ASME Pressure Rating

The table summarizes the results obtained by simulations performed following the Div 2, Part 5 directions. It **shows** that the desired MAWP is achieved both at RT and CT.



Protection against plastic collapse

✓ GC1 : $p_{collapse}$	= 2.23 bar	@ RT (P+D)
✓ GC2 : $p_{collapse}$	= 2.78 bar	@ RT (P+D+T_1)
✓ GC2 : $p_{collapse}$	= 8.97 bar	@ CT (P+D+T_1+T_2)

Protection against local failure

✓ (P+D)	$\epsilon < 1$
✓ (P+D+T1)	$\epsilon < 1$
✓ (P+D+T2)	$\epsilon < 1$
✓ (P+D+T1+T2)	$\epsilon < 1$

MAWP

> 2 bar **at 293K**

> 4 bar **at 2K**

Protection against collapse from buckling

✓ (P+D)	*$p_{collapse}$ = 13.44 bar*
✓ (P+D+T1)	*$p_{collapse}$ = 13.24 bar*
✓ (P+D+T2)	*$p_{collapse}$ = 11.2 bar*
✓ (P+D+T1+T2)	*$p_{collapse}$ = 11.2 bar*

Protection against cyclic loading

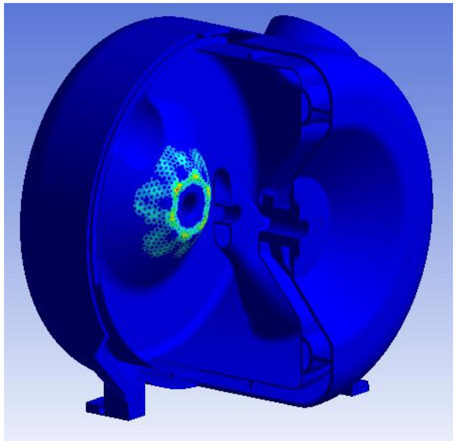
Ratcheting
✓ There is no plastic deformation in the overall dimension of the SSR1 resonator

Fatigue Assessment
✓ No fatigue analysis is necessary

ASME Pressure Rating - Results

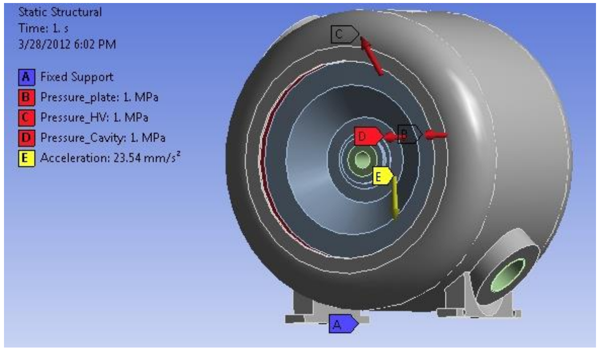
Protection Against Plastic Collapse:

Load Combination: 2.4 (P+D)



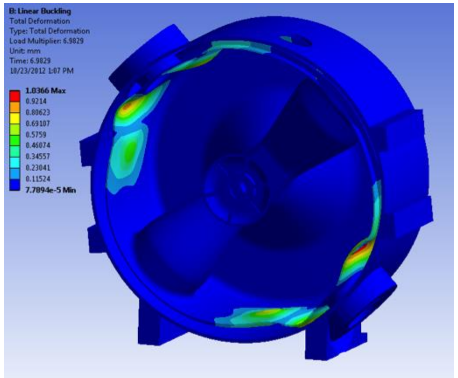
The elastic plastic stress analysis at 293K shows that the plastic collapse occurs on the *area of the Endwall* (bellows side), connected to the *Daisy ribs*, under a pressure of 5.35 bar (77.6 psi)

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



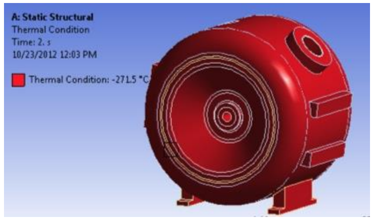
Protection Against Collapse from buckling:

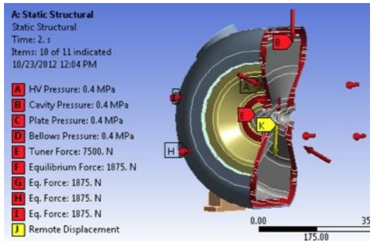
Load Combination: $(P+D+T_1+T_2)$



The load is applied in two steps, first the cooldown and then all other loads. The element that buckle first determines the MAWP for this failure mode. In the case under analysis the buckling occurs at the cavity

$$MAWP_{RT} = \frac{27.9bar}{2.5} = 11.2bar\ (162.4\ psi)$$

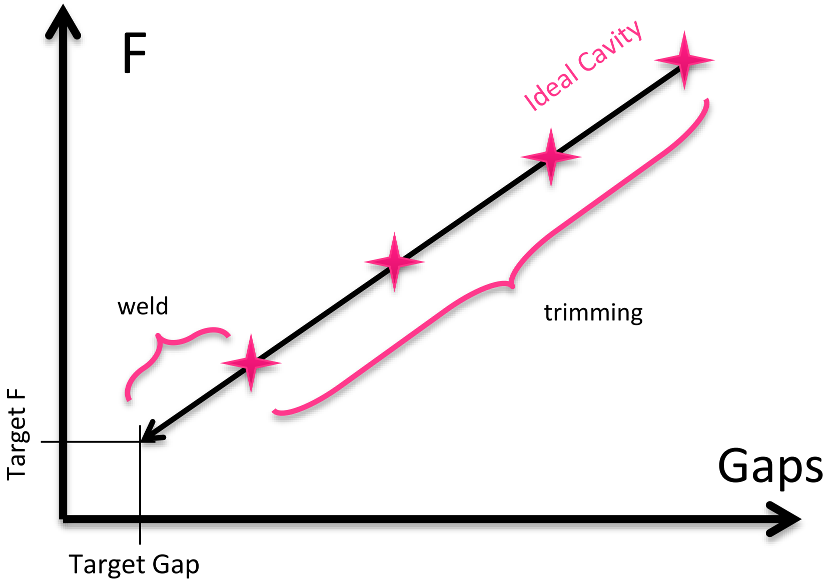


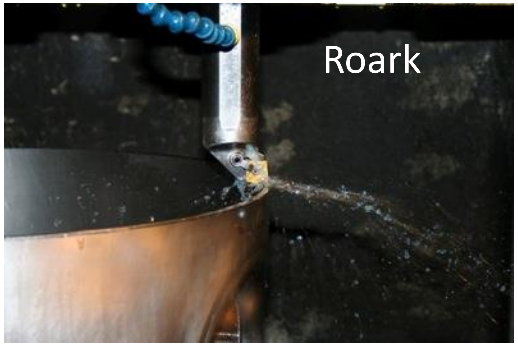


Trimming before final weld

- 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



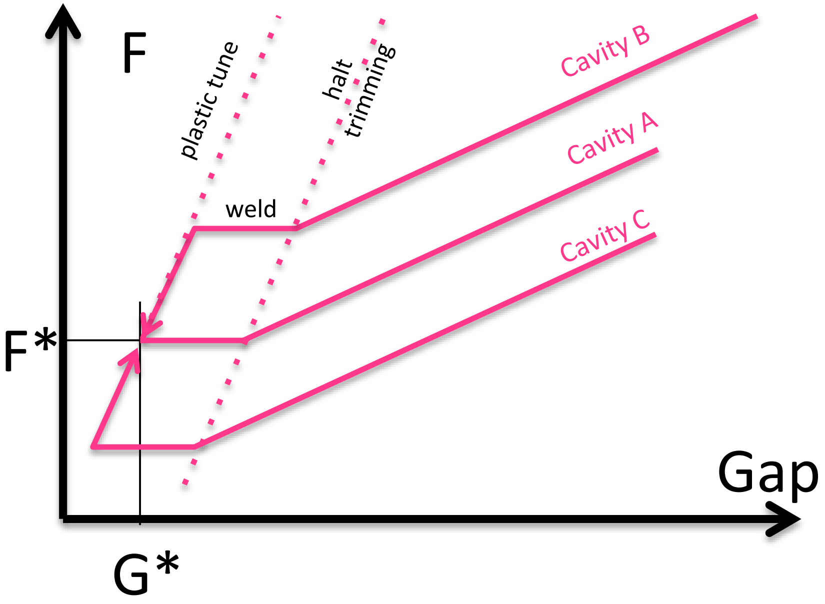


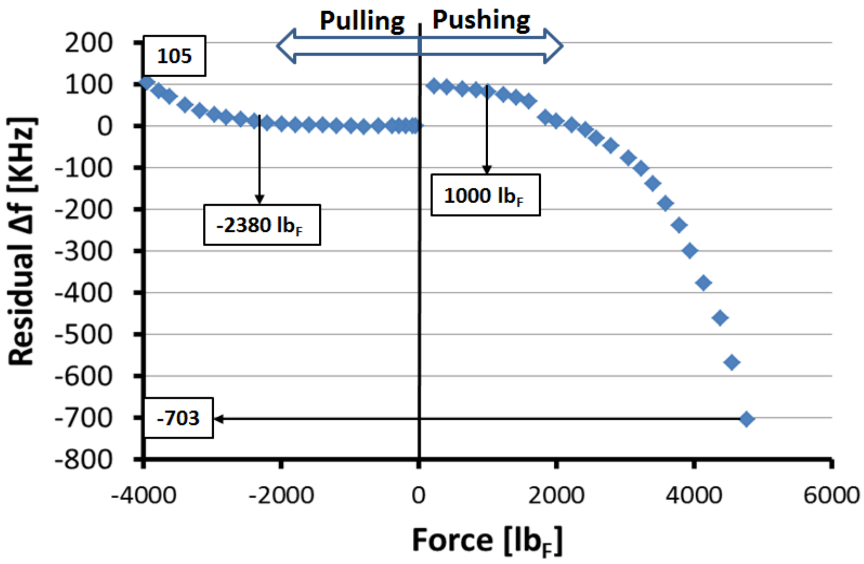
Trimming and Plastic Tuning

- 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

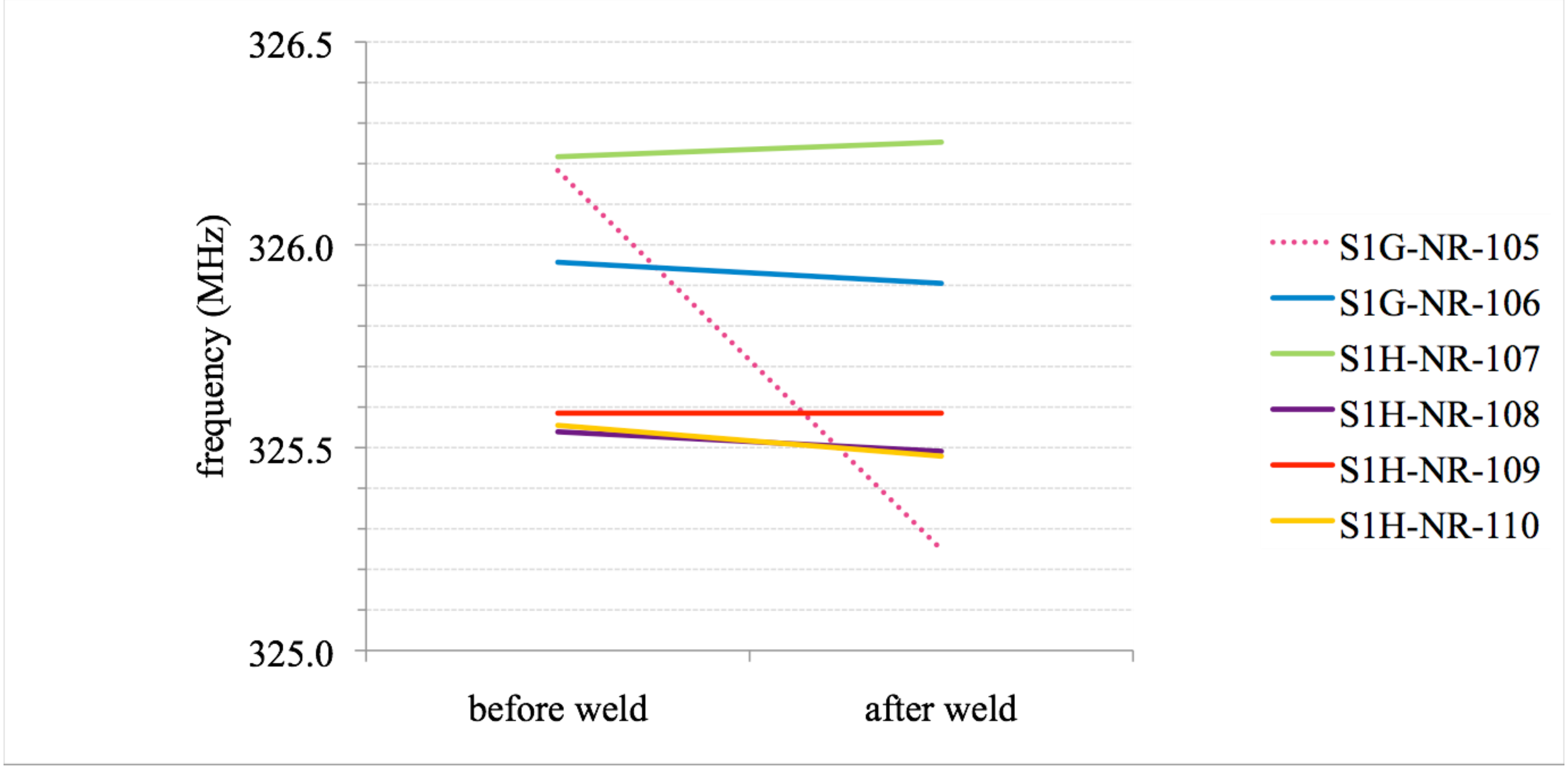
kHz/mm	measured (avg)
trimming	345 (320-370)
plastic tune	465
elastic tune	585

Elastic and Plastic sensitivities are different due to different deformed shapes





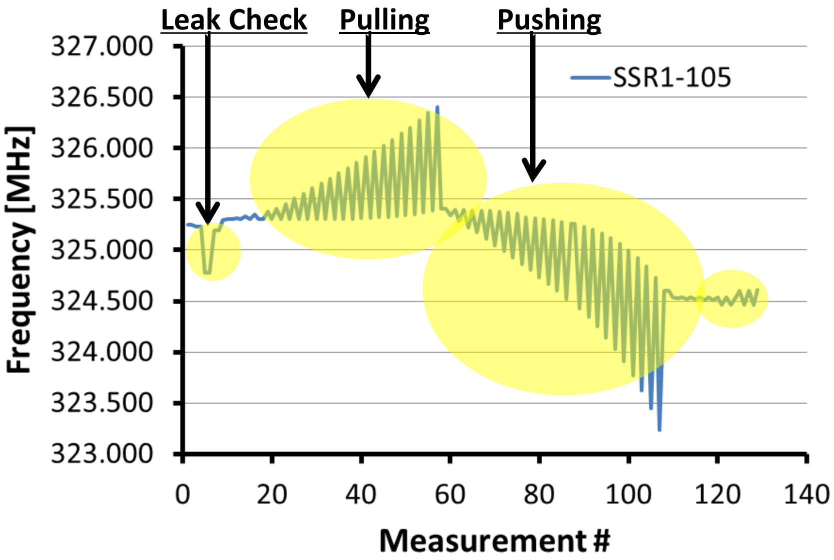
Shifts due to final welding (Roark)



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

Permanent tuning (FNAL)

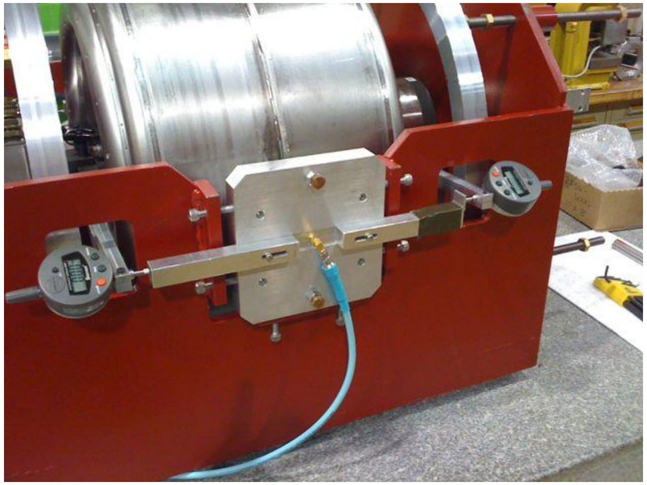
(T. Khabiboulline, M. Hassan, P. Berrutti)



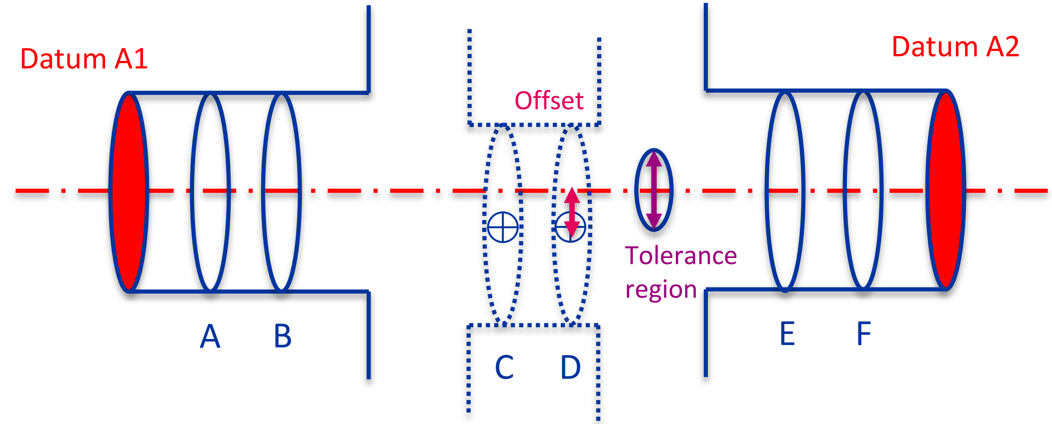
Importance of work hardening before installation in helium vessel.

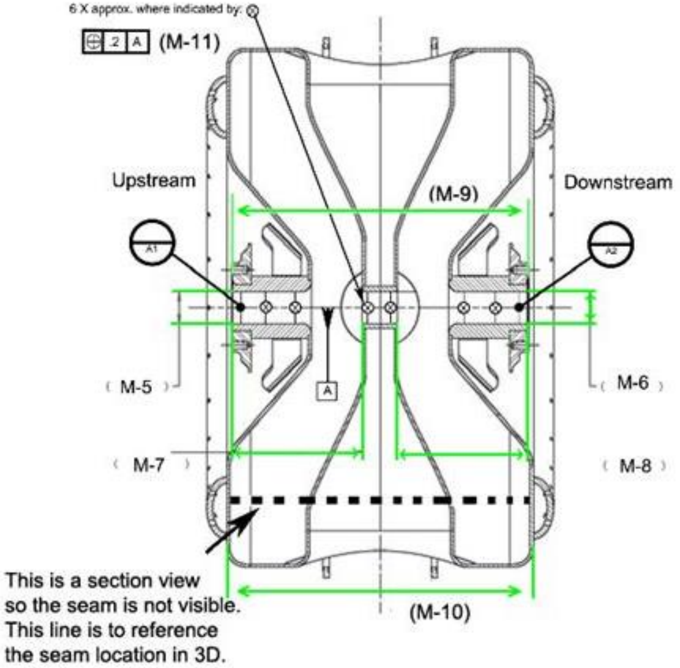
Elastic tuning range is increased by several times.

Work hardening is directional.



Drift tube offset measurements

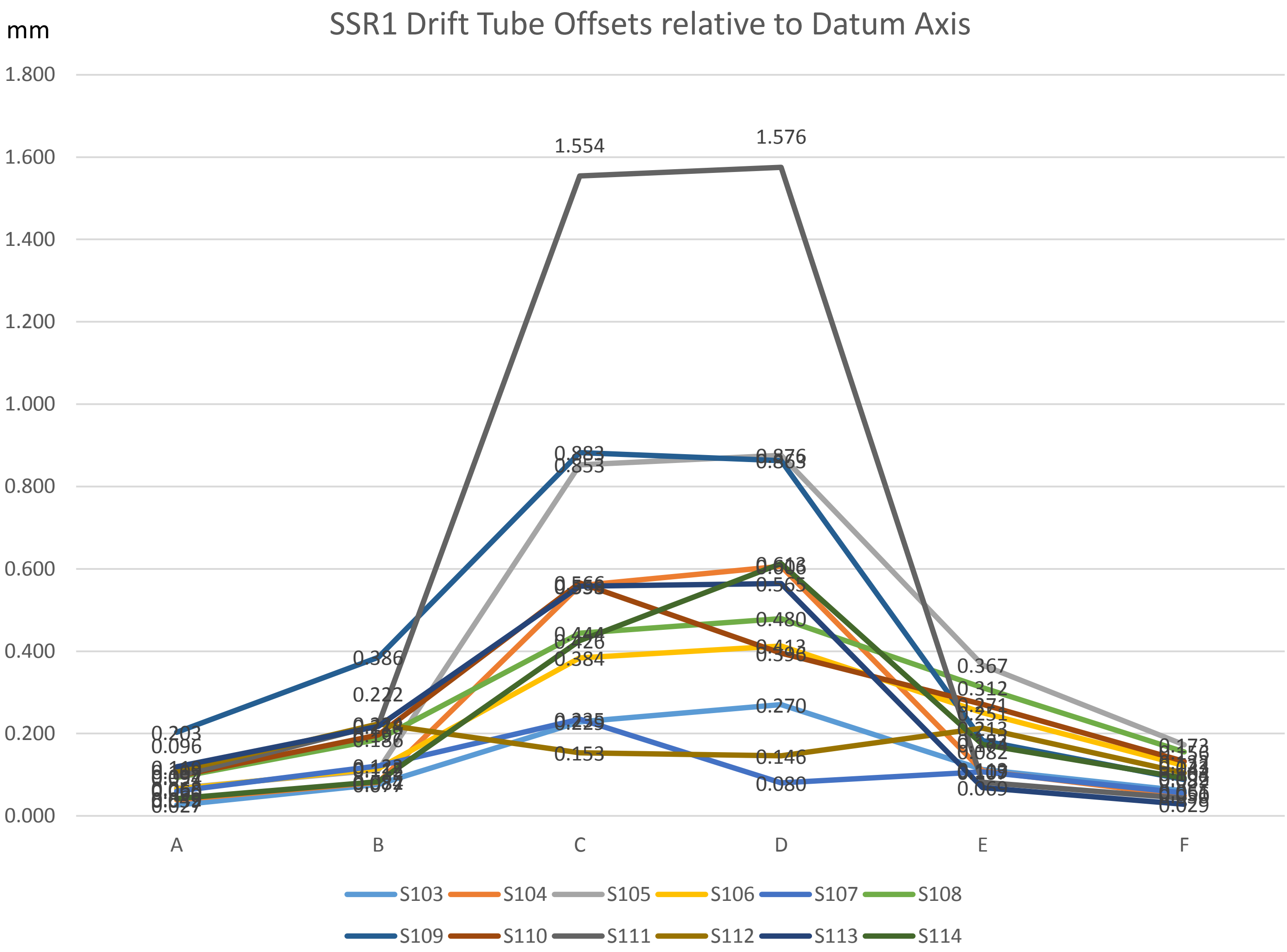




This is a section view so the seam is not visible. This line is to reference the seam location in 3D.

- Datum axis is defined with center points of Datum A1 and A2 near beam-pipe flanges
- At 6 locations (A-F) the center points are computed
- Offsets are given relative to Datum axis
- Caution: Cordax reports show an offset 2x larger, this is intended as the tolerance region.

Cordax Measurements on 12 SSR1 Resonators

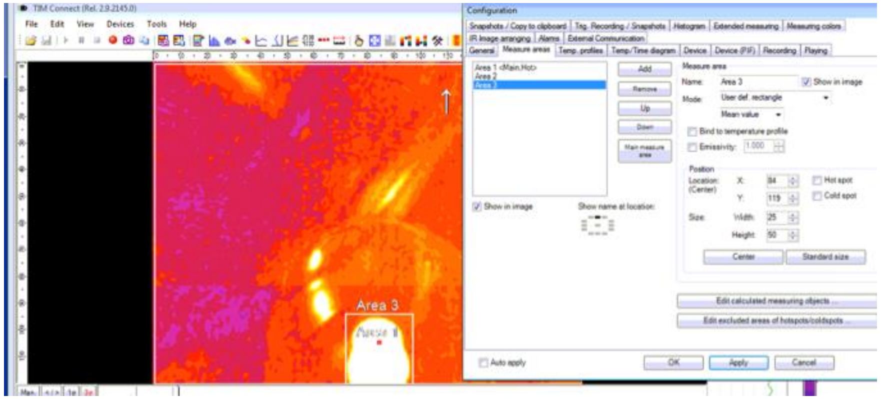


Jacketing operations

D. Passarelli, M. Hassan, P. Berrutti

Thermal cameras insertion tubes (above)

Screenshot of remote connection from FNAL



Area 1 <Main.Hot>
Area 2
Area 3

☑ Show in image

Show name at location:

Measure area

Name: Area 3 ☑ Show in image

Mode: User def. rectangle

Mean value

☐ Bind to temperature profile

☐ Emissivity: 1.000

Position

Location: (Center) X: 84 Y: 119

☐ Hot spot

☐ Cold spot

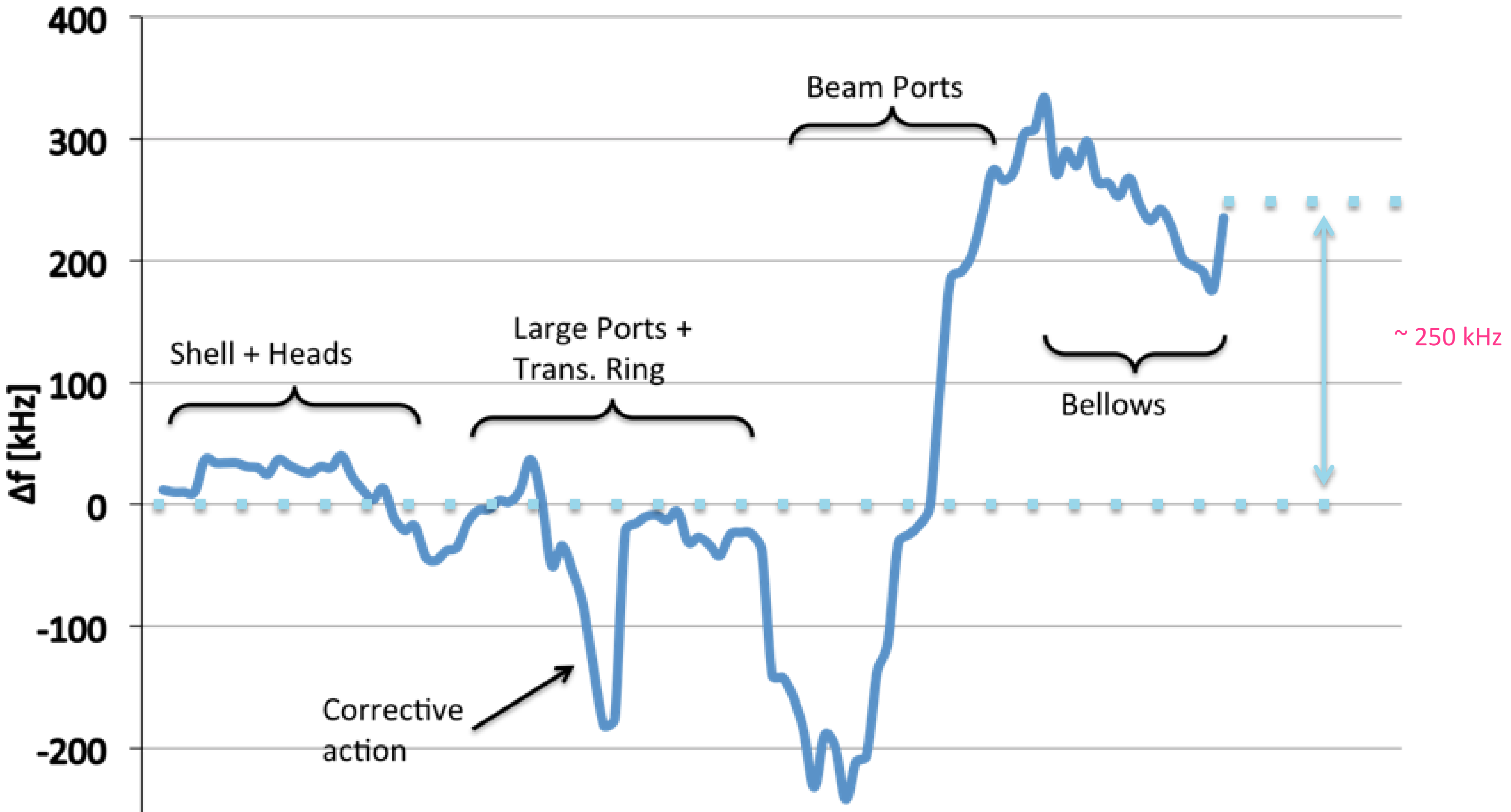
Size Width: 25 Height: 50

☐ Auto apply

Welding inch-by-inch on 6 mm thick steel

Large fixtures needed to control warping

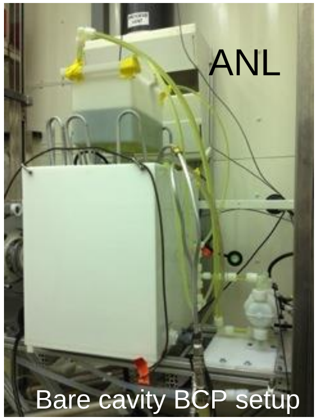
Shifts caused by jacketing



courtesy:
P. Berrutti

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

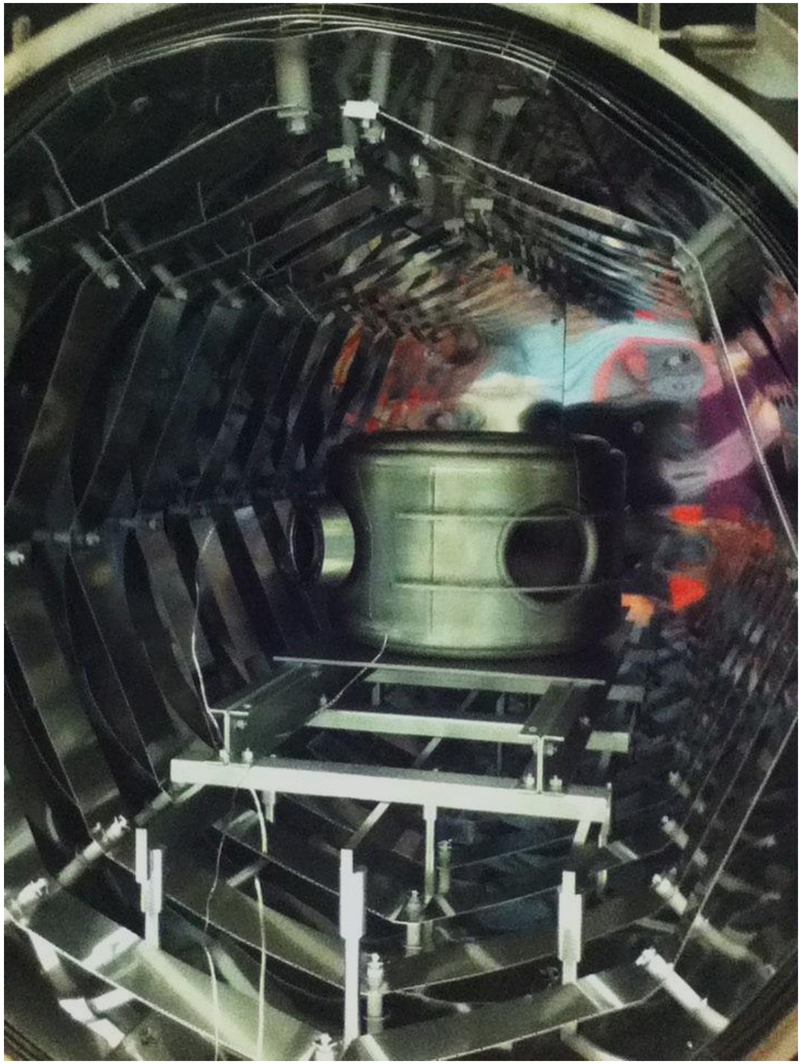


Low-Temp Ovens
(<300’C)

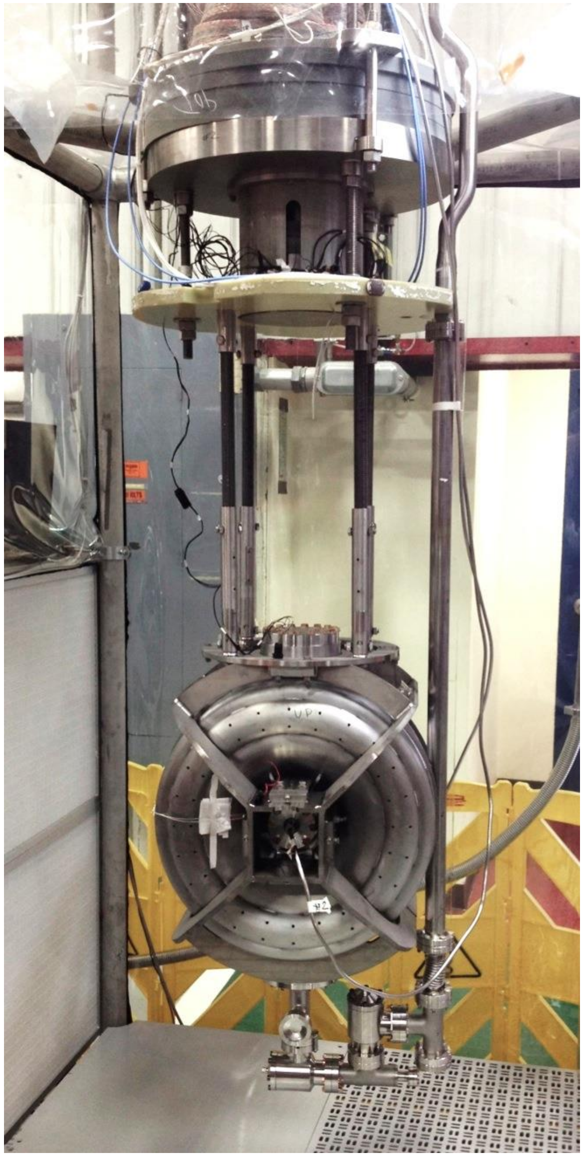
Hydrogen Degassing

- 600 C
- 10 h
- < 5 C/min

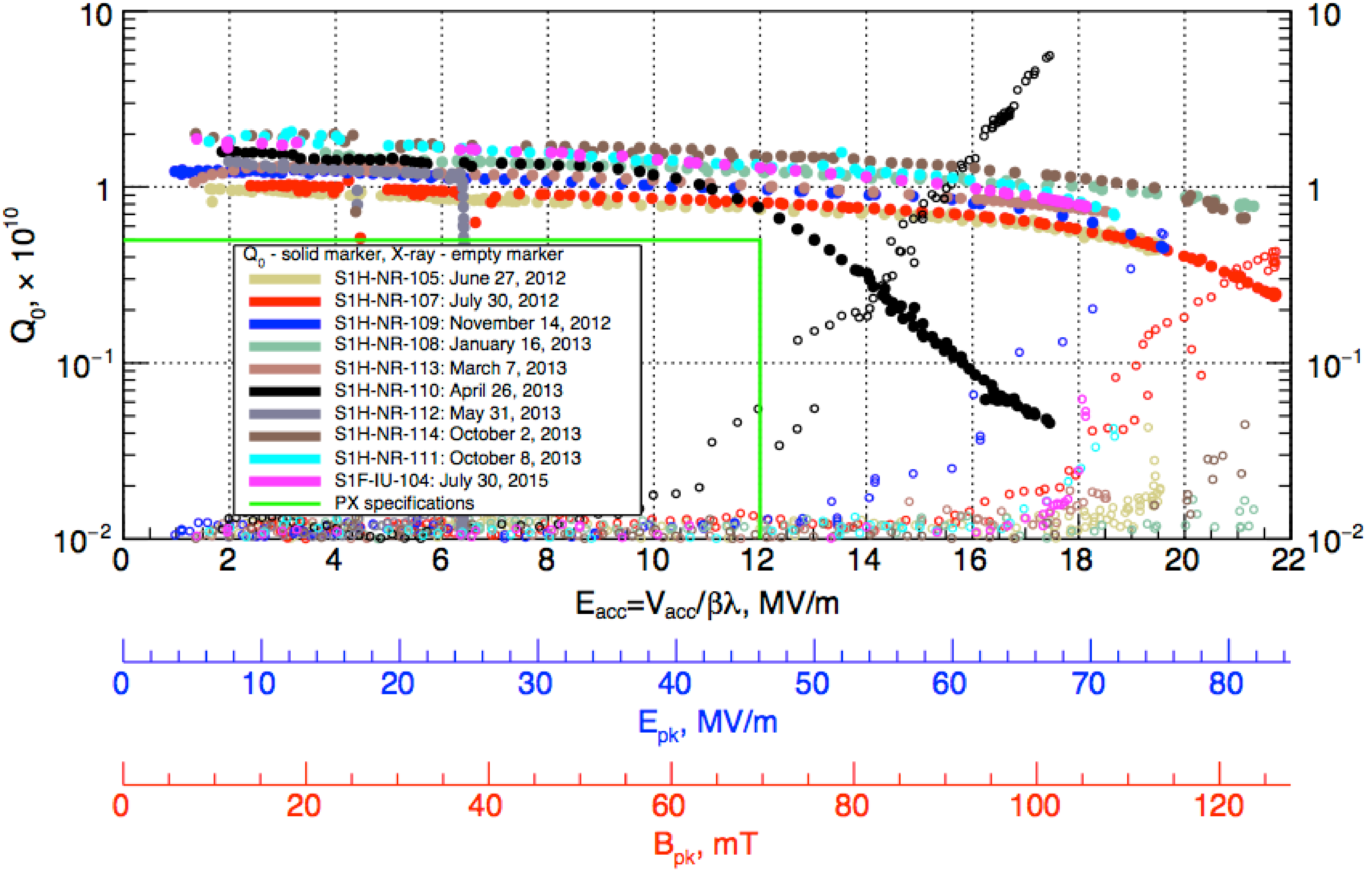
- Concern about baking vacuum flanges at 800 C due to Cu-Braze joints



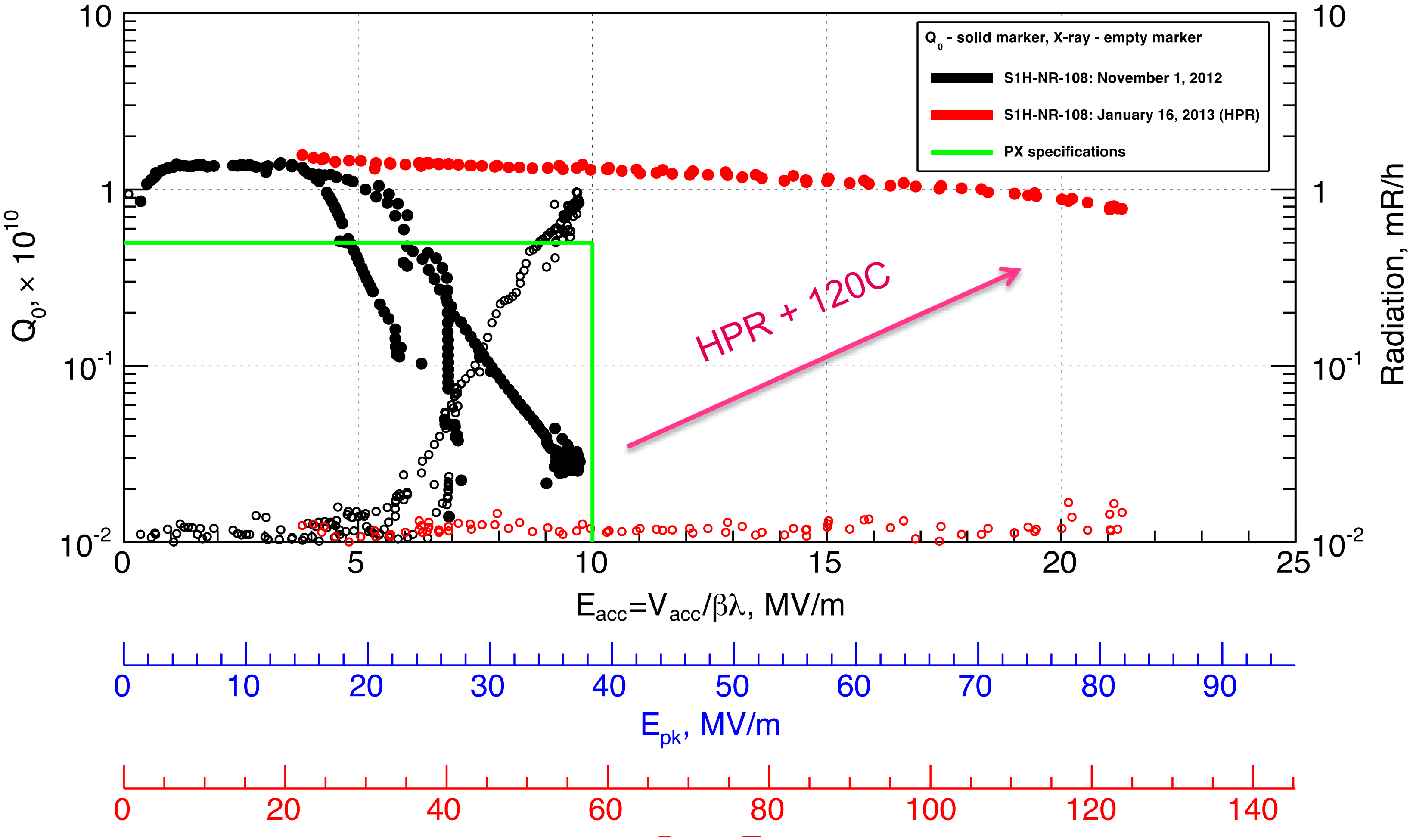
Installation on Top-Plate



Vertical Tests of 10 SSR1 Cavities (bare)

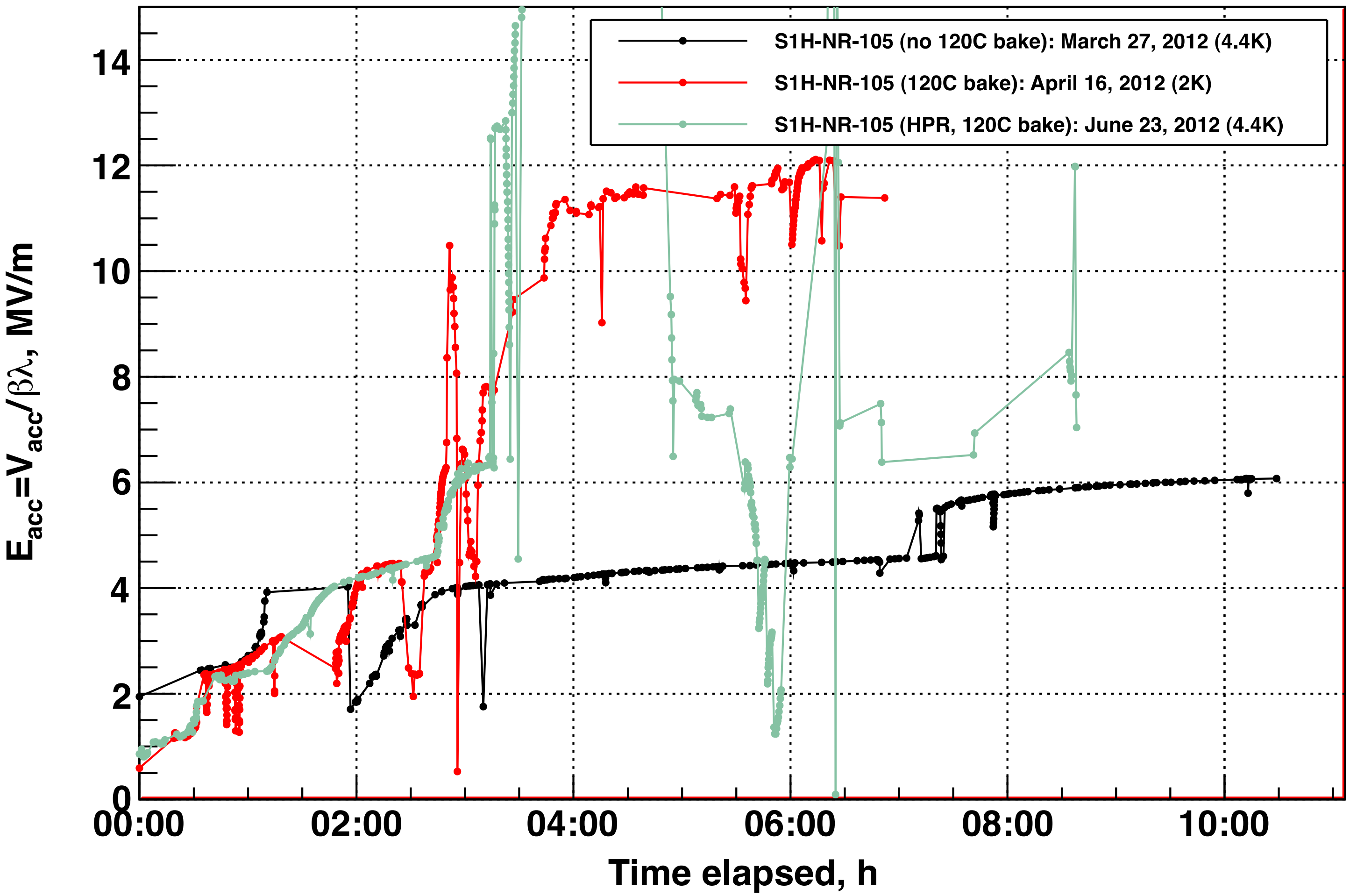


Example of S108 – 1st and 2nd pass



courtesy:
A. Sukhanov

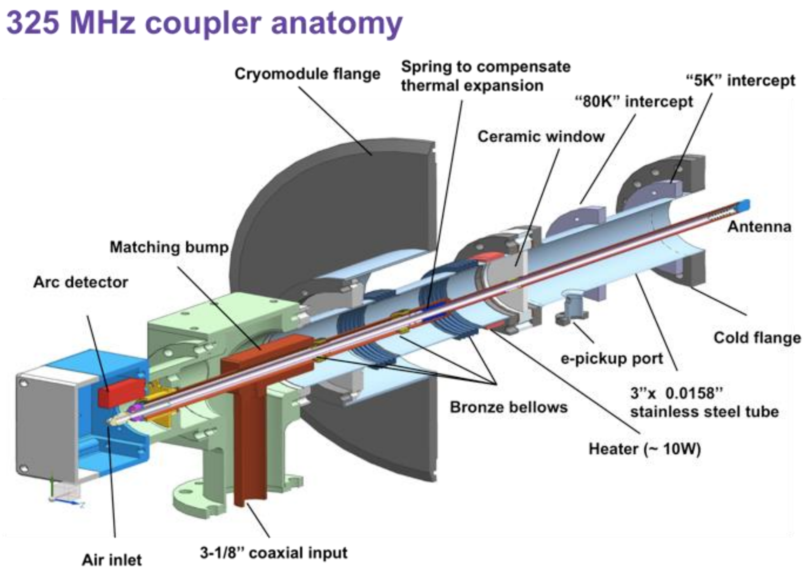
Multipacting Processing vs. 120C Bake



SSR1 325MHz Coupler: Status

Design specifications

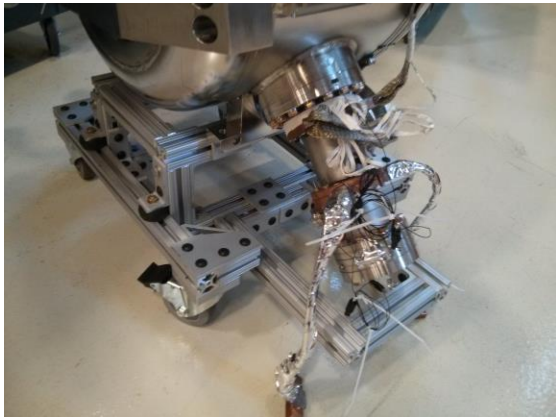
- Beam power gain per cavity (CW): ~2 kW.
- Maximum design power (PIP-II, 5 mA): ~30 kW.
- One ceramic window at room temperature.
- No external adjustment.
- Air cooled center conductor.



Prototype Couplers

Three prototype couplers successfully tested to 8.5 kW at room temperature.

One prototype coupler tested in STC at the maximum design power of 30 kW.



Production couplers

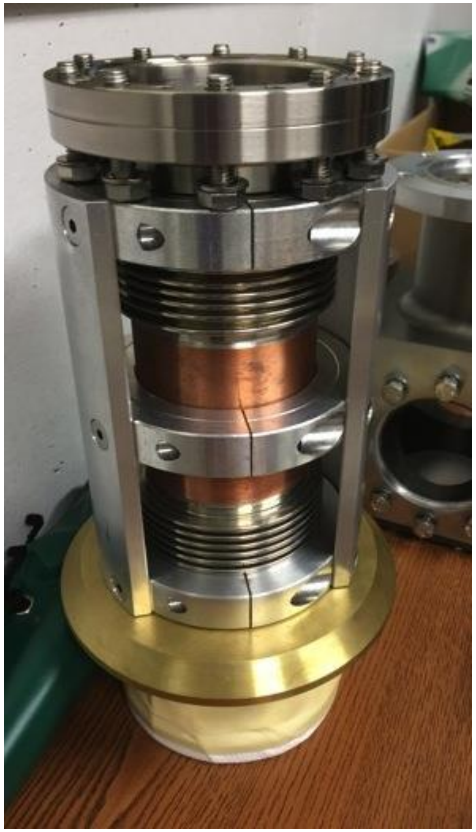
There is some delay on the production couplers because the design was changed to address several issues.

All 10 production couplers (cold-ends) will arrive at Fermilab in mid-December.

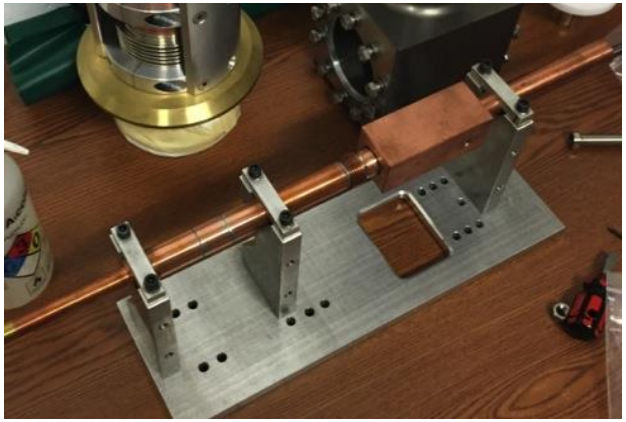
They are needed for qualification of cavities in STC.

Status of 325 MHz Main Couplers for PXIE, S. Kazakov, Proceedings of LINAC2014, Geneva, Switzerland

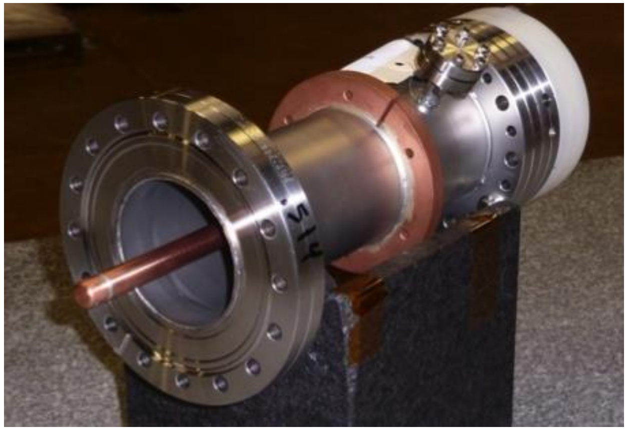
SSR1 325MHz Coupler: prototypes



Warm Outer conductor
Electro-deposited bellows
(Cu-Ni layers)



Warm Inner conductor

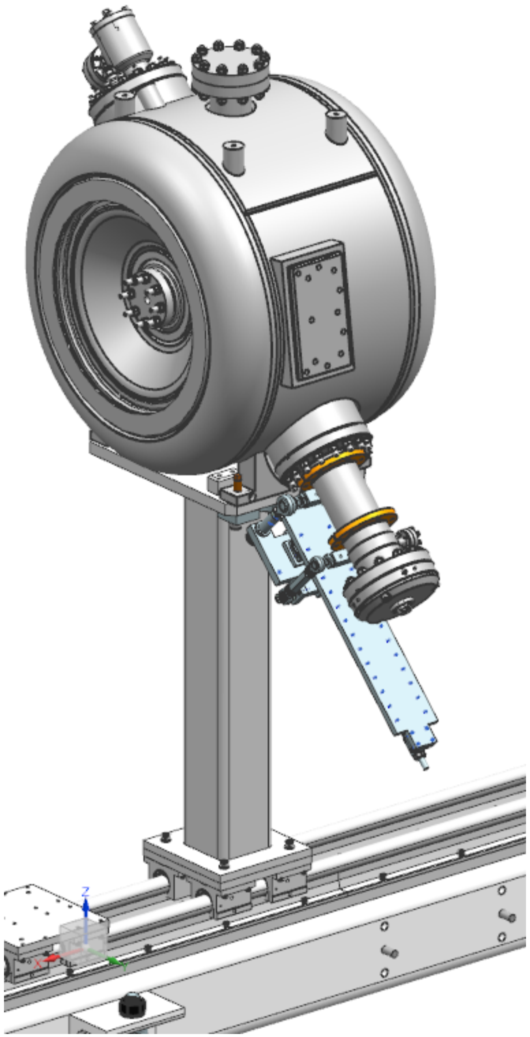


Cold-end assembly

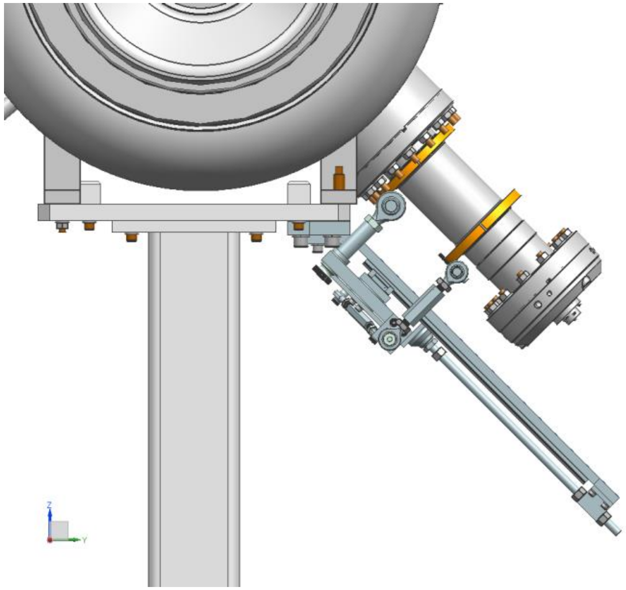
RF test stand

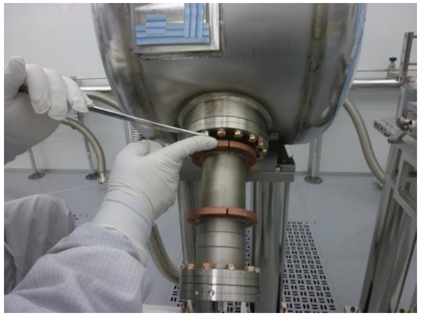
Test Stand for 325 MHz Power Couplers, S. Kazakov, Proceedings of LINAC2014, Geneva, Switzerland

SSR1 325MHz Coupler: installation



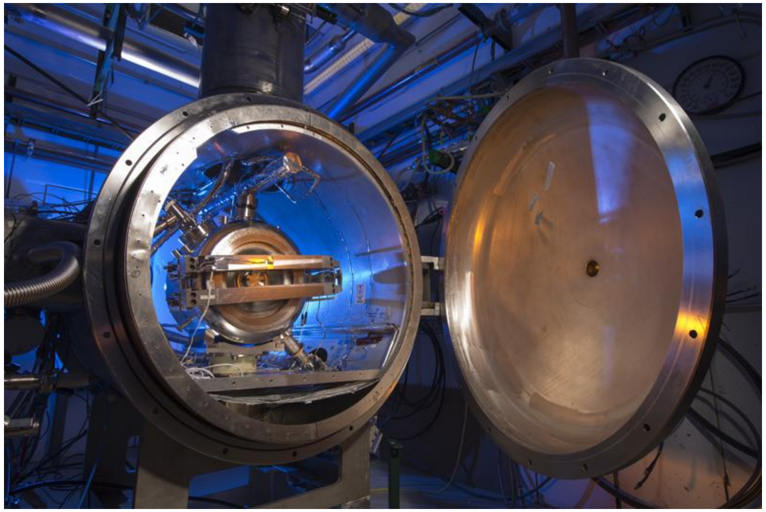
The cold-end of the coupler will be assembled on the cavity in a cleanroom (Class 10) using a specific tool and procedure for a “particle-free installation”.





Unity coupler was replaced with prototype high-power coupler

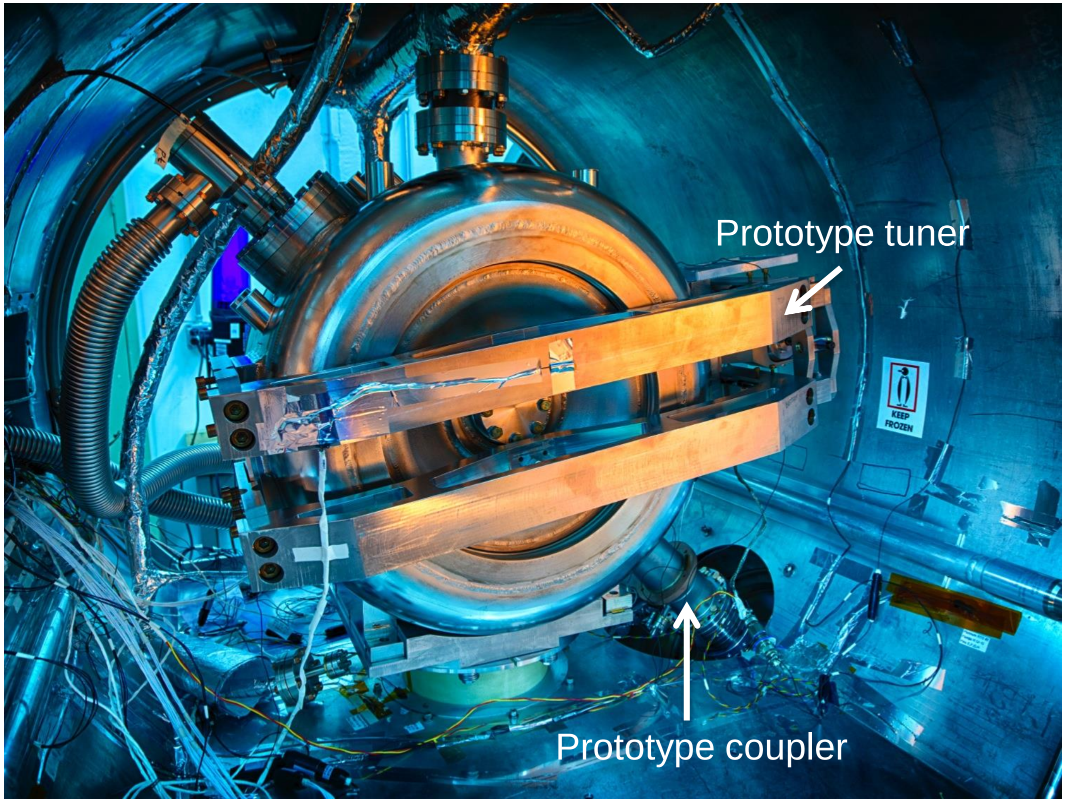
Fully Integrated Test in the Spoke Test Cryostat



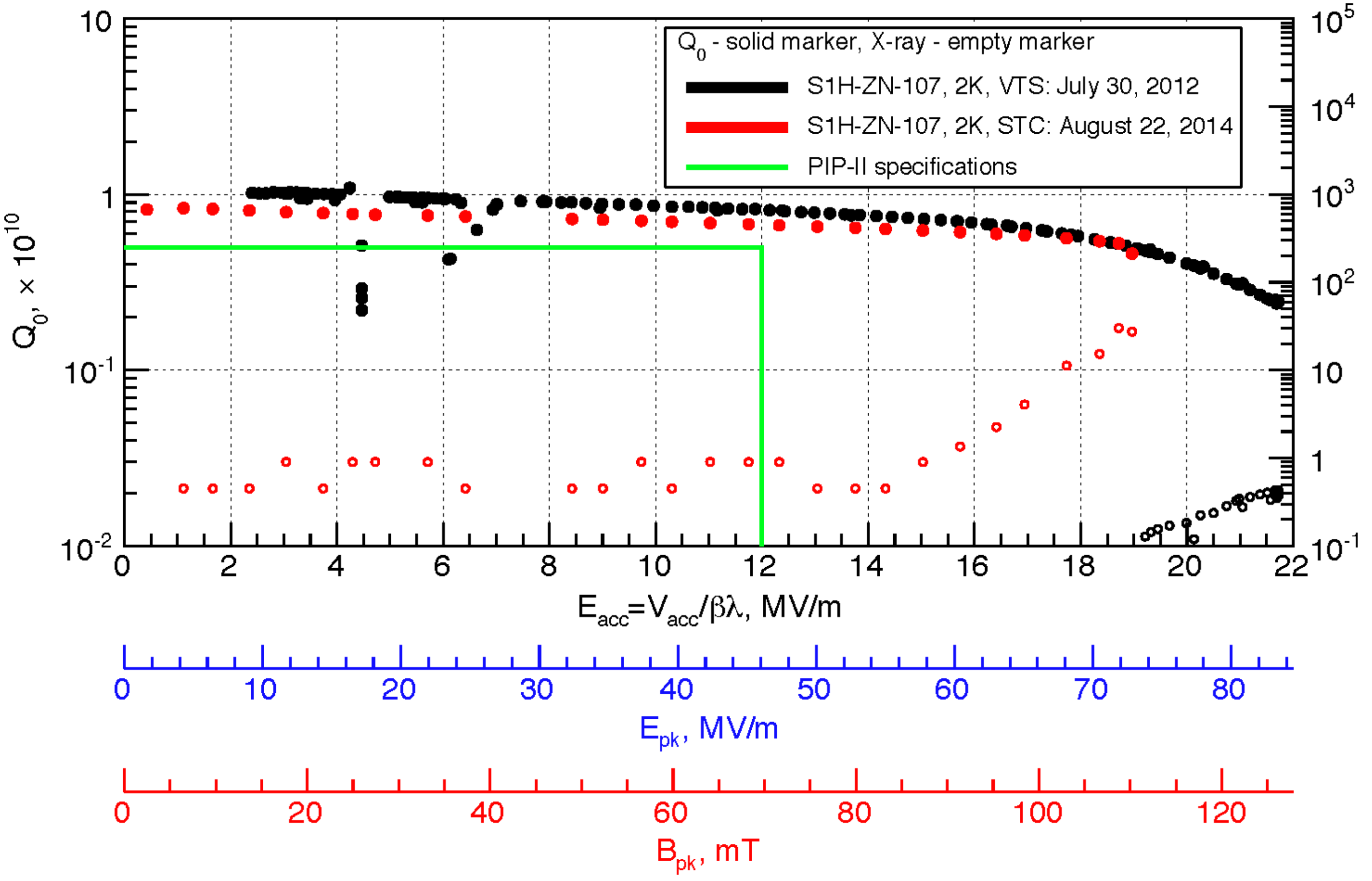
The jacketed SSR1 cavity (S1H-NR-107) dressed with prototype coupler and tuner was tested in the Spoke Test Cryostat at 2K. The performance of the power coupler and the frequency-tuning system were tested making sure they didn't interfere or degrade the performance of the cavity.

Results:

- Design of coupler validated: Prototype successfully tested to maximum power 30 kW.
- Design of Tuner validated…
- Jacketed cavity exceeds the specifications…

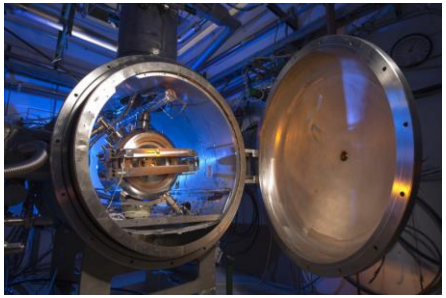


Testing at STC: Q_0 vs. E_{acc} curve (S1H-NR-107)



No Q_0 degradation compared to VTS results → Manufacturing process of the jacketed cavity validated.

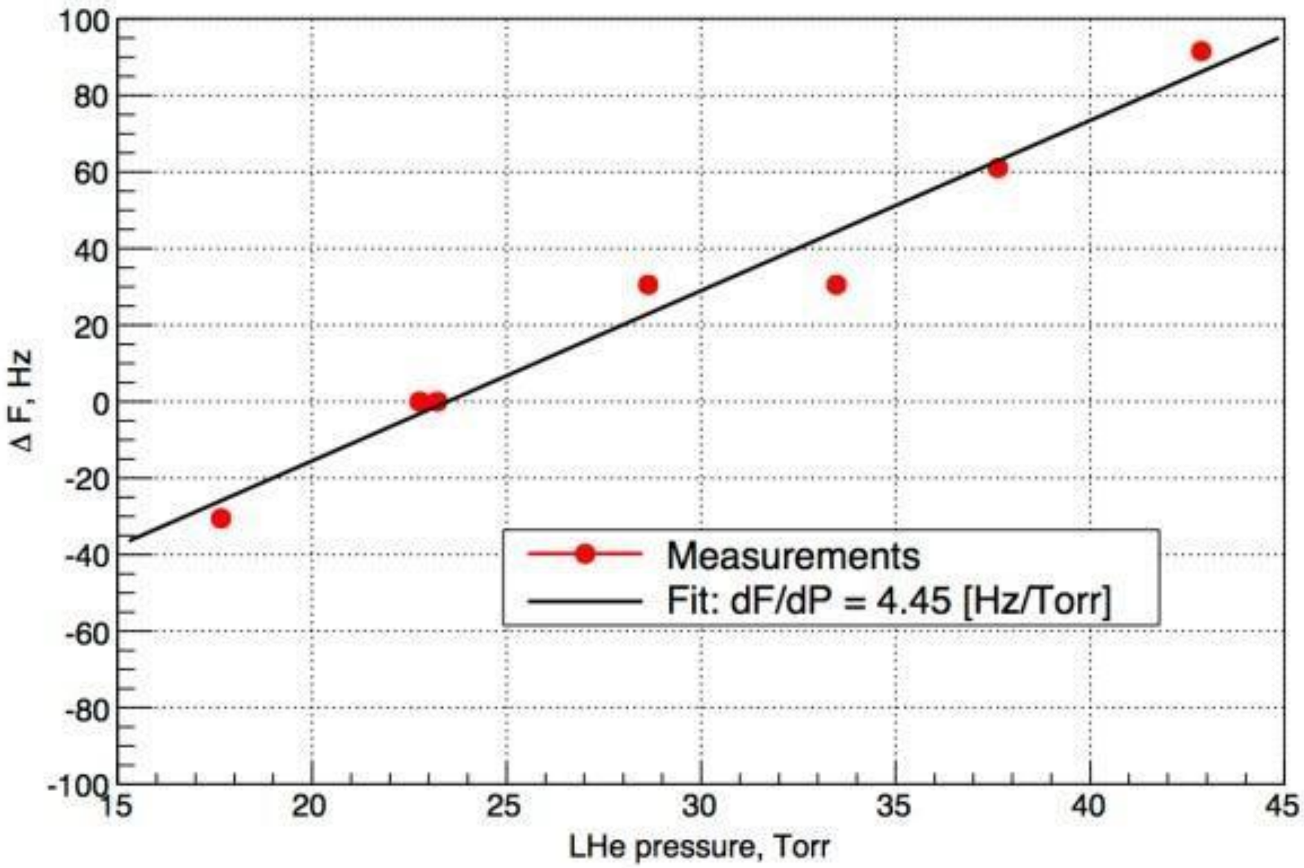
PIP-II specification:
Q_0 > 5 E9 at
E_{acc} = 12MV/m



Result of Cold Tests of the Fermilab SSR1 Cavities, A. Sukhanov et al., Proceedings of LINAC2014, Geneva, Switzerland

Testing at STC: Cavity Pressure Sensitivity (@ 2K)

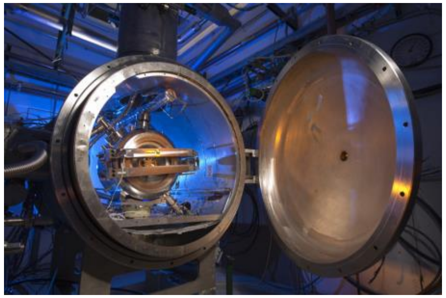
Pressure sensitivity measured with Tuner engaged (as in operating condition)



PIP-II specification
df/dp ≤ 25 Hz/Torr

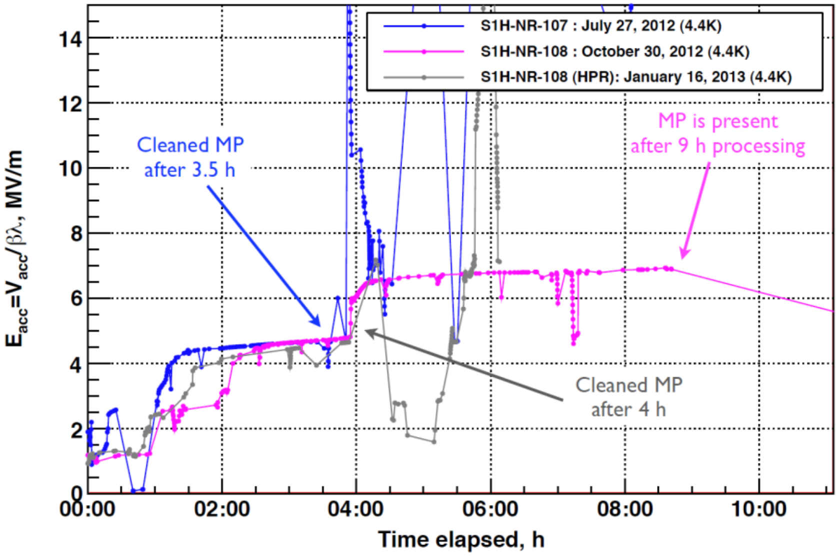
Design procedure to minimize the pressure sensitivity of the jacketed cavity with tuner is validated.

Estimated at room temperature:
df/dp = 4 Hz/Torr

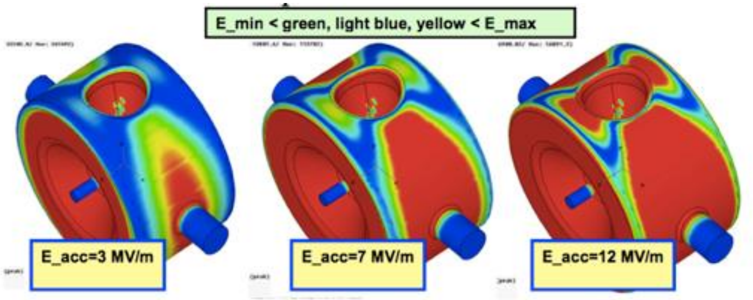


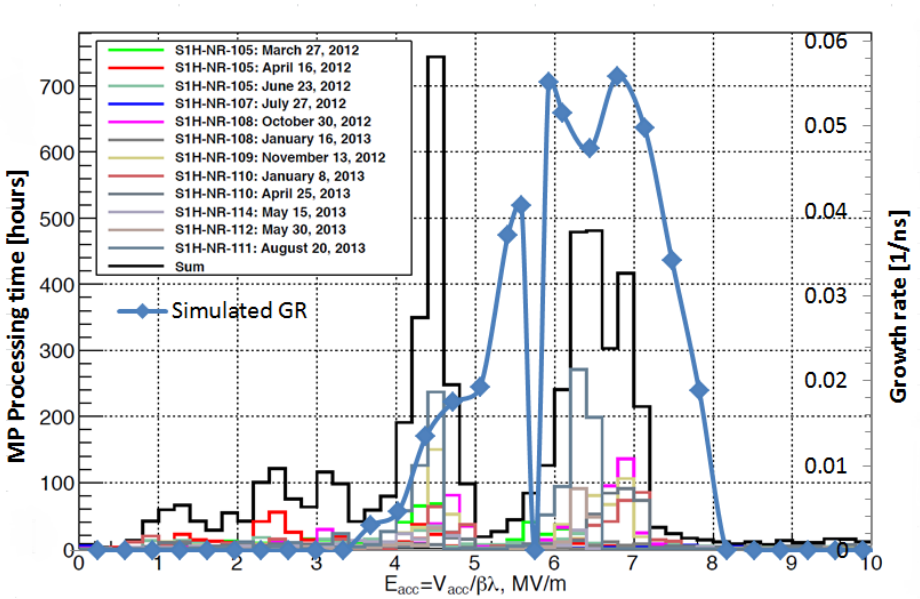
RF Tests of Dressed 325 MHz Single-Spoke Resonators at 2K, A. Hocker et al., Proceedings of LINAC2014, Geneva, Switzerland

Testing at STC: Multipacting



Multipacting was simulated in SSR1 cavities for PIP-II, the results of SSR1 simulations have been compared with experimental data and the agreement seems very good.





Simulation of Multipacting in SC Low Beta Cavities at FNAL, *G. Romanov et al., Proceedings of IPAC 2014, Richmond, VA, USA*
Multipacting Simulations of SSR2 Cavity at FNAL, *P. Berrutti et al., Proceedings of NA-PAC 2013, Pasadena, CA, USA*

SSR1 Tuner: Requirements and data

Parameter	*Value*	*Notes*
Total Frequency Range	> 135 kHz	From FRS
Frequency Resolution of stepper motor	< 20 Hz	From FRS
Piezo Frequency Range	> 1 kHz	From FRS
Tuner Passive spring constant	30 kN/mm	Derives from df/dP requirement
Sensitivity of end-wall	540 kHz/mm	Simulation/Experimental
Cavity wall spring constant (K_{cav})	30 kN/mm	Simulation/Experimental

Parameter	*Value*	*Notes*
Stepper motor max force	± 1300 N	Symmetrical
Stepper motor resolution*	0.1 µm (100 nm)	At interface with 2^{nd} lever
Piezo stroke @ RT	64 µm ± 2%	Measured
Piezo stroke @ operating T	15µm (25% of RT)	
Piezo max rated force	3360-5040 N	4200 N ± 20% (blocking force)
Piezo max operating force	2688 N	3360 · 80%

Parameter	*Value*	*Notes*
Motor Travel at beam pipe	> 0.25 mm	135/540 kHz
Piezo Travel at beam pipe	> 1.85 µm	1/540 kHz
Maximum Force at beam pipe	7500 N	0.25 mm · 30000 N/mm
Motor Resolution at beam pipe	< 37 nm	20/540000 mm
Motor Tuning Efficiency (Te)	< 37 %	37/100 nm
Motor Mechanical Advantage (M)	> 5.8	7500/1300 N, **picked 6**
Piezo Tuning Efficiency (Te)	> 12 %	1.85/15 µm
Piezo Mechanical Advantage (M)	> 1.4	0.5^{*} · 7500/2688 N, **picked 2**
Piezo Elastic Efficiency (E)	> 24 %	2 · 12 % (Te · M)

SSR1 Tuner

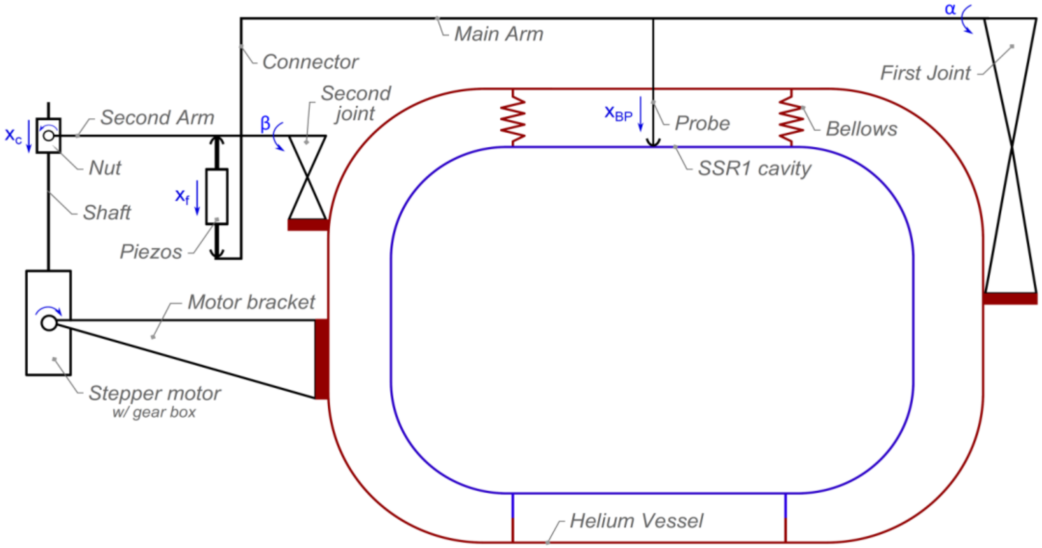
Specification

- Fine tuning >1 kHz
- Coarse tuning > 135 kHz
- Made of SS316L

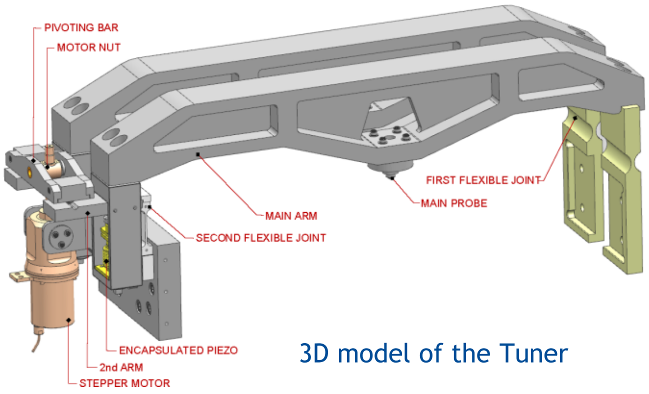
Double lever Tuner

- Well known technology
- Adjustable mechanical advantage
- Piezos and motor in series
- Piezos away from the beam
- Estimated efficiency and stiffness
- Respect of the following maximum forces at the actuating components:

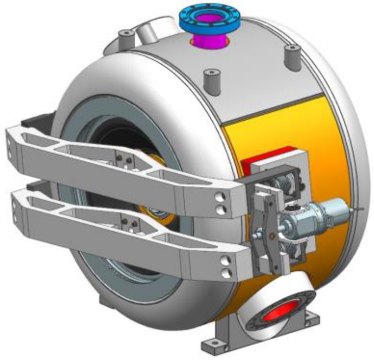
Parameter	**Value**
Stepper motor with gear box	
Max force	1300 N
Resolution	0.1 µm
Piezo	
Stroke (x_f) at 293 K	68 µm
Stroke (x_f) at 20 K	15 µm
Max operating force	2700 N
Min operating force	840 N



Schematic representation of the working principle of the SSR1 tuner.



3D model of the Tuner



3D model of the Tuner assembled on the SSR1-G3 cavity

SSR1 Tuner Mechanism: Passive and Active Device, D. Passarelli et al., Proceedings of LINAC2014, Geneva, Switzerland.

SSR1 Tuner: Testing

Operating mode

Coarse tuning *135 kHz measured*
$\Delta f_c \geq 135\,kHz \rightarrow x_{BPc} \geq 250\mu m$

*Active compensation of **uncertainty** due to **cooldown**, **preload** the system*

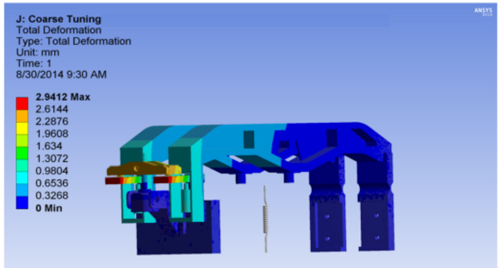
Fine tuning *2.5 kHz measured*
$\Delta f_f \geq 1\,kHz \rightarrow x_{BPf} \geq 1.85\mu m$

*Actively compensate the frequency shifts due to **microphonics***

Passive tuning *+4.5 Hz/Torr measured*
$k_{pass} \geq 30\,N/\mu m \rightarrow \frac{df}{dp} \leq \mathbf{25\,Hz/Torr}$

*Passively minimize the **pressure sensitivity** of the cavity*

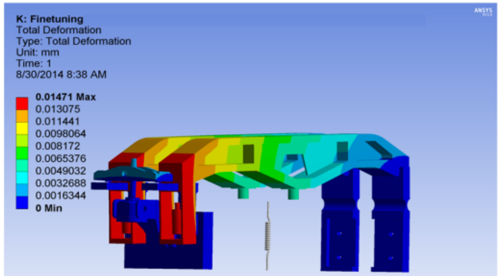
- FE analyses to simulate the three operating conditions and verify the value of stiffness and efficiency *…and Testing Results*



5.5% measured

$$E_{ct} = \frac{x_{BPc}}{x_c} = \frac{260}{2500} = 10.4\% \leq \mathbf{37\%}$$

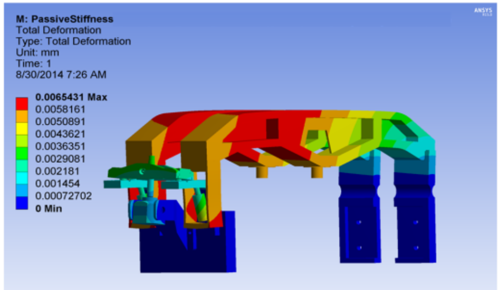
$$x_{BPc} = \frac{F_m^{max}}{k_c} = 260\mu m \geq \mathbf{250\mu m}$$



44% measured

$$E_{ft} = \frac{x_{BPf}}{x_f} = \frac{5.30\mu m}{15\mu m} = 35\% \geq \mathbf{17\%}$$

$$x_{BPf} = \frac{F_p^{max}}{k_f} = 5.30\mu m \geq \mathbf{1.85\mu m}$$

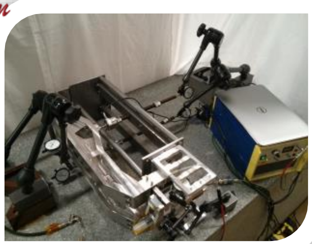


$$k_{pass} = \frac{F_{BP}}{x_{BP}} = 40\,N/\mu m \geq \mathbf{30\,N/\mu m}$$

+4.5 Hz/Torr measured

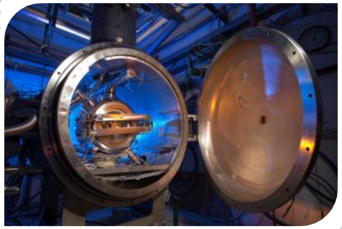
$$\frac{df}{dp} = \frac{F_{BP}}{x_{BP}} = +4\,Hz/Torr \leq \mathbf{25\,Hz/Torr}$$

Tests at Room Temperature



Tuner mounted on a test stand for initial measurement at room temperature.

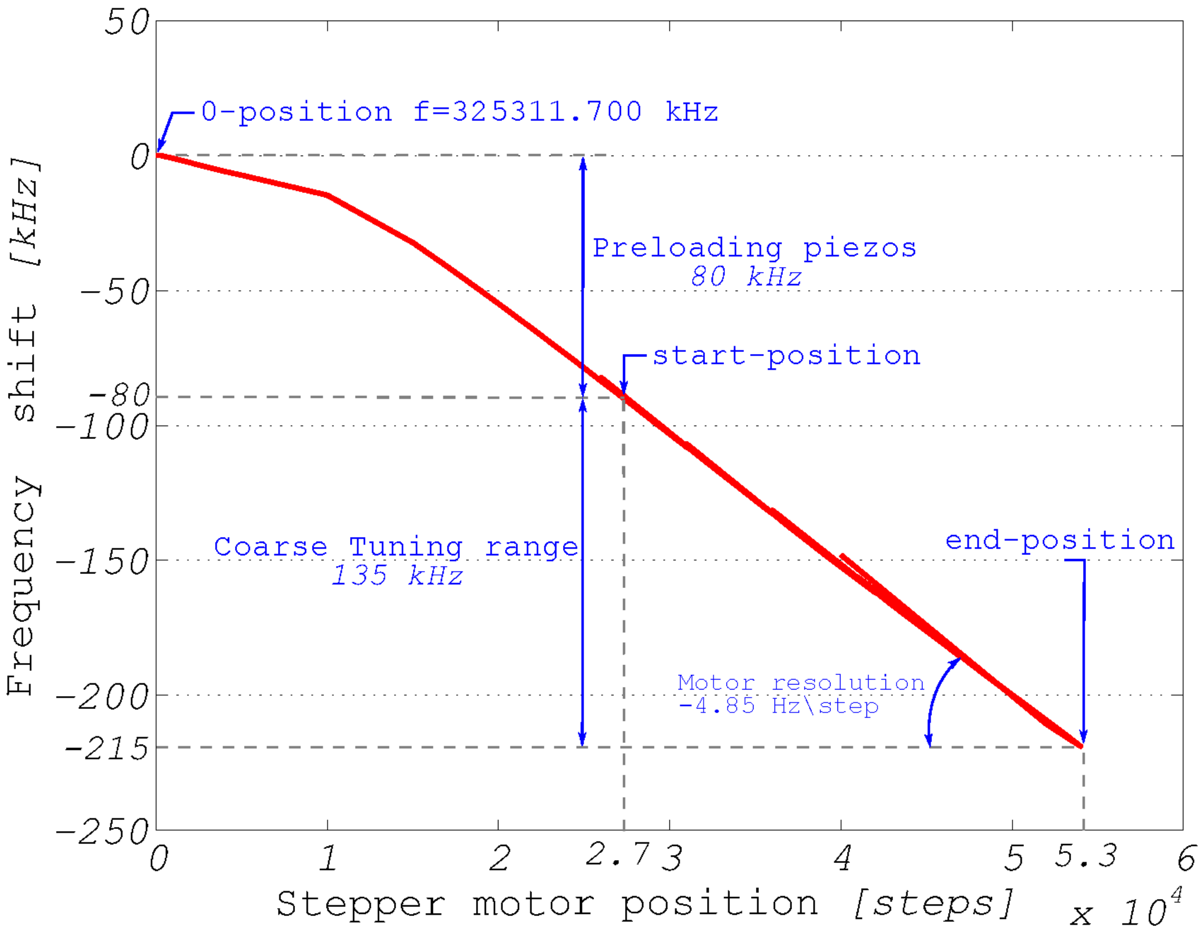
Tests at Cold Temperature

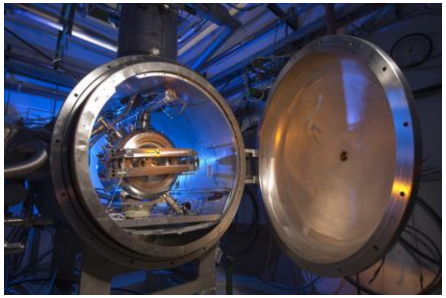


Installation of SSR1 cavity (S1H-NR-107) with tuner and coupler into the Spoke cavity Test Cryostat (STC) at Fermilab.

SSR1 Tuner Mechanism: Passive and Active Device, D. Passarelli et al., Proceedings of LINAC2014, Geneva, Switzerland.

SSR1 Tuner: Testing



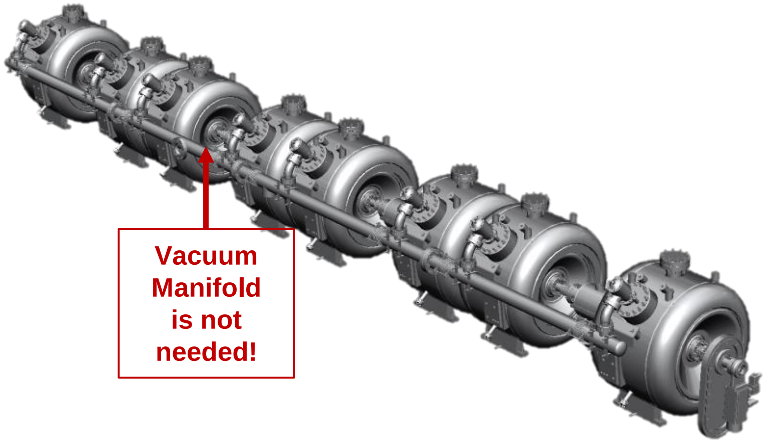


Studies of microphonics control of the SSR1 cavity have being carried out using this tuner mechanism.

Performance of the Tuner mechanism for SSR1 Resonators During Fully Integrated Tests at Fermilab, D. Passarelli et. al., Proceedings of SRF2015, Whistler, Canada, THPB061

SSR1 String Assembly: Beam-line vacuum

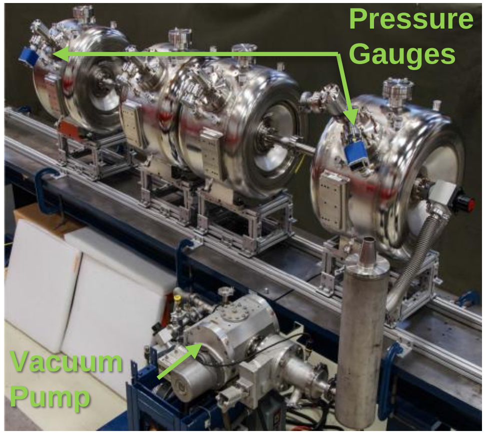
High vacuum level (< 5E-5 Torr) is needed inside the beam line volume before the introduction of liquid helium in less than 12 hours.

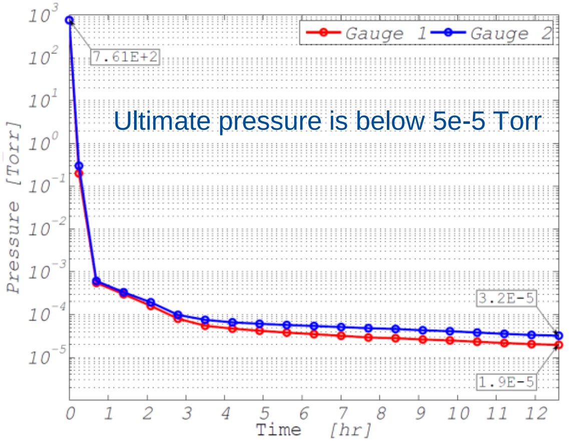


Vacuum Manifold is not needed!

The high-vacuum level at room temperature can be achieved pumping down by the beam ports only. Furthermore, simulations performed on the entire string with clean components show that the achievable pressure would be of 7E−8 Torr pumping from both ends.

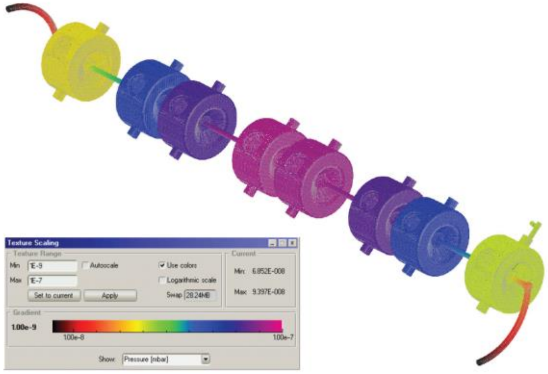
- ➢ Measurements (very conservative conditions)





Ultimate pressure is below 5e-5 Torr

- ➢ Vacuum simulation (best scenario)



Texture Scaling

Texture Range

Min 1E-9

Max 1E-7

☐ Autoscale

☑ Use colors

☐ Logarithmic scale

Swap 28.24MB

Current

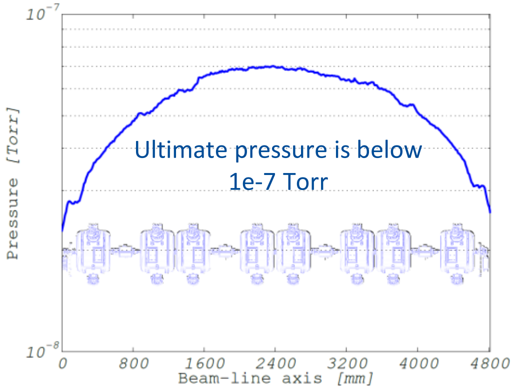
Min: 6.852E-008

Max: 9.397E-008

Gradient

1.00e-9

Show: Pressure [mbar]



Ultimate pressure is below 1e-7 Torr

High-vacuum Simulations and Measurements on the SSR1 Cryomodule Beam-line, D. Passarelli et al., Proceedings of SRF2015, Whistler, BC, Canada

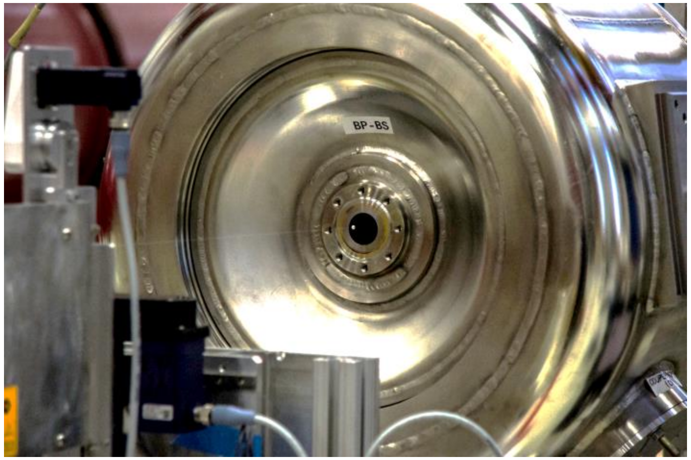
SSR1 String Assembly: Alignment (in progress…)

Alignment specifications (ED0001316)

Transverse cavity alignment error, mm RMS	<1
Angular cavity alignment error, mrad RMS	≤10
Transverse solenoid alignment error, mm RMS	<0.5
Angular solenoid alignment error, mrad RMS	<1

Estimation of cavities and solenoids misalignments due to the cooldown (293K --> 2K)

Referencing the electric axis of the cavity to external fiducials (beadpull + optical measurements + laser tracker). Error: ~ ±150μm

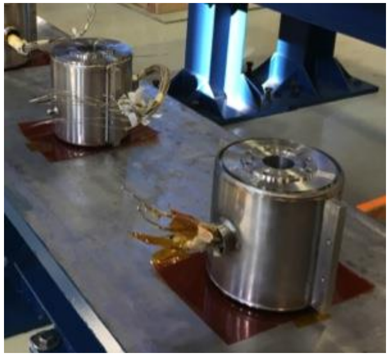


The positioning of the components in the string assembly will be defined starting from these results…

SSR1 String Assembly: components available

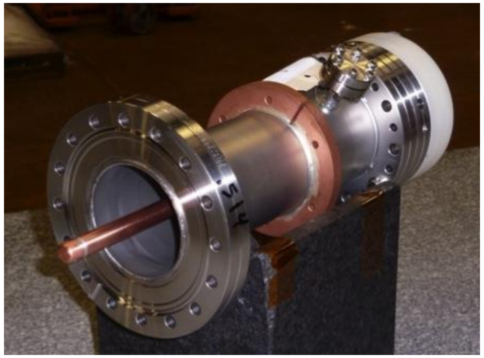
All components of the SSR1 string assembly were ordered and most of them are received.

Jacketed SSR1 cavities
(4 Type-A, 4 Type-B)

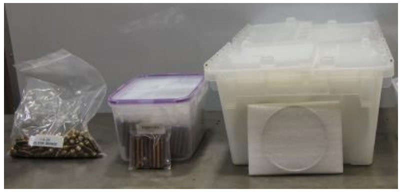


4 Solenoids

4 BPMs

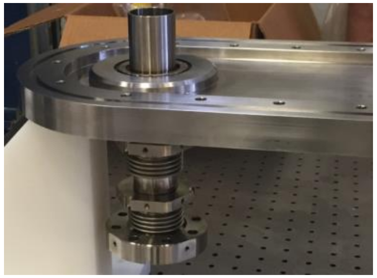


Production Couplers will
arrive in mid-December



All Hardware and Seals

Interconnecting Bellows



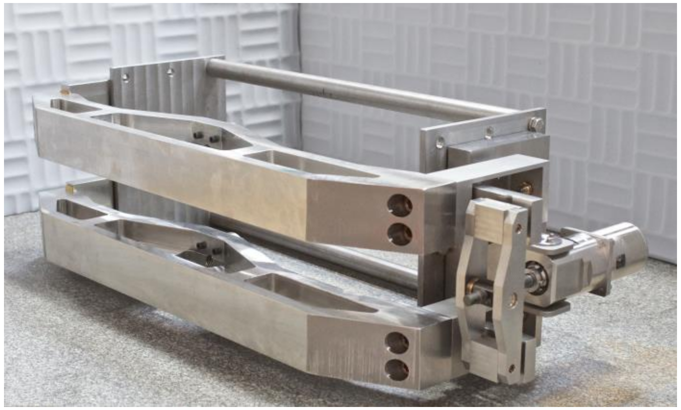
Warm-end transitions
and gate valves

Tooling

Other cryomodule components received as of today..

Vacuum vessel

Support Posts



Prototype Tuner mechanism

Strong-back