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SSR1 cryomodule

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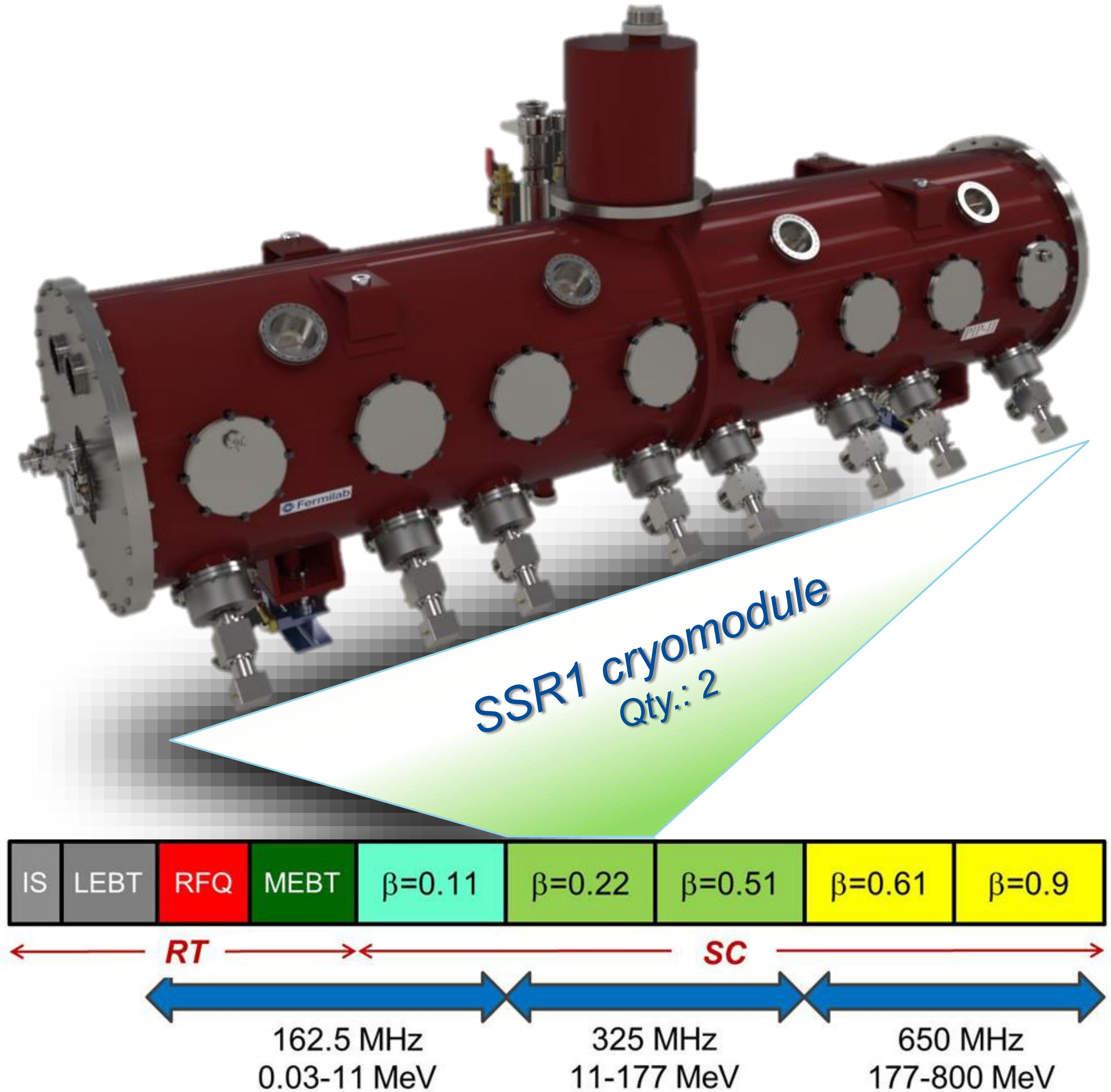
PIP-II Collaboration Meeting

9-10 November 2015

Outline

- SSR1 cryomodule for PXIE
  – Specifications and Goals
  – SSR1 String Assembly
    - Overall status of the design and procurements
    - Cavities
      – Mitigation of pressure sensitivity
      – Status of manufacturing
    - Couplers
    - Solenoids
    - Beam position monitors
    - Tuners
  – Qualification of main components in the Spoke Test Cryostat
  – Conclusions

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.

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

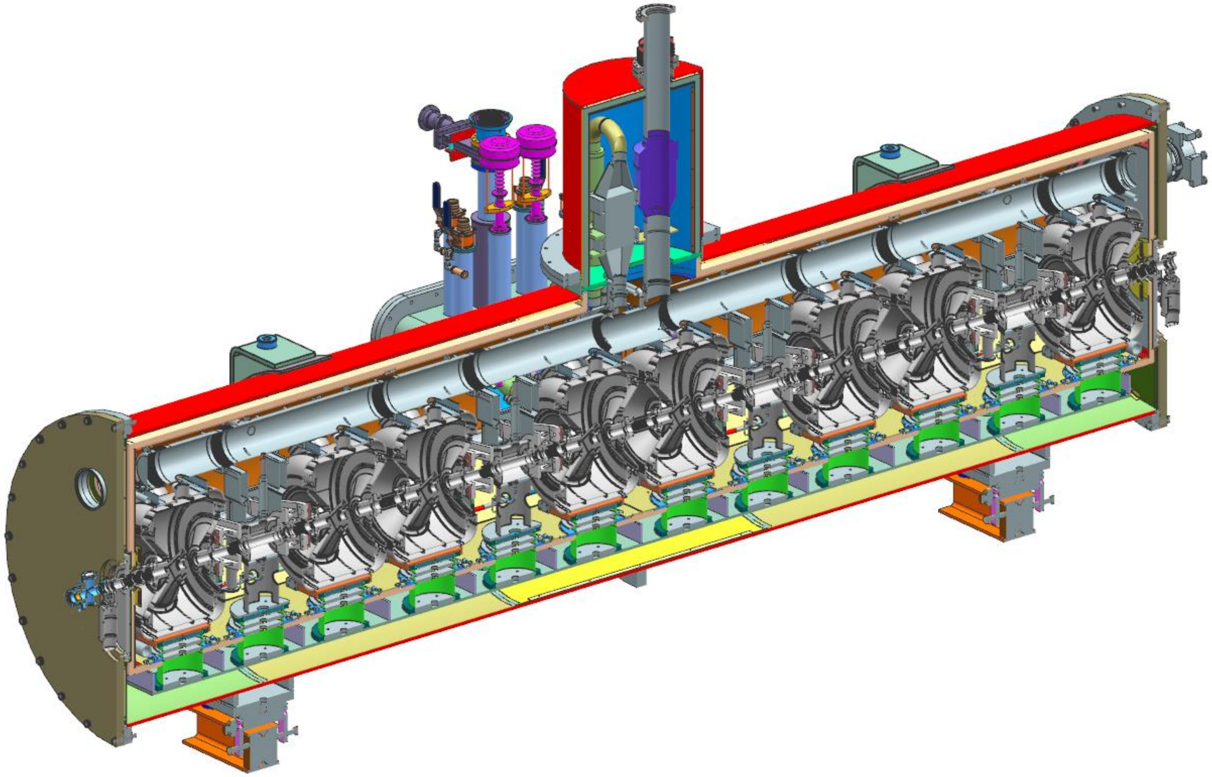
SRF Cavities	
Number, total	8
Frequency, MHz	325
β geometric	0.22
Operating temperature, K	2
Operating mode	CW
Operating energy gain at β=0.22, MV/cavity	2.05
Coupler type – standard coaxial with cold part impedance, Ω	105
Coupler power rating, KW	>20
Solenoids	
Number, total	4
Operating temperature, 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.

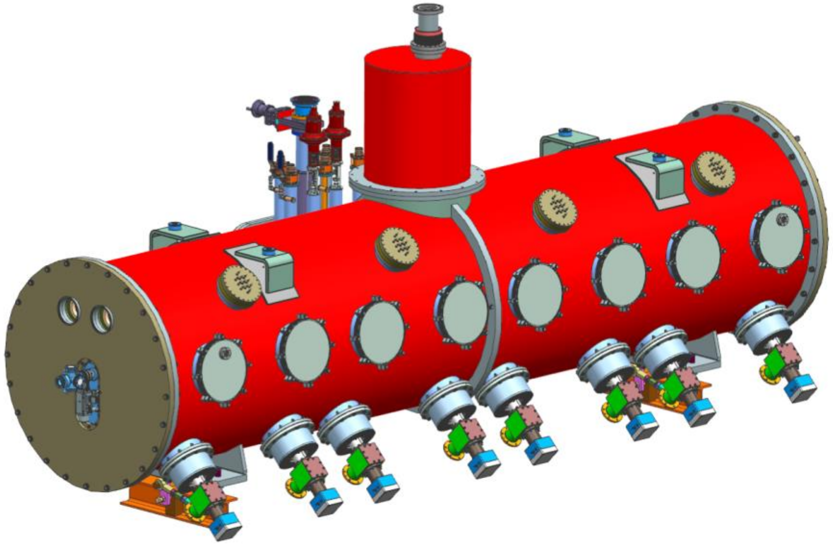
Cutview of the prototype SSR1 cryomodule



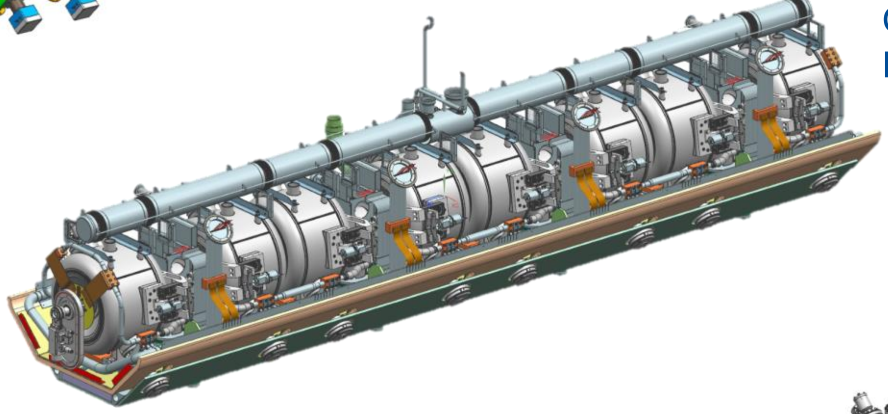
- SSR1 cryomodule contains eight cavities and four solenoids in the following order:
  C–S–C–C–S–C–C–S–C–C–S–C
- Warm aluminum strongback and individual supports for each magnet and cavity
- Fine segmentation: insulating vacuum and the cryogenic circuits are confined to an individual cryomodule
- All connections to the cryogenic, RF, and instrumentation systems are external to the vacuum vessel

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

Design of the prototype SSR1 Cryomodule

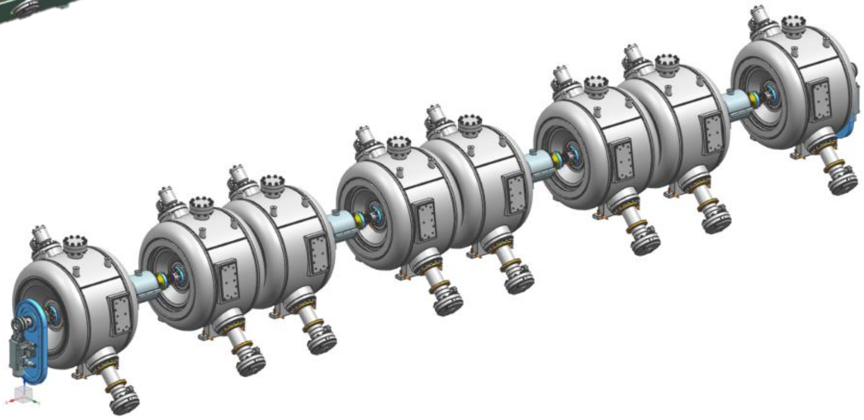


SSR1 cryomodule – Top assembly
Conceptual design: completed
Final design: ~80% completed

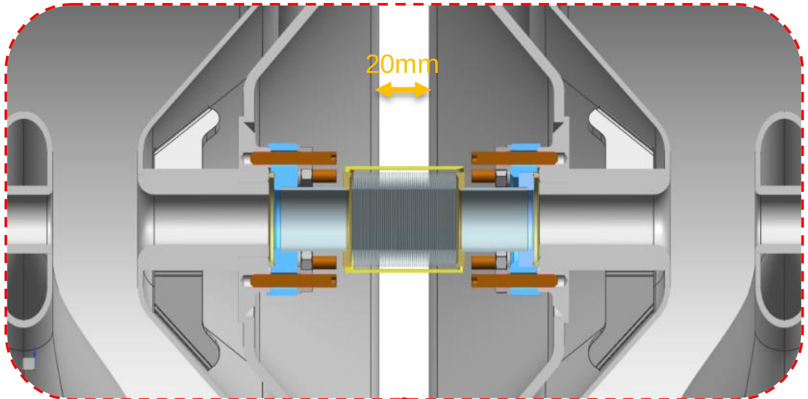


SSR1 coldmass
Conceptual design: completed
Final design: ~80% completed

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

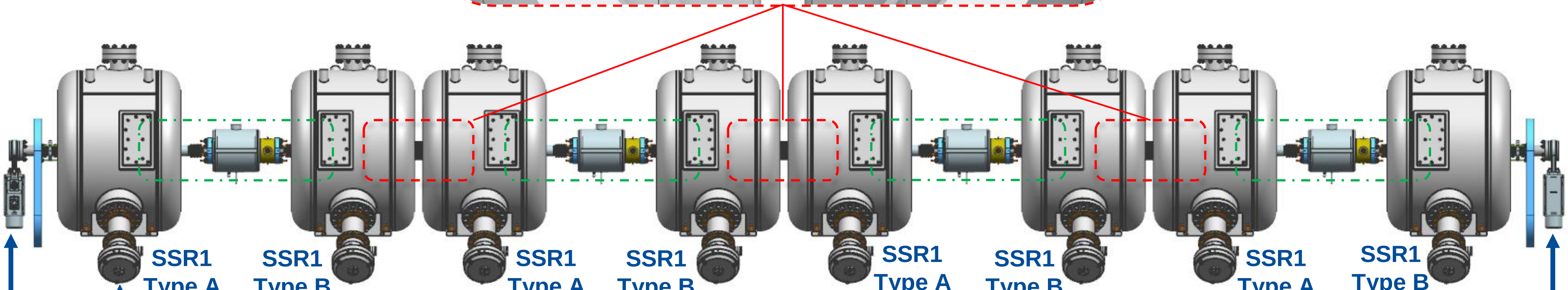


SSR1 String Assembly: design features

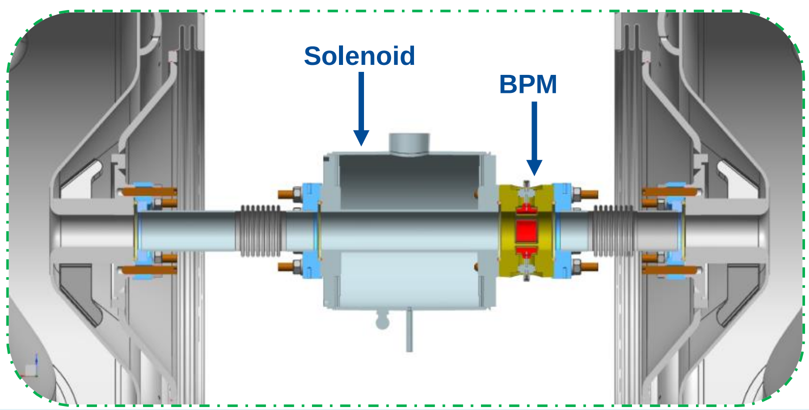


Edge-welded bellows assembly
Al-diamond seals
SiBr set screws
316L stainless nuts and washers

Interconnection cavity-cavity



Interconnection cavity-magnet-BPM-cavity

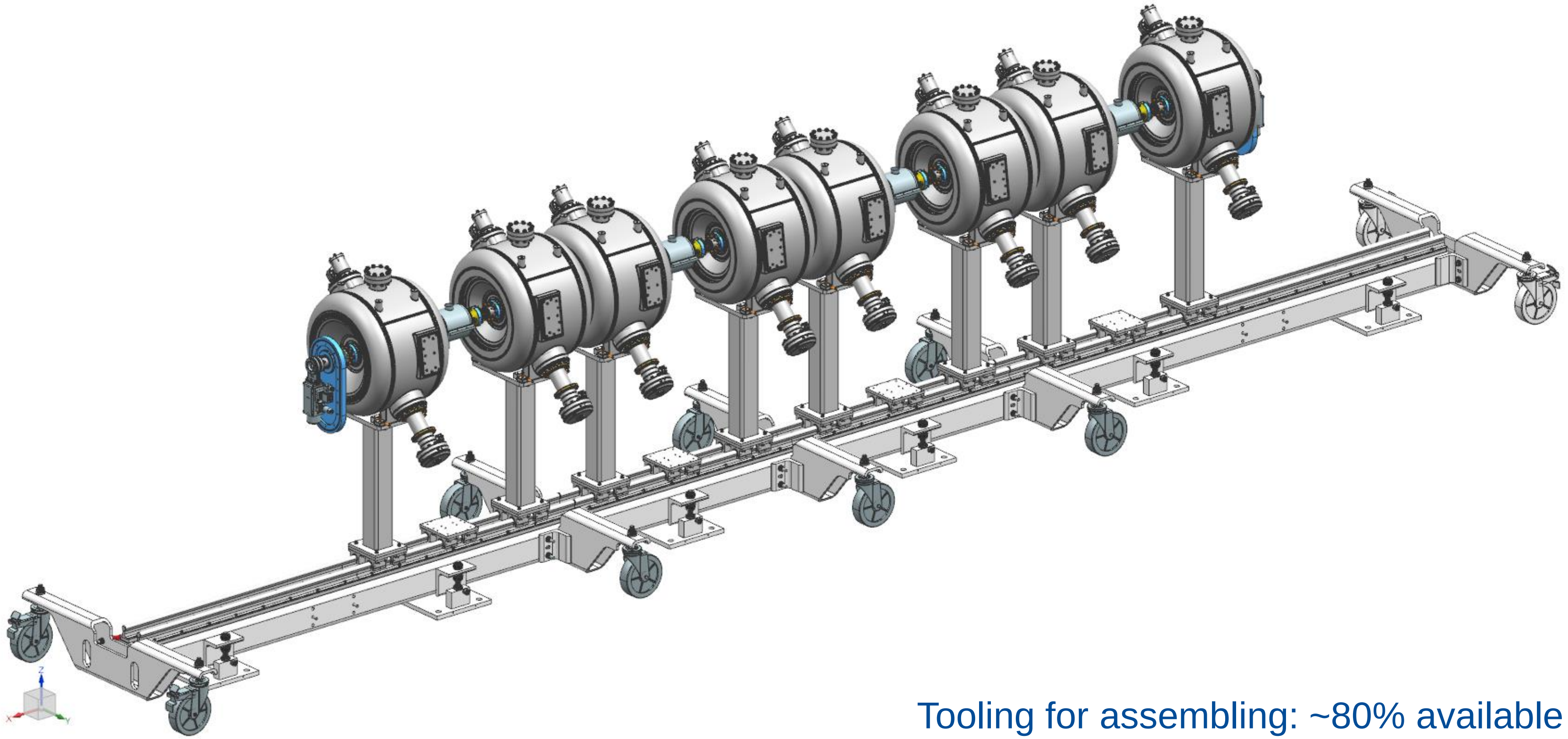


Hydro-formed bellows assemblies
Al-diamond seals
SiBr set screws
316L stainless nuts and washers

SSR1 String Assembly in cleanroom

Key aspects:

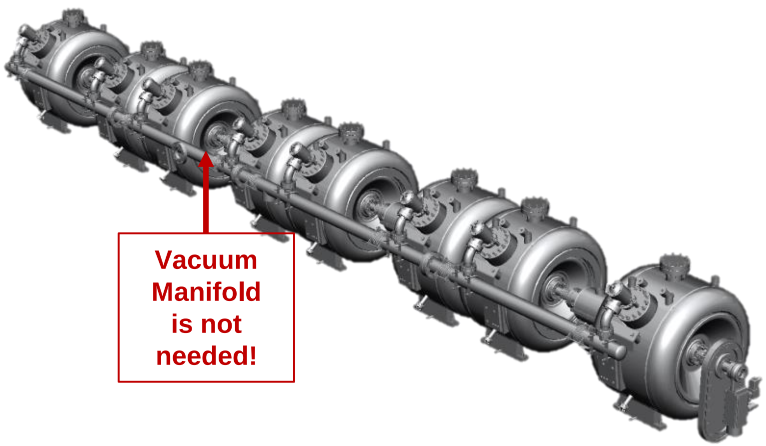
- Particles-free assembling in a cleanroom class 10
- Alignment of cavities (electric axis) and magnets (magnetic axis) with a datum.
- Handling of the string assembly (minimum deformations)



Tooling for assembling: ~80% available

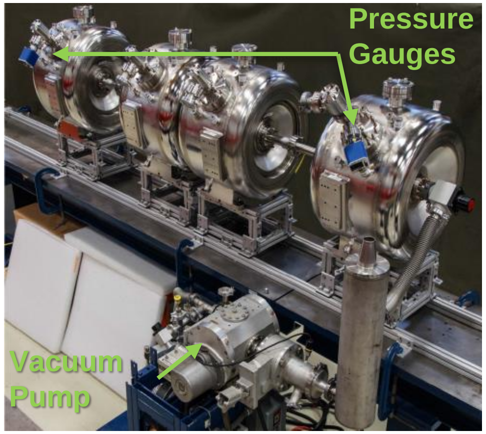
SSR1 String Assembly: Beam-line vacuum

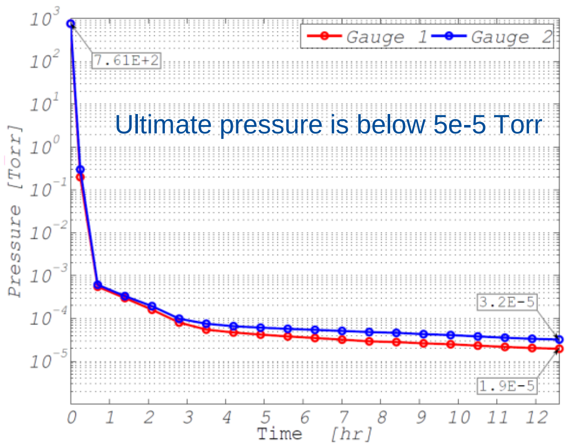
High vacuum level (< 5E-5 Torr) is needed inside the beam line volume before the introduction of liquid helium in less than 12 hours.



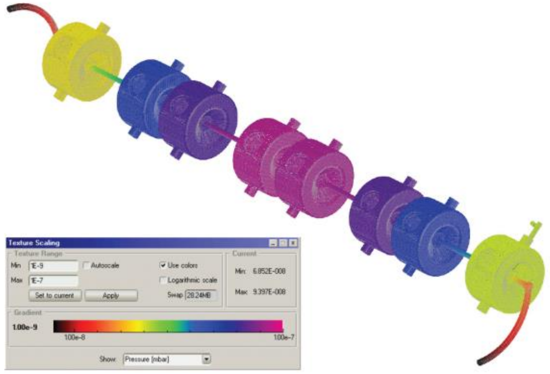
The high-vacuum level at room temperature can be achieved pumping down by the beam ports only. Furthermore, simulations performed on the entire string with clean components show that the achievable pressure would be of 7E−8 Torr pumping from both ends.

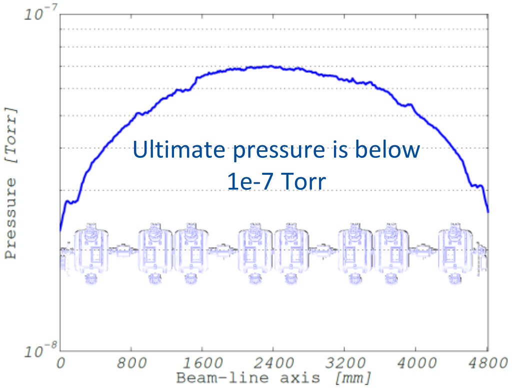
- Measurements (very conservative conditions)





- Vacuum simulation (best scenario)





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

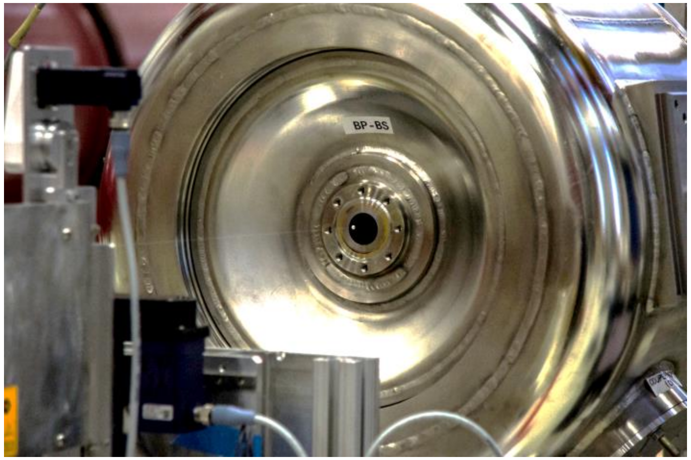
SSR1 String Assembly: Alignment (in progress…)

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

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

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



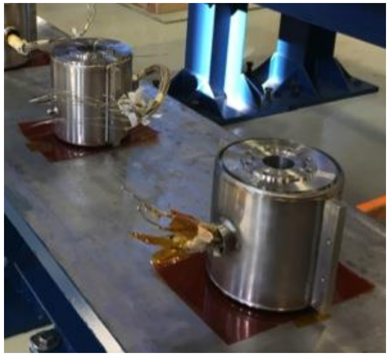
The positioning of the components in the string assembly will be defined starting from these results…

Fermilab PIP-II

SSR1 String Assembly: components available

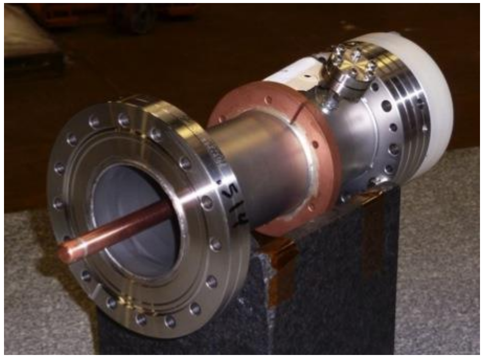
All components of the SSR1 string assembly were ordered and most of them are received.

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

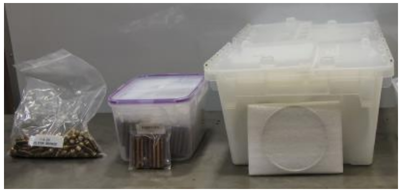


4 Solenoids

4 BPMs

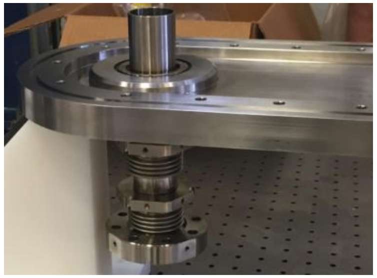


Production Couplers will arrive in mid-December



All Hardware and Seals

Interconnecting Bellows



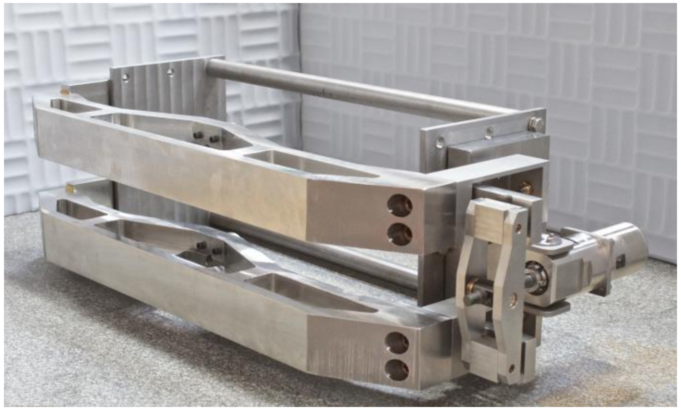
Warm-end transitions and gate valves

Tooling

Other cryomodule components received as of today..

Vacuum vessel

Support Posts



Prototype Tuner mechanism

Strong-back

SSR1 Cavities: requirements

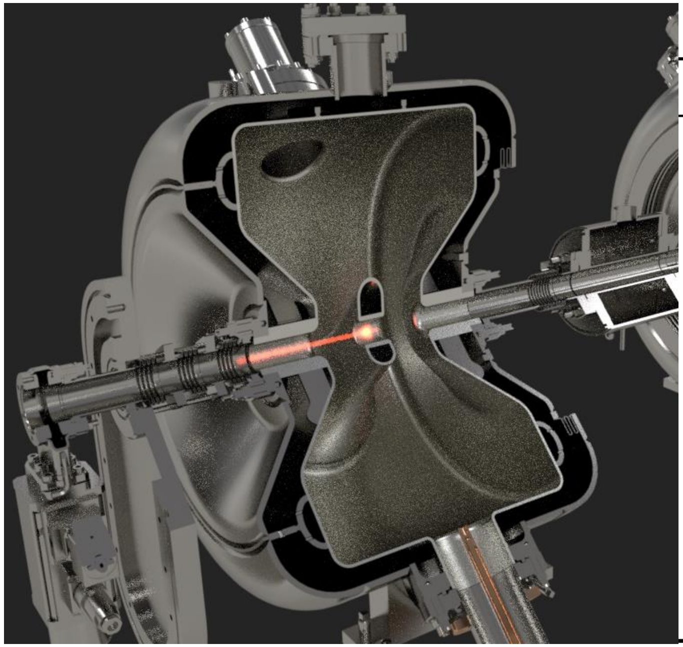
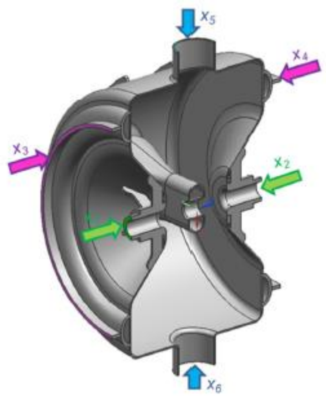


Table 1: Cavity operational and test requirements

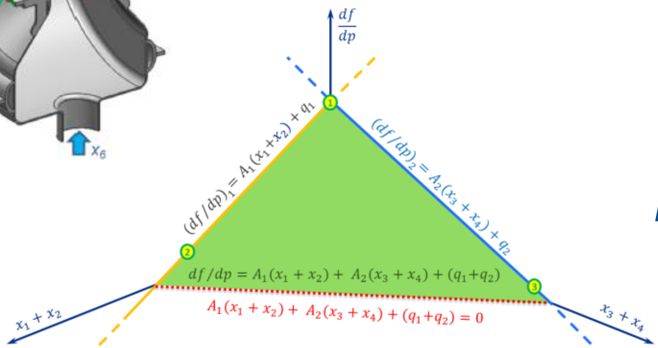
Parameter	Value
RF resonant frequency	325 MHz
Bandwidth	±20 Hz
Operating accelerating gradient (E_{acc})	12 MV/m
Quality factor (Q_0) at E_{acc}	$> 5 \cdot 10^9$
Operating gain per cavity	2 MeV
Maximum power dissipation at 2 K	5 W
Sensitivity to He pressure fluctuations	< 25 Hz/Torr
Field flatness	±10%
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

Teamcenter document numbers ED0001317

SSR1 Cavities: pressure sensitivity



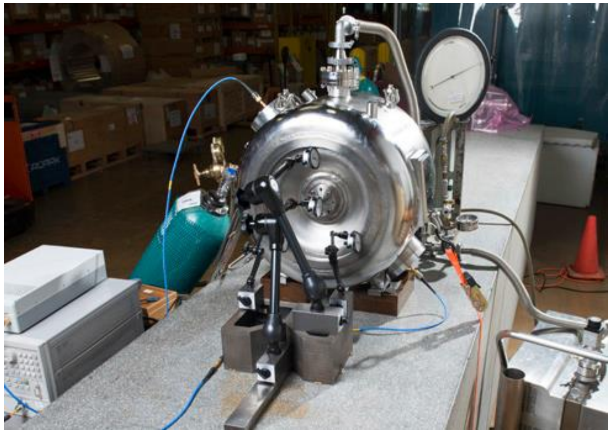
The jacketed SSR1 cavities were designed to have very low sensitivity to helium pressure fluctuations (microphonics).
We physically coupled the Nb cavity and the helium vessel such that we obtain a combination of cavity walls deformations $(x_1 + x_2)$ and $(x_3 + x_4)$ giving a $df/dp = 0$.



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

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

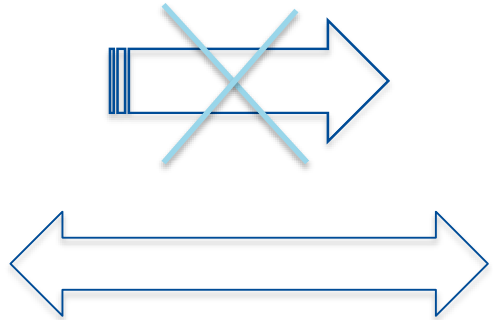
	df/dp [Hz/Torr]	S106	S107	S108	S109	S110	S111	S112	S113	S114
Measured	Bare cavity (with transition ring)	-564	-561	-553.5	-555.1	-568.8	-525.8	-524.6	-544.7	-557.2
	With He Vessel (without Tuner)	8	8	-1.2	5.4	7.9	2.7	9.0	6.3	10
	Fully integrated	4*	4	0*	2*	4*	2*	5*	3*	5*



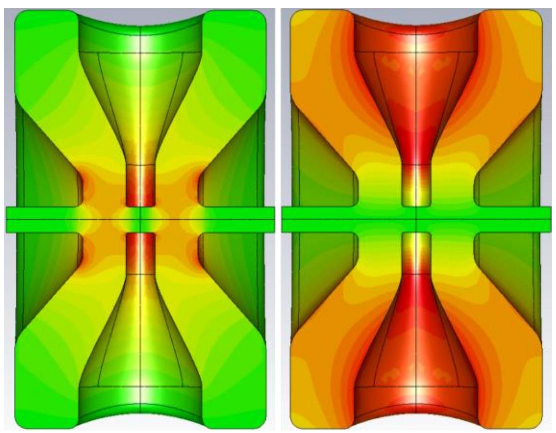
* Not measured yet (best guess)

SSR1 Cavities: design features

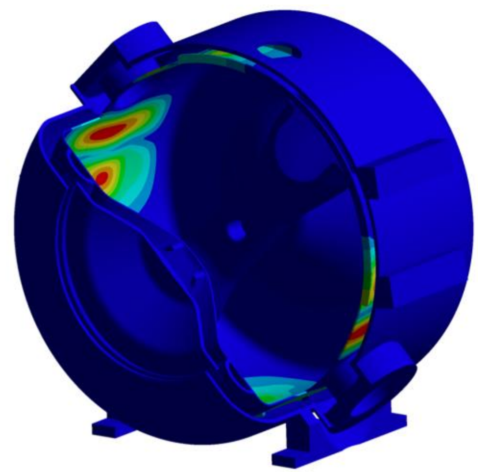
Electromagnetic Design
- Shape optimization
- Multipacting analysis
- Higher order modes
- Kick analysis
- Multipole effect
- Pressure Sensitivity
- Lorentz force detuning



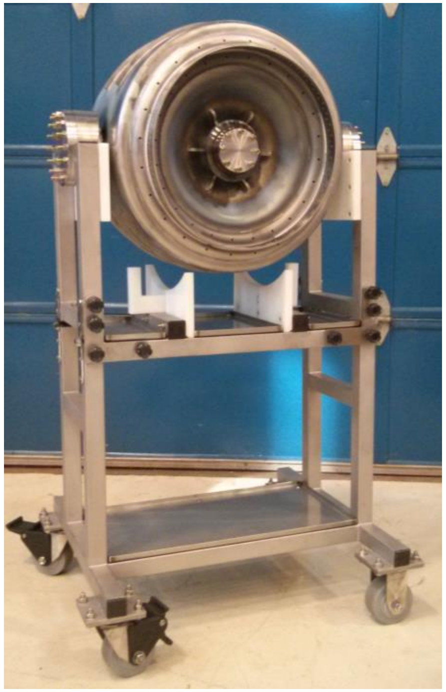
Mechanical Design
- Niobium shell design
- Vessel design
- Shape optimization
- Pressure Rating
- Stiffening and detuning
- Modal analysis
- Tuner Design



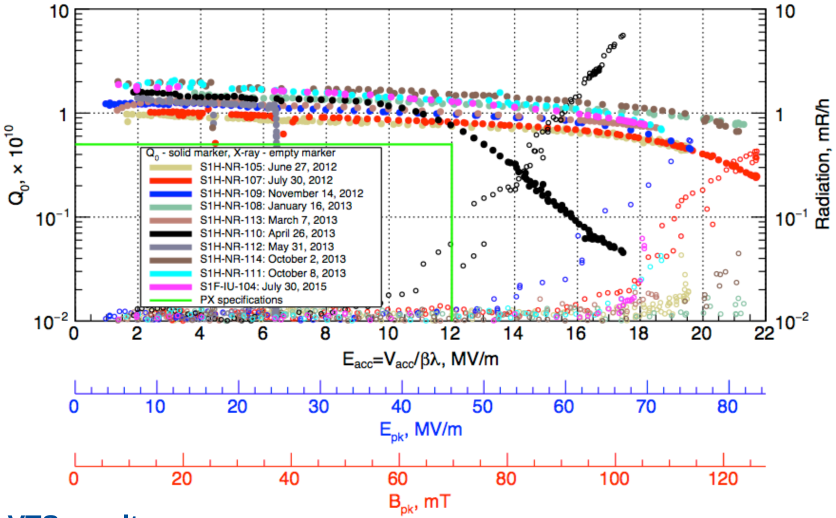
The parallel approach in performing RF/Mech analyses benefits the final design…



SSR1 Cavities: Status

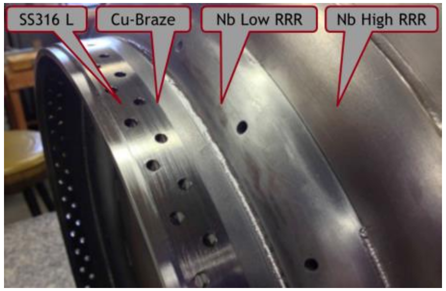


Bare cavity with transition ring



VTS results

Jacketed cavities



Transition ring

Status as today

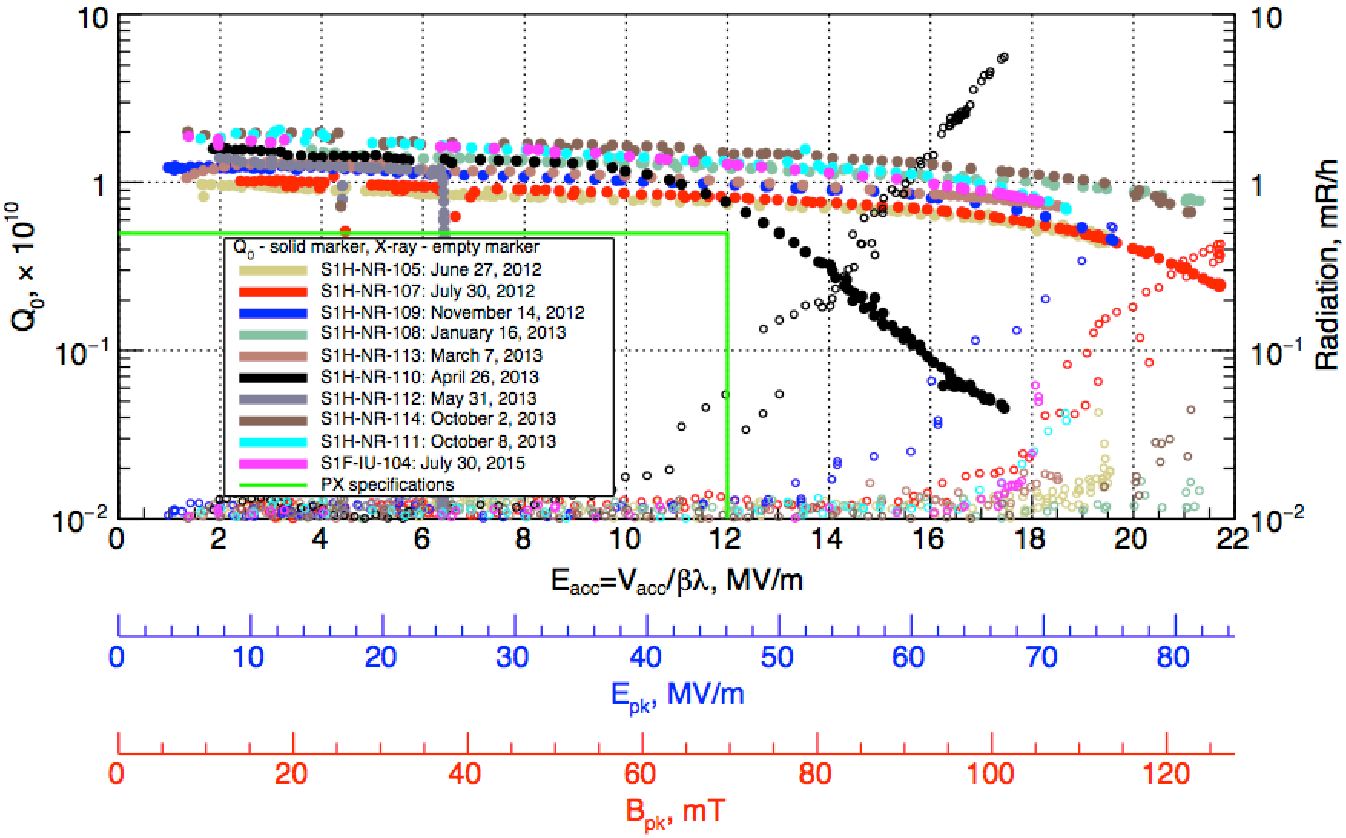
- All the ten bare cavities were qualified in VTS
- The transition ring (Nb-stainless steel) was added to all cavities
- 9 out of 10 SSR1 cavities were jacketed with the helium vessel
- QC inspections: visual, pressure test, leak check, CMM
- Inelastic tuning (target: 325MHz at 2K with the tuner engaged)
- Referencing the electric center to outside fiducials (in progress)

Next (starting in Dec. 15)

- BCP, HPR, installation of coupler (cold-end)
- Qualification of cavities dressed with coupler in STC

SSR1 Cavities from IUAC (Q_0 vs E_{acc} @ 2K)

Two SSR1 cavities were received from IUAC (India) part of the Indian Institutions and Fermilab Collaboration (IIFC). The summary plot shows one IUAC cavity (S1F-IU-104, magenta) together with all Fermilab cavities tested so far.

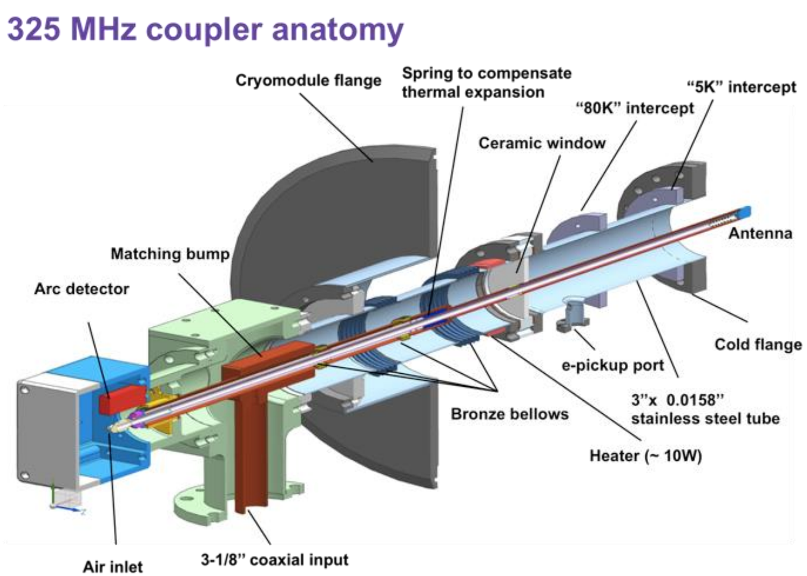


[Cold Tests of SSR1 Resonators Manufactured by IUAC for the Fermilab PIP-II Project](), L. Ristori et. al, SRF15 Conference

SSR1 325MHz Coupler: Status

Design specifications

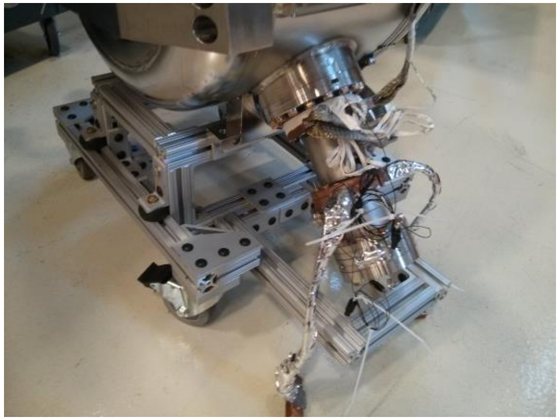
- Beam power gain per cavity (CW): ~2 kW.
- Maximum design power (PIP-II, 5 mA): ~30 kW.
- One ceramic window at room temperature.
- No external adjustment.
- Air cooled center conductor.



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

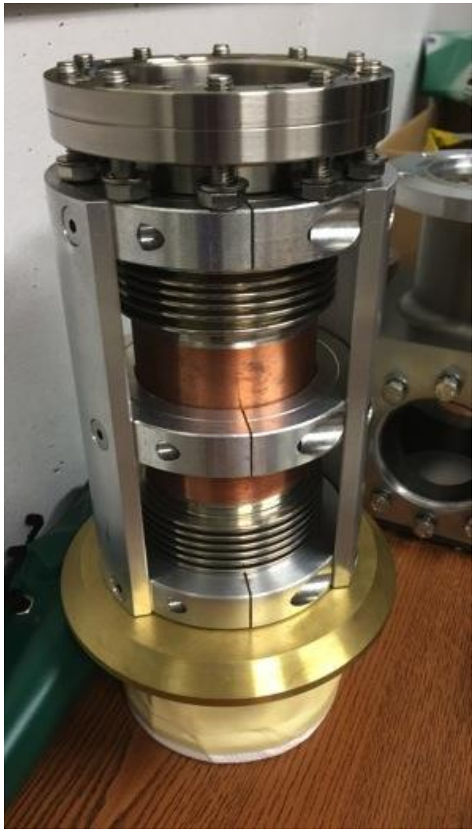
There is some delay on the production couplers because the design was changed to address several issues.

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

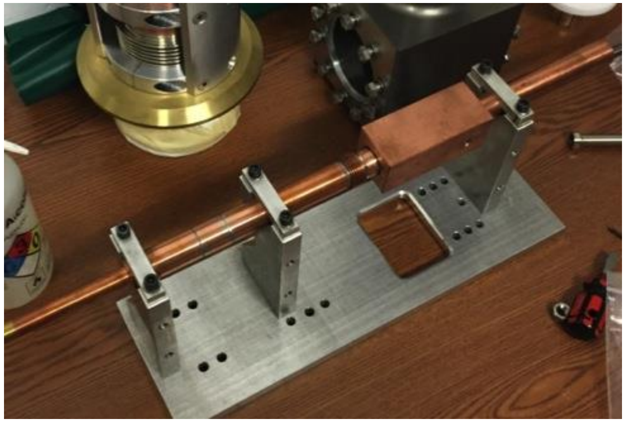
They are needed for qualification of cavities in STC.

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

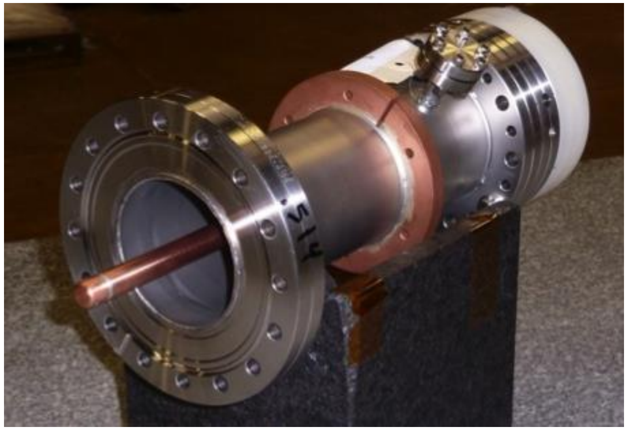
SSR1 325MHz Coupler: prototypes



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



Warm Inner conductor

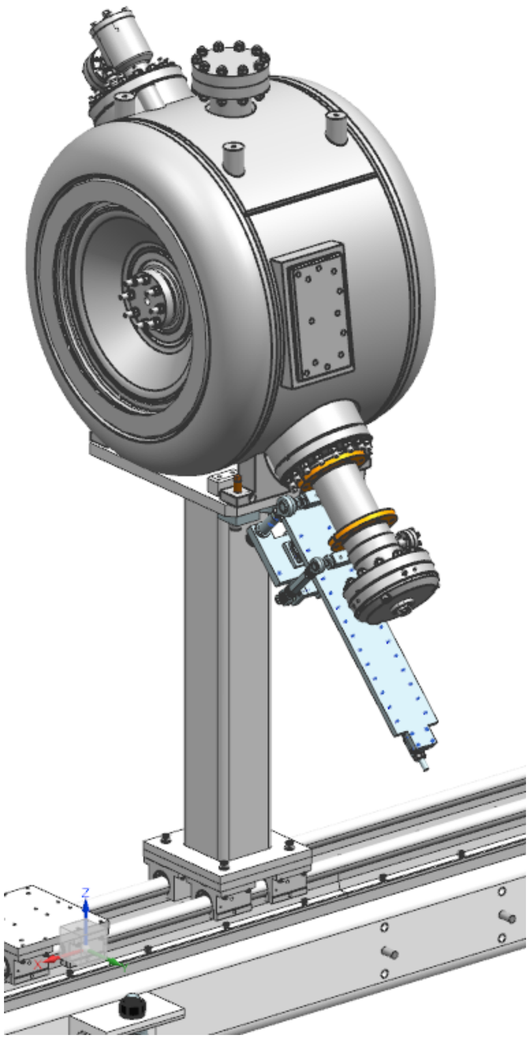


Cold-end assembly

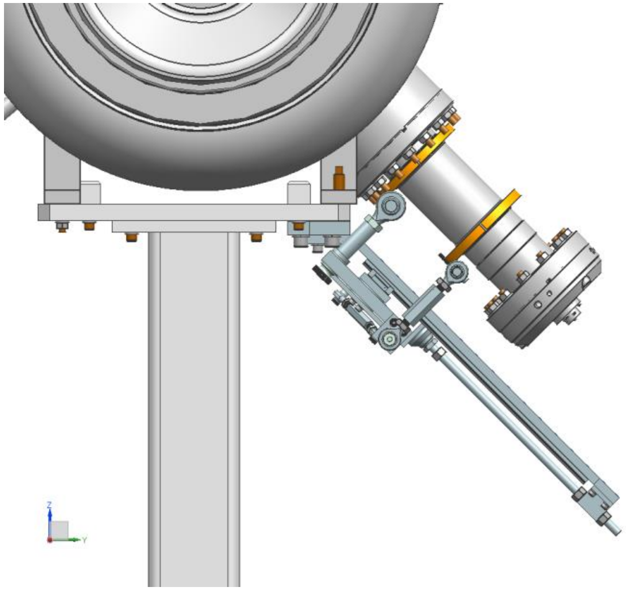
RF test stand

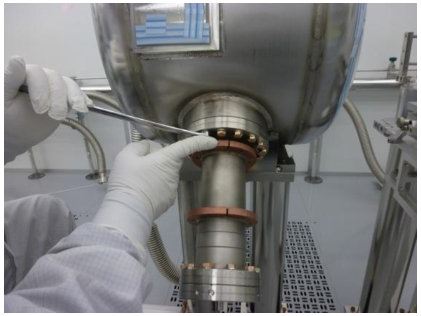
Test Stand for 325 MHz Power Couplers, S. Kazakov, Proceedings of LINAC2014, Geneva, Switzerland

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”.



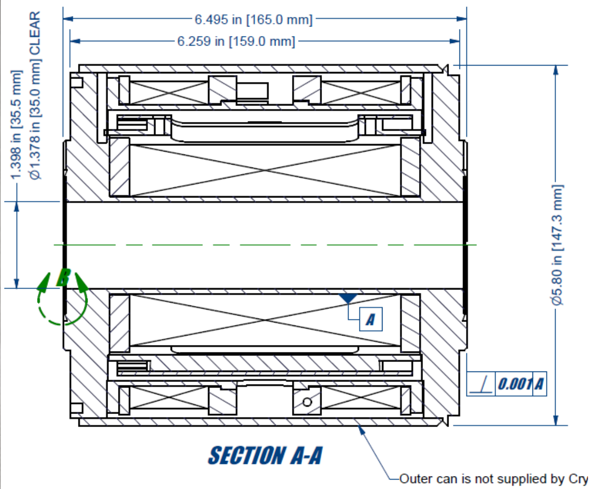


Unity coupler was replaced with prototype high-power coupler

SSR1 Solenoids

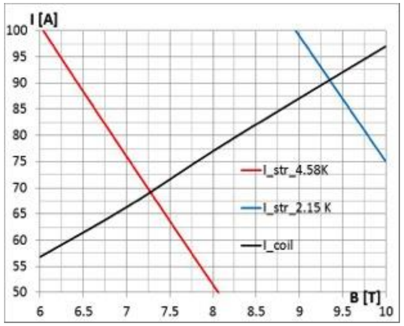
Specifications

Lens strength ($T^2 \cdot m$)	4
Steering dipole strength ($T \cdot m$)	$2.5 \cdot 10^{-3}$
Insertion length, max. (mm)	160
Ferromagnetic shielding	NO
Magnetic field on Cavity, max. (μT)	0.5·Q0 criterion
Transverse misalignment (mm)	0.5 RMS
Angular misalignment (mrad)	1 RMS

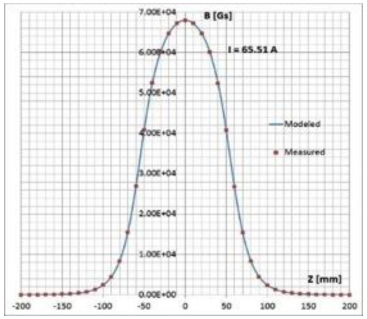


Prototype Solenoids

- Prototype lens' cold mass procured and tested at 2 K
- The lens assembled and re-tested
- Position of magnetic axis was measured by the vendor and at Fermilab: ΔR < 0.2 mm; Δα < 0.7 mrad



Quench Performance at 4 K and 2 K



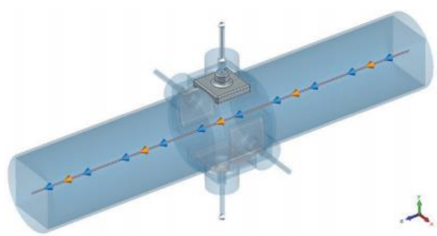
Axial Field: Measured vs Predicted

Production Solenoids

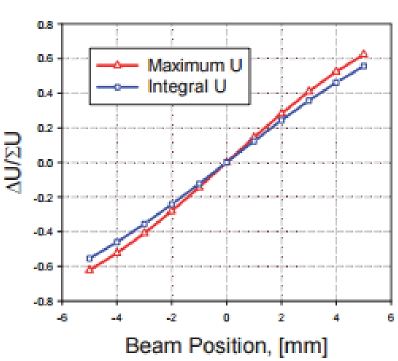
- Four production lenses' cold masses procured and tested at 4 K by the vendor.
- The lenses were also tested in the VTS (Fermilab) at 2 K.
- Excellent agreement between predicted and measured performances

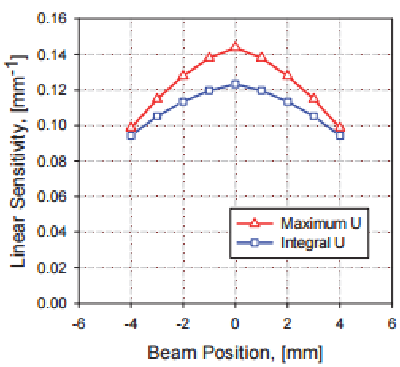
SSR1 Beam Position Monitors

Production BPMs
The finished BPM assembly is comprised of the 316L stainless steel body, a 50 Ohm SMA weldable feedthrough, alumina pins and an electrode.
ANL has fabricated 4 Beam Position Monitors (BPMs) and delivered to Fermilab.
Electrical continuity checks, final thermal cycling and leak checking, and the post fabrication cleaning were performed at ANL.



Low-beta button BPM 3D model

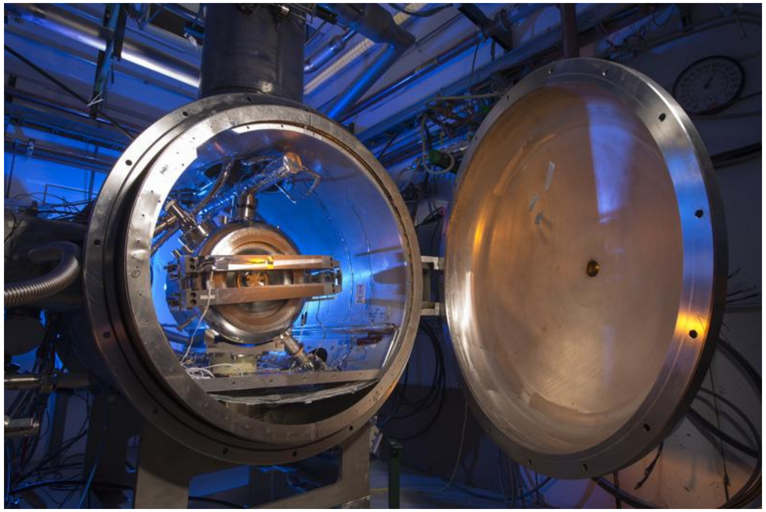




Characterization
Linear response of the BPM anticipated by simulations using CST Particle Studio, to be confirmed by stretched-wire measurements. This method will also allow the location of the electrical center of the BPM with respect to external fiducials.

Development of a Low-beta Button BPM for PXIE Project, A. Lunin et al., Proceedings of IBIC2013, Oxford, UK

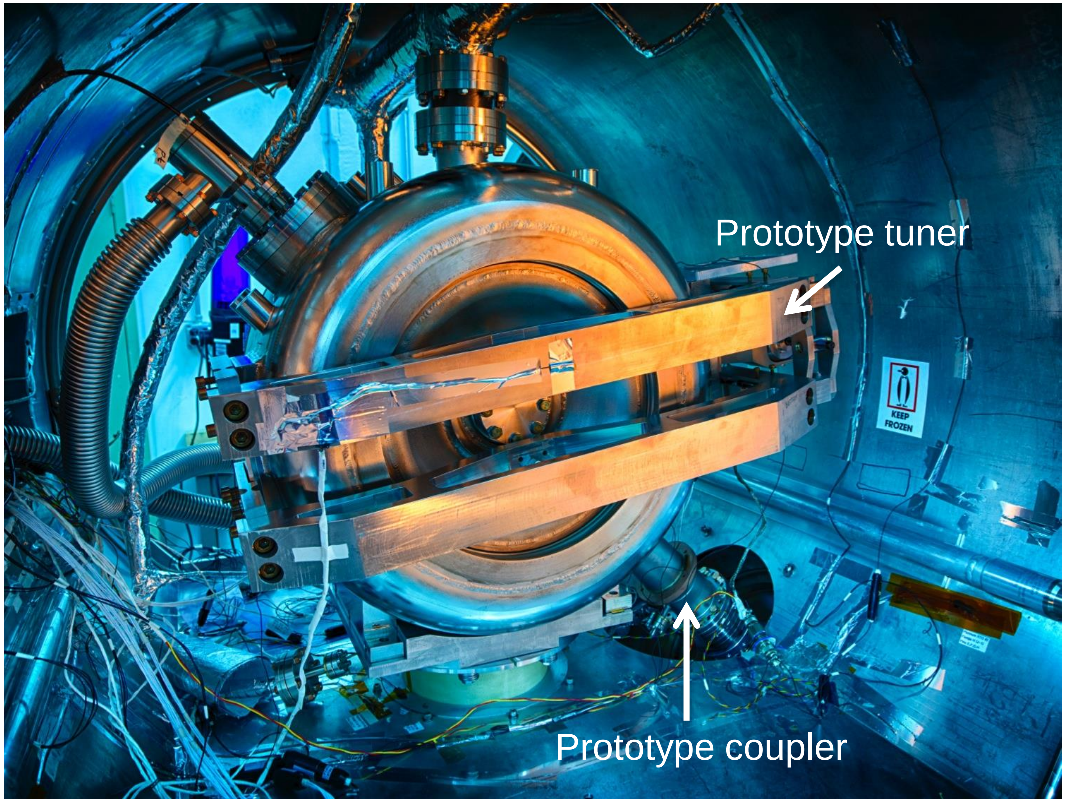
Fully Integrated Test in the Spoke Test Cryostat



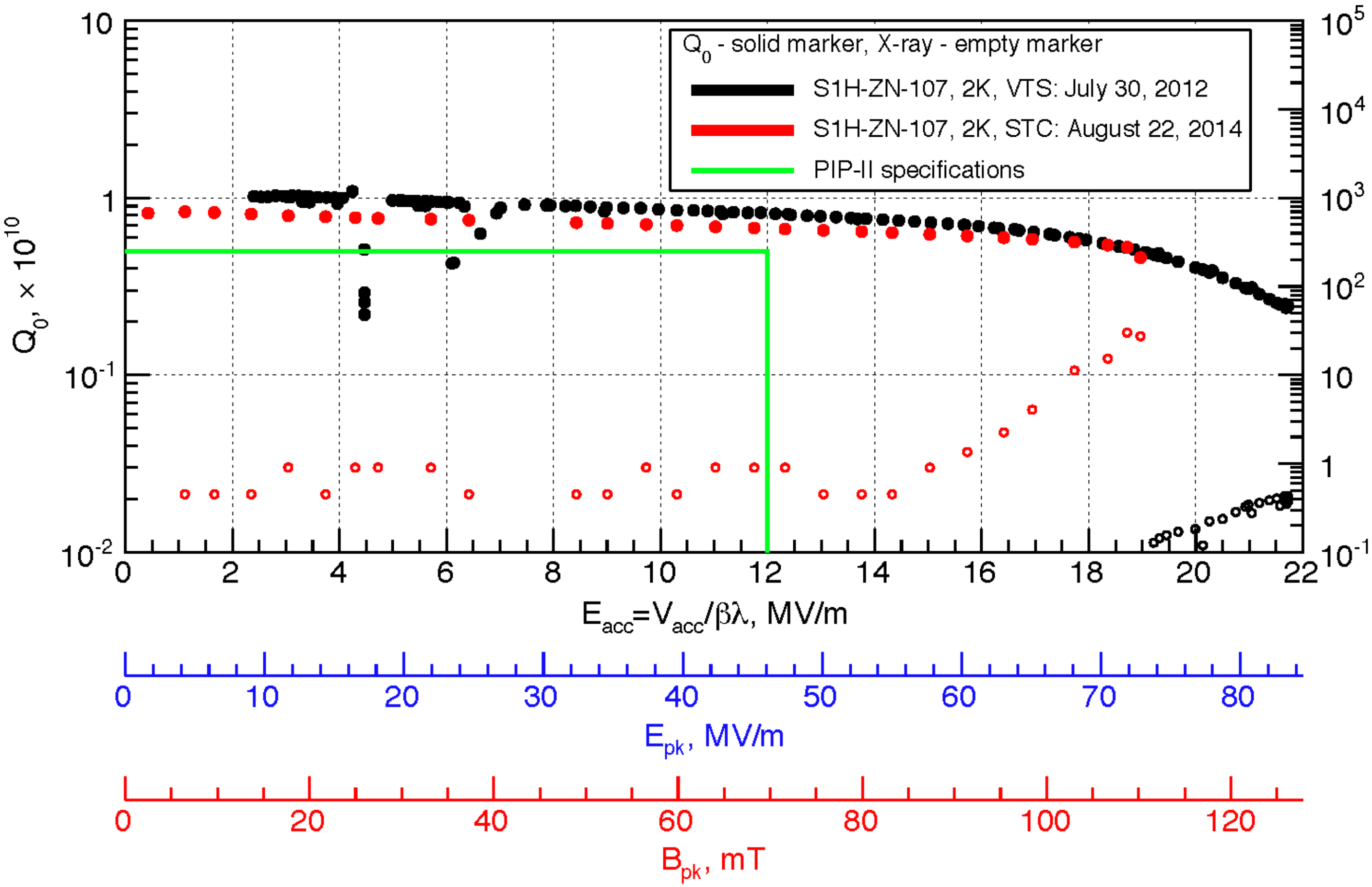
The jacketed SSR1 cavity (S1H-NR-107) dressed with prototype coupler and tuner was tested in the Spoke Test Cryostat at 2K. The performance of the power coupler and the frequency-tuning system were tested making sure they didn't interfere or degrade the performance of the cavity.

Results:

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

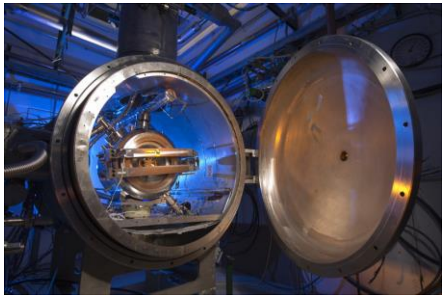


Testing at STC: Q_0 vs. E_{acc} curve (S1H-NR-107)



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

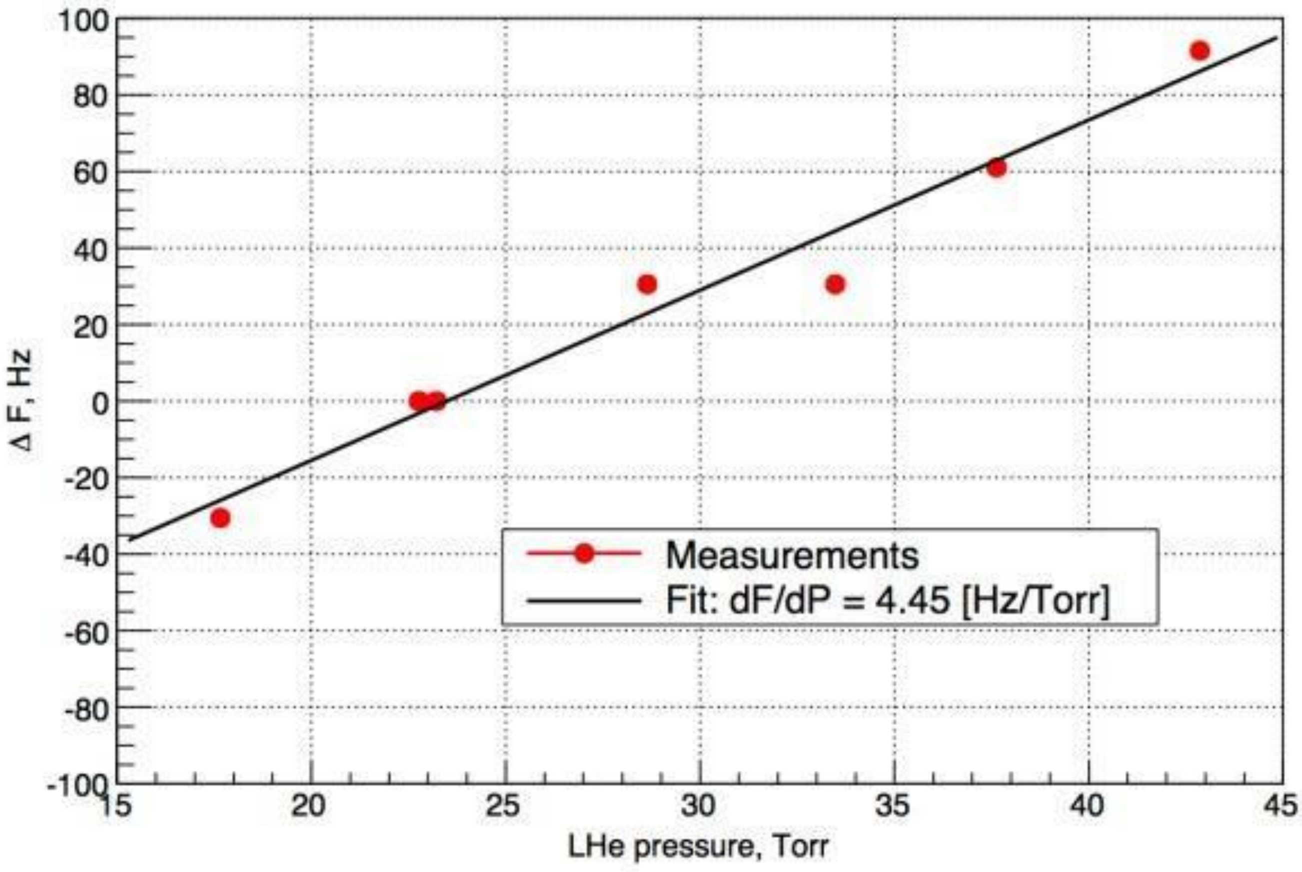
PIP-II specification: Q_0 > 5 E9 at E_{acc} = 12MV/m



[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)

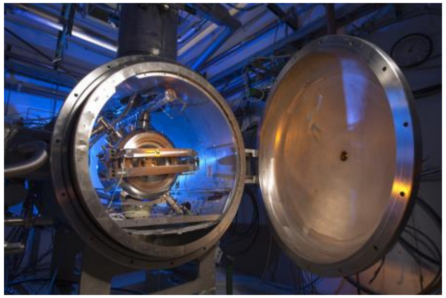
Pressure sensitivity measured with Tuner engaged (as in operating condition)



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

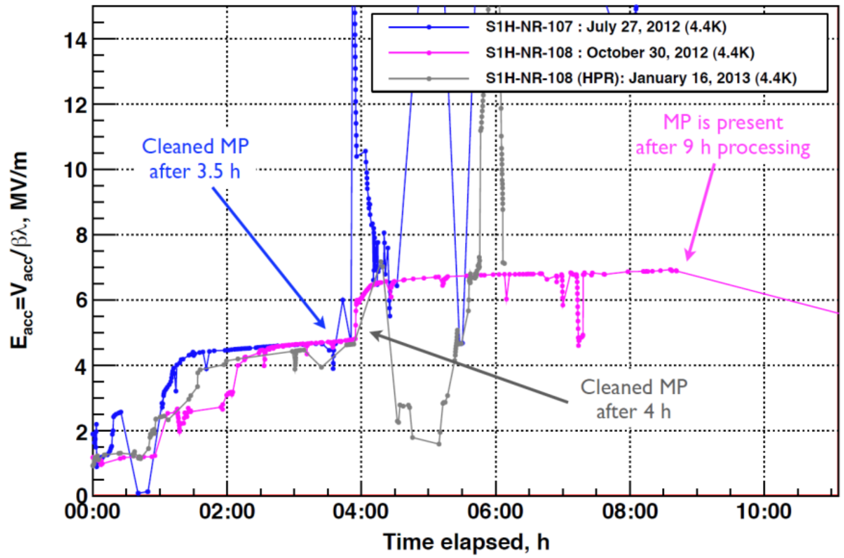
Design procedure to minimize the pressure sensitivity of the jacketed cavity with tuner is validated.

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

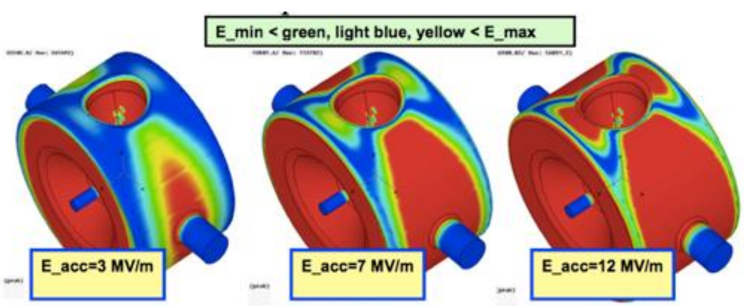


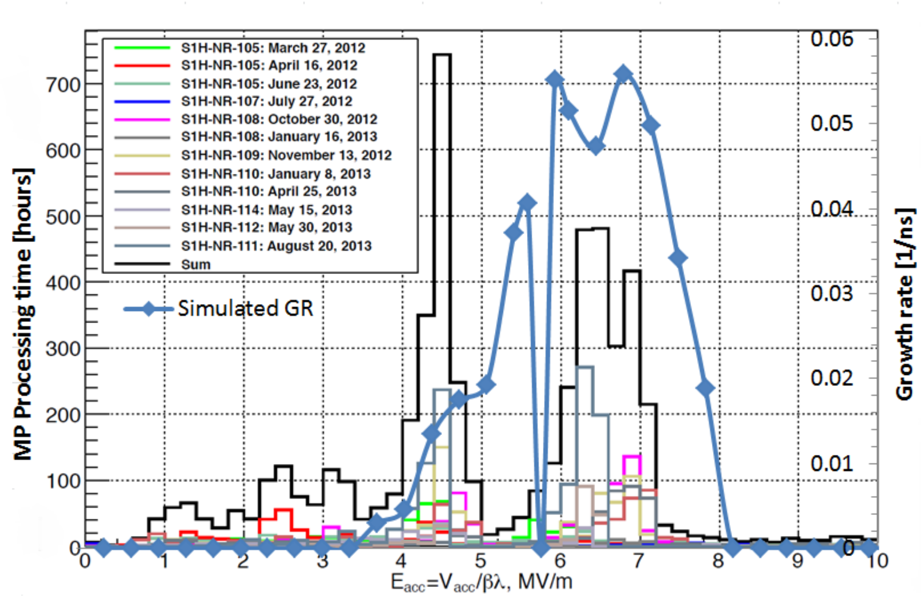
[RF Tests of Dressed 325 MHz Single-Spoke Resonators at 2K](), A. Hocker et al., Proceedings of LINAC2014, Geneva, Switzerland

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.





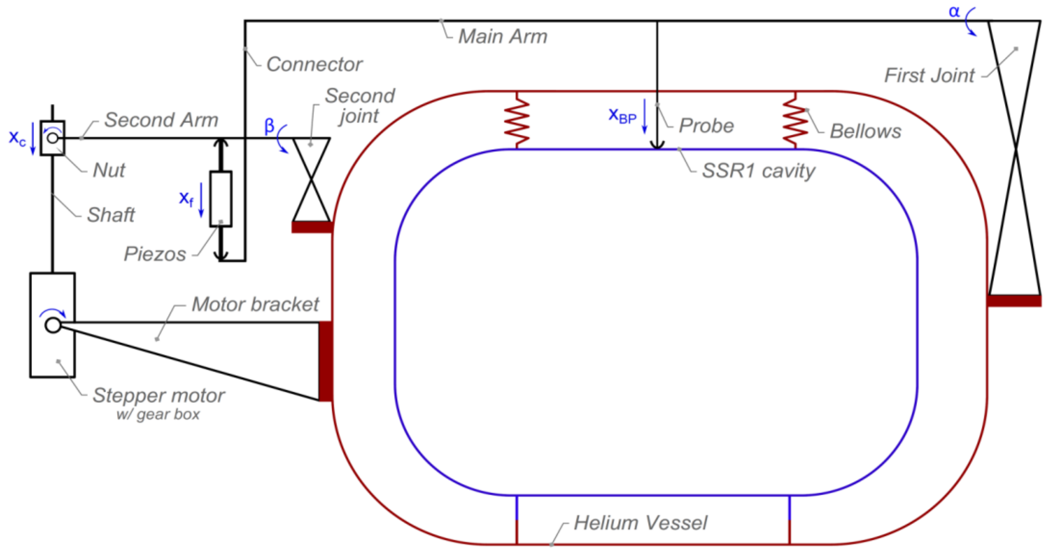
Simulation of Multipacting in SC Low Beta Cavities at FNAL, G. Romanov et al., Proceedings of IPAC 2014, Richmond, VA, USA
Multipacting Simulations of SSR2 Cavity at FNAL, P. Berrutti et al., Proceedings of NA-PAC 2013, Pasadena, CA, USA

SSR1 Tuner

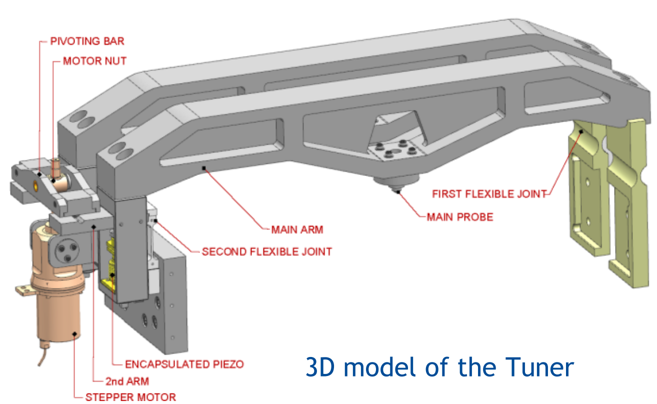
Specification
- Fine tuning >1 kHz
- Coarse tuning > 135 kHz
- Made of SS316L

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:

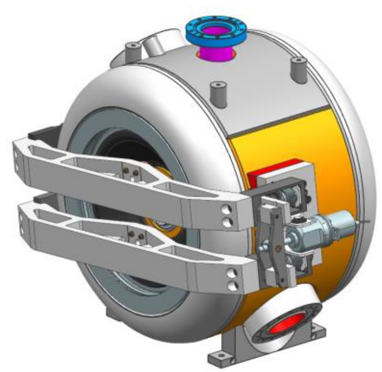
Parameter	**Value**
Stepper motor with gear box	
Max force	1300 N
Resolution	0.1 μm
Piezo	
Stroke (x_f) at 293 K	68 μm
Stroke (x_f) at 20 K	15 μm
Max operating force	2700 N
Min operating force	840 N



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*

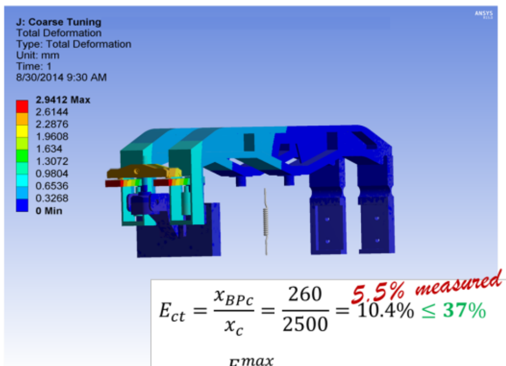
Fine tuning *2.5 kHz measured*
$\Delta f_f \geq 1\,kHz \rightarrow x_{BPf} \geq 1.85\mu m$

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

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

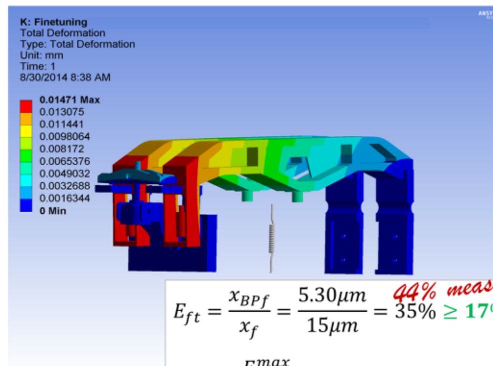
Passively minimize the ***pressure sensitivity*** *of the cavity*

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



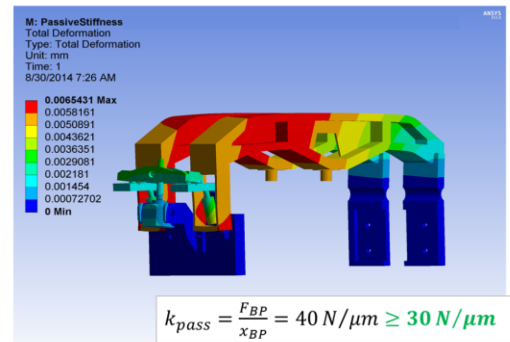
$$E_{ct} = \frac{x_{BPc}}{x_c} = \frac{260}{2500} = 10.4\% \leq 37\%$$ *5.5% measured*

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



$$E_{ft} = \frac{x_{BPf}}{x_f} = \frac{5.30\mu m}{15\mu m} = 35\% \geq 17\%$$ *44% measured*

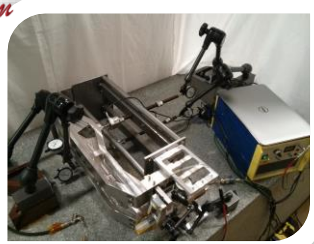
$$x_{BPf} = \frac{F_p^{max}}{k_f} = 5.30\mu m \geq 1.85\mu m$$



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

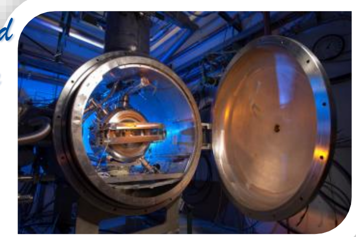
$$\frac{df}{dp} = \frac{F_{BP}}{x_{BP}} = +4\,Hz/Torr \leq 25\,Hz/Torr$$ *+4.5 Hz/Torr measured*

Tests at Room Temperature



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

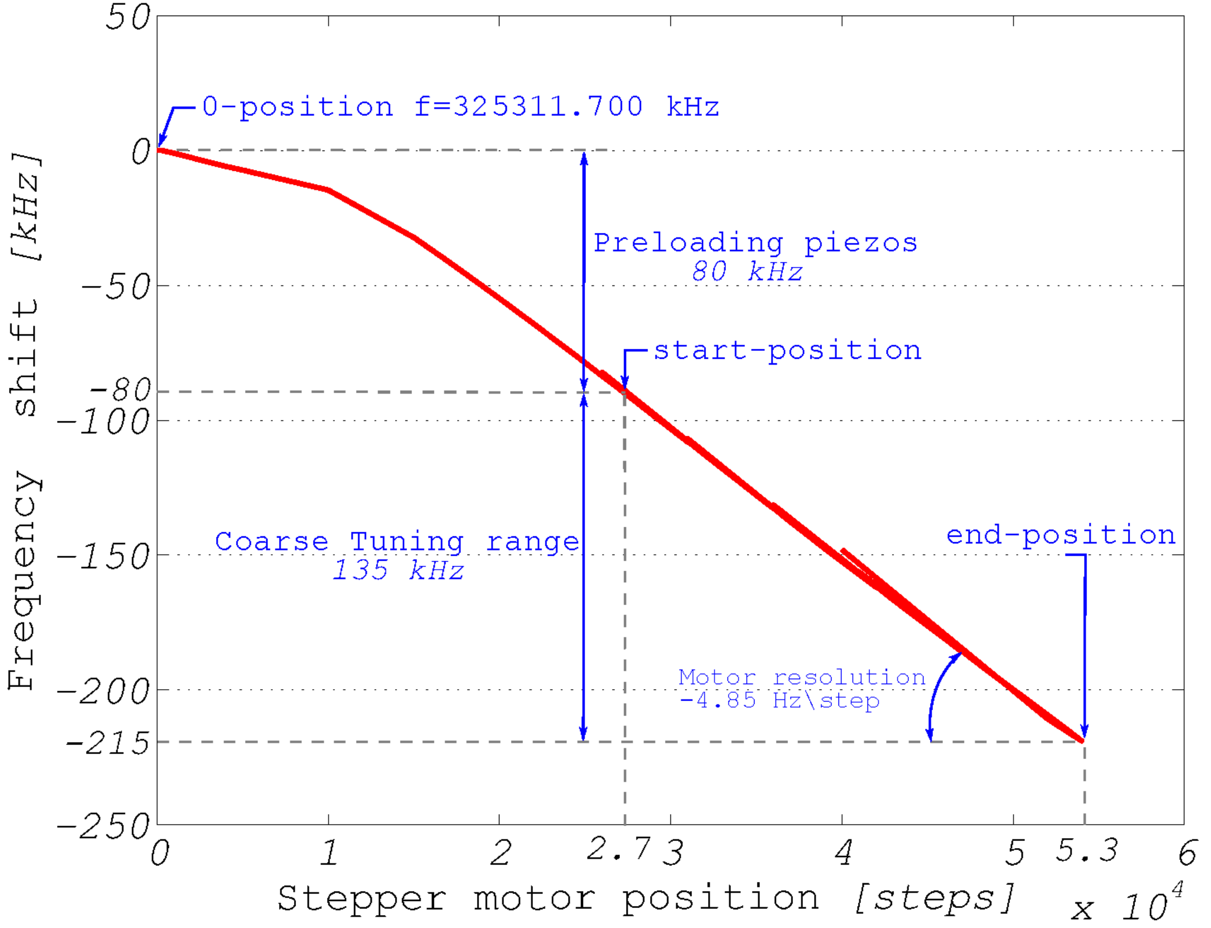
Tests at Cold Temperature

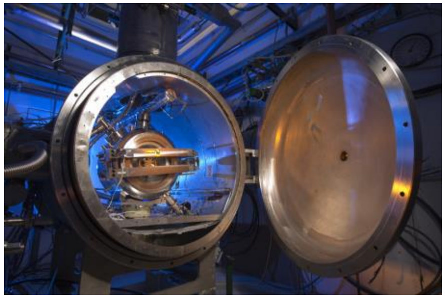


Installation of SSR1 cavity (S1H-NR-107) with tuner and coupler into the Spoke cavity Test Cryostat (STC) at Fermilab.

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

Fermilab
PIP-II

Conclusions

- All the components of the “string assembly” were ordered and many of them are at Fermilab
- The design of main components was validated by testing the prototypes (Jacketed cavity, Coupler, Tuner, Solenoid…)
- The final design of the “Top Assembly” and “Coldmass” needs to be completed
- FY 2016 Goals:
  - Qualify all the components of the “String assembly”.
  - Install the entire “String assembly”.
  - Finalize the design of the “Coldmass” and tooling.
  - Advance the microphonics control…
  - Consolidate the Indian Collaboration (IIFC): SSR1 cavities.

Acknowledgements

The progress of these activity are possible thanks to…

- Mechanical group in TD
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- Testing activities (VTS, STC)
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- Indian Collaboration


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GOZAIMASHITA
EFCHARISTO
JUSPAXAR
BOLZÏN
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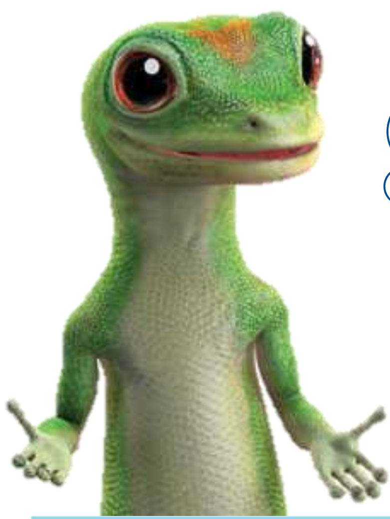


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