Development of SC Spoke Resonators at FNAL

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4th SPL Collaboration Meeting with ESS

Lund, Sweden – July 1st 2010

Project-X Evolution

- In the last year Project-X has evolved within the financial constraints of DOE to better meet the physics mission of US HEP community along 3 major lines of research:
  - Long baseline neutrino beam
  - High intensity, low energy protons for kaon and muon based precision experiments
  - A path toward a future muon facility – neutrino factory or muon collider
- Initial Configuration 1 (IC-1)
  - 8 GeV Linac in MI, ILC paramters
- Initial Configuration 2 – v1
  - 2 GeV CW Linac + 2-8 GeV RCS
- Initial Configuration 2 – v2 (IC-2v2)
  - 3 MW @ 3 GeV CW Linac

CW nature requires SCRF acceleration from very low energies (2.5 MeV)

PrX – Beam Physics "Gospel"

- The zero-current phase advances of transverse and longitudinal oscillations should be kept below 90° per focusing period to avoid instabilities at high current.
- The wavenumbers of transverse and longitudinal particle oscillations must change adiabatically along the linac. This feature minimizes the potential for mismatches and helps to assure a current-independent lattice.
- Minimize derivative of zero-current longitudinal phase advance along lattice, to reduce halo excitation.
- Avoid the n=1 parametric resonance (zero current) between the transverse and longitudinal motion.
- Avoid energy exchange between the transverse and longitudinal planes via space-charge resonances either by providing beam equi-partitioning or by avoiding instable areas in Hofmann's stability charts .
- Provide proper matching in the lattice transitions to avoid appreciable halo formation.
- The length of the focusing period must be short, especially in the front end.
- Beam matching between the cryostats: adjust parameters of outermost elements (solenoid fields, rf phase)

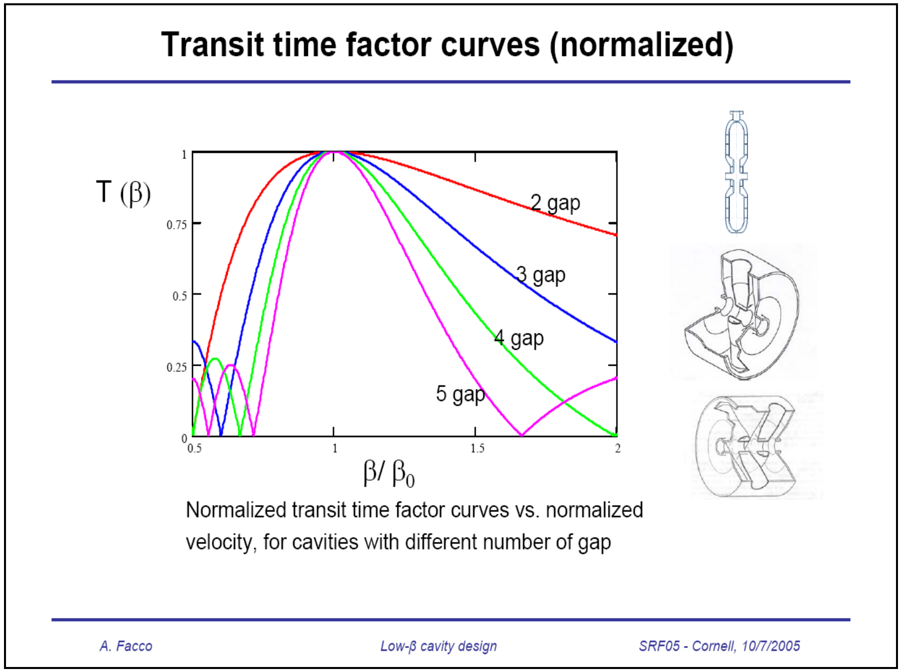
See: P. Ostroumov talk, Feb.2, 2010, FNAL

Choice of Cavities

- To be efficient at low-β
  - Low cryogenic losses
    - High (R/Q)G
  - High Gradient
    - Low E_p/E_{acc} and low B_p/E_{acc}
  - Large Velocity acceptance
    - Few accelerating gaps
  - Frequency Control
    - Low sensitivity to microphonics & low energy content

$$P_o = \frac{V_a^2}{R} = \frac{V_a^2}{\left(\frac{R}{Q}\right)Q} = \frac{V_a^2}{\left(\frac{R}{Q}\right)G}R_s = \frac{V_a^2}{\left(\frac{R}{Q}\right)G}(R_{BCS} + R_{res})$$

$$R_{BCS} = 2\text{x}10^{-4}\frac{C_{RRR}}{T_K}\left(\frac{f_{GHz}}{1.5}\right)^2 \exp\left(-\frac{17.67}{T_K}\right)$$

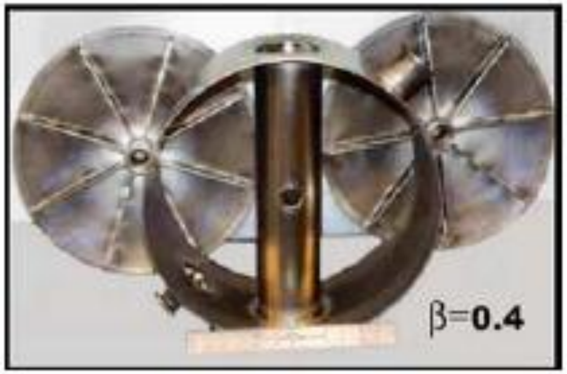


http://www.lns.cornell.edu/public/SRF2005/talks/sunday/SuA04_talk_srf2005.pdf

Spoke Resonators

- Advantages
  - No dipole Steering
  - High performance
  - Lower R_{sh} than HWRs
  - Wide β range
- Potential Problems
  - Not easy access
  - Difficult to tune
  - Larger size the HWRs
  - More expensive than HWRs
  - Quadrupole Steering

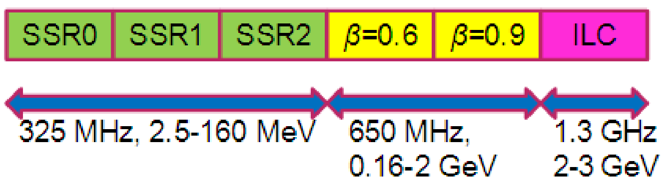
325 < f < 805MHz, 0.15 < β < 0.6



LANL β=0.2
SPOKE

PrX - Initial Configuration 2

- For historical reasons(2005 Proton Driver) SSR(1) was the first SC low-β cavity developed at FNAL within the context of a pulsed 8 GeV Linac with SC cavities from 10 MeV.
- CM segmentation, number of cavities/CM and the gap between CMs



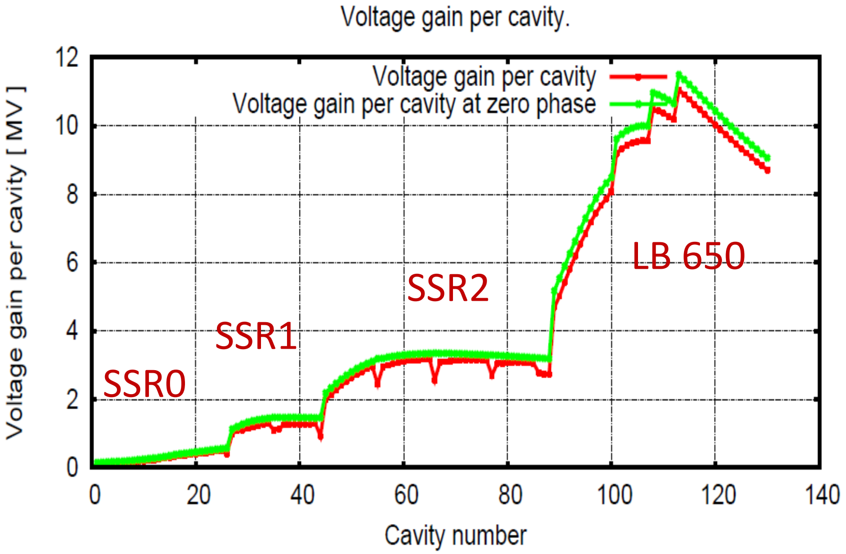
– 88 SSRs (325 MHz)
– 138 Ellipt. (650 MHz)
– 64 Ellipt. (1.3 GHz)

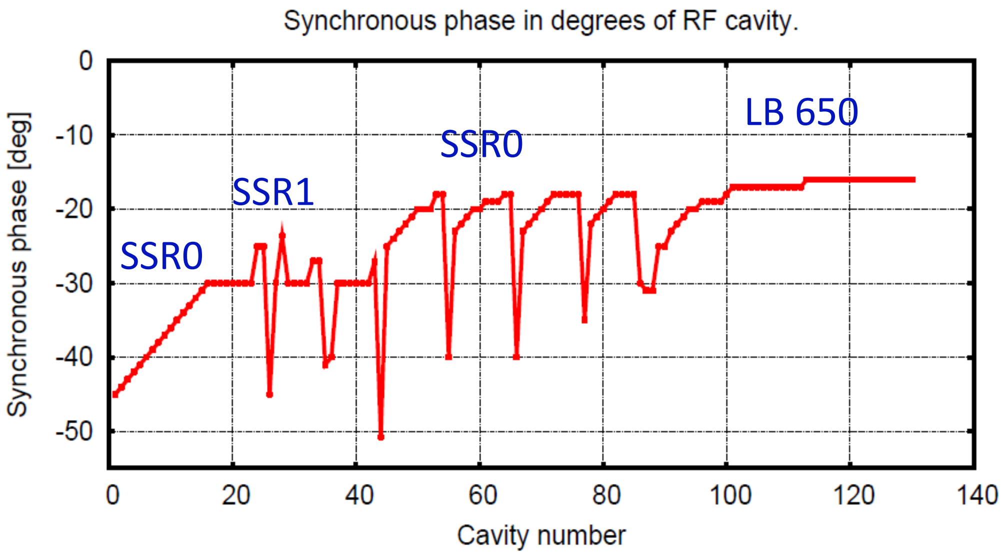
Section	Energy range MeV	β	Number of cavities*	Type of cavities	Maximal power per cavity**, kW
SSR0 (β_G=0.11)	2.5-10	0.073-0.146	26	Single spoke cavity.	0.5
SSR1 (β_G=0.22)	10-32	0.146-0.261	18	Single spoke cavity.	1.5
SSR2 (β_G=0.4)	32-160	0.261-0.52	44	Single spoke cavity.	3.2
650 MHz (β_G=0.6)	160-500	0.52-0.758	42	Elliptic cavity	11.5
650 MHz (β_G=0.9)	500-2000	0.758-0.95	96	Elliptic cavity	18.5
1300 MHz (β_G=1)	2000-3000	0.95-0.97	64	Elliptic cavity	16

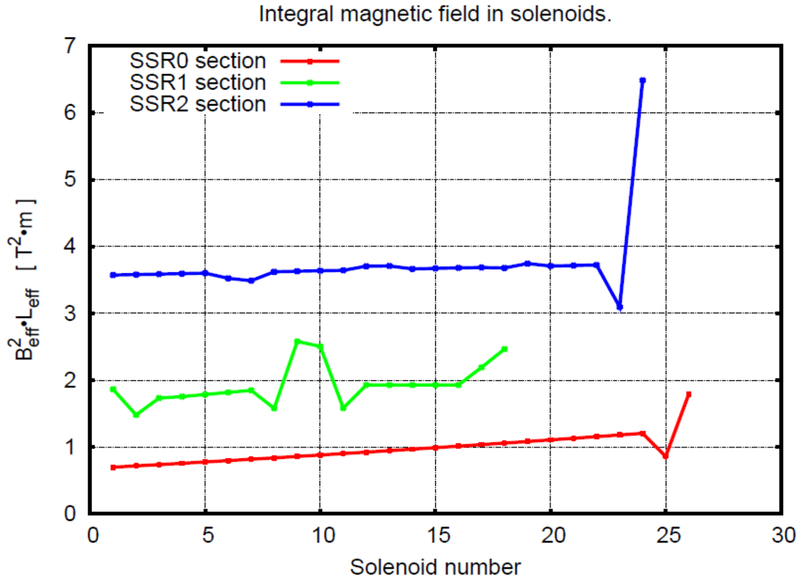
(Initial) Performance Goals

Freq (MHz)	B_{pk}(mT)	G (MV/m)	Q	@T (K)
325	60	15	1.4E10	2
650	72	16	1.7E10	2
1300	72	15	1.5E10	2

PrX – Initial Beam Elements Specs





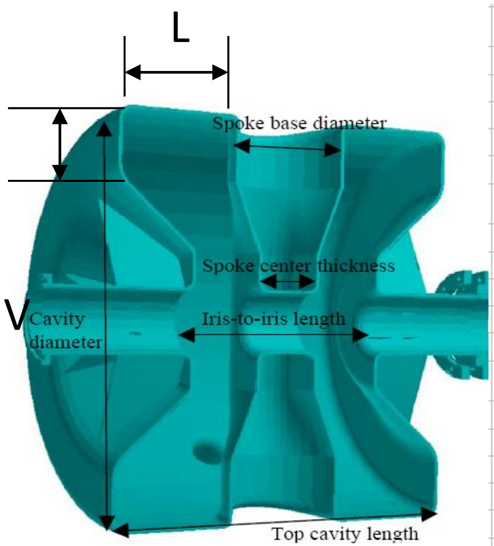


Spoke Resonator Challenges

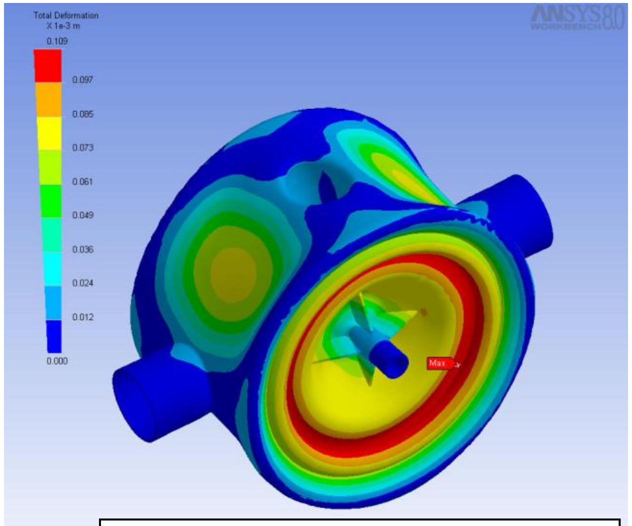
- Design Optimization (SSR1)
- Construction
  - (Feasibility of) Assembly
  - Engineering Safety
- Operations
  - Gradient and Q_0 performance
  - Tunability
    - Lorentz Force Detuning (Pulsed) and Microphonics (CW)
  - High Power Operations
- Cryomodule Integration and Test Facility
  - (Beamline) Integration
    - Focusing Elements
    - Instrumentation
  - Cryomodule Assembly & Commissioning
  - Meson Detector Building Test Facility

SSR1 Design Optimization

- RF Design optimization
- Mechanical analysis and optimization



	R/Q			
V \ L	50	60	70	80
30	234.19	236.89	238.16	239.8
55	240.67	243.76	246.19	249.14
80	248.41	251.77	256.2	259.61
105	257.27	262.66	267.63	272.24
	Epeak/Eacc			
	50	60	70	80
30	2.86	2.83	2.73	2.69
55	2.83	2.74	2.72	2.66
80	2.84	2.69	2.64	2.62
105	2.69	2.64	2.61	2.55
	Q			
	50	60	70	80
30	1.41E+09	1.44E+09	1.39E+09	1.45E+09
55	1.44E+09	1.50E+09	1.55E+09	1.51E+09
80	1.49E+09	1.53E+09	1.60E+09	1.65E+09
105	1.52E+09	1.58E+09	1.65E+09	1.71E+09
	Bpeak/Eacc			
	50	60	70	80
30	7.06	6.30	5.83	5.35
55	6.86	6.22	5.71	5.23
80	6.65	6.02	5.52	5.08
105	6.50	5.88	5.36	4.87

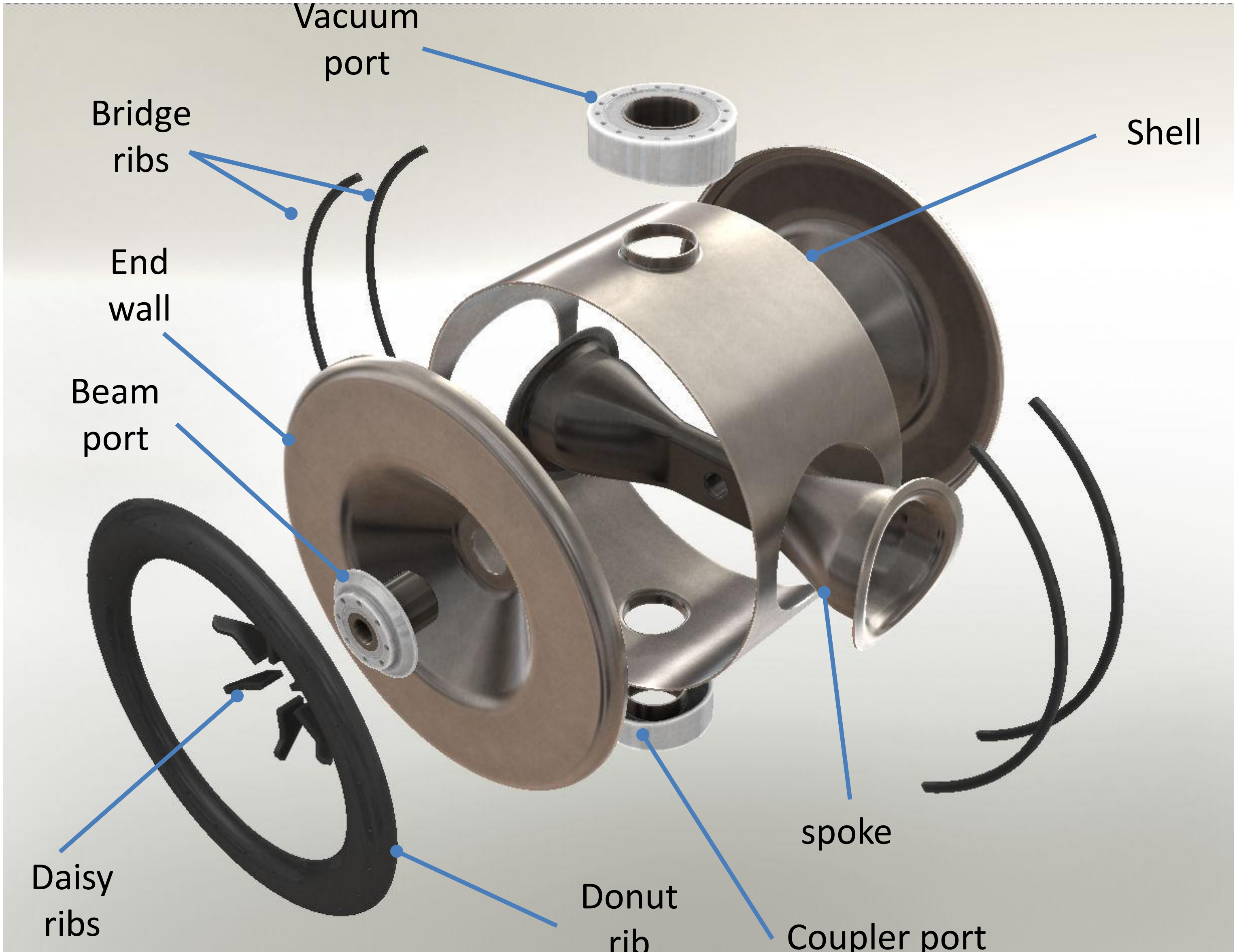


Total Deformation at 2 atm.

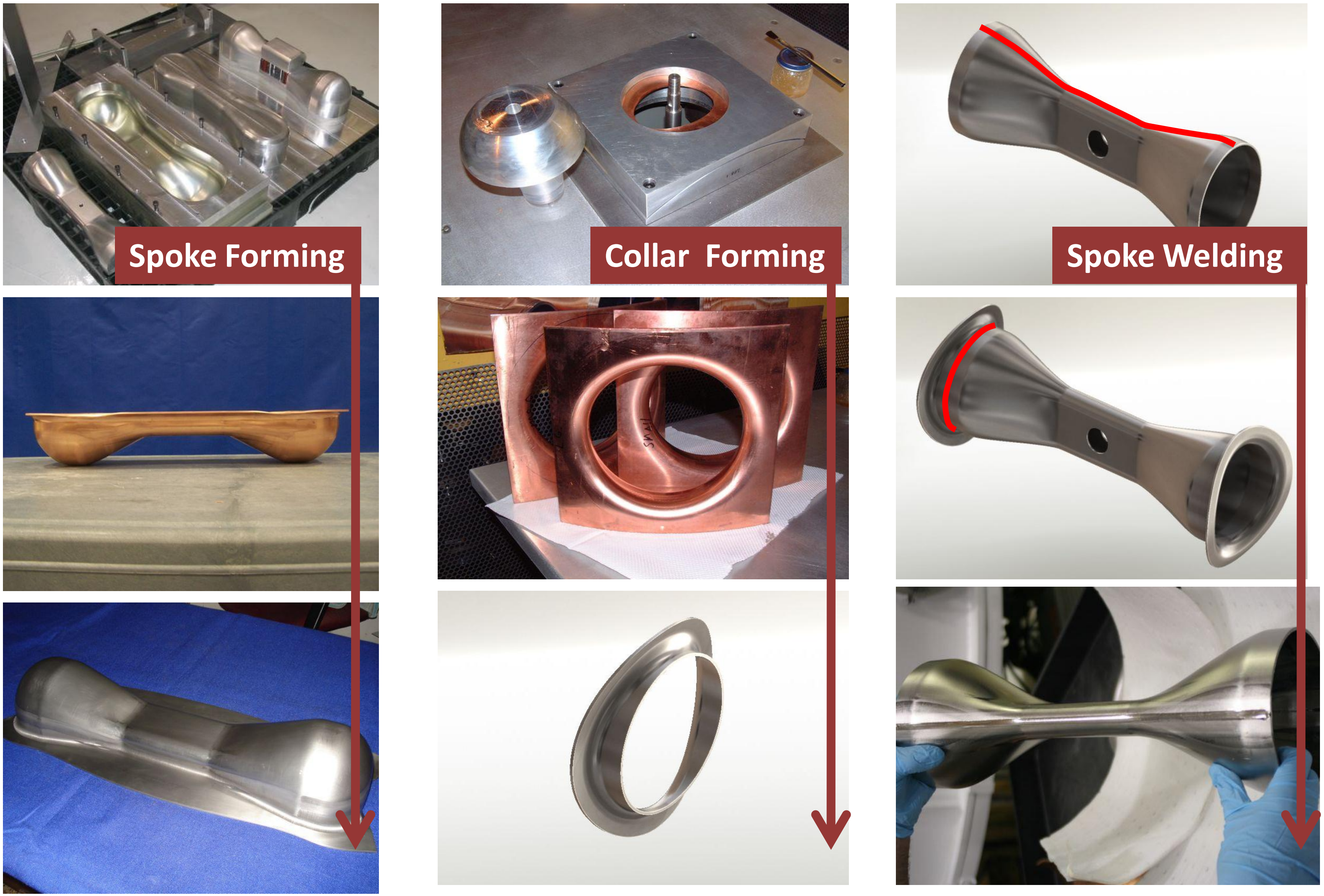
Reinforcement Type	Total Deformation	Von Mises [MPa]
none	329	352.8
flat	283	256.0
tubular	266	254.4
Flat + gussets	137	65.08
Tubular + gussets	109	65.85

- Built 2 prototypes + 2 additional from IUAC (India).

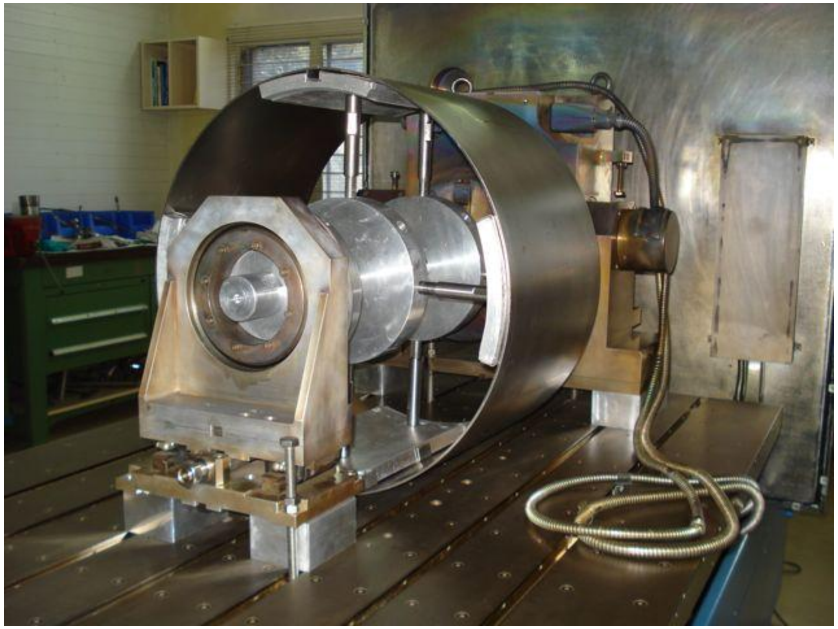
Assembly Model

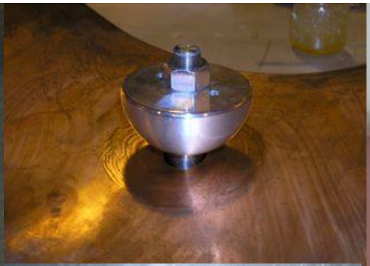


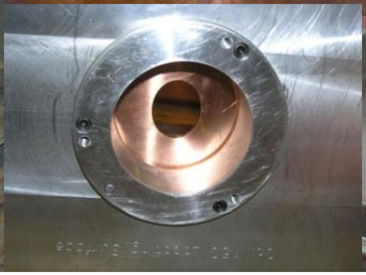
Spoke Assembly



Shell Assembly





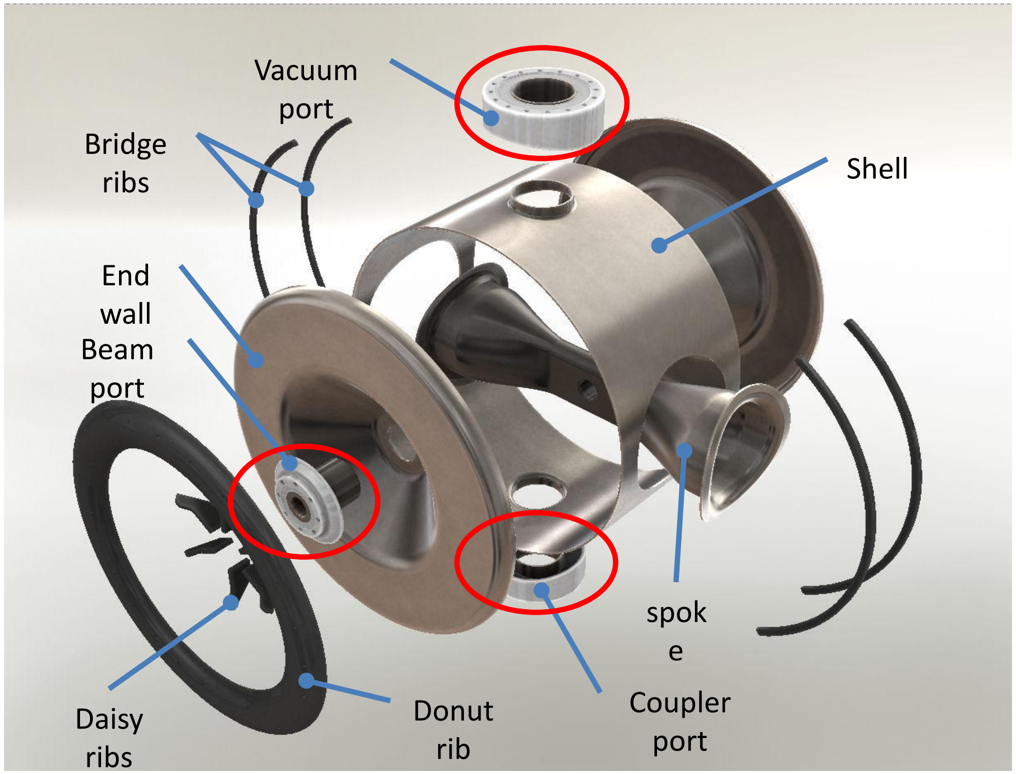


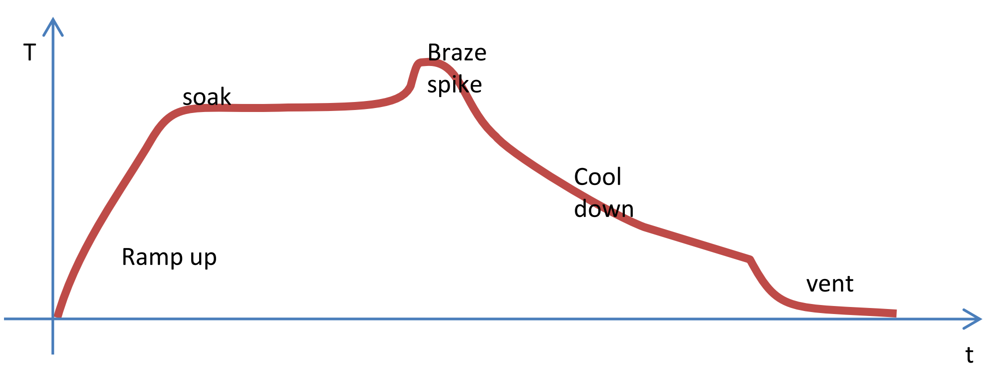
End-walls Forming

“Stiffening” Ribs

Caveat: Ribs designed for Pulsed Operation Stiffening

Brazed Ports for He Vessel





- Brazing Process
  - Initially developed at CERN (1987) later modified at ANL (2003)
  - Filler metal: CDA-101 high purity copper wire
  - SST flanges pre-machined, stress relieved at 1100 C and finished
  - Yield limit 6700 lbs
  - Allows assembly of SS He-Vessel

Project X

Cavity Tuning

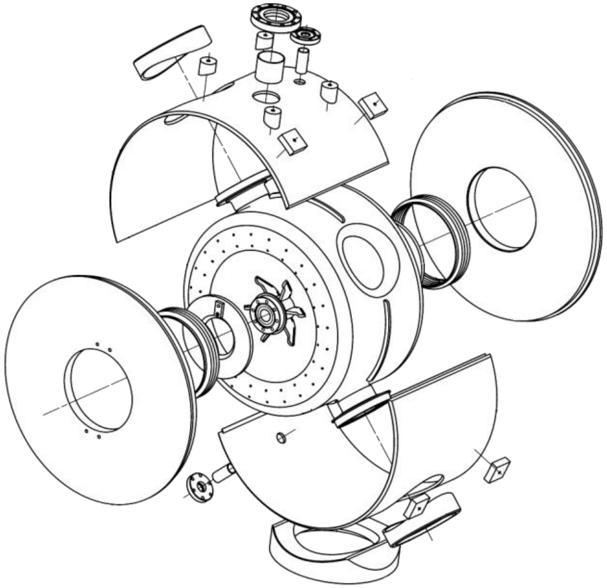
SSR cavity tuning fixture with cavity SSR1-01.

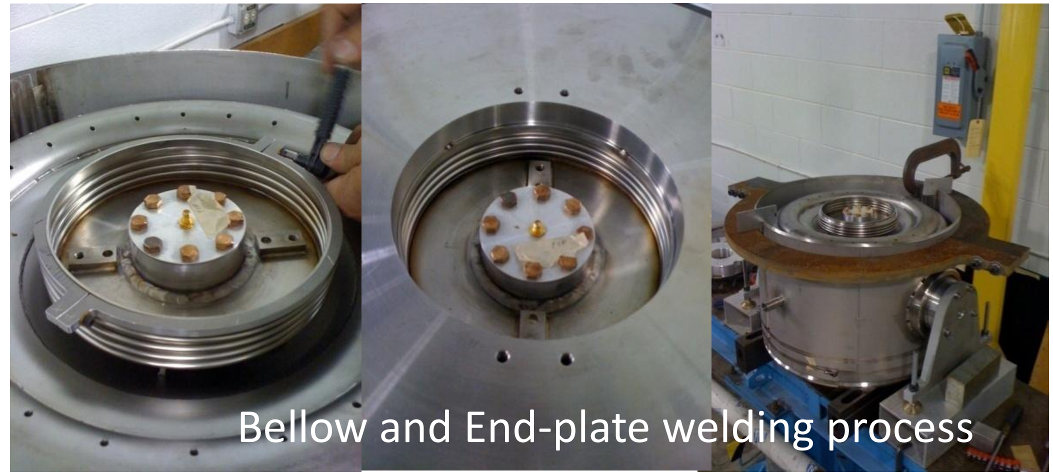
4 Position Sensors and 2 Dynamometers. Cavity can be hold on coupler and vacuum port flanges or by 2 rings on equator near C-shape stiffening rings.

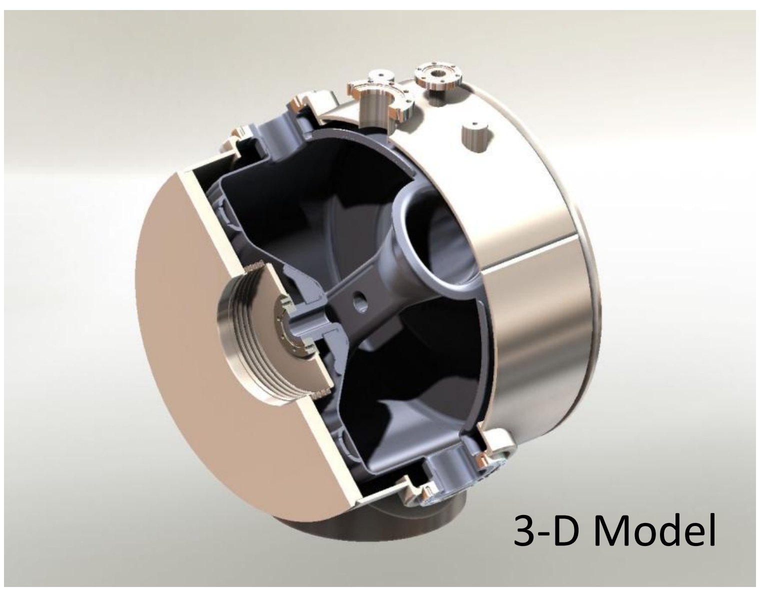
MHz/mm	lb/mm	N/mm
566	4507	20053

At a glance	
Weight	~ 40 kg
Length	342 mm
Height	615 mm
Nb thickness	2.8 - 3.2 mm
RRR Nb	~ 18 ft^2
RG Nb	~ 5 ft^2
Transitions	Cu Braze
MAWP	34 psi
Spring K	~ 20 N/µm

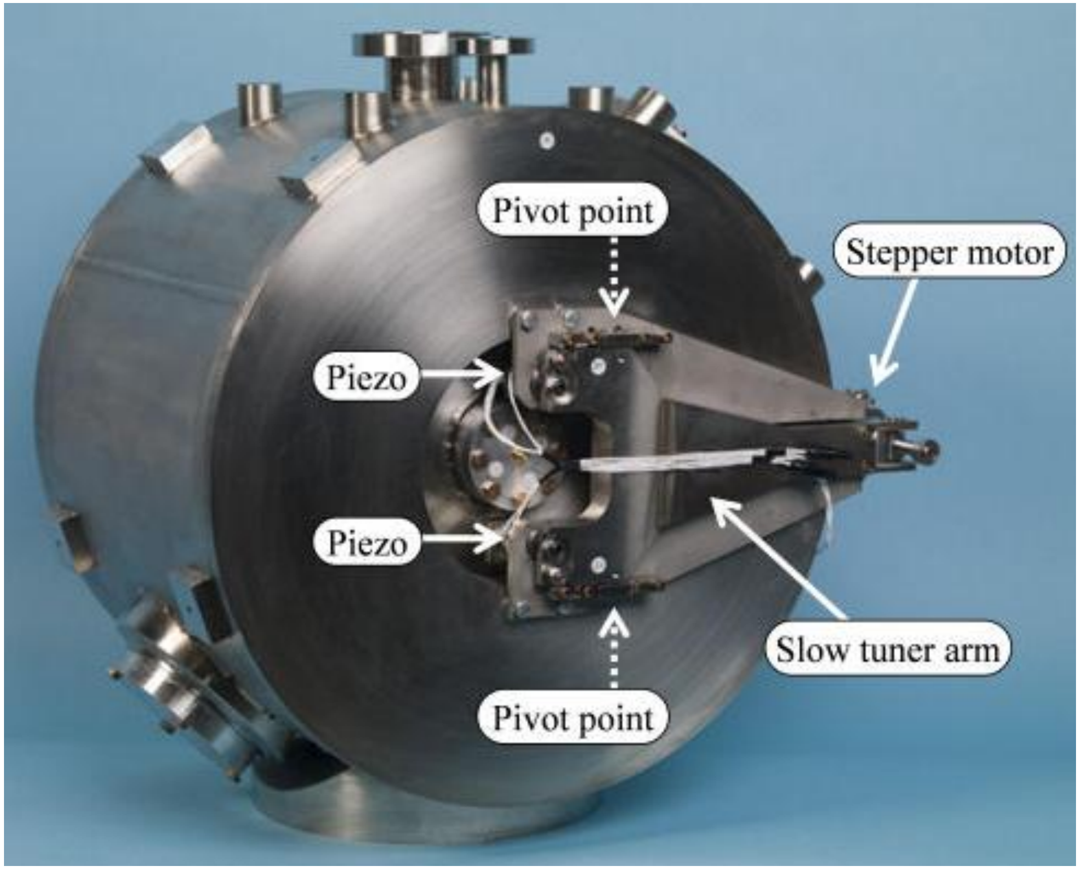
Helium Vessel Assembly

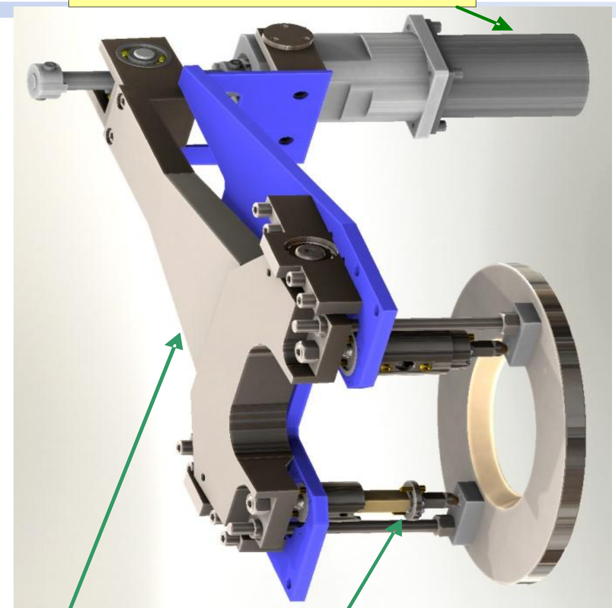


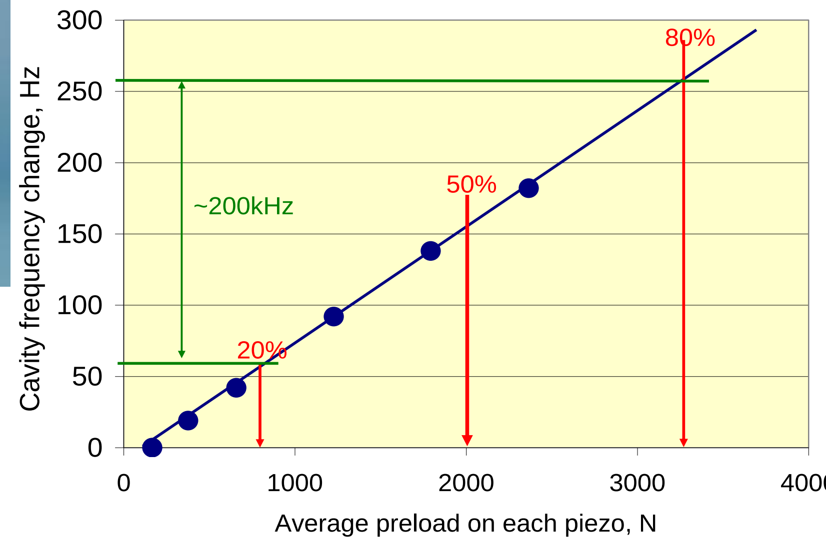




SSR Tuner


Pivot point
Stepper motor
Piezo
Piezo
Slow tuner arm
Pivot point


Stepper Motor & Harmonics Drive
Slow Tuner Arm
“Safety Rod” attached cavity flange to slow tuner arm


Cavity frequency change, Hz
300
250
200
150
100
50
0
0
1000
2000
3000
4000
Average preload on each piezo, N
80%
50%
20%
~200kHz

Engineering Note & Safety

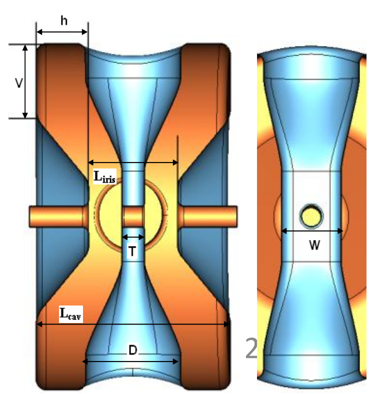
- "ASME Boiler and Pressure Vessel" code (US) introduced in 1905 to address exploding boilers (before then, individual state regulations).
  - Δp > 15 psi (~1 atm.) & Dimension > 6 in (15 cm)
- EU has "Pressure Equipment Directive" (PED) since ~2005, individual countries regulations before then
  - Δp > 0.5 atm & Volume > 1 L
- SCRF assemblies cannot meet fully the requirements of the US-ASME code (ex: Nb is not a code-allowed material)
- (Possible) strategies:
  - Director's "magic wand" for exceptional vessel approval
  - SNS/JLAB approach: coded cryomodule vacuum vessels as pressure containment
  - Develop standards such that necessary deviation from code (Nb) are handled by special procedures (measuring the mechanical properties of samples of the niobium from the lot of material from which the cavities are made)

Engineering Analysis

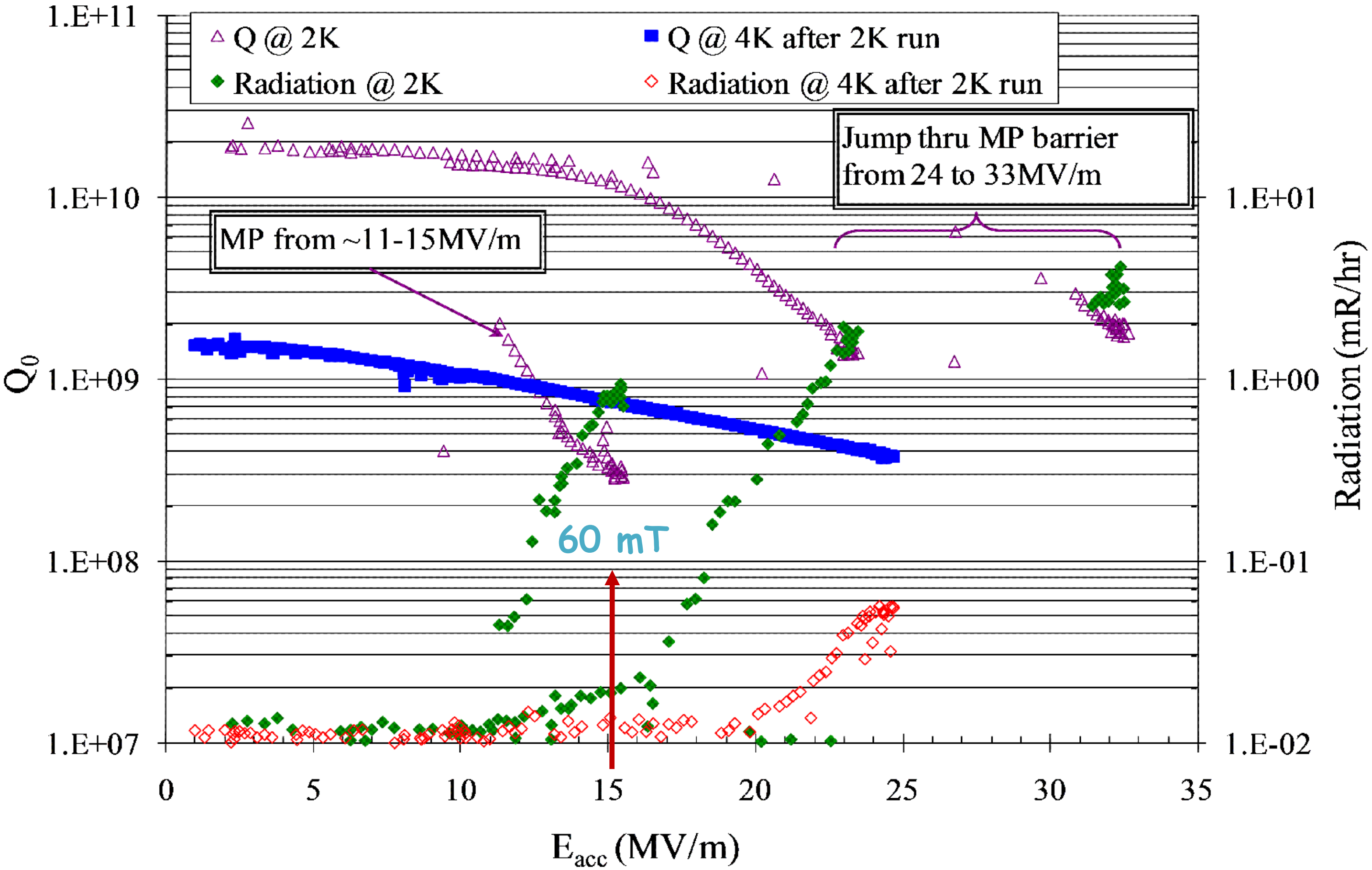
- Present Strategy:
  - Minimize number of “exceptions” to code
    - Use of Nb (not explicitely allowed by the code)
    - No ultrasonic examination of EB welding along entire length
    - Lack of WPS (Weld Procedure Specs) PQR (Procedure Qualification Records) and WPQ (Welder Performance Qualification) for Nb and SS assemblies
    - Nb-SS brazing did not have a Brazing Procedure Specification
  - Demonstrate safety by engineering analysis and pressure testing

Spokes Cavity Vertical Test

- SSR1-1
  - Four VTS tests between March 2008 and March 2009
  - Vacuum problems in first two tests
  - Active pumping added to VTS before 4^{th} test
  - 4^{th} test included cool-down dwell at 100° K in attempt to induce Q-disease
  - Will next be tested in new test cryostat in coming months
- SSR1-2
  - One VTS test in 2009
  - Reached gradient – 33MV/m
  - E_{acc}=Acc. Voltage/L_{iris}
    =Acc. Voltage/2/3 $\beta\lambda$

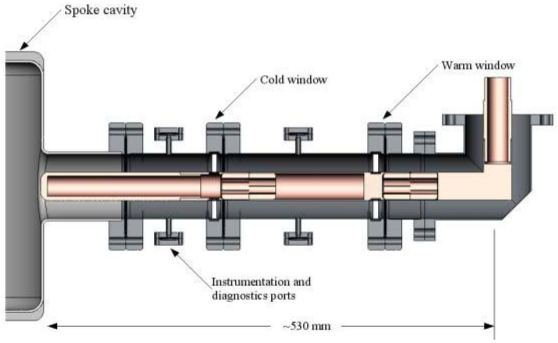


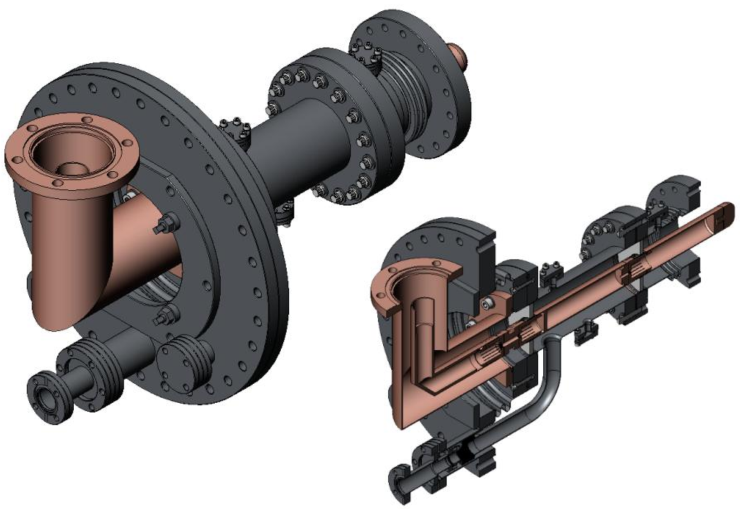
SSR1-2 First VTS Test

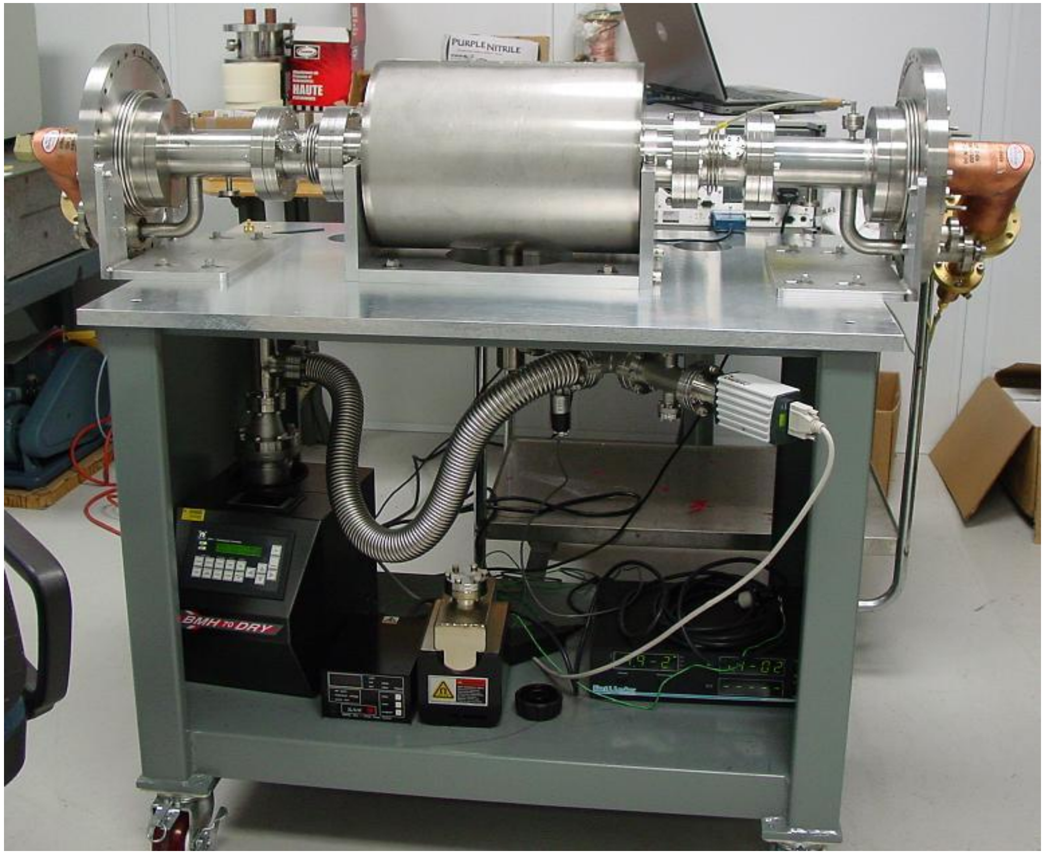


Project X

PC High Power Test Fixture







- Three Fermilab-designed couplers produced and in house
- Average power of 4.2 kW (2 Hz, 3 ms, 700 kW) was sustained for 2 hours, and an additional 3 hour test at 3.3 kW (2 Hz, 3 ms, 550 kW) was performed.

High Power Test

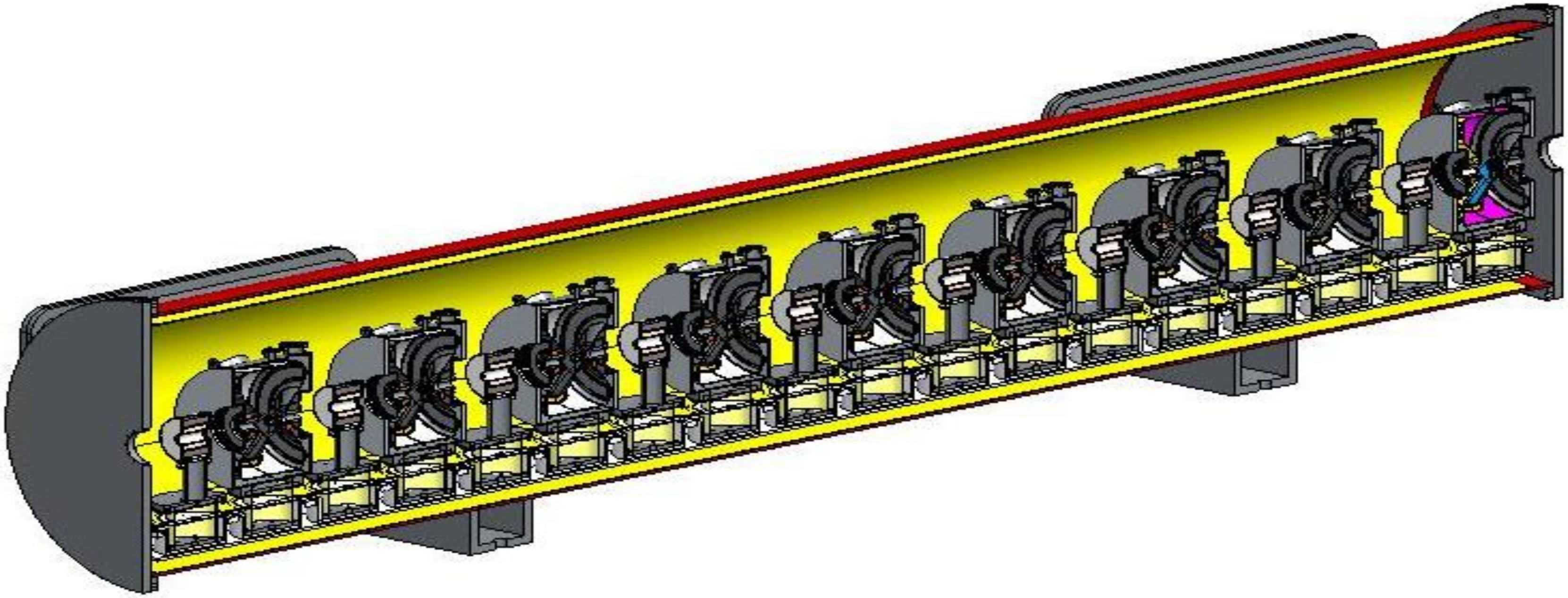
- Horizontal Test Cryostat for High Power (~250 kW) SSR testing

Spoke Resonator Challenges

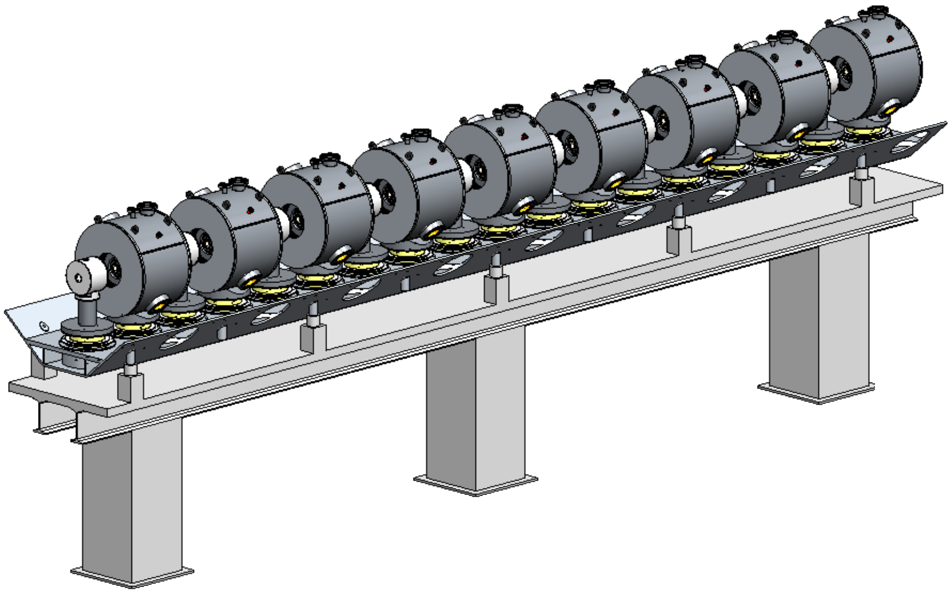
- ✓ Design Optimization (SSR1)
- ✓ Construction
  - √ (Feasibility of) Assembly
  - √ Engineering Safety
- ✓ Operations
  - √ Gradient and Q_0 performance
  - √ Tunability
    - Lorentz Force Detuning (Pulsed) and Microphonics (CW)
  - ~ High Power Operations
- Cryomodule Integration and Test Facility
  - (Beamline) Integration
    - Focusing Elements
    - Instrumentation
  - Cryomodule Assembly & Commissioning
  - Meson Detector Building Test Facility

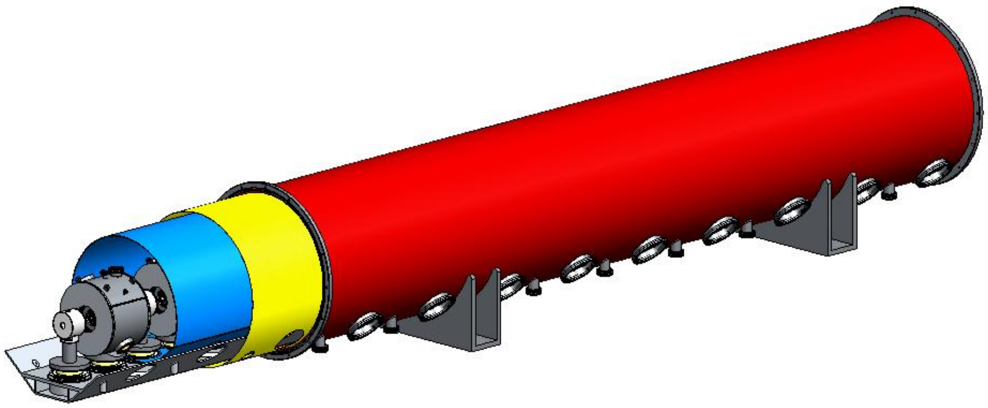
SSR1 Cryomodule Model

- Present concept of SSR1 Cryomodules
  - Contain 9 SSR1 cavities and 9 solenoids
  - Project X expects that these designs could be extended to SSR0 and SSR2 requirements



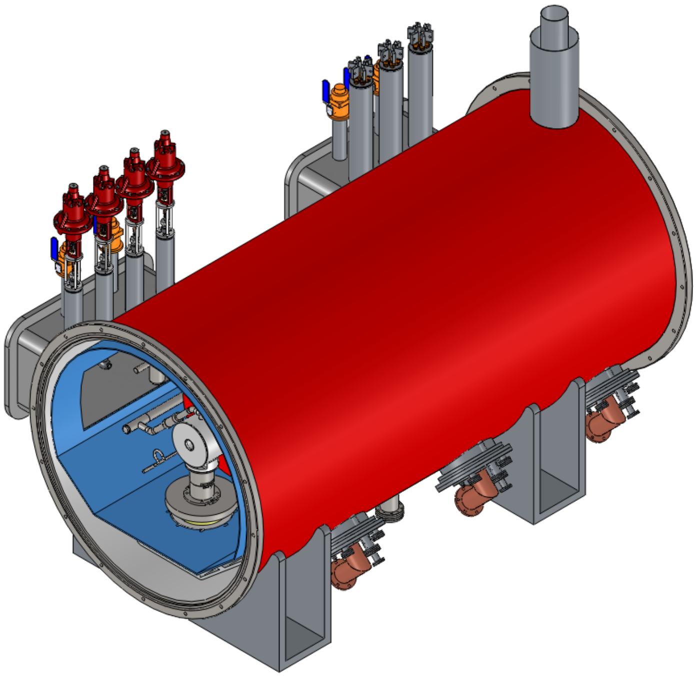
Cryomodule Assembly

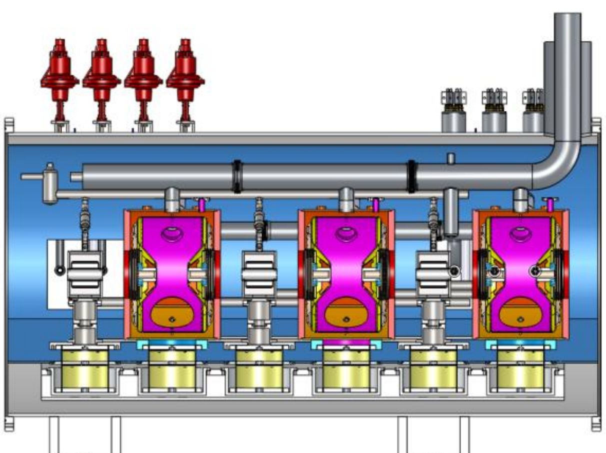


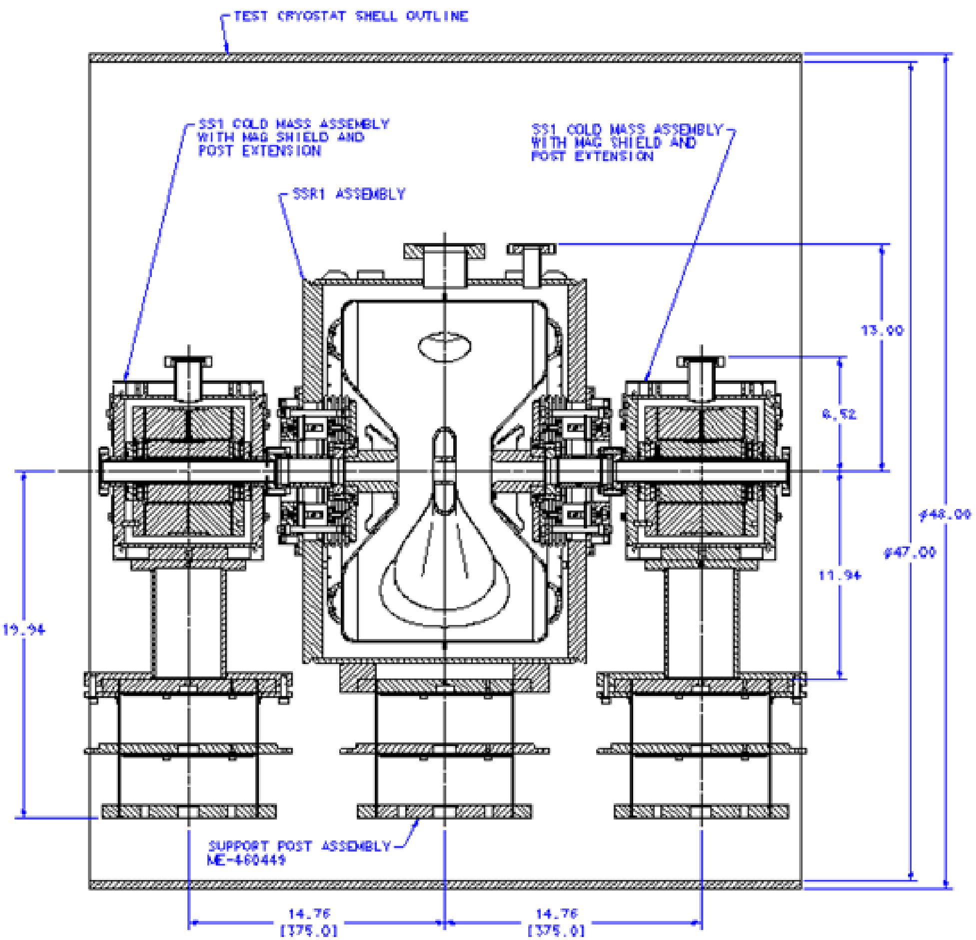


- Assembly performed using the same or similar tooling to that used for 1.3 GHz (XFEL/ILC) final assembly
- Also studying the advantages/disadvantages of “bath-tub” assembly

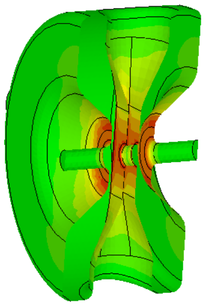
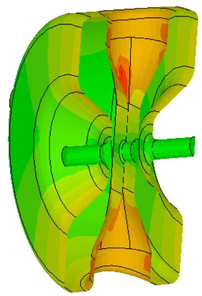
3-Cavity Cryomodule Concept



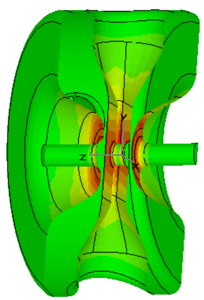
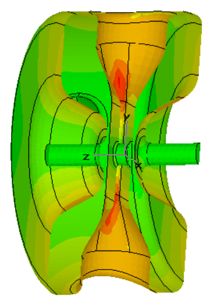




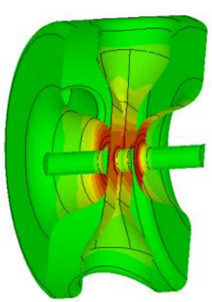
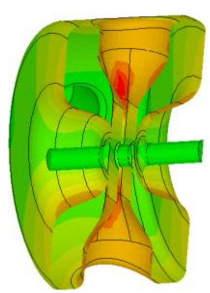
SSR0 RF Design Optimization

blue

red

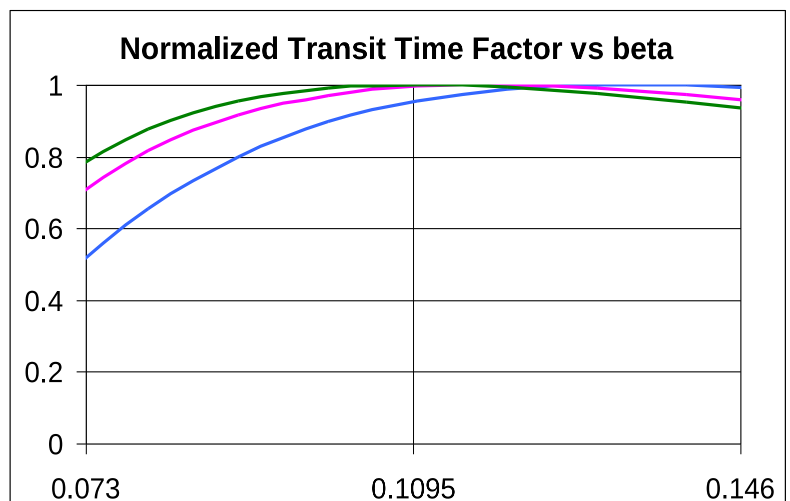



green

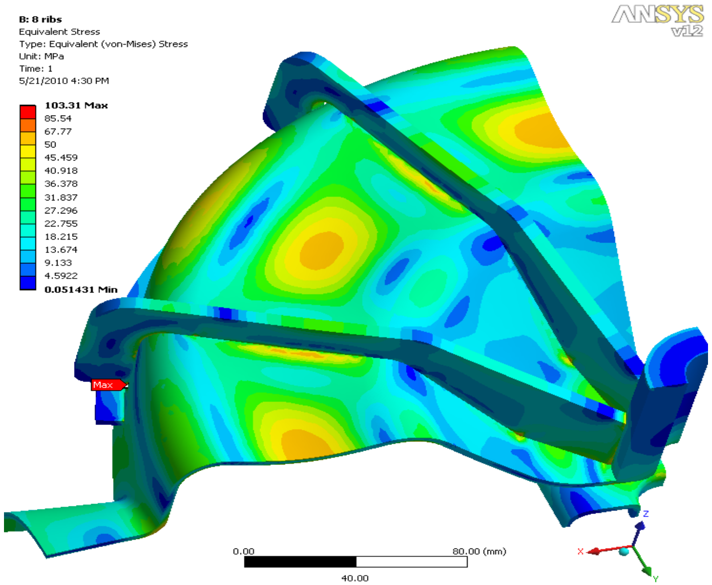
E Field B Field

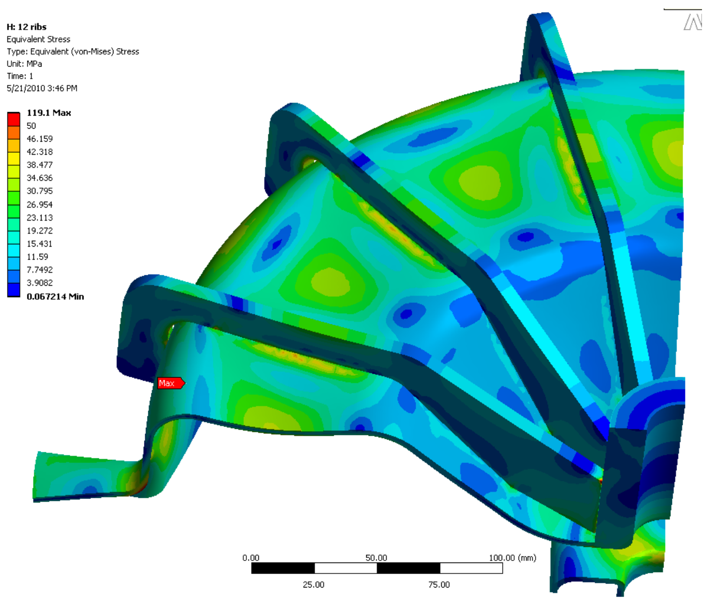
F(MHz)	325	**325**	325	325
$\beta_{optimal}$	0.135	**0.117**	0.11	0.22
R_{cavity},mm	210	**191.5**	180	245.6
R/Q, Ω	150	**130**	120	240
TTF, Average	0.891	**0.944**	0.953	0.952
E_{max}/E_{acc}/E_{max}/E_{acc*}	5.4/6.1	**6.8/7.1**	7.0/7.3	3.9/4.1
H_{max}/E_{acc}/H_{max}/E_{acc*} (mT/MV/m)	10.9/12.3	**10.3/11**	10.8/11.3	5.8/6.1
$D_{eff}=(2*\beta\lambda/2)$,mm	124.6	**108**	101.5	203

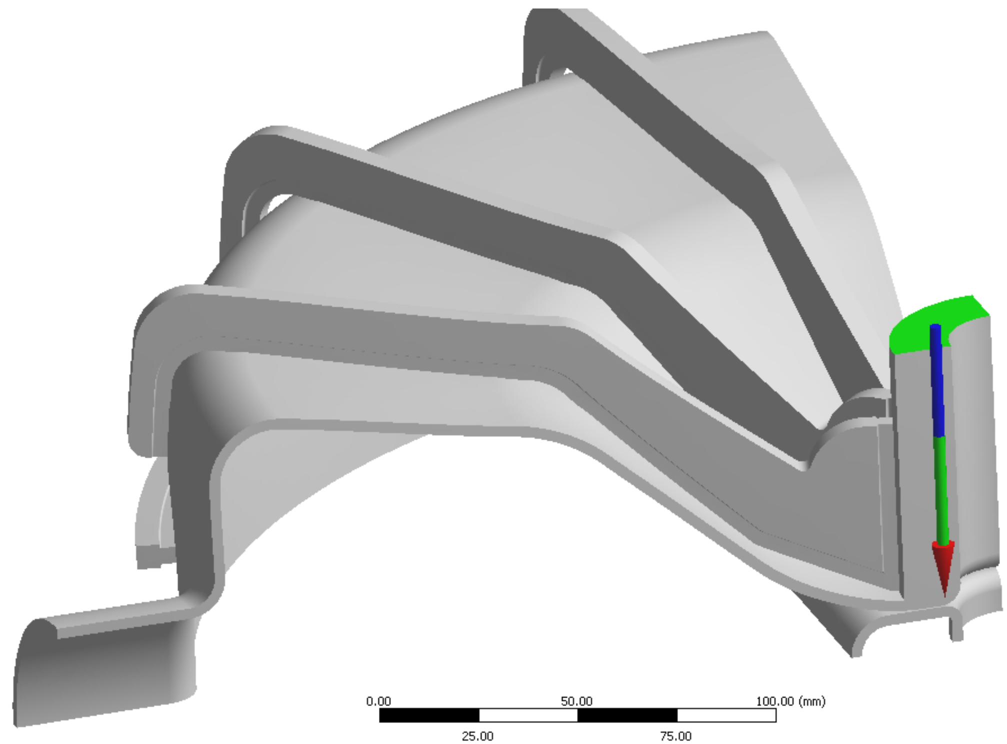
$E_{acc*}=E_{acc}(\beta_{optimal})$* TTF, Average



SSR0 Mechanical Optimization







Displacement 0.1 mm

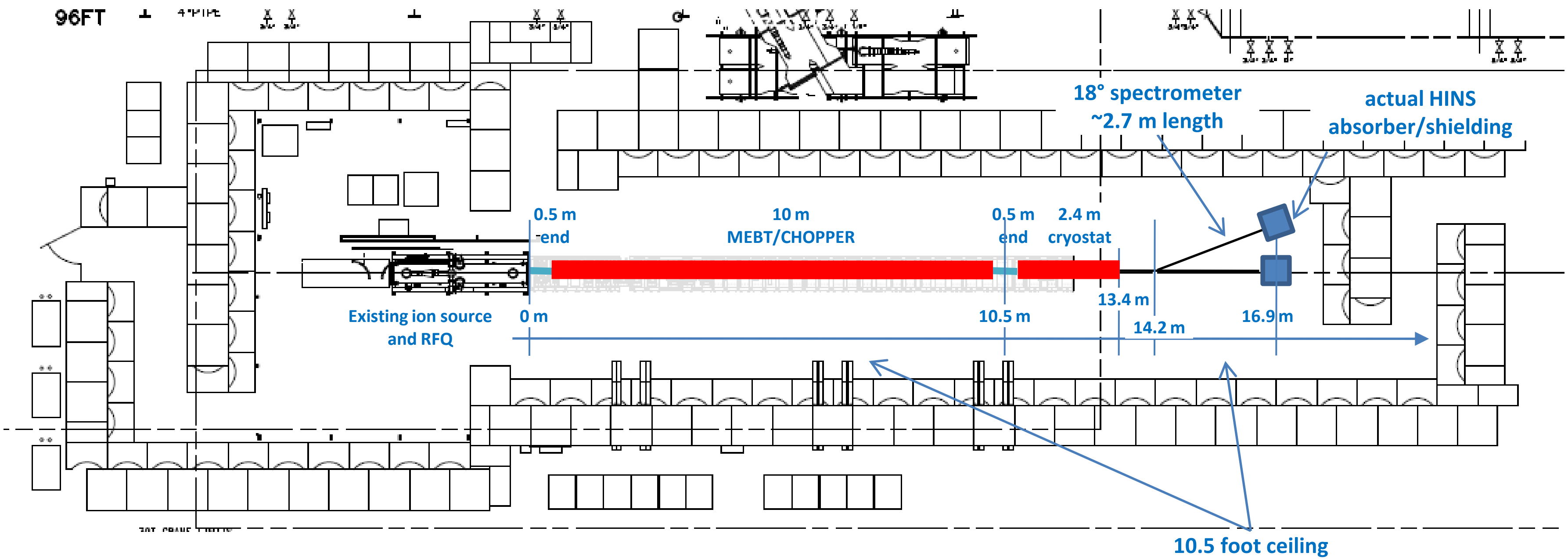
Force reaction 315 x 4

K = 315*4/0.1 = 12600 N/mm **~ 13 N/µm**

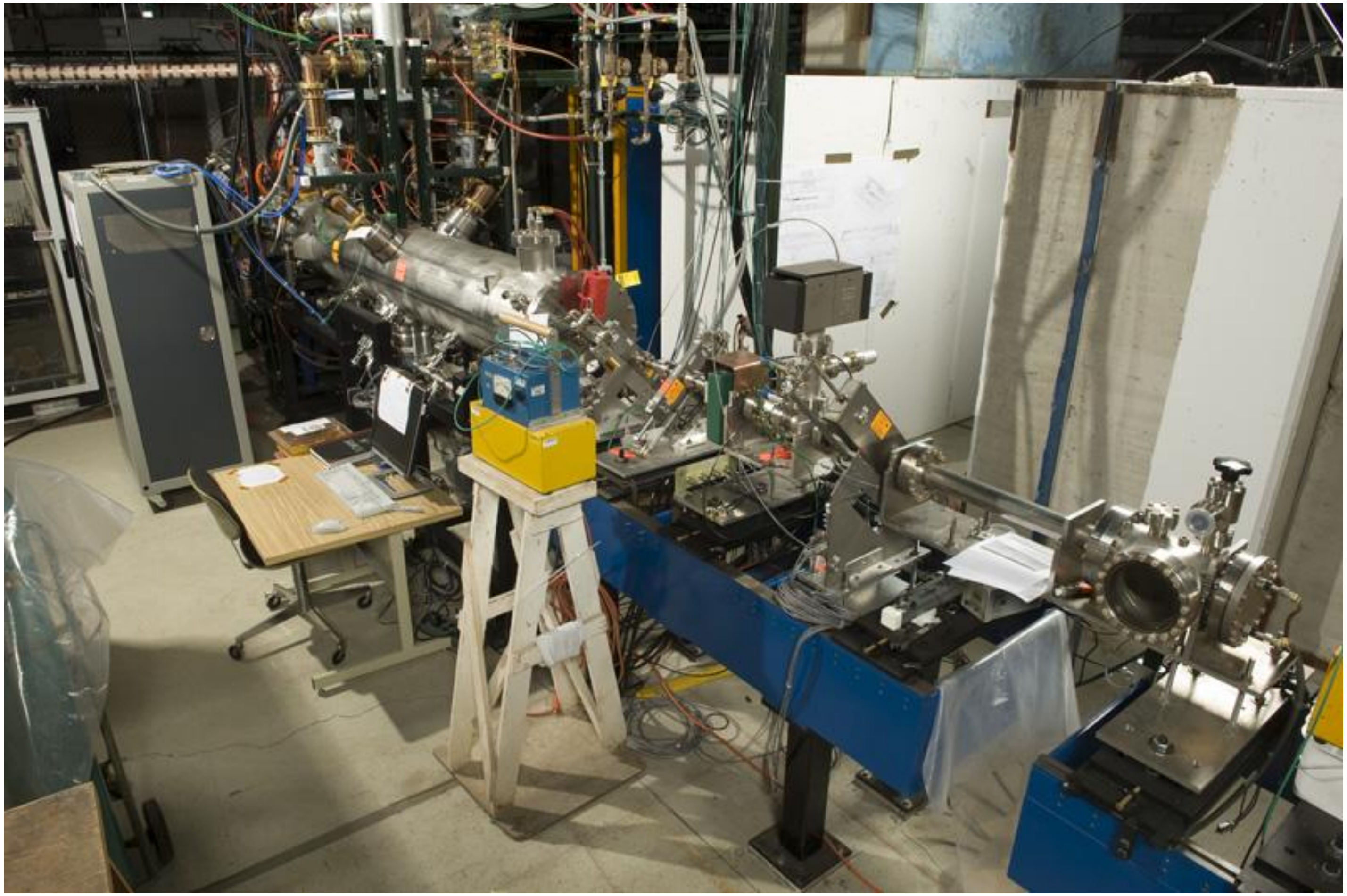
Meson Detector Building Setup

- MDB/HINS initially (2005) conceived as development ground for 325 MHz Front End for the initial Project X configuration (8 GeV Pulsed Linac, SC from 10 MeV)
- Initial Goals:
  - Testing ground/conditioning for all 325 MHz equipment
  - Accelerate beam from 0 to ~60 MeV through RFQ, MEBT, RT section (2.5-10 MeV) and SC SSR1 section (10-60 MeV)
  - Control RF power to cavities
  - Beam Chopper Development
  - Beam Instrumentation Development
- Revised Goals:
  - In CW design, RT section eliminated. Probably replaced by “short” SSR0 cryomodule (~3 cavities) for “proof of principle” acceleration with SSRs
  - Testing ground for MEBT section, chopper and beam diagnostic

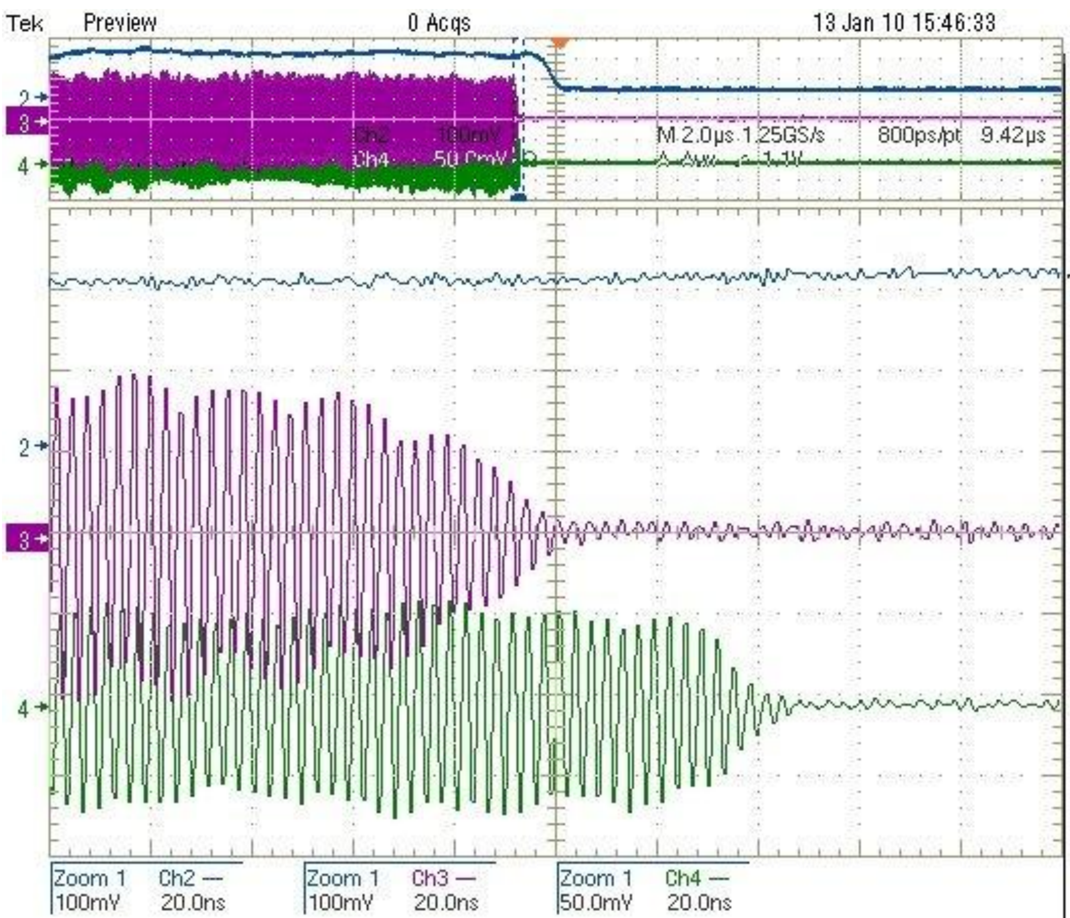
Layout for 3-Cavity SSR0 Cryostat



RFQ and 2.5 MeV Beamline



First 2.5 MeV Beam through RFQ



Signals from toroid and two BPM buttons, all downstream of the RFQ

Upper display: 2 µsec/div
Lower display: 20 nsec/div

Lower display shows the 44nsec delay expected for transit of 2.5 MeV beam between the BPM two buttons separated by 0.96 meters

Beam current is about 3 mA

Conclusions

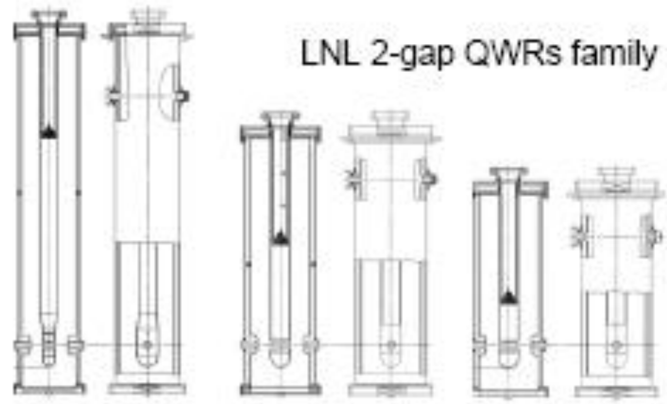
- Project X has adopted Superconducting Spoke Resonators for the Front End
- Design and development of bare cavities is by now a “routine” operation
- Valuable experience is being gained in the assembly and operation of “dressed” cavities.
- Design of the SSR cryomodule is still in its early stages.

Supporting Slides

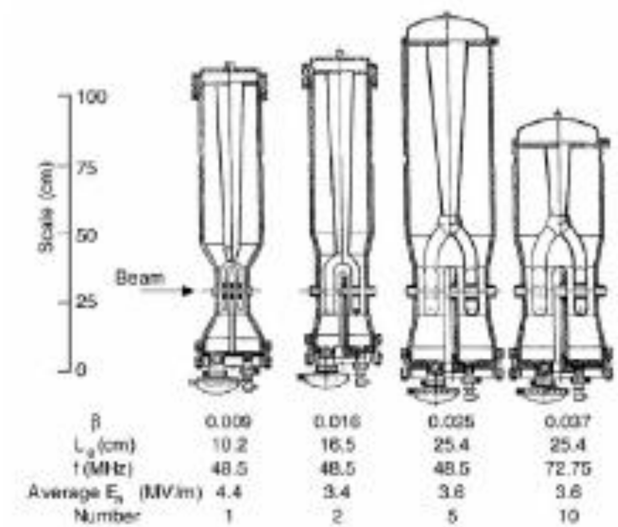
Quarter Wave Resonator

- Advantages
  - Compact
  - Modular
  - High performance
  - Low Cost
  - Low Beta
- Potential Problems
  - Field asymmetry (to be compensated by dipole steering or gap shaping)
  - Mechanical Stability

40 < f < 160 MHz, 0.001 < β < 0.2



OPERATING



Half-Wave Resonator

- Advantages
  - No dipole Steering
  - High performance
  - Lower E_p than QWR
  - Wide β range
  - Very compact
- Potential Problems
  - Not easy access
  - Difficult to tune
  - Less efficient than QWRs

$160 < f < 350$MHz, $0.09 < \beta < 0.3$

MSU 322 MHz β=0.28

The first 355 MHz SC HWR ANL - β=0.12

ACCEL 176 MHz SC HWR β=0.09

PrX – Beam Physics "Gospel" (cont.)

- Provide proper matching in the lattice transitions to avoid appreciable halo formation. In the perfect "current-independent" design, matching in the transitions is provided automatically if the beam emittance does not grow for higher currents.

- Stability for zero current beam, defocusing factor should be < 0.7. (Defocusing factor is less for lower frequencies for given E_m)

$$\Delta_s = \frac{\pi}{2}\frac{1}{(\beta\gamma)^3}\frac{S_f^2}{\lambda}\frac{eE_m \sin\varphi_s}{m_0 c^2}$$

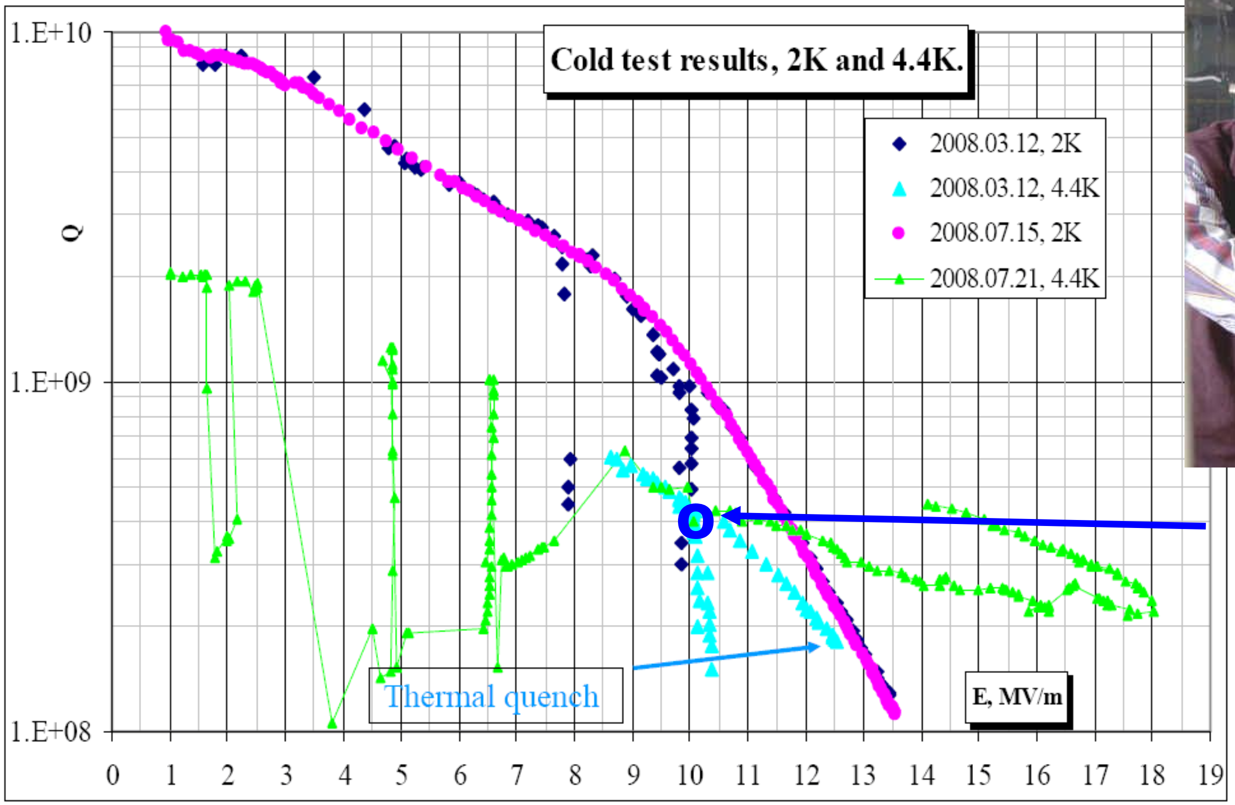
- The length of the focusing period must be short, especially in the front end.

- Beam matching between the cryostats: adjust parameters of outermost elements (solenoid fields, rf phase)

- In the frequency transition, the longitudinal matching is provided by 90° "bunch rotation", or bunch compression

SSR1-1 Early VTS Results

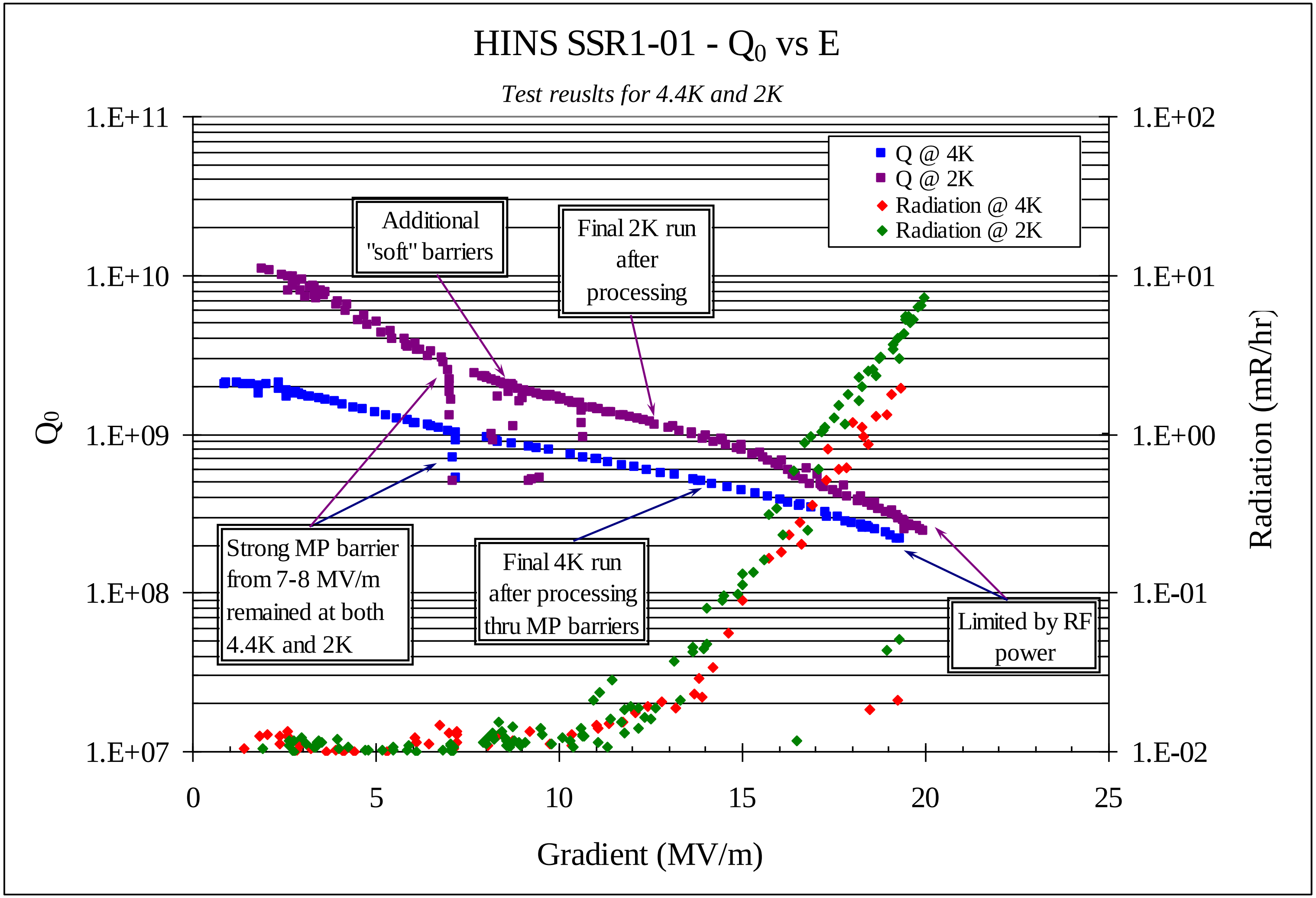
SSR1-1 Q vs. E



Accelerating Gradient MV/m

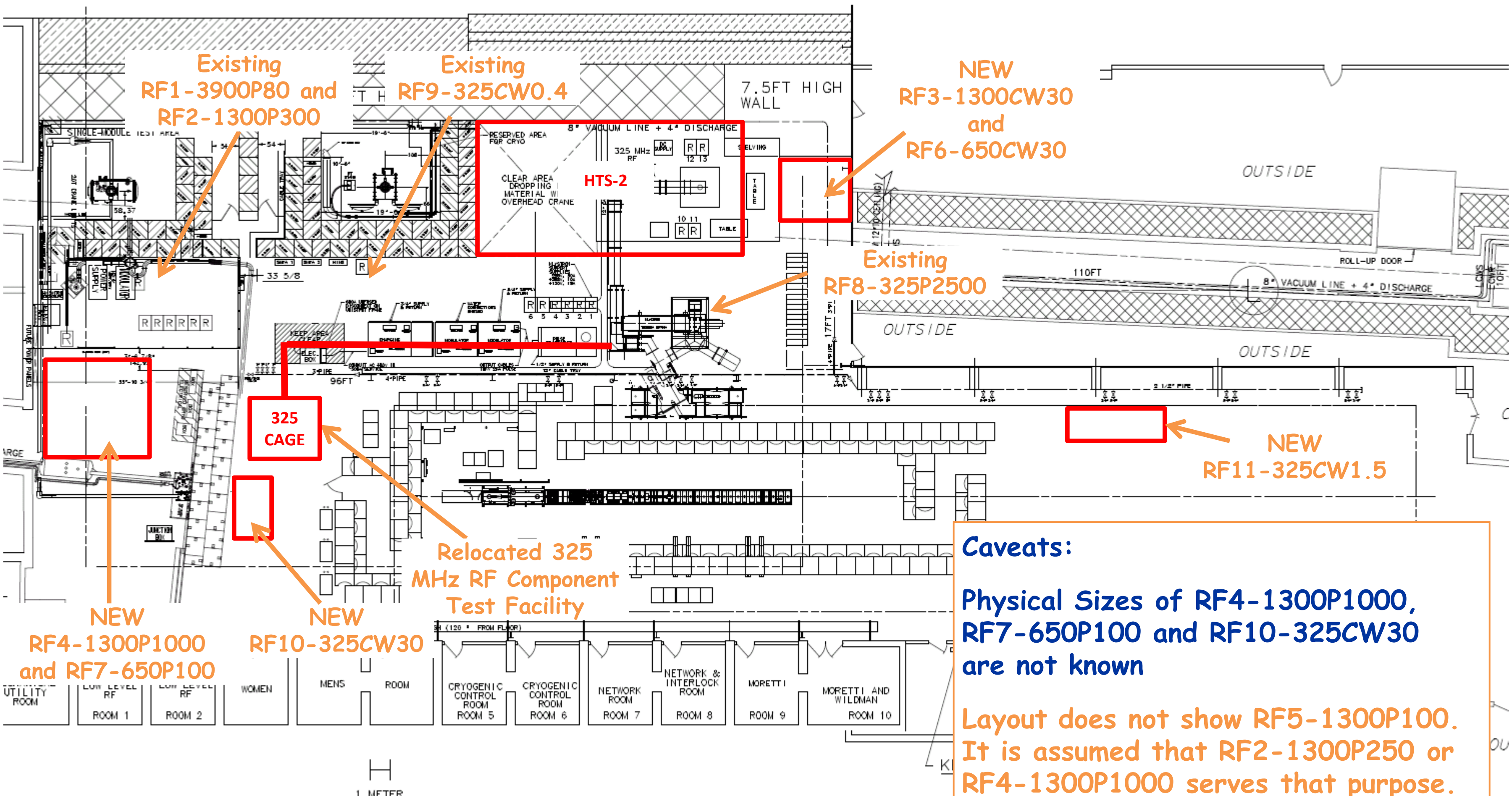
- Dressed Cavity Operating Goal @ 4 K (Pulsed)
- This test ended when multipacting due to poor cavity vacuum became unacceptable.

SSR1-1 Final Test Results



Spoke Cavity Horizontal Test Cryostat in MDB

"Complete" Layout



Caveats:

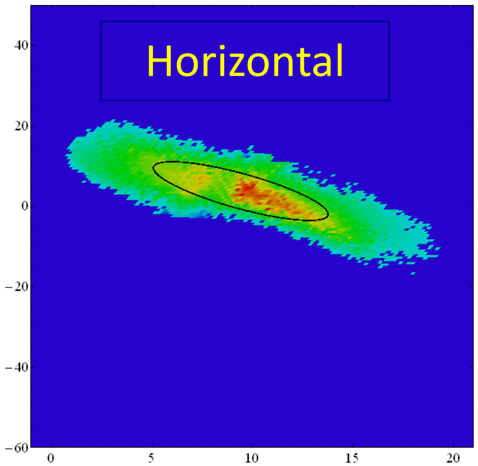
Physical Sizes of RF4-1300P1000, RF7-650P100 and RF10-325CW30 are not known

Layout does not show RF5-1300P100. It is assumed that RF2-1300P250 or RF4-1300P1000 serves that purpose.

Goals

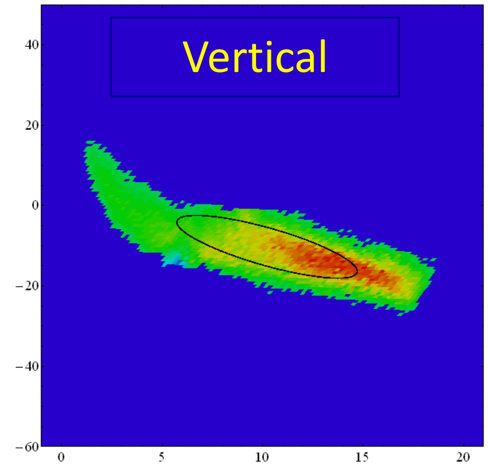
- Complete “Six-Cavity Test” – June 2011
  - Demonstrate individual Phase/Amplitude control with DQM shifters.
- Demonstrate that solenoid beam axis can be aligned to 0.5 mm rms – by Oct 2011
- Select bunch frequency (162.5 or 325) by demonstrating a broad-band chopper – by July 2013 (CD2)
- Complete test of SSR0 “short” cryomodule (3/4 cavities, 4/5 solenoids + correctors, BPMs) (prototype for a “long” cryomodule) with beam and broad-band chopper – by Sept 2014
- Ongoing development of instrumentation, optics, couplers, LLRF

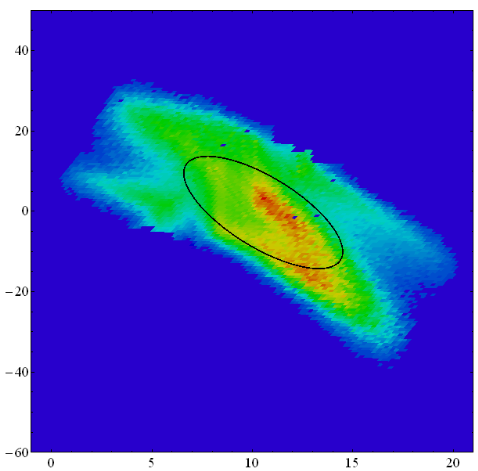
Ion Source Emittance Scan Data



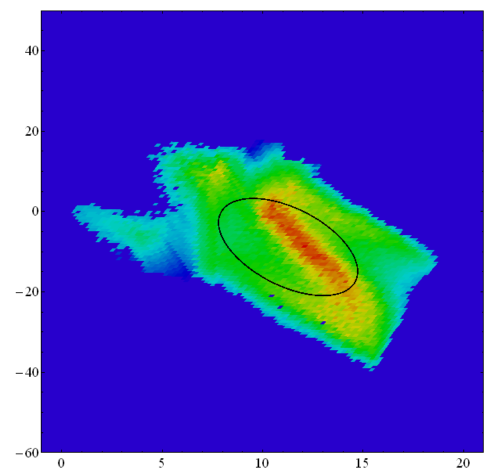
50 keV beam from HINS proton ion source

I_b = 4 mA

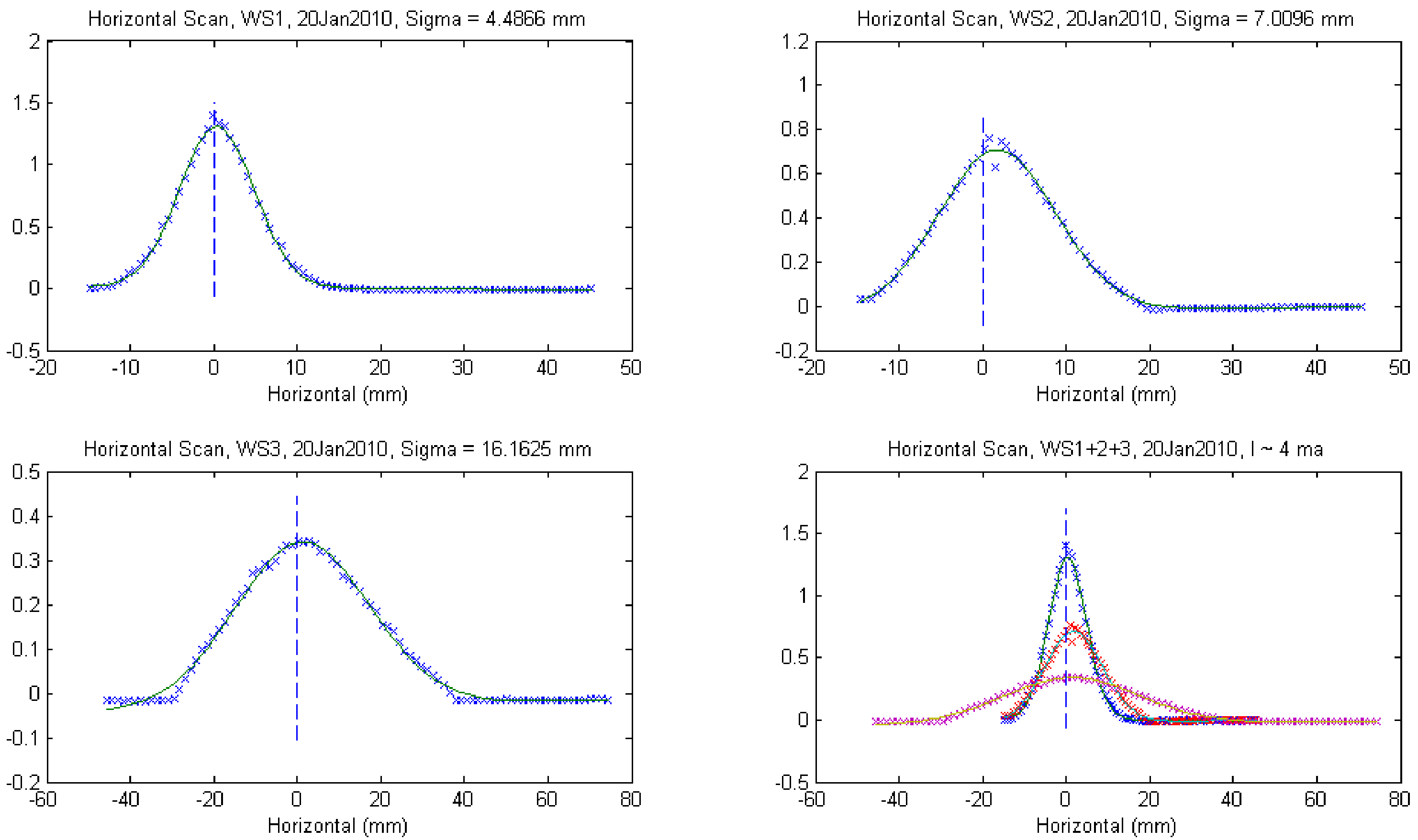




I_b = 12 mA



HINS 2.5 MeV Beam Profiles



Linac Enclosure
(Under Construction)

RFQ Problem & its solution