APS SPX cavity and cryomodule

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For the SPX project team

12/14/12

Outline

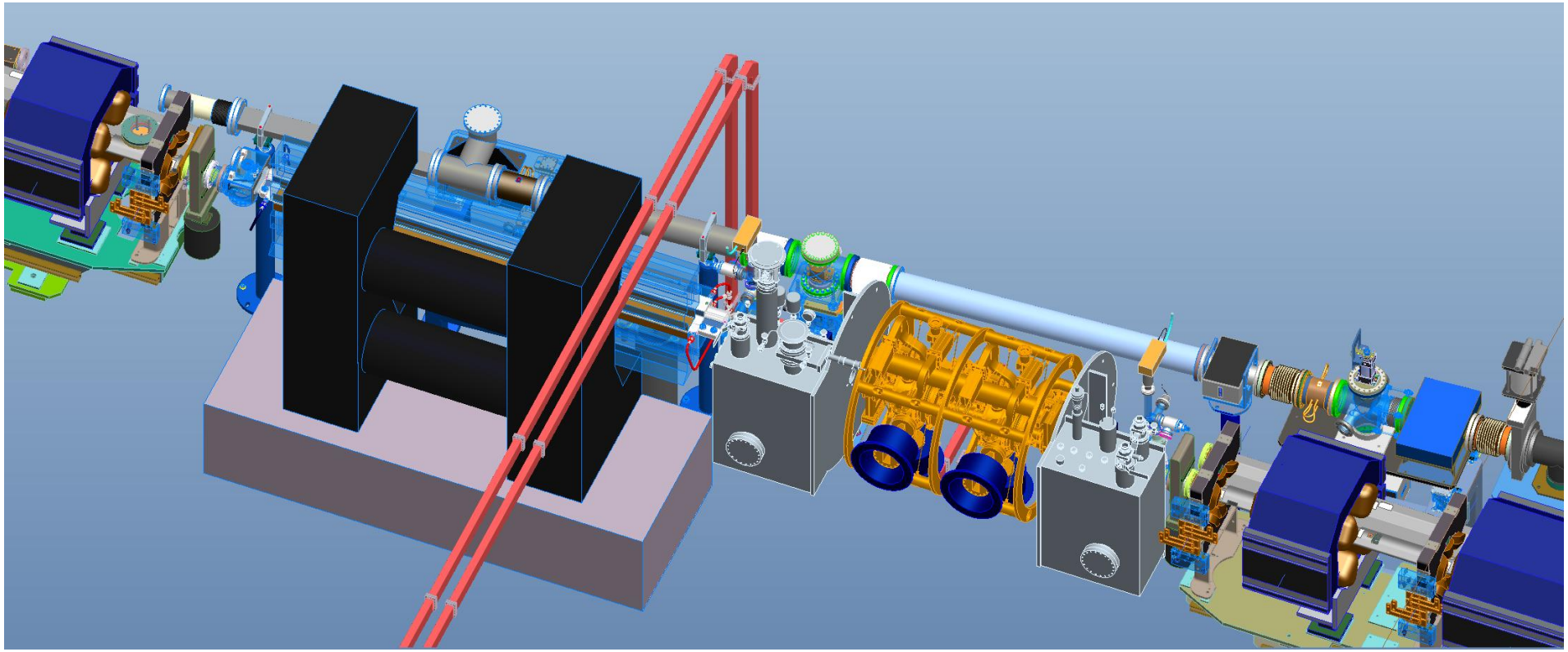
- SPX requirements
- Approach and concepts
- Cavity status
- Cryomodule
- Alignment concept
- Conclusions

Requirements

- Project in two phases:
  - SPX0 functional test, one module 2 cavities
  - SPX final configuration, two modules 4 cavities each
- Must be transparent to other users
  - Closed crabbing, no residual orbit distortion
  - No emittance growth
  - No beam instabilities
  - No beam trips
  - No significant degradation of lifetime
- Must fit in existing or extended straight sections

SPX0 for APS-U

Must fit in very tight space in existing straight section



Operation modes

- Normal user operation
  - RF is off
  - Cavity detuned
  - 80K
  - Beam steering (To be determined)
  - Beam current up to 100 mA (150 mA high current study, if possible)
- Beam studies
  - Cavity tuned
  - 2K
  - RF input
  - Users go offline
  - Beam current up to 100 mA
  - Beam steering allows +/-0.66 mm off nominal beam axis* (+/- 1mm if an additional corrector is added)

*Information from V. Sajaev

SPX0 Main Parameters

Quantity	Value
Electron beam current	100 mA
Number of cavities	2
Total voltage	1.0 MV
RF Frequency	2815.486 MHz
Cavity tunability	200 kHz
Source tunability	1.5 kHz
Operating temperature	2 K
Longitudinal non-deflecting mode impedance	<0.44 MΩ-GHz
Horizontal non-deflecting mode impedance	<1.3 MΩ/m
Vertical non-deflecting mode impedance	<3.9 MΩ/m

Alignment specification

Table 7: Alignment requirements for SPX0 cavities (full range).

	Cryomodule alignment	Cavity inside cryomodule
ΔX	$\pm$500 μm	$\pm$500 μm
ΔY	$\pm$200 μm	$\pm$200 μm
ΔZ	$\pm$1000 μm	$\pm$1000 μm
Yaw	$\pm$10 mrad	$\pm$10 mrad
Pitch	$\pm$10 mrad	$\pm$10 mrad
Roll	$\pm$10 mrad	$\pm$10 mrad

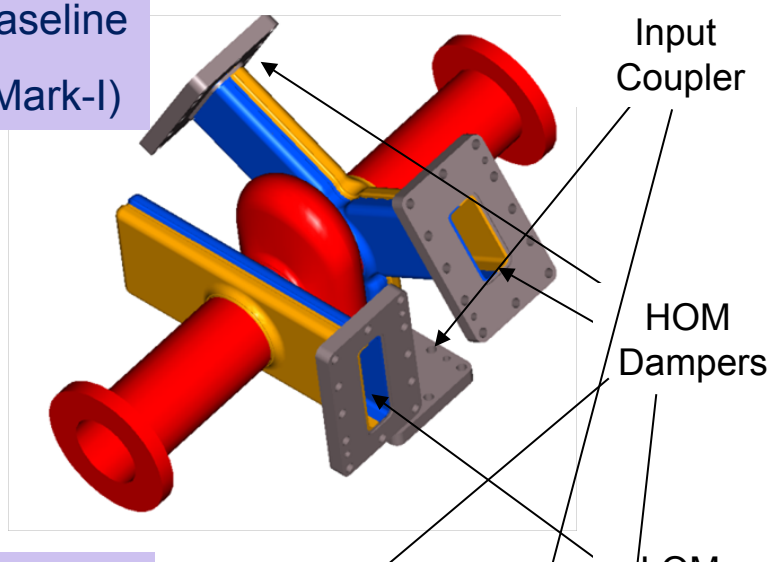
- Each cavity's electrical center should be within +-0.2mm (Y-direction) relative to a beam axis.

Approach and concepts

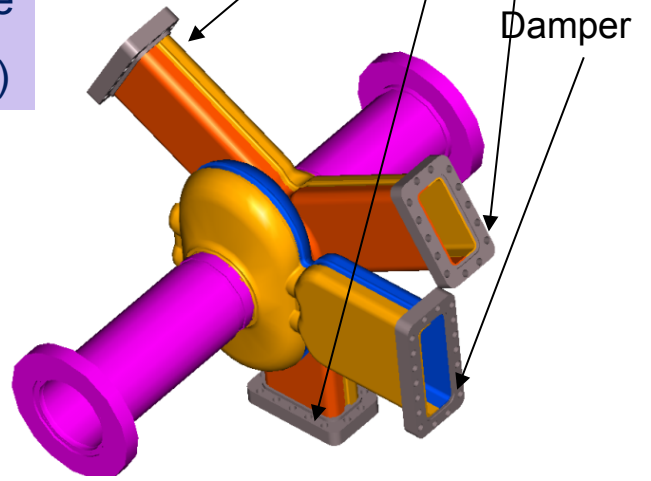
- Tight space requirements > compact design
- High frequency (2815 MHz specified by APS), large aperture
- Choose squashed elliptical cavity
- Strong HOM damping, high power > waveguides
- Fabrication by machining from ingot Nb
- JLab style cryostat
- Improvements in transverse alignment needed
  - Fiducialized “pair” configuration
  - Possible active or cold-adjustable alignment
- SPX0 proof of concept before final production

Two Types of Bare Crab Cavity for Down Selection

Baseline (Mark-I)



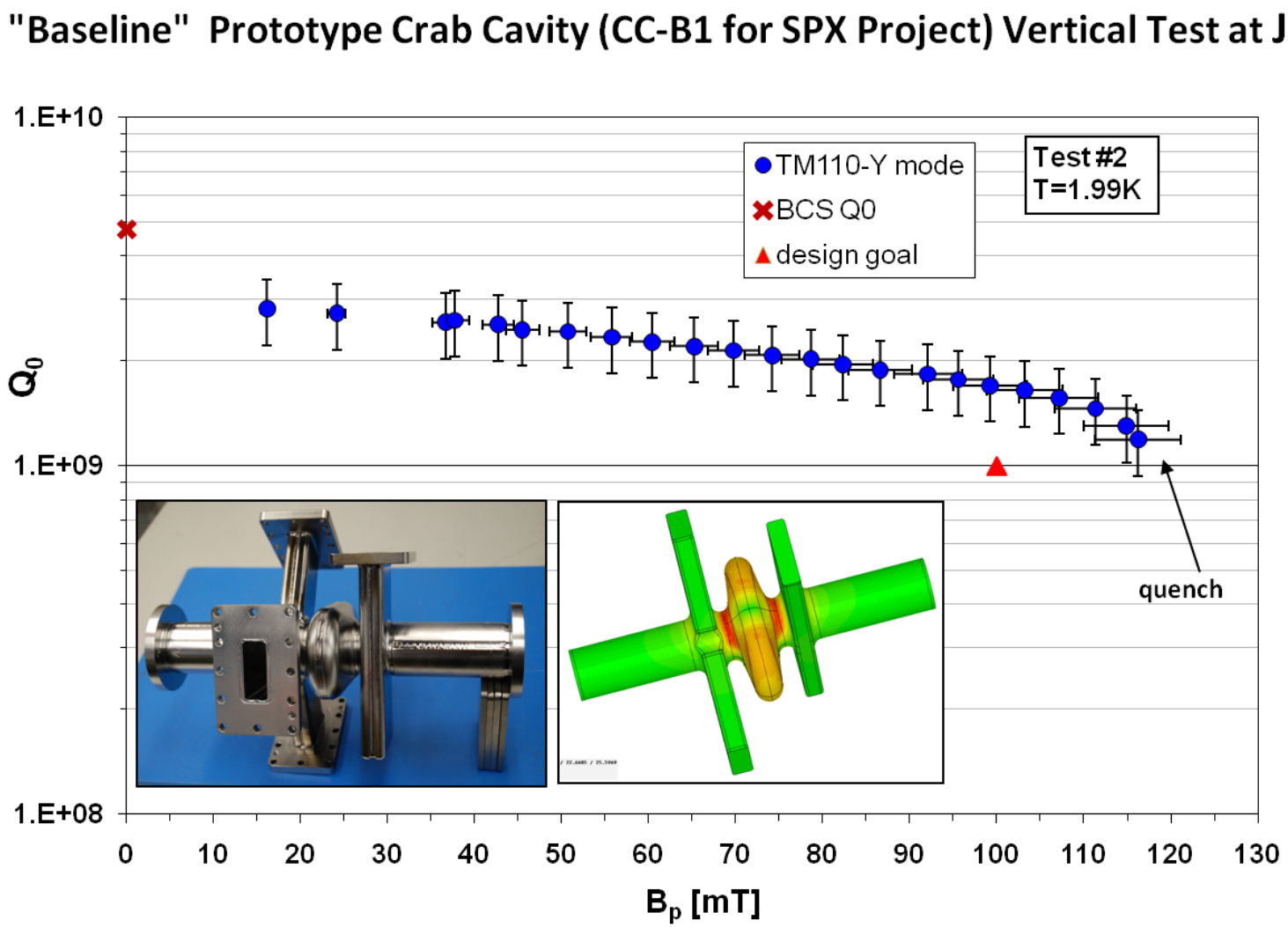
Alternate (Mark-II)



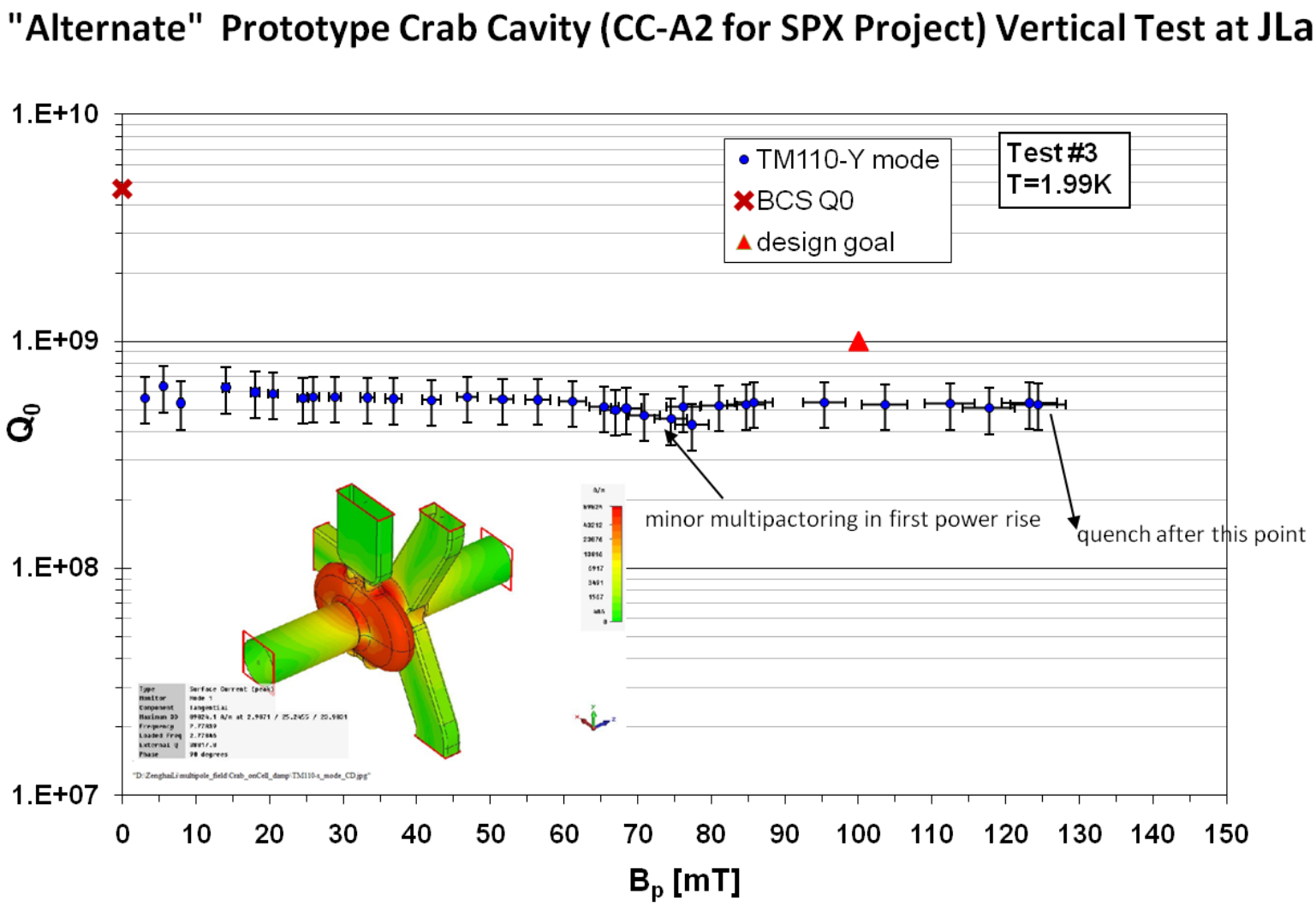
Parameter	Value	Unit
Basline Cavity		
Frequency	2.815488	GHz
Cavity Type	elliptical	
Fundamental Mode	TM110-y-0	vertical kick
Rt/Q including TTF	35.8	Ω
Crabbing Voltage Vt at Bs=100mT	0.5	MV
Peak Surface Bs Field/Vt	195.6	mT/MV
Peak Surface Es Field/Vt	82	1/m
Geometry Factor	227.5	Ω
Material Thickness	3	mm Nb
Cavity Iris Radius	25	mm
Cavity Active Gap Distance	53.24	mm
Operational Q0	>1.0E+09	at 2K
Cell Number	1	
HOM + FPC Couplers	3	"Y" WGs
LOM Coupler	1	WG+stub
TM110-x Mode	3.56	GHz

Alternate Cavity		
Rt/Q including TTF	37.1	Ω
Crabbing Voltage Vt at Bs=100mT	0.5	MV
Peak Surface Bs Field/Vt	200.8	mT/MV
Peak Surface Es Field/Vt	81.5	1/m
Geometry Factor	227.8	Ω
Material Thickness	4	mm Nb
LOM Coupler	1	On-cell

The Baseline Cavity CCB1was Qualified in the 2nd RF Test

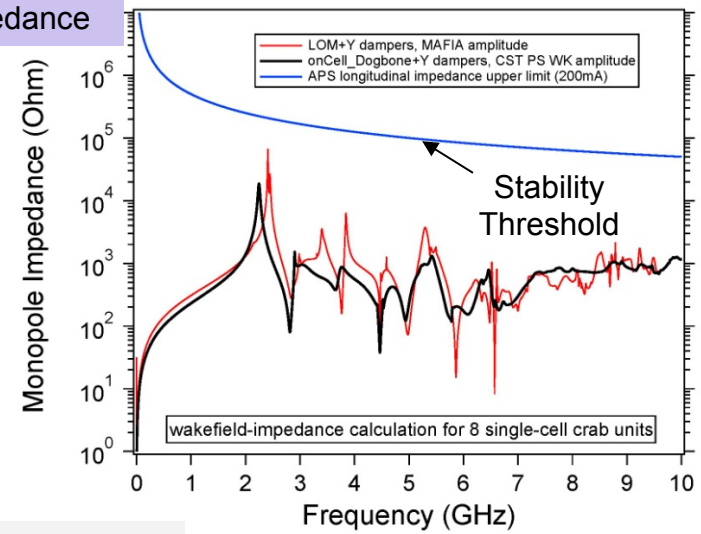


Cold Test Result for CC-A2 Cavity

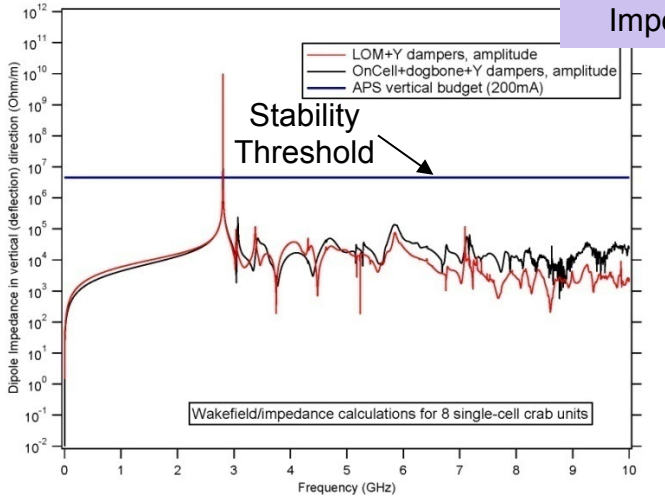


Longitudinal and Transverse Impedance*

Monopole Impedance



Vertical Dipole Impedance

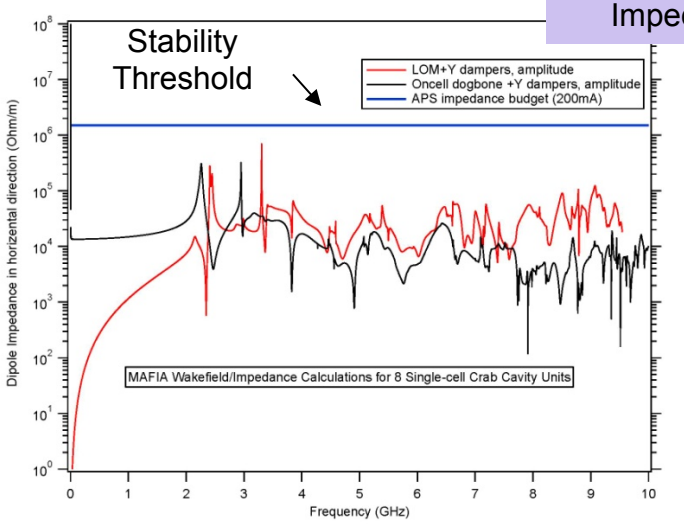


Monopole Stability Threshold

$$R_s * f_p < 0.44 M\Omega - GHz \quad R_s = \frac{V^2}{2P_l}$$

Total HOM/LOM power for Mark-II: <0.5/1.8kW for APS 200mA, 24 beam bunch mode

Horizontal Dipole Impedance



Dipole Stability Threshold

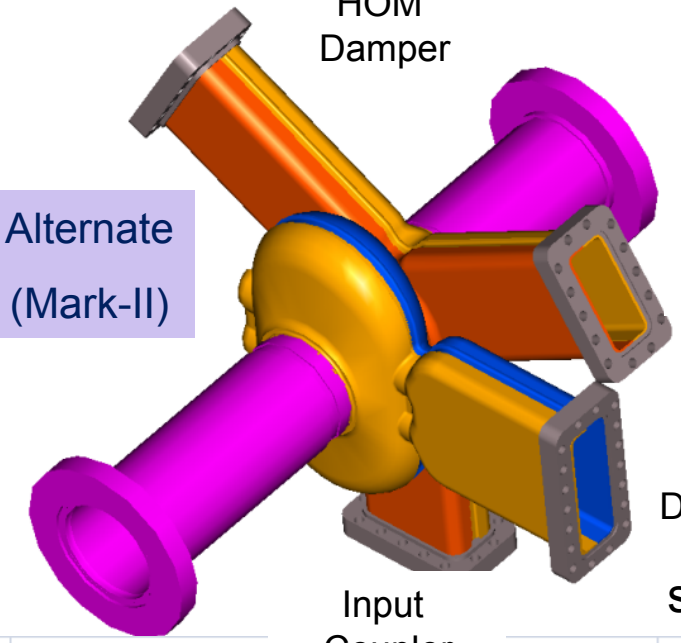
$R_t < 1.3 M\Omega / m$ Horizontal dipole

$R_t < 4.5 M\Omega / m$ Vertical dipole

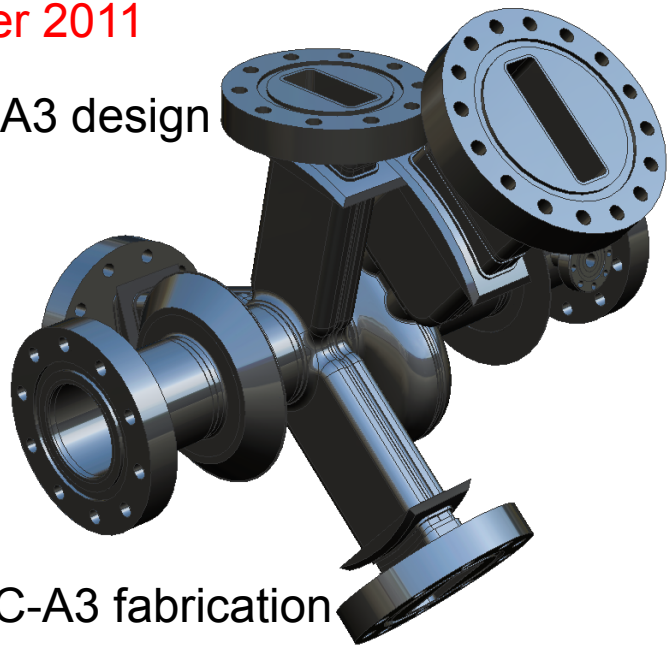
$$R_t = \frac{V^2\big|_{r=r_0}}{2\,P_l\,k\,r_0^2}$$

Cavity design down-selection has been Mark-II type with LOM on-cell damper

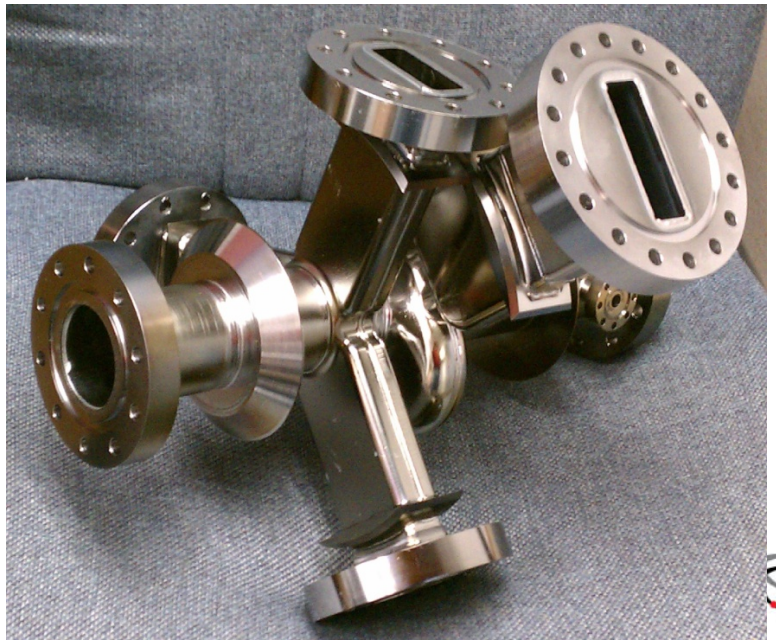
Decision made September 2011



CC-A3 design



CC-A3 fabrication



specification

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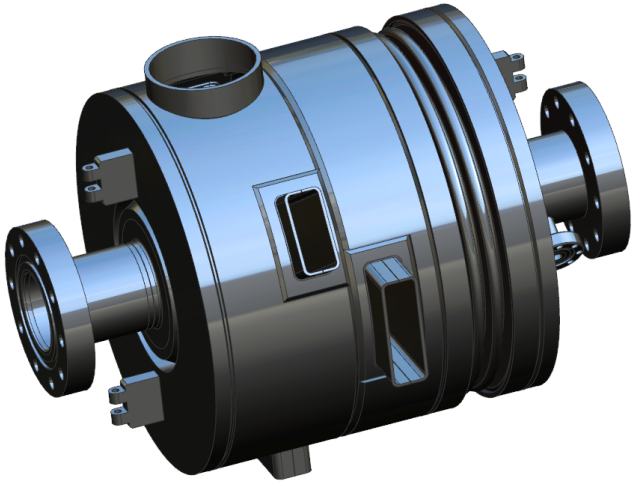
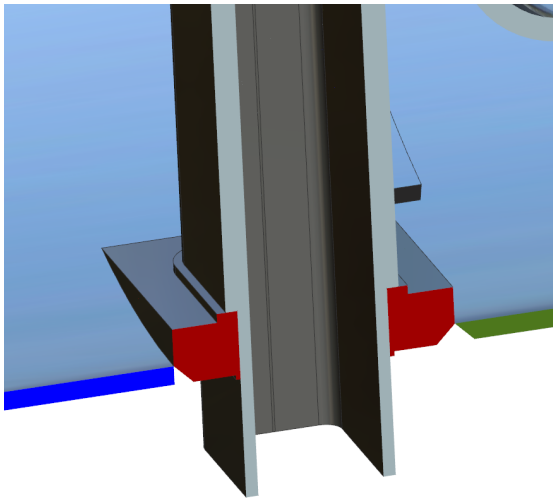
Geometry Factor	227.8	Ω
Material Thickness	3	mm Nb
Cavity Iris Radius	25	mm
Cavity Active Gap Distance	53.24	mm
Operational Q0	>1.0E+09	at 2K
Cell Number	1	
HOM + FPC Couplers	3	"Y" WGs
LOM Coupler	1	On-cell
TM010 Mode (LOM)	2.275	GHz

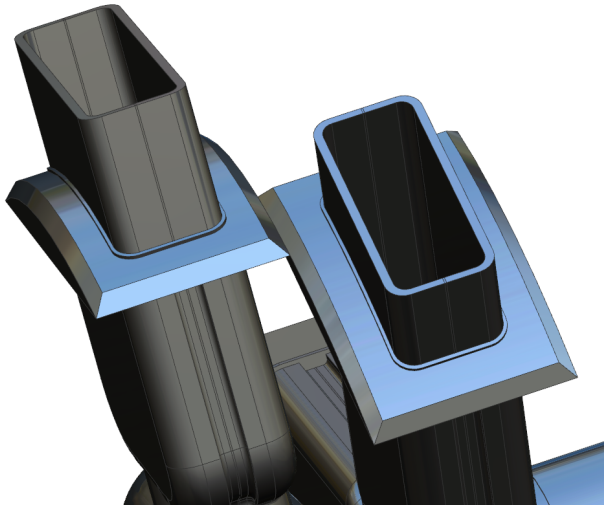
Cavity status

- Baseline and alternative cavities developed and tested
- Down select to alternative “on-cell damper” version (CCA3)
- Prototype completed and qualified
- 3 pre-series cavities fabricated for SPX0
- Cavities in qualification (one already passed spec)
- Helium vessel design iteration complete
  - Waiting on bellows for He vessel welding
- Tuner parts procured
- HOM loads and windows in procurement/Fabrication (ANL)

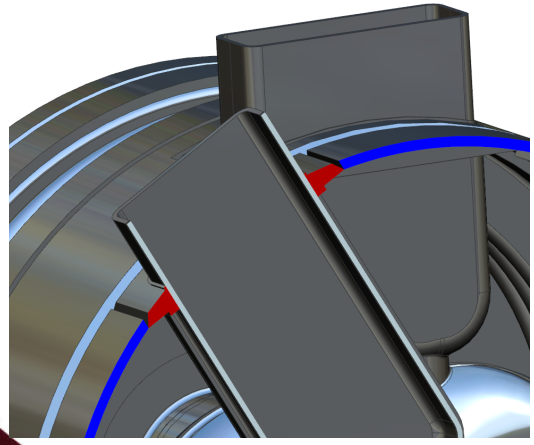
Helium Vessel (Katherine Wilson)



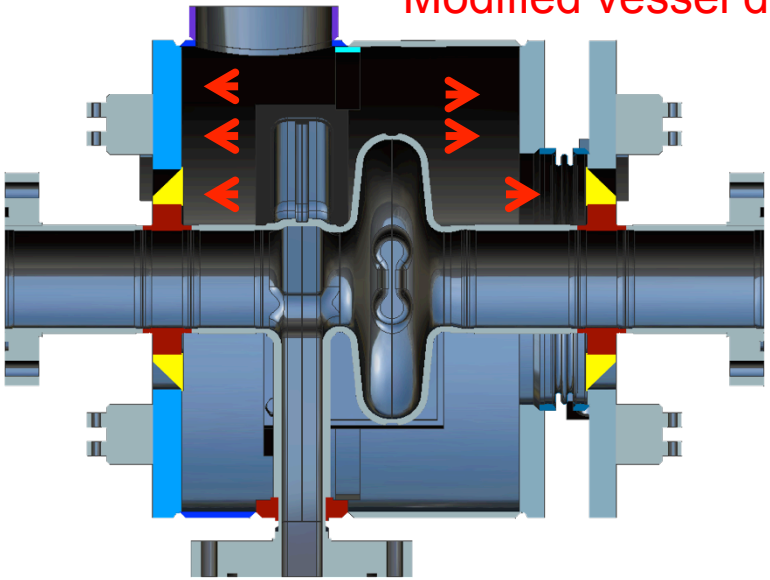




Old helium vessel design

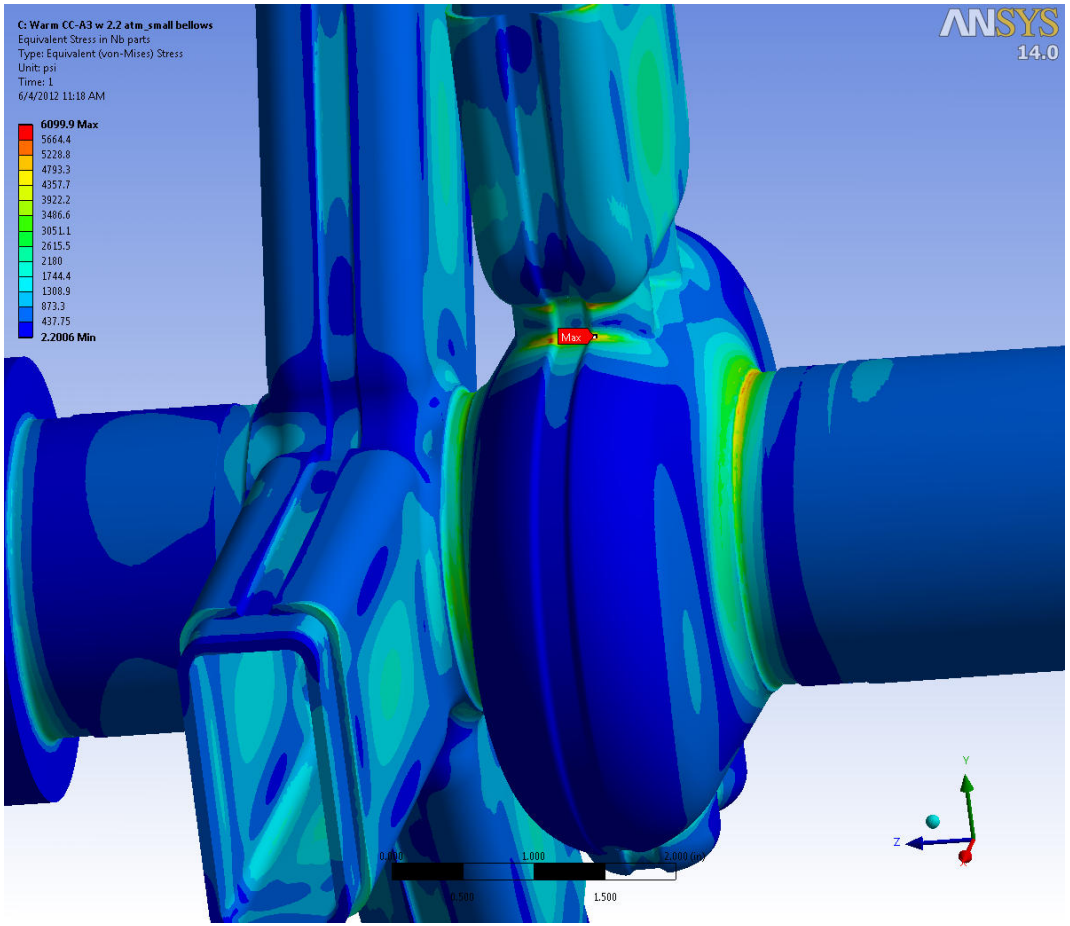


Modified vessel design



Stress Analysis with Modified Design

- With the small bellows design, the peak stress in warm CC-A3 cavity dropped to 6,100 psi, which is below the allowable of 6,310 psi. (Conservative to design to peak stress.)



SPX Tuner Status

SPX Tuner Design Specifications

		12Gev Upgrade C100 Style Cavity	SPX CC-A3 3.5mm wall
Cavity Related Info*			
Tuning Sensitivity	kHz / mm	310	9000
Stiffness	lbs / in	9851	170000
Deflection required for 200 kHz frequency shift	um	645	22
Force required for 200 kHz frequency shift	lbs	250	149
Tuner Related Info			
Stepper Motor Resolution	Steps/rev	200	800
Harmonic Drive Ratio		100	100
Ball Screw Pitch	mm/rev	5	2
Resolution from Stepper**			
full step	Hz / increment	13.6	31.6
half step	Hz / increment	6.8	15.8
quarter step	Hz / increment	3.4	7.9
Piezo Range			
(drive axis)	um	60	60
(cavity axis)	kHz	3.3	75.8
Piezo Resolution			
(drive axis)	nm	0.13	0.13
(cavity axis)	Hz	0.01	0.16

Tuning Range

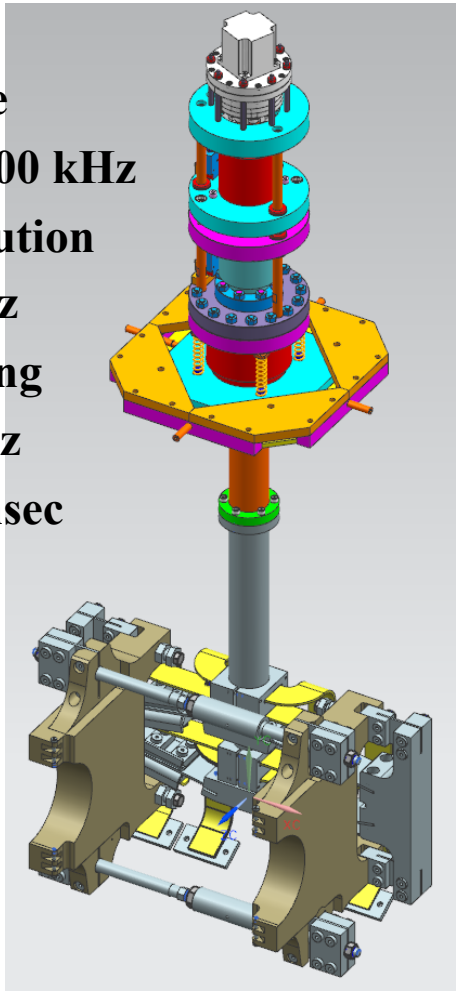
- +/- 200 kHz

Tuning Resolution

- 40 Hz

Rapid Detuning

- 3 kHz
- < 1msec



* - SPX numbers taken from J. Liu FEA

** - Stepper controller enables up to 1/256 microstepping. As smaller steps are used there is a tradeoff of resolution for torque. Testing is required to determine what level of micro-stepping is achievable.

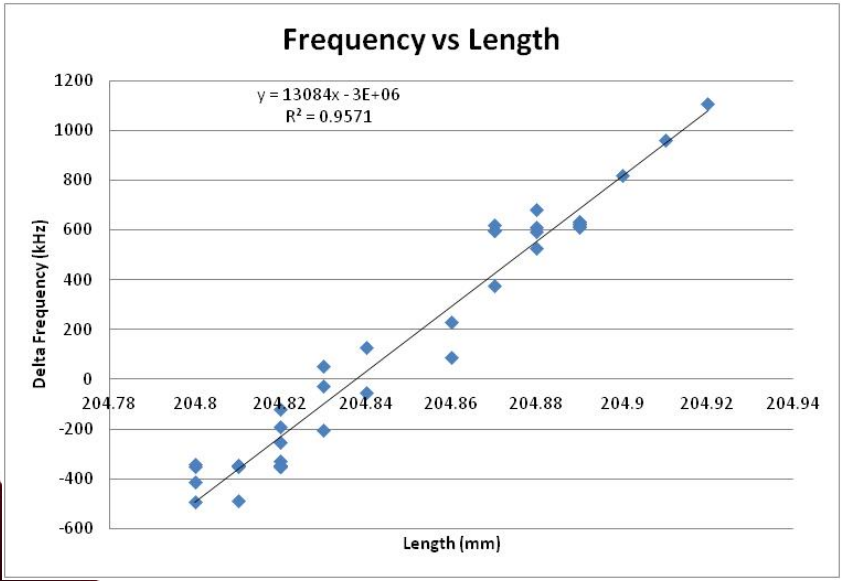
SPX Tuner Design Status: Cavity Measurements

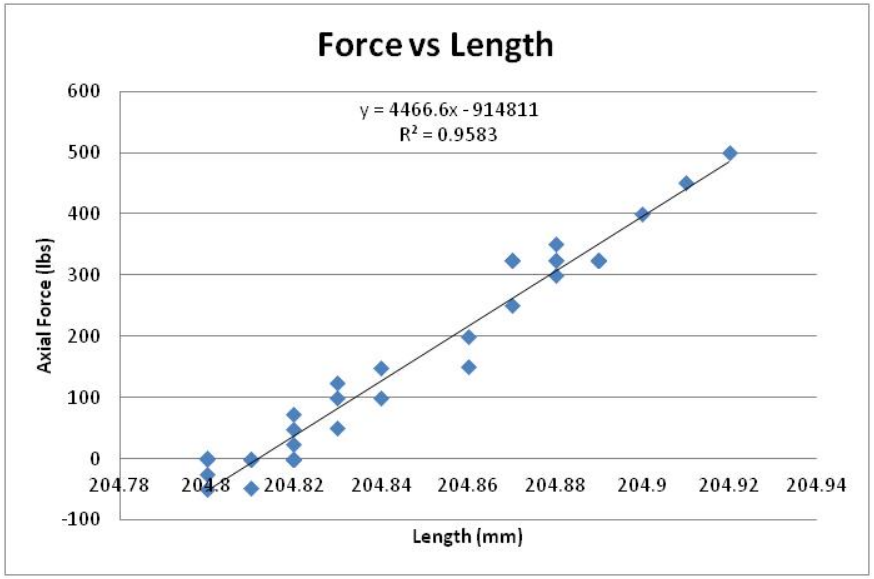
	Tuning Sensitivity (Mhz/mm)*	Cavity Stiffness (klbs / in)**
Predicted	12.2	113.5
Measured	13.0	101.6

✓ Modeling Validated

* - The tuning sensitivity with a He vessel is expected to decrease by 26%

** - The stiffness with a He vessel is expected to increase by 12%



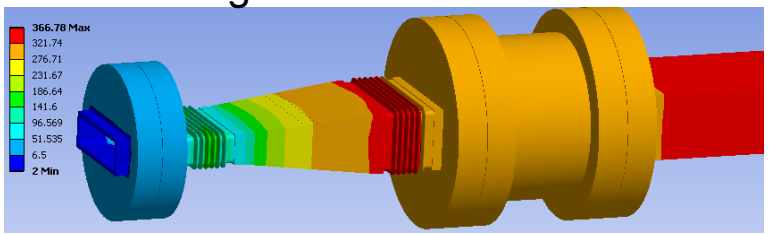


Other components:

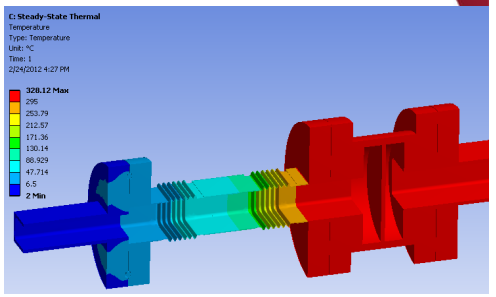
HOM , FPC and LOM Analysis and Cooling:

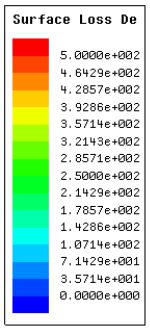
Geoff Waldschmidt, ANL

LOM Waveguide

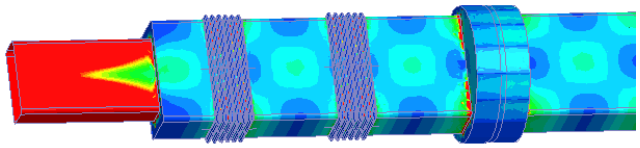


FPC Waveguide & windows

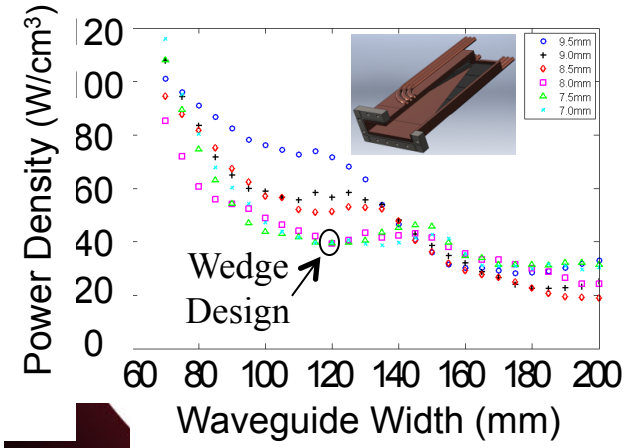




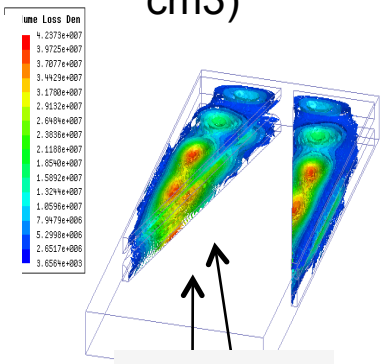
Beam loaded



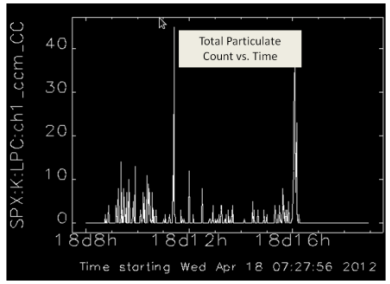
LOM/HOM Dampers:



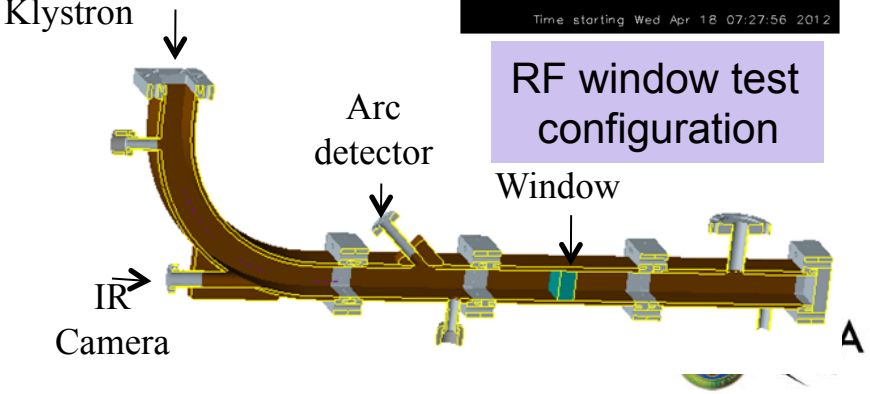
Distribution of power density (W/cm3)



Load (400A) Testing

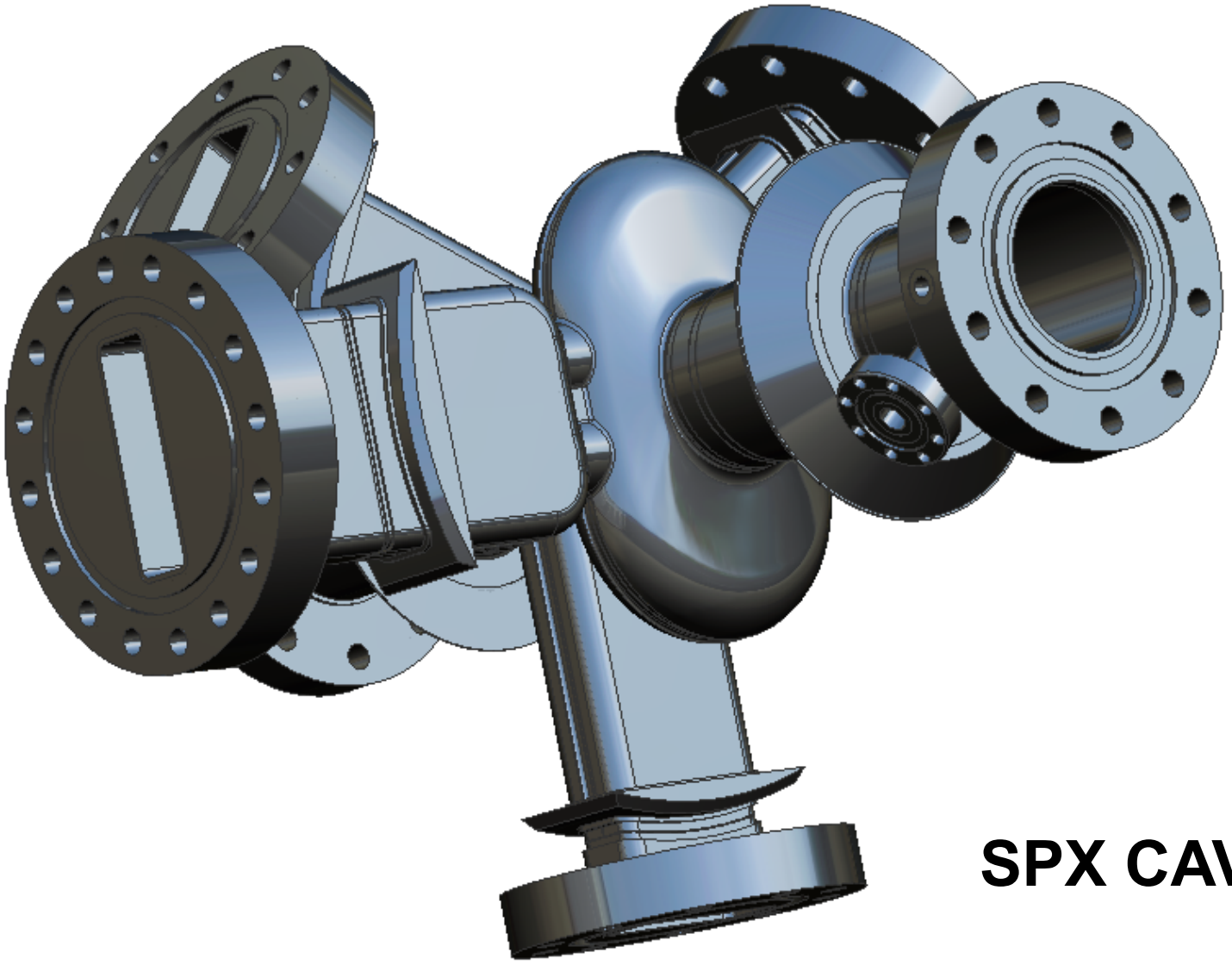


RF window test configuration



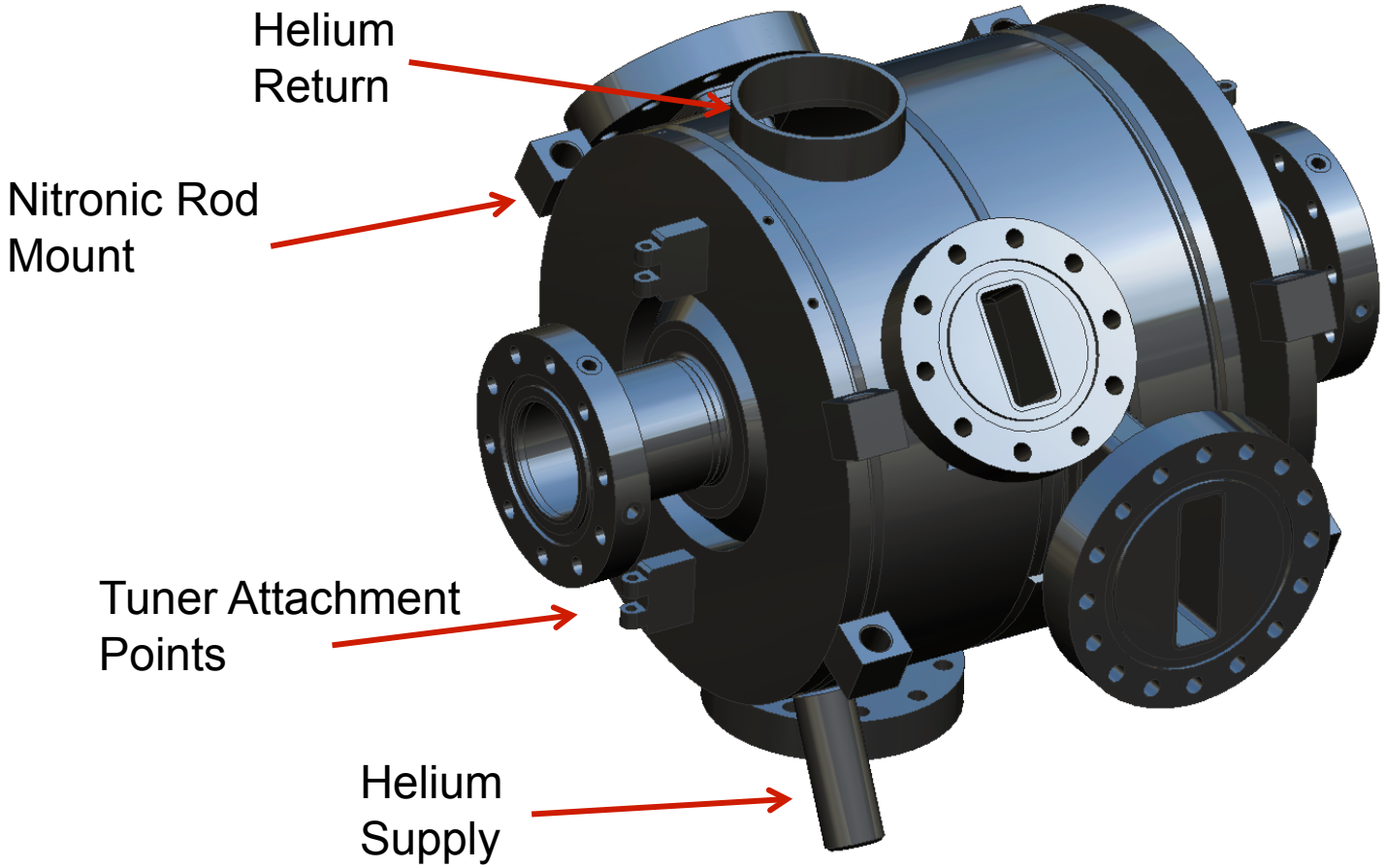
Cryomodule status

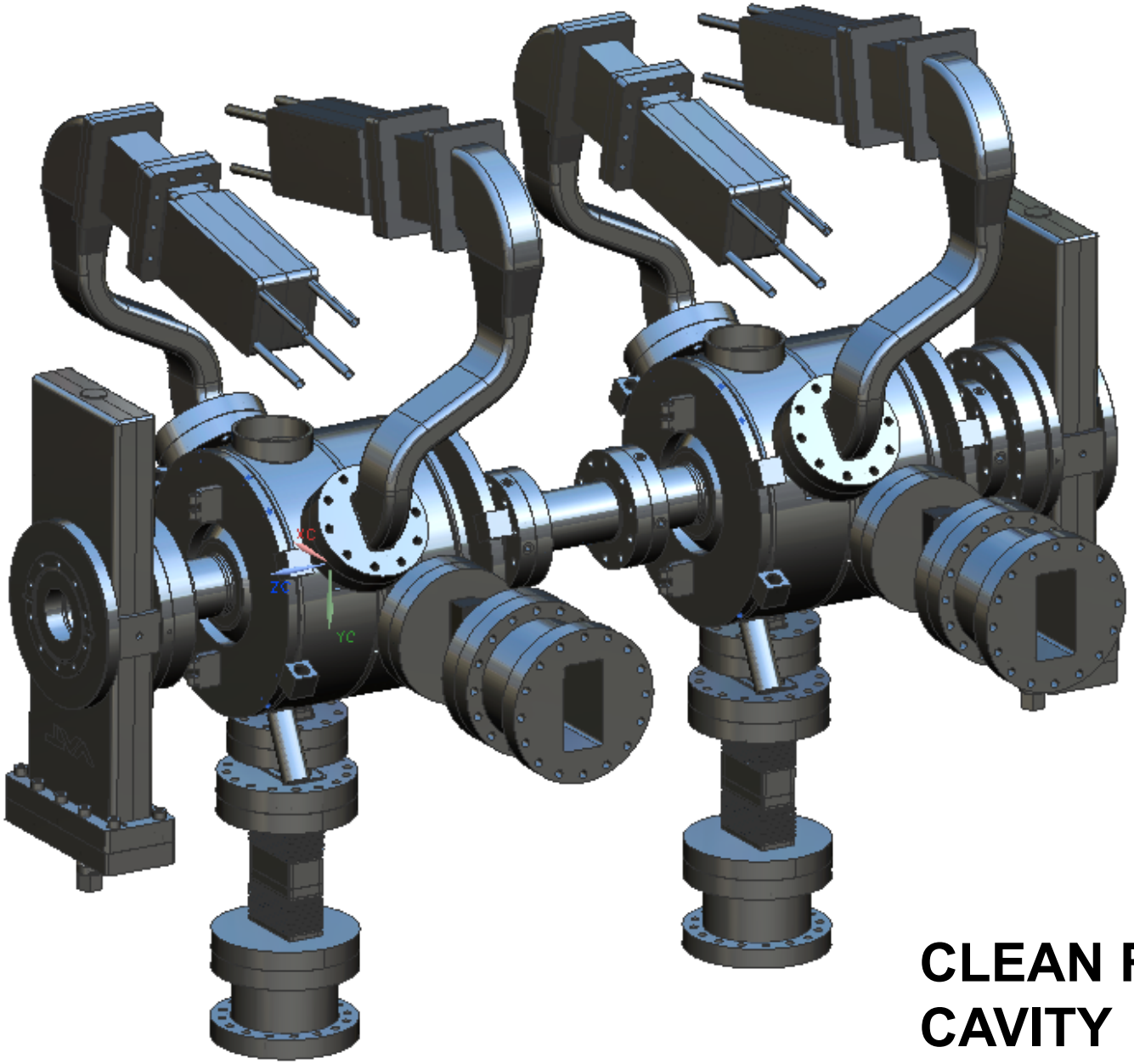
- SPX0 cryostat based on modified Jlab design
  - Space frame support
  - Existing end cans (new SNS-upgrade type under discussion)
  - Shielded all metal VAT valves
  - Low impedance bellows (new or APS type)
- New cold mass uses features adapted from C100
  - Individual He vessels
  - Scissor-jack tuner
- Test features for SPX where possible
- Timeline for SPX may allow for further improvements



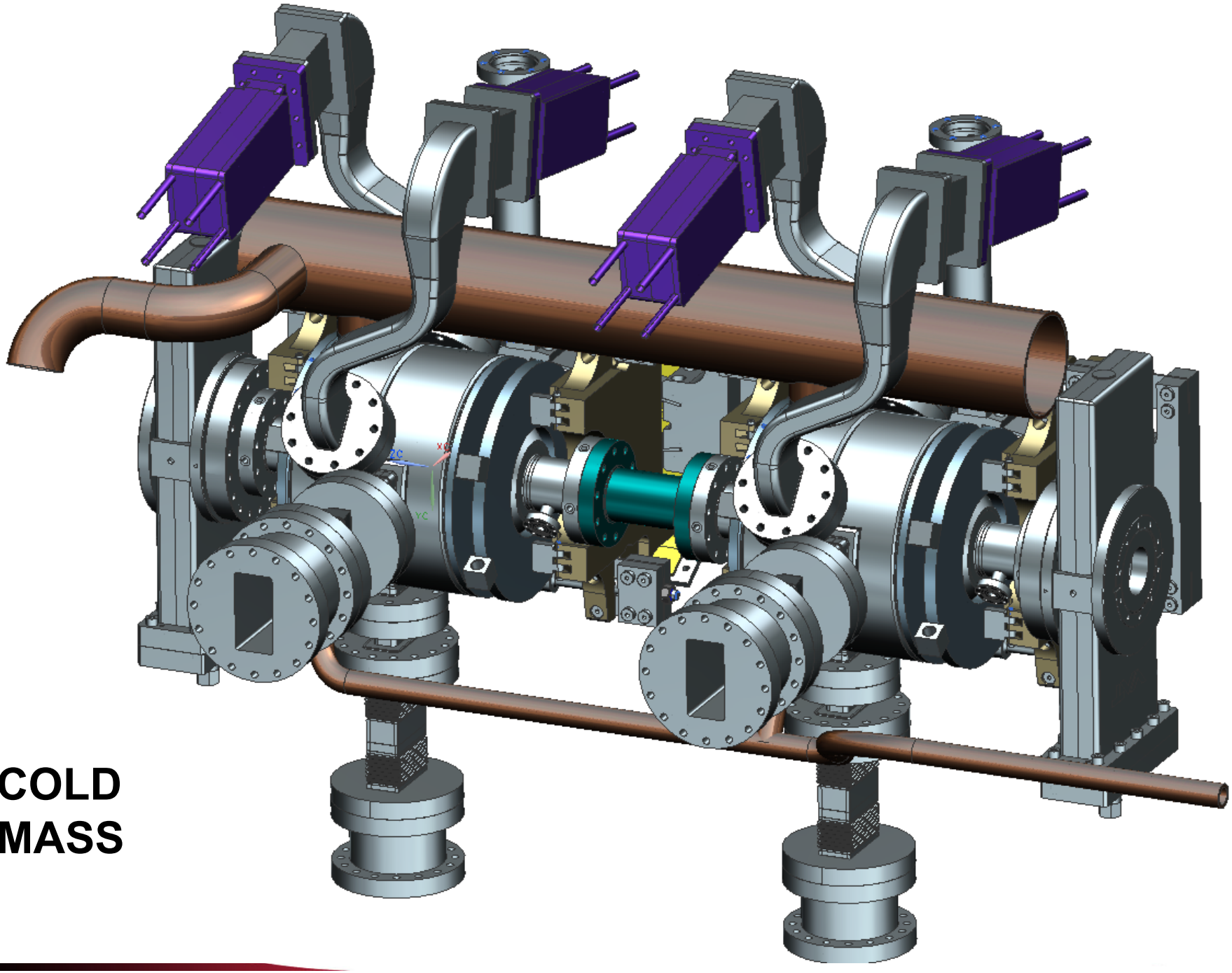
SPX CAVITY

Cavity in helium vessel



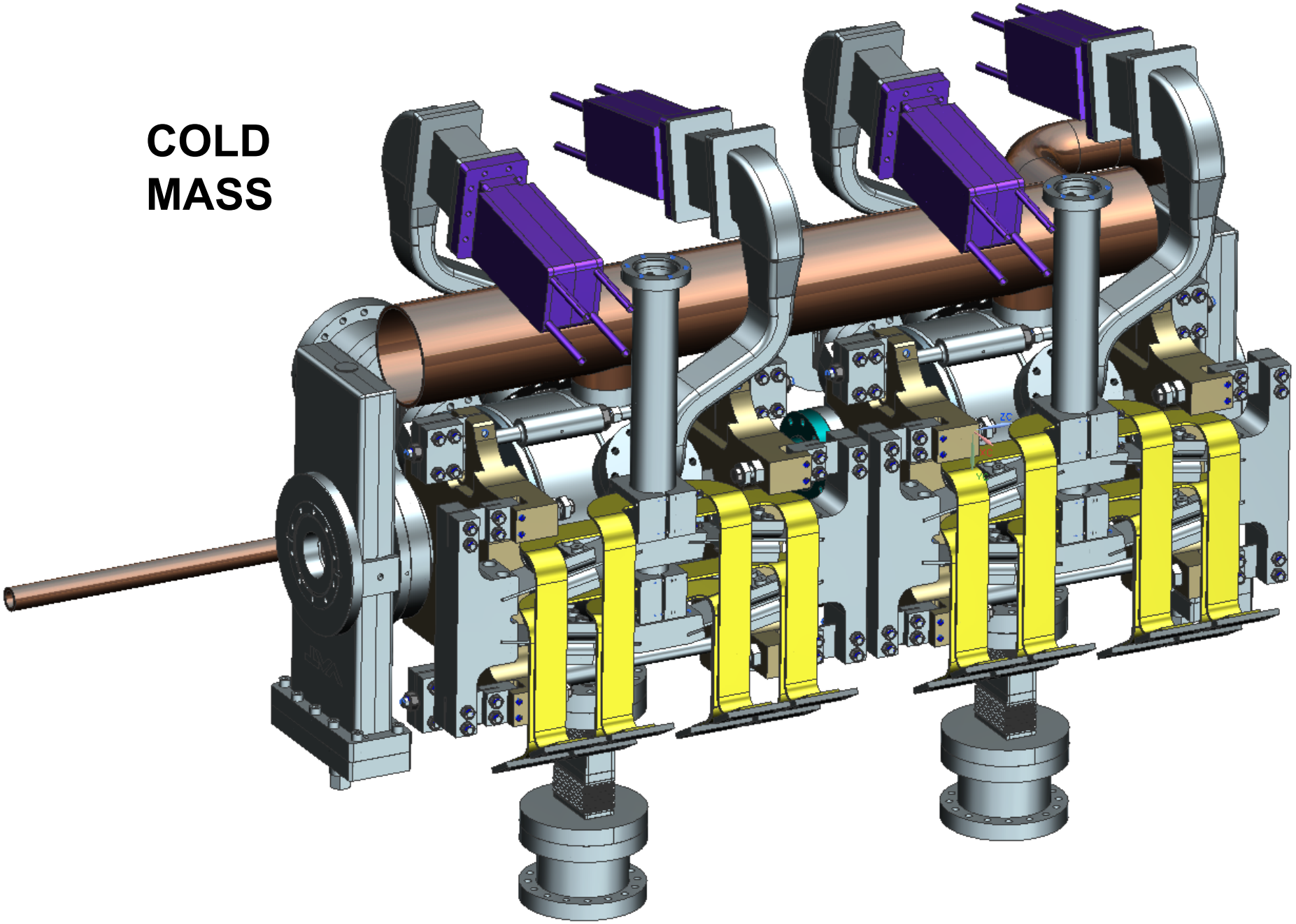


CLEAN ROOM CAVITY STRING

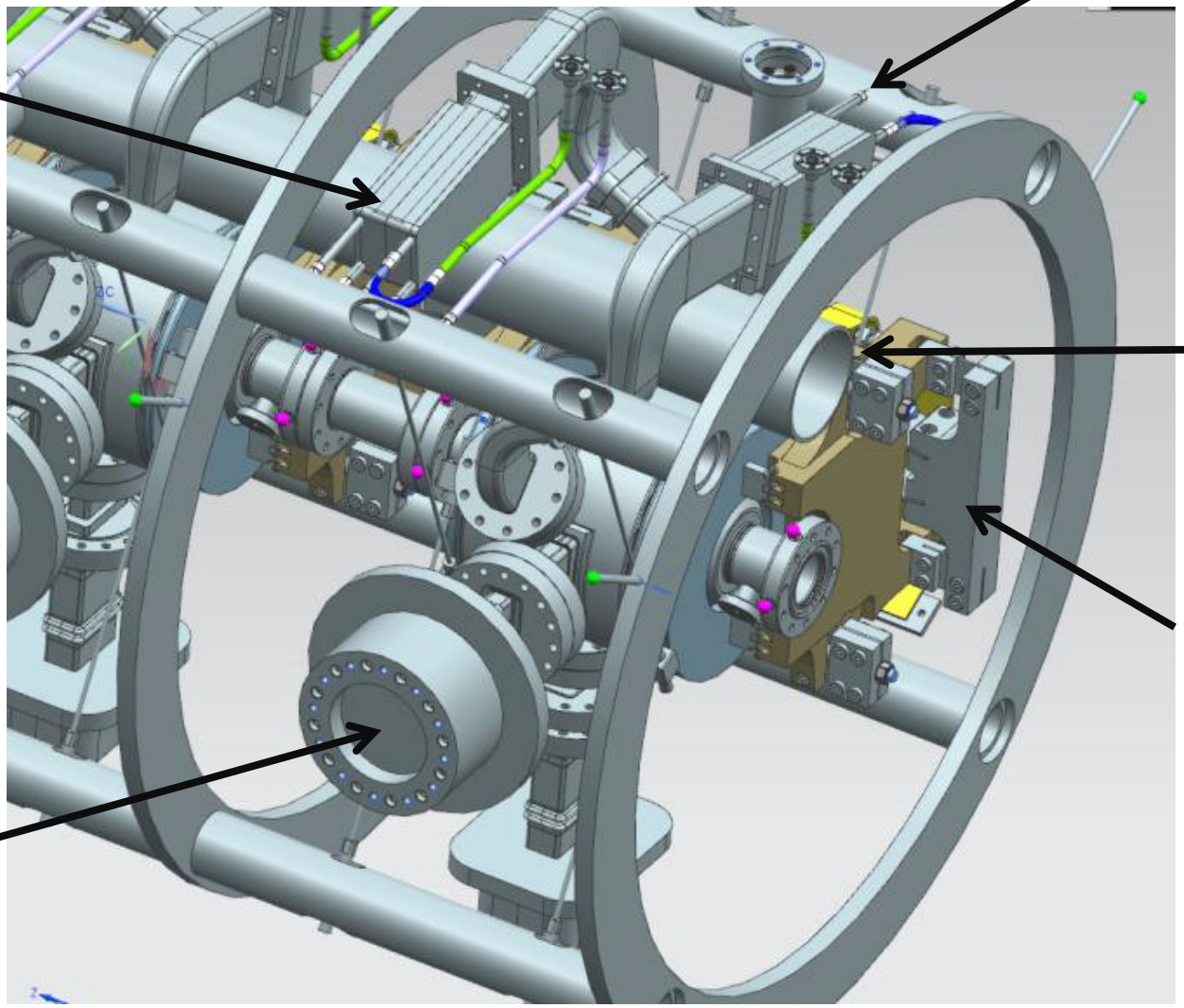


COLD MASS

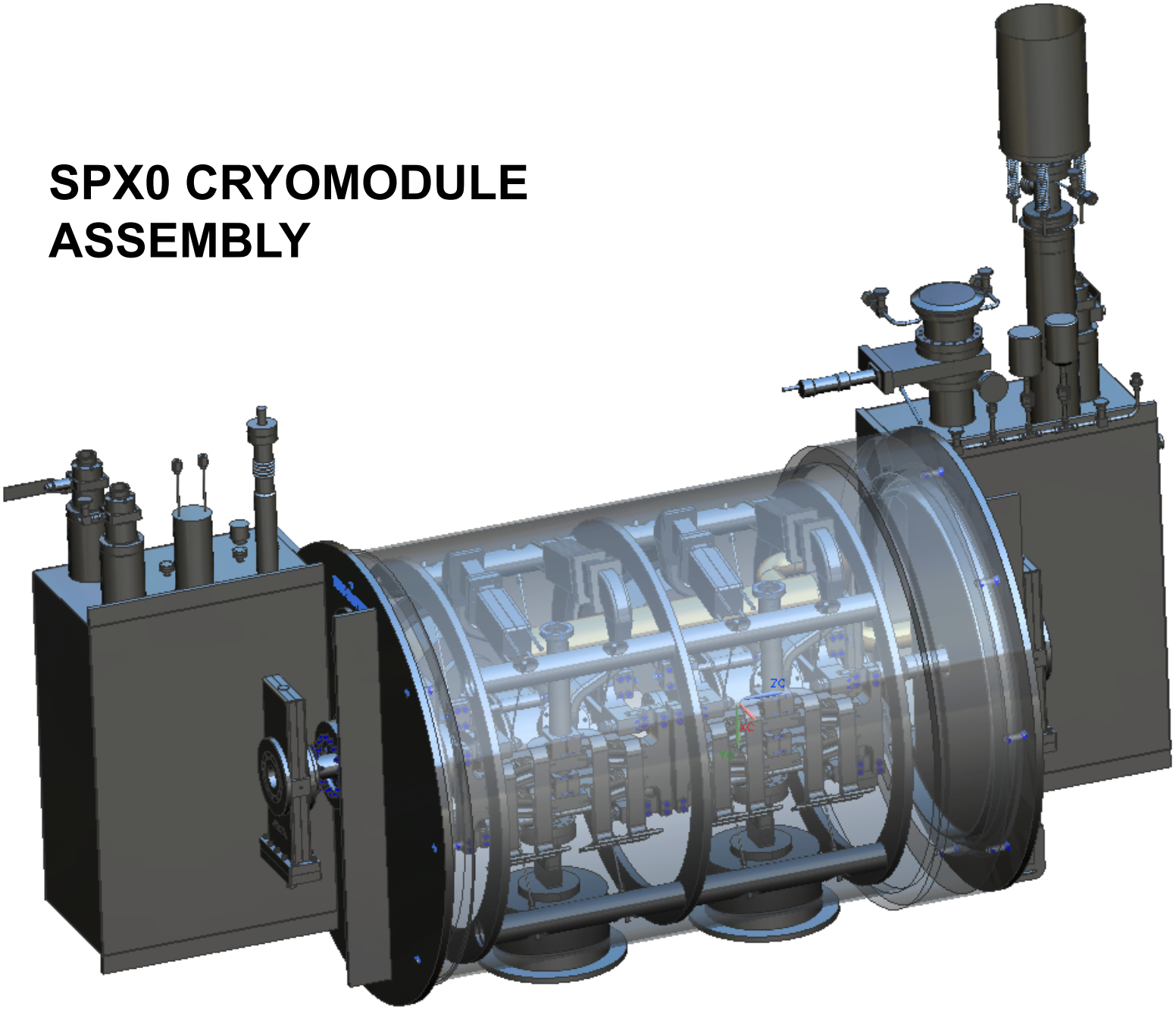
COLD MASS



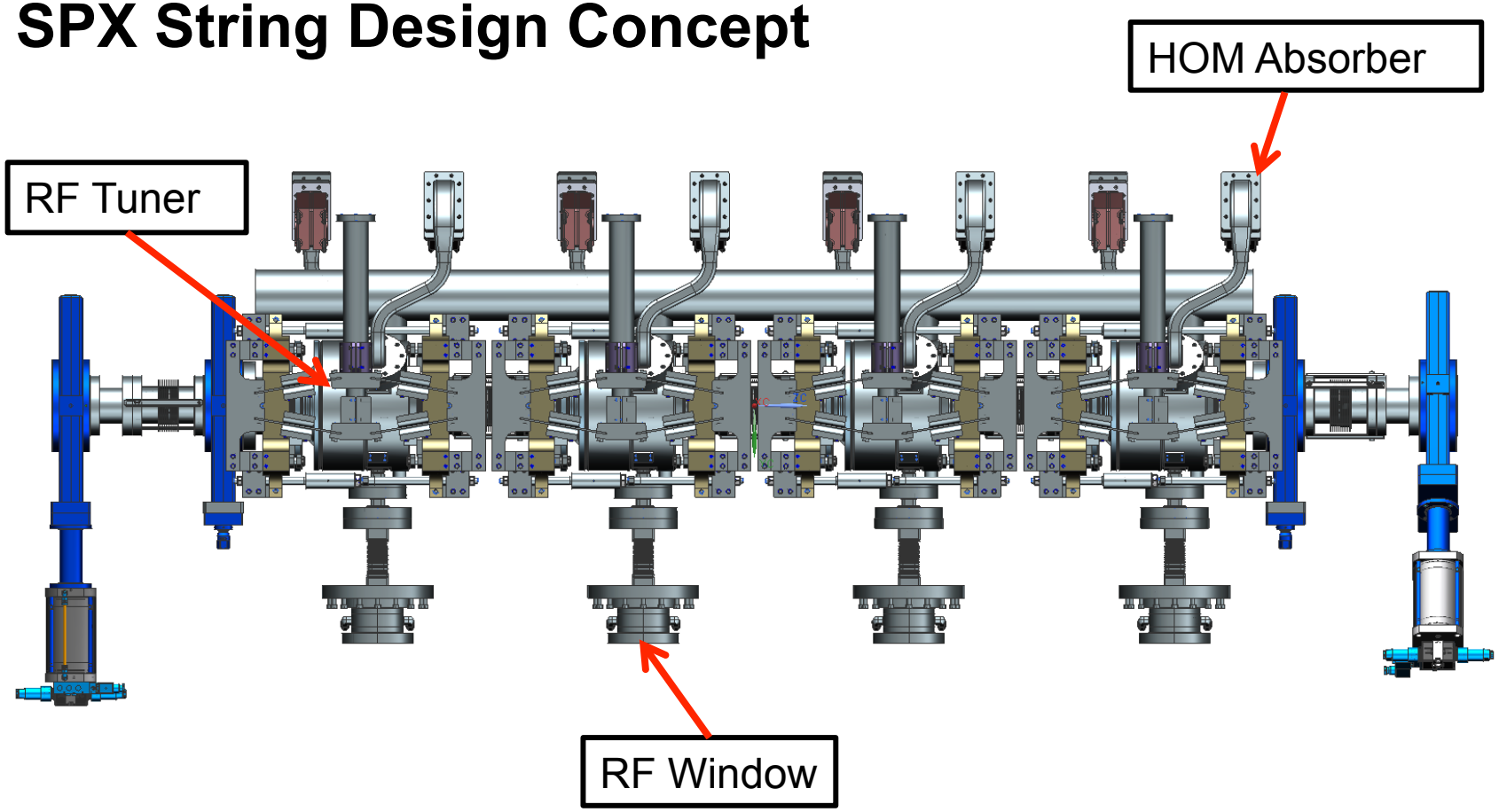
Cryomodule Concept



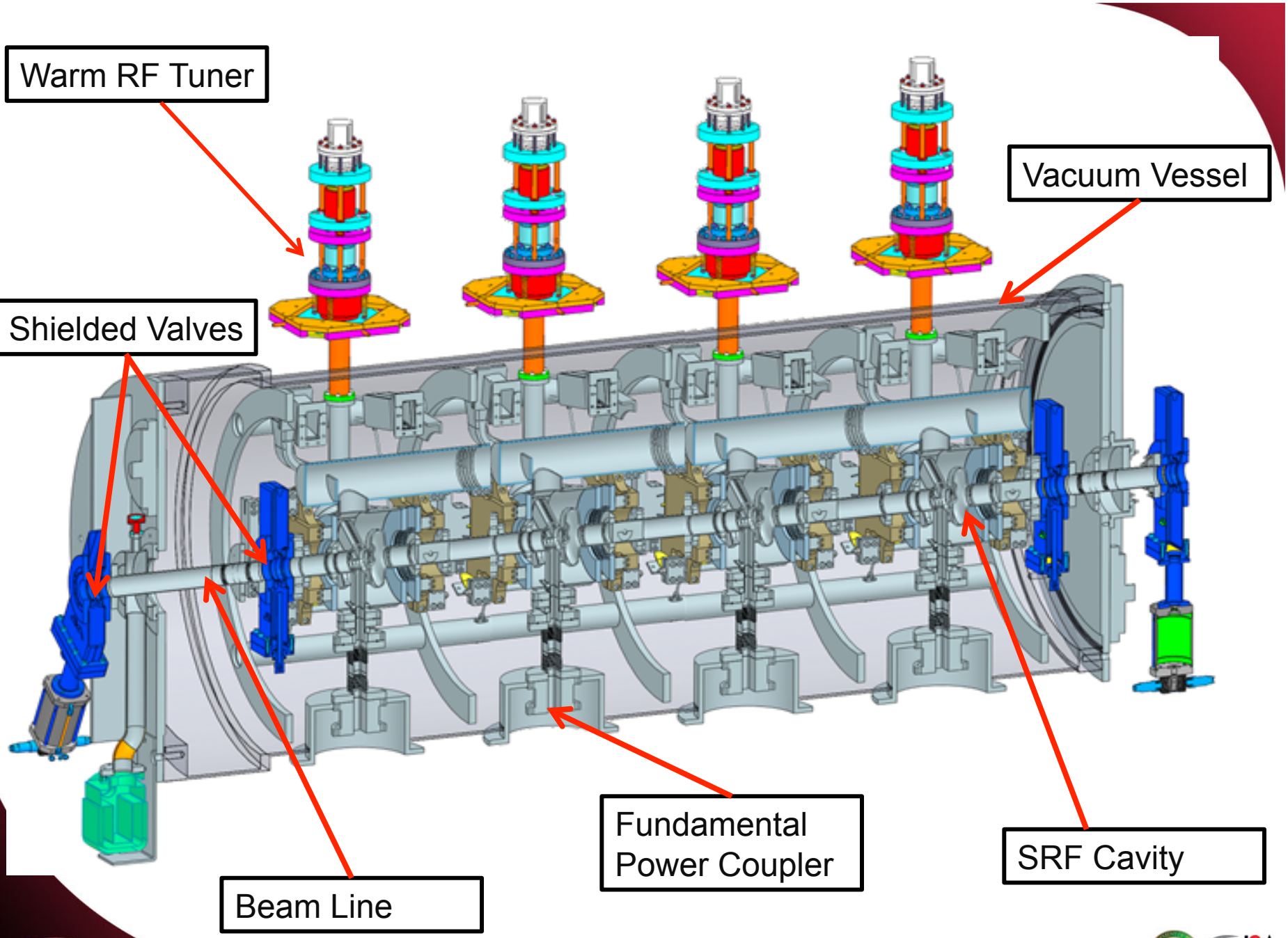
SPX0 CRYOMODULE ASSEMBLY



SPX String Design Concept



4 Crab Cavities Providing 2MV Chirp (Deflection) to the APS Beam


Warm RF Tuner
Vacuum Vessel
Shielded Valves
Fundamental
Power Coupler
SRF Cavity
Beam Line

Alignment of Cavities

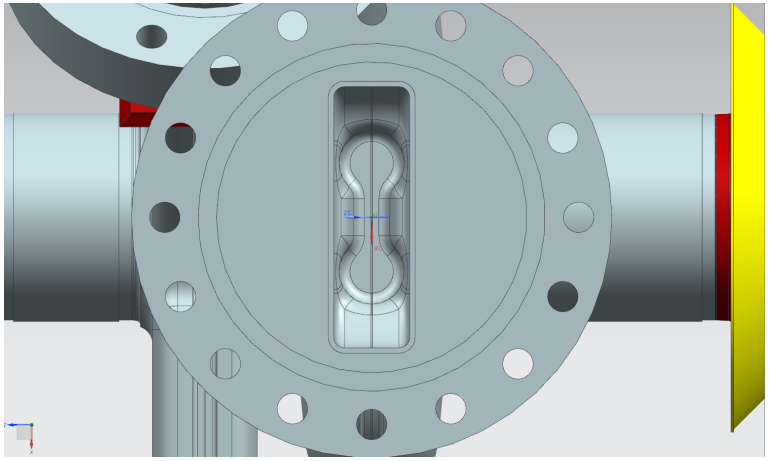
- An alignment plan has been developed for the full cryomodule design but current focus is on the SPX-0 (2 cavity version) reduced alignment specifications.
- Cavities will have fiducials machined in and measurements translated to their electrical centers by stretched wire methods

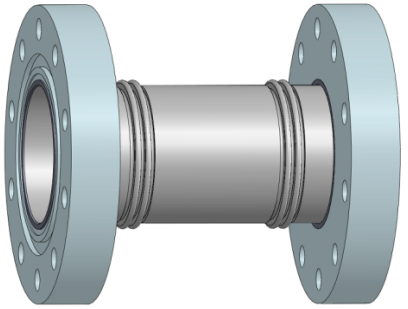
• SPX-0 cavity shown in the stretched wire setup. Actuators at each end of the cavity move a fine wire in the beam pipe to find the electrical center.

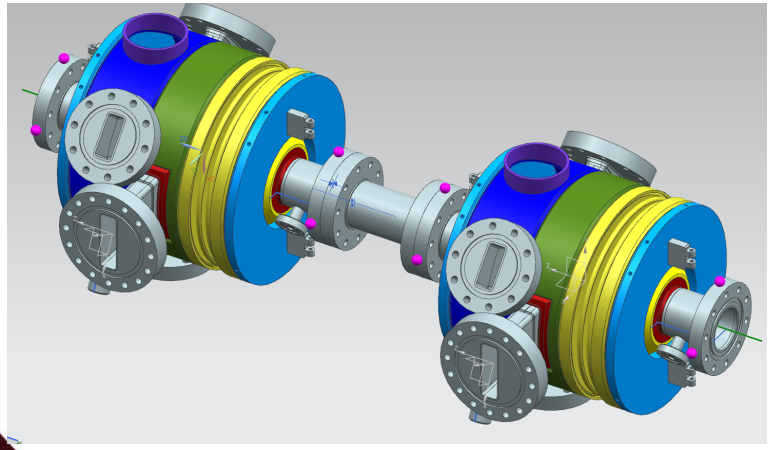
• Standard alignment methods with CMM or Laser Tracker will be used to define the wire position

Low Impedance bellows needed

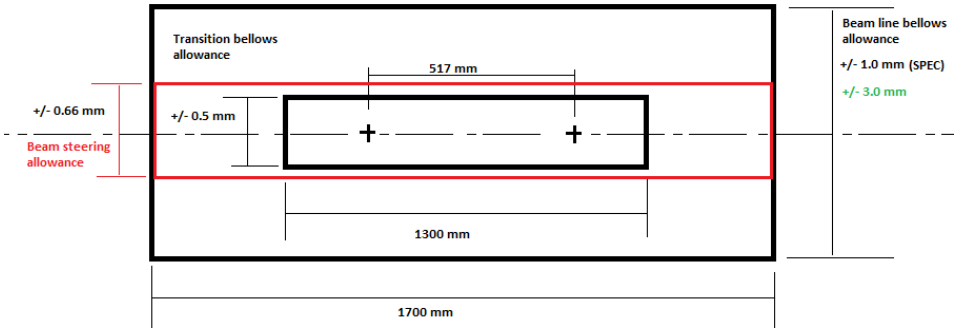
Alignment Requirements and Plans, Gate valves and Warm to Cold Transitions and Analysis: Josh Feingold/Genfa Wu







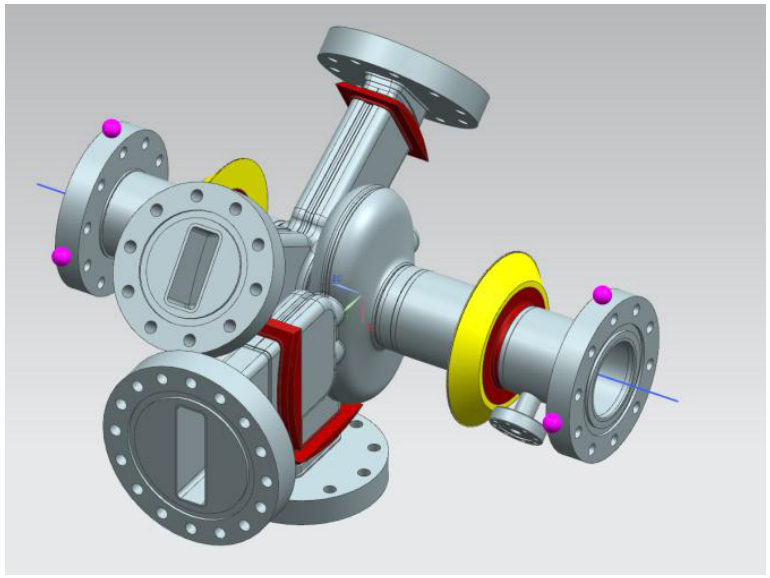
This alignment accuracy can be only confirmed by the APS beam in the ring test!

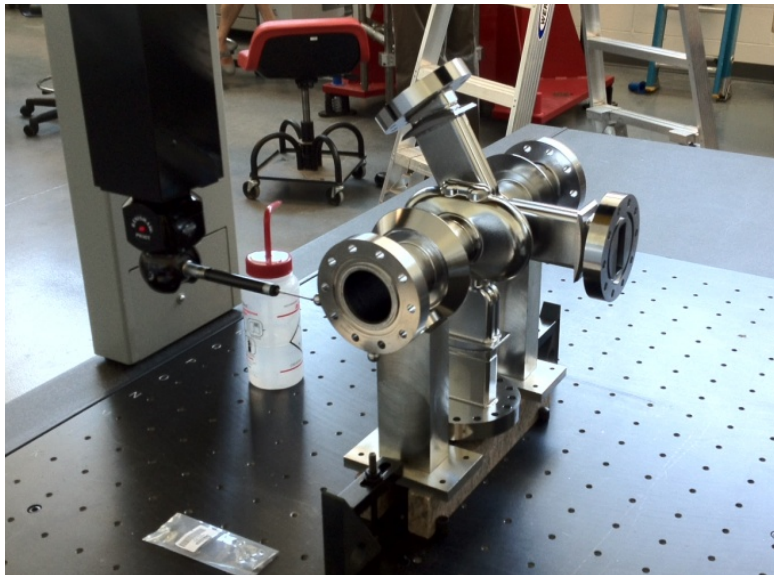


Alignment Concept

Alignment Procedure for Cryomodule

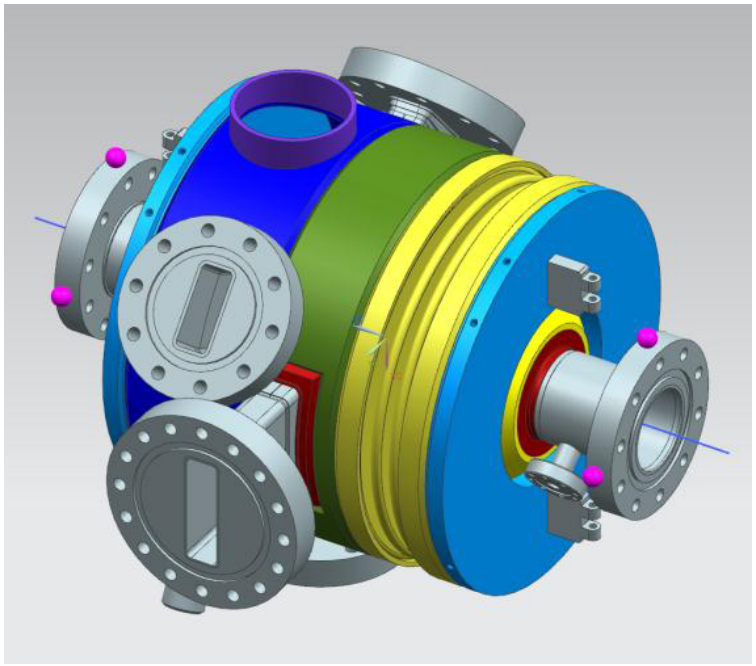
1. Fiducialize each cavity to the electrical center on CMM using the stretched wire setup (scan a wire in vertical "Y" plane, measure mechanical center in the horizontal "X" plane)
   - Cavity flanges machined for fiducial balls (shown in pink)

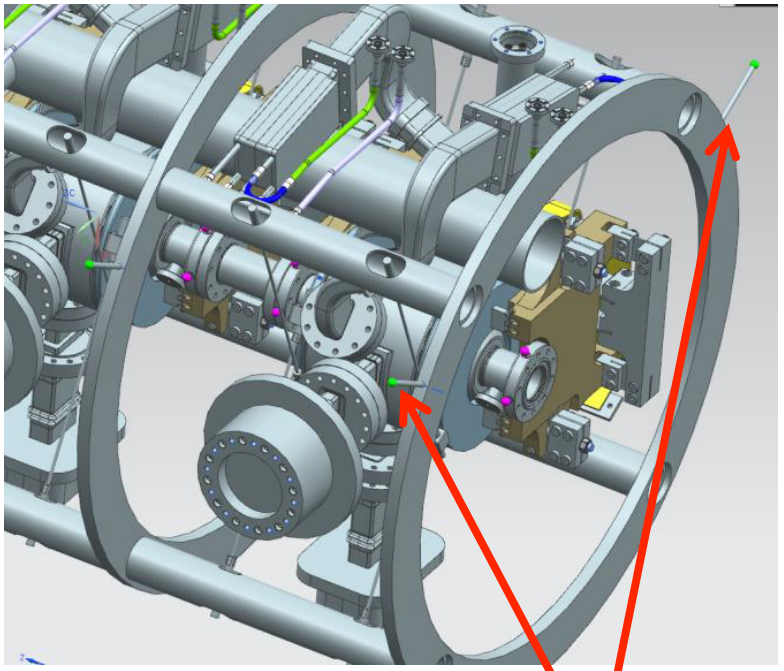




Cryomodule Alignment

2. Weld helium vessels on the four cavities and recheck vertical alignment on CMM





3. Transfer alignment to space frame (fiducial features on space frame)

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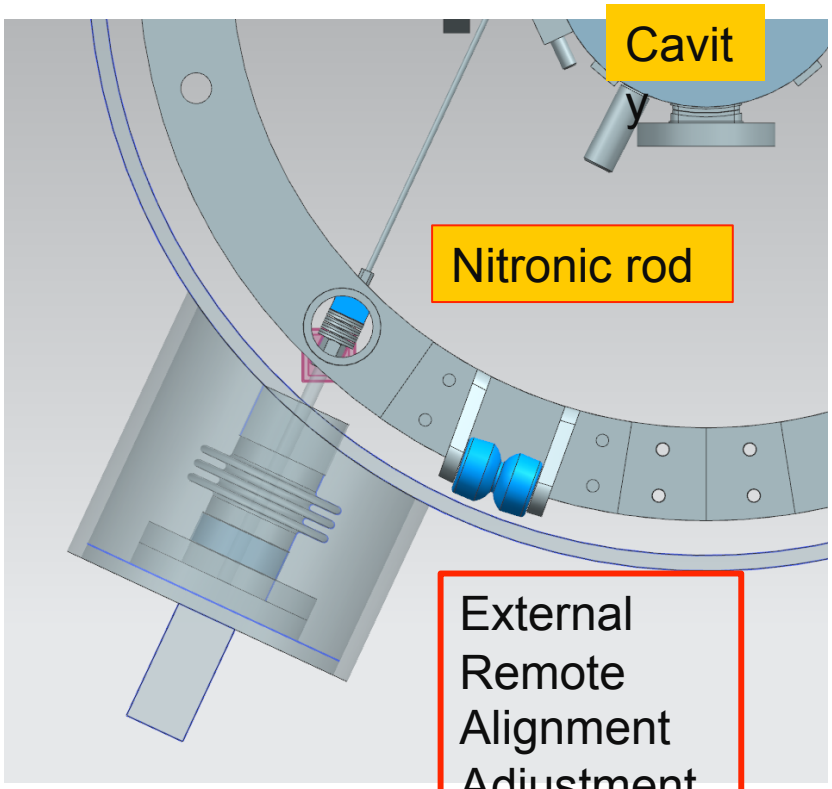
Cryomodule Active Alignment Concept

- Complete cryomodule assembly (access ports for checking alignment)
- Transfer alignment to vacuum shell (fiducial features outside shell)
- Align cryomodule in APS, support stand adjustment of cryomodule in place
- Perform low power beam test and use active alignment to positions cavities and optimize alignment

  - Remote alignment concept
  - (4) Nitronic rods support the cavity
  - External mechanical adjustment
    - Allows for 2 mm movement of each rod



Vacuum Vessel Design Concept

Cryomodule design will be based on the SNS redesign:

- Vacuum vessel will be the pressure boundary
- End cans and Vacuum Shell will be pressure stamped to meet 10CFR851
- Cryogenic heat exchanger inside end can

SNS First Spare HB Cryomodule

Vacuum Vessel Pressure Stamped in Industry!!

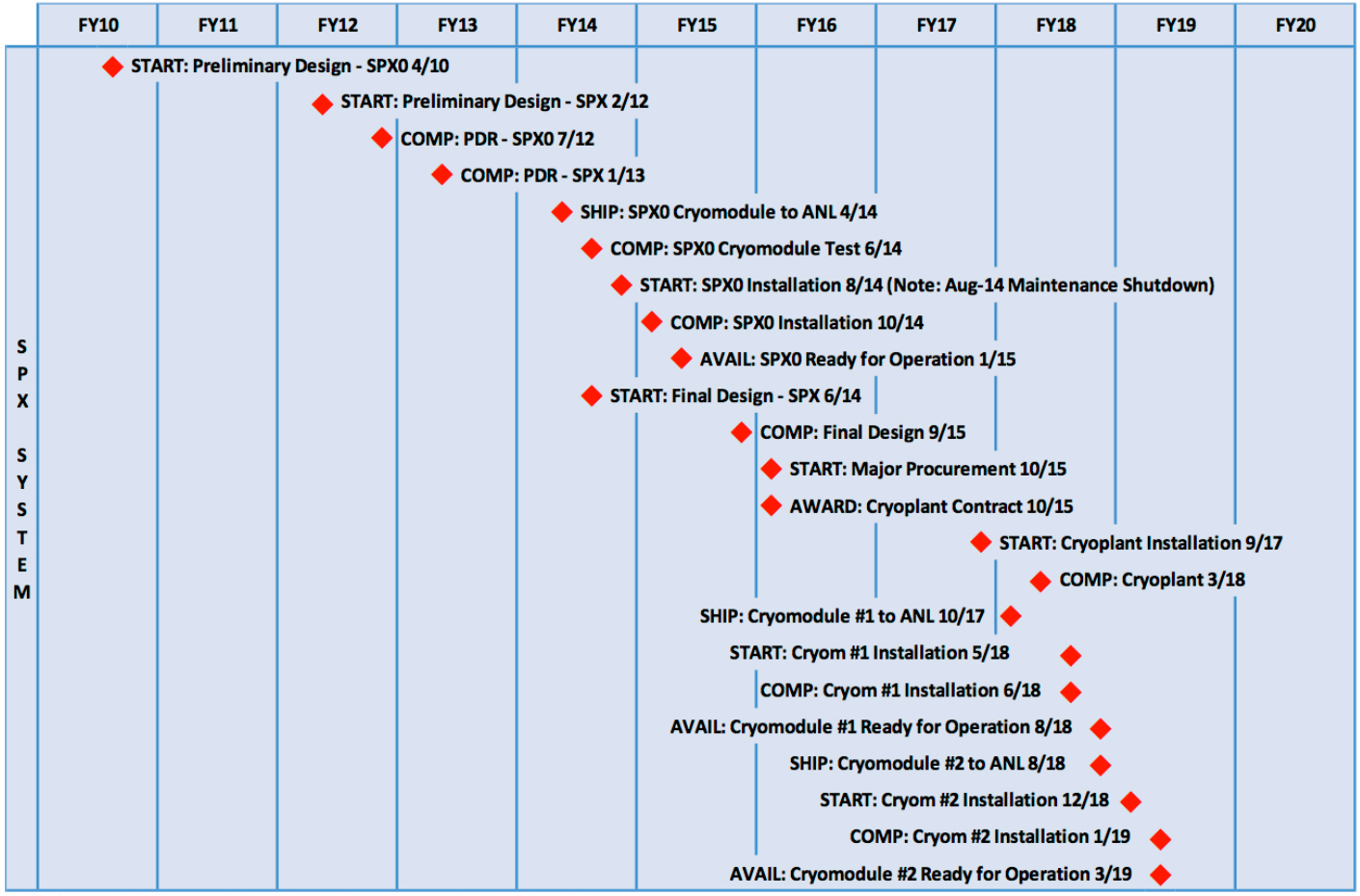
Summary

- Design solutions have been developed for APS SPX system
- Space is tight
- This is a high current application
  - Vertical alignment is critical
  - HOM damping must be very strong
  - HOM power must be managed carefully
- Cavity prototypes qualified
- Cryomodule based on JLab/SNS concepts
- Passed CD2 review Dec. 2012
- SPX0 install 10/14, Final system 3/19

Back up slides

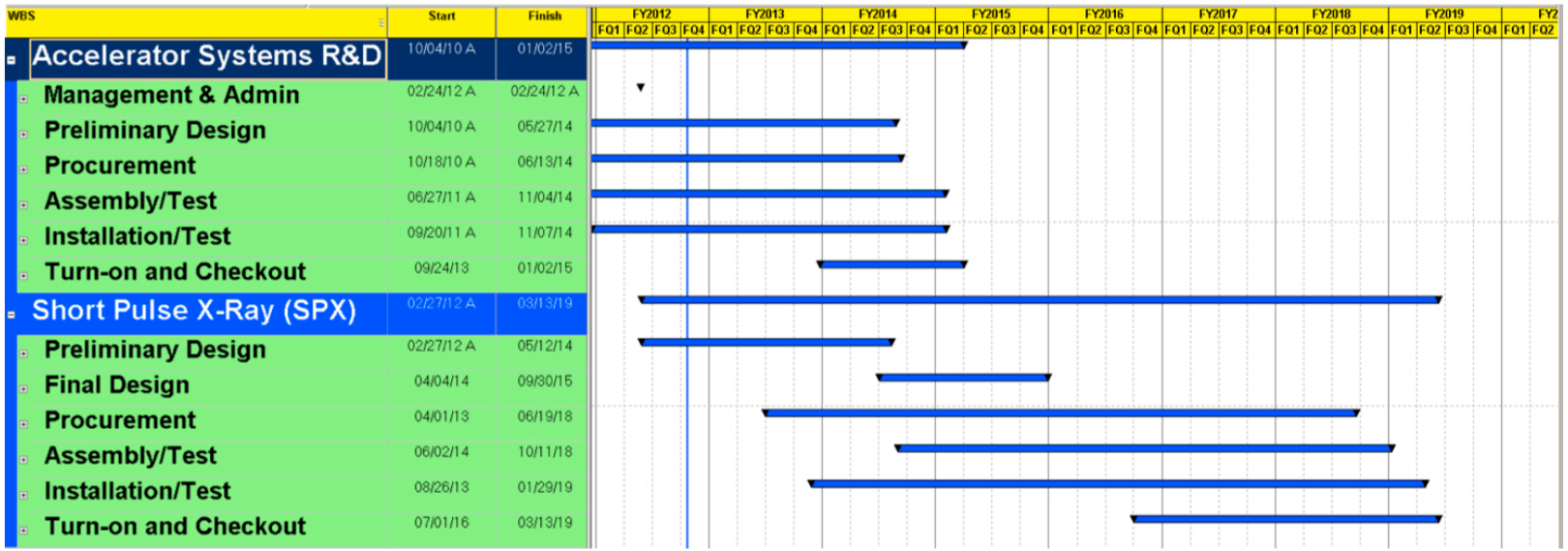
SPX milestones

SPX R&D and Production Milestones U1.02.01.03 & U1.03.03



SPX timeline

SPX R&D and Production Summary Schedule U1.02.01.03 & U1.03.03



WBS	Start	Finish
Accelerator Systems R&D	10/04/10 A	01/02/15
Management & Admin	02/24/12 A	02/24/12 A
Preliminary Design	10/04/10 A	05/27/14
Procurement	10/18/10 A	06/13/14
Assembly/Test	06/27/11 A	11/04/14
Installation/Test	09/20/11 A	11/07/14
Turn-on and Checkout	09/24/13	01/02/15
Short Pulse X-Ray (SPX)	02/27/12 A	03/13/19
Preliminary Design	02/27/12 A	05/12/14
Final Design	04/04/14	09/30/15
Procurement	04/01/13	06/19/18
Assembly/Test	06/02/14	10/11/18
Installation/Test	08/26/13	01/29/19
Turn-on and Checkout	07/01/16	03/13/19

PCR #004 implemented in Oct 2012

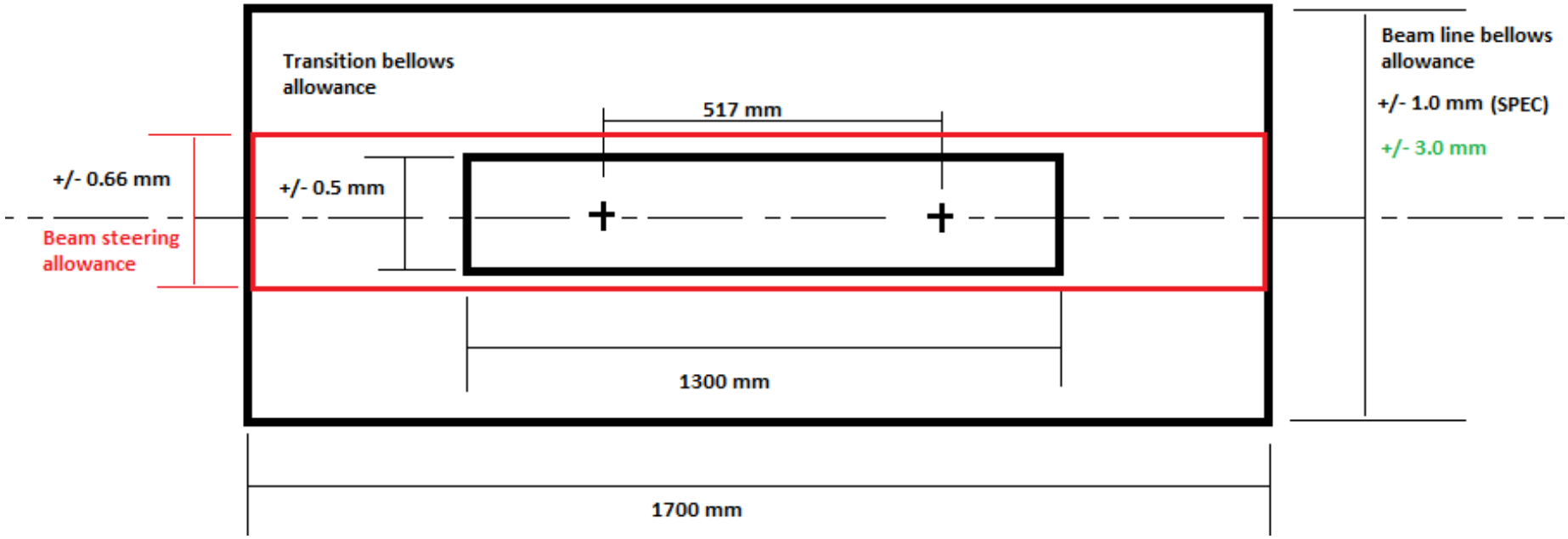
- Six (6) months delay in SPX0 Dampers delivery to JLAB June 2013
- Dampers delivery previously scheduled for Dec 2012
- No schedule impact to milestone Ready for CD4 Mar 2019

SPX0 Cryomodule Beam Test Goals

- Test and evaluate performance of deflecting cavities
  - In-phase on zero crossing
  - Cross-phase on zero crossing
  - Cross-phase on crest
- Test and evaluate performance of RF dampers
  - RF and thermal power handling
  - Meeting damping specs
- Test and evaluate alignment capabilities
- Test and evaluate cryogenic performance
- Demonstrate cavity voltage and phase control to beam deflecting specification
- Demonstrate the timing and synchronization at femto-second level
- Demonstrate SPX is transparent to storage ring operation with cavities detuned
- Demonstrate SPX concept when SPX0 is turned on
  - Proof of principle of beam deflecting operation – shorter X-ray pulses (10 ps, in phase)
  - Evaluate injection efficiency, beam life time, beam size, orbit stability, single bunch accumulation limit

Bellows adjustment and beam steering ranges

Adjustment bounding boxes

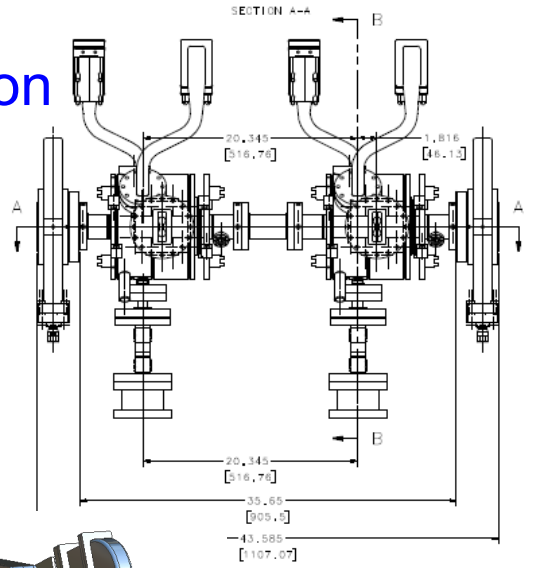


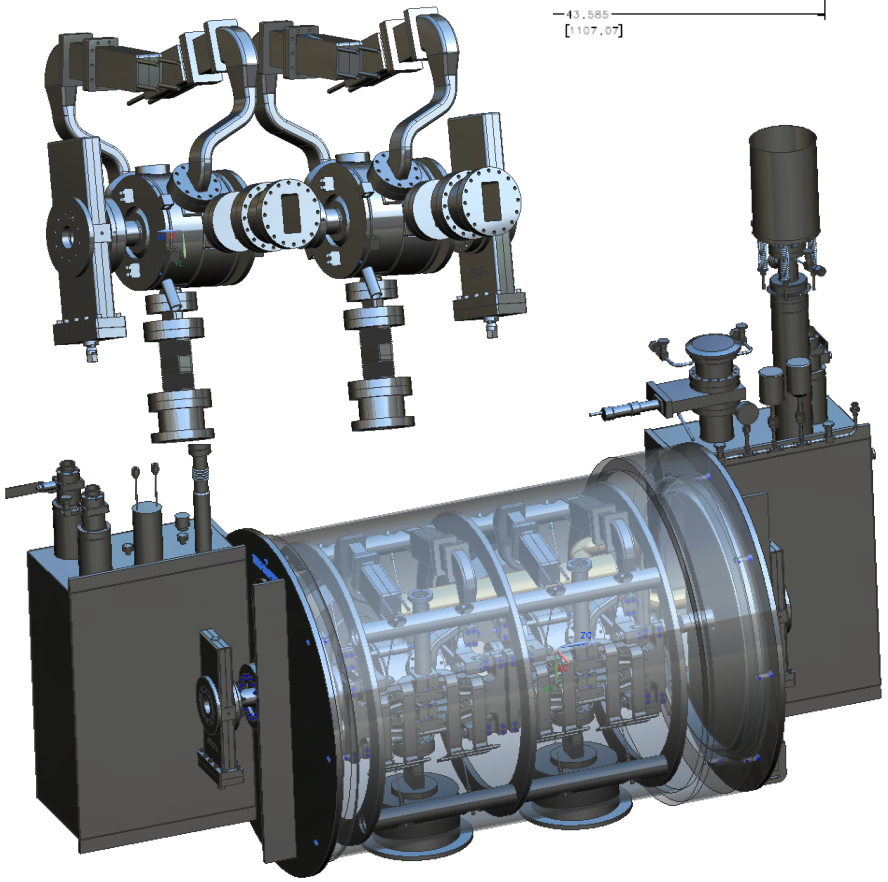
- Transition bellows allows +/- 0.5mm
- Beam line bellows allows +/- 1.0 mm
- Beam steering during beam studies allows +/- 0.66mm

If cavity misses beam line by +0.5 mm, adjusting cryomodule only can bring cavities back to perfect alignment of electric centers.

SPX (SPX0) Cryomodule Design and Specification

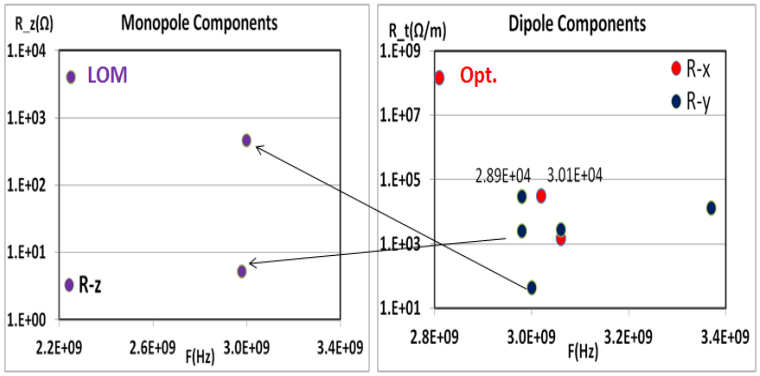
- SPX Upgrade project will be 2 modules with 4 crab cavities each
- SPX0 will be the prototype of half module as in SPX and tested at APS ring
- SPX0 will be the same specs of SPX proportion except the cavity-to-cavity alignment

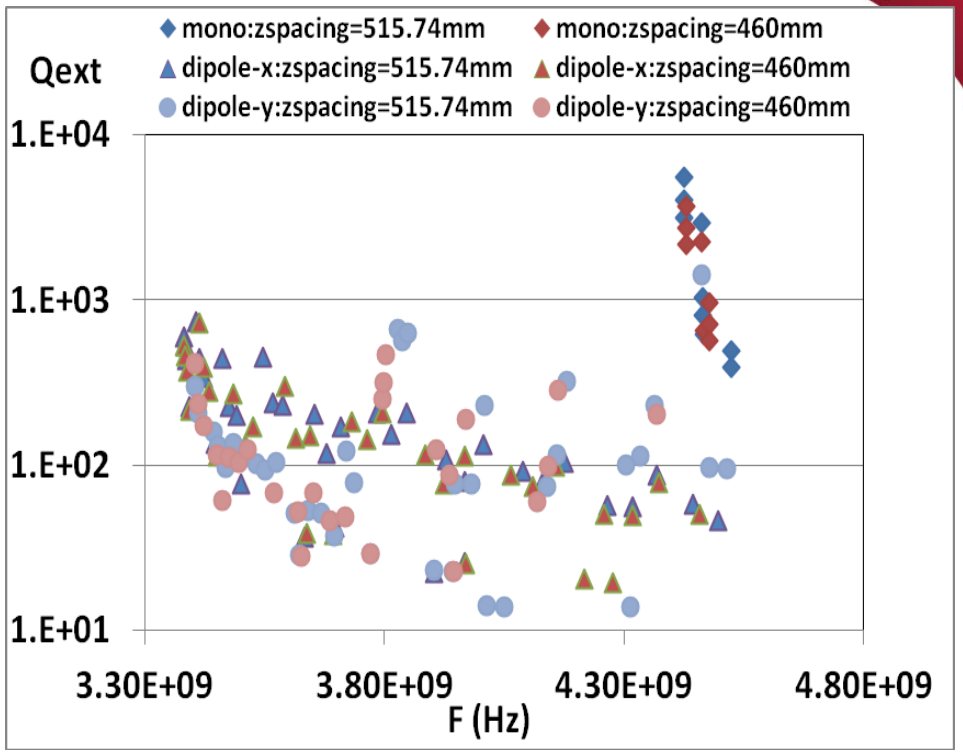


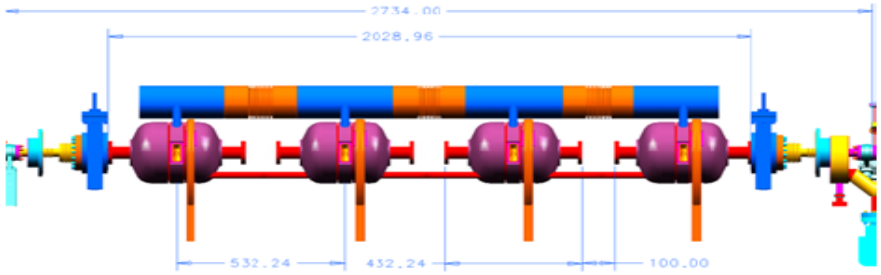


Cryomodule for SPX	Value	Unit
Lorentz Force Detune (cal. max.)	<30	Hz/(MV/m)^2
Tuner Coarse Range, +/-	200	kHz
Tuner Fine Range, +/-	25	kHz
Tuner Fine Resolution	<40	Hz, w/o pieco
Warm Piezo Tunning Range/Response	3-<1	kHz-ms
Helium pressure sensitivity	<99	Hz/Torr
Operational Crabbing/decrabing Voltage	2	MV
Module Number	2	
Cavity Number per module	4	
Qext, TM110-y-0, +/- %	1E+06, 20	
Klystron Power per Cavity	10	kW
Microphonic Amp. +/- 6σ	<100	Hz
Cavity Q0 at 2.0K	>1.0E+09	
Cavity to Cavity Center to Center Distance	>300	mm
Cavity Misalignment X/Y--Y/P/R, +/-	<500-<10	μm--mrad
80K Static Heat Load	<180	W
80K Dynamic Heat Load (HOM/LOM/FPC WGs)	<16/40/24	W
5K Static Heat Load	<5	W
5K Dynamic Heat Load (HOM/LOM/FPC WGs)	<5/13/12	W
2K Static Heat Load	<10	W
2K Dynamic Heat Load (Cavity/HOM/LOM/FPC WGs)	<28/0.2/0.5/0.5	W
Magnetic Shielding	<5	mGauss
Axial Magnetric Shielding Factor	>100	
HOM Longitudinal Impedance Upper Limit Rs*fhom (monopole HOMs, Rs=V^2/(2P))	<0.44	MΩ-GHz
HOM Horizontal Impedance Upper Limit Rt (dipole x-HOMs)	<1.3	M Ω/m
HOM Vertical Impedance Upper Limit Rv (dipole y-HOMs)	<4.5	MΩ/m

Trapped HOM modes in 4-crab cavity cryomodule, Omega3P simulation studies by ACD group at SLAC
IPAC WEPPC086 publication







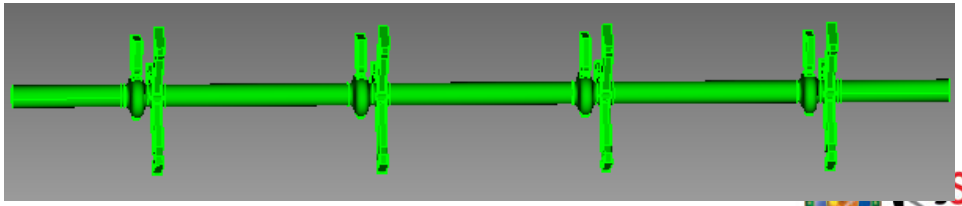
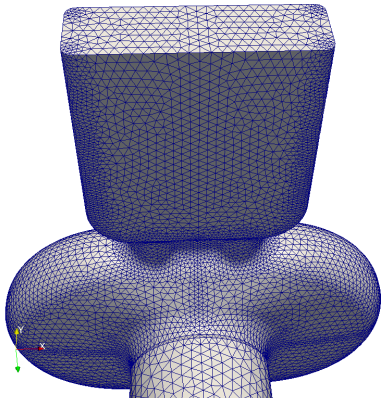


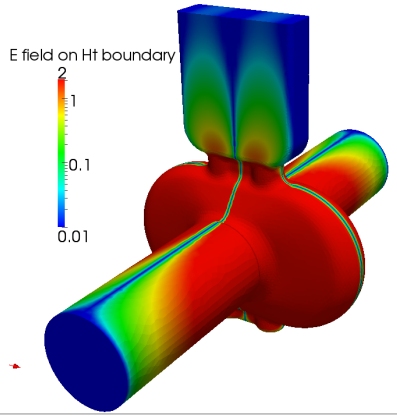
Figure 2: The trapped modes shunt impedances in the single SPX deflecting cavity without the FPC and LOM coupler windows. (a) monopole impedances and (b) dipole impedances in vertical and horizontal directions.

*Courtesy: L. Xiao, Z. Li of SLAC

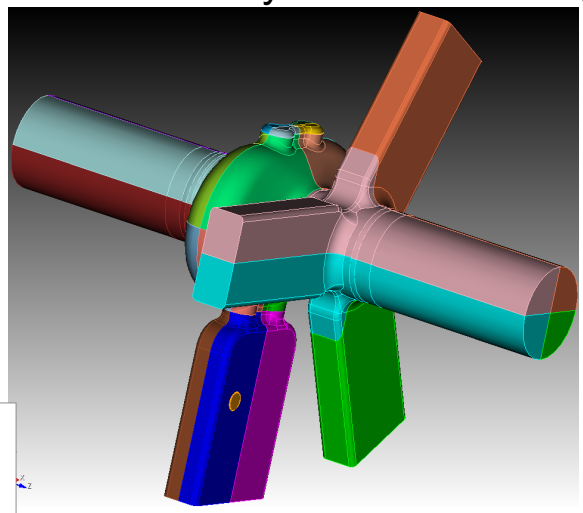
DFM Power Leakage to LOM Waveguide Port

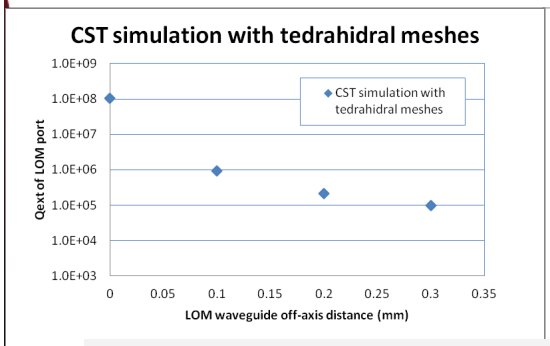
- Accurate TRL with adaptor removal bench measurement can quantify
- The remedy to this problem is to tune this cavity after the bulk chemistry
- Notch filter on the LOM WG can minimize the power leaking out if needed

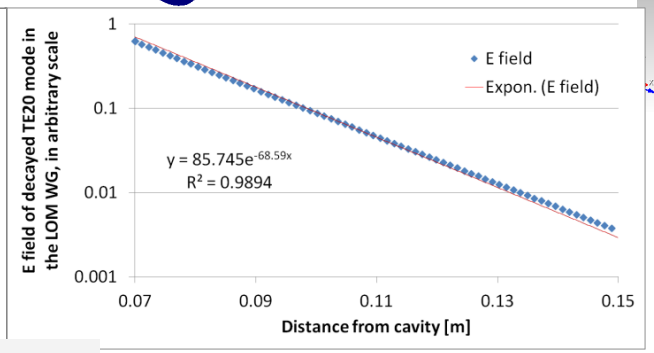


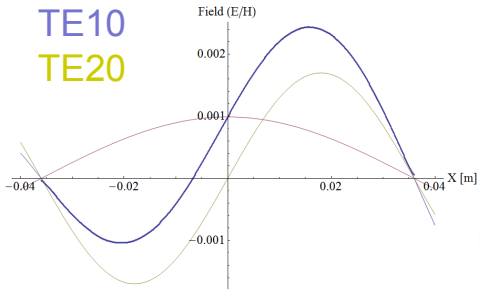


Port field on asymmetric meshing









*Courtesy: F. He of Peking Uiv. and Y. Yang of Tsinghua Univ.

SPX Cryomodules Design Requirements:

Physics parameters	Value	Unit
Total crabbing voltage	2	MV
Total de-crabbing voltage	2	MV
Beam current	<=150	mA
Number of cryomodules	2	
Length of section, including magnetic elements	3.034	m
Cryomodule length beam-line flange to flange	TBD	
Number of cavities per cryomodule	4	
Cavities		
Type	Superconducting	
Duty cycle	CW (8th harmonic)	
Design	Mark II	
Operating Frequency Deflecting Mode	2815.488	MHz
Geometric factor	227.5	W
R/Q'	18.6	W
Operating deflecting voltage	0.5	MV
Active length	53.24	mm
End flange to end flange distance	389.76	mm

SPX Cryomodules Alignment Requirements:

Alignment per module for APS installation	Value	Units
X misalignment (Horizontal)	±500	μm
Y misalignment (Vertical)	±200	μm
Z misalignment (Longitudinal)	±1000	μm
Yaw misalignment	±10	mrad
Pitch misalignment	±10	mrad
Roll misalignment	±10	mrad

Alignment per cavity in cryomodule	Value	Units
X misalignment (Horizontal)	±500	μm
Y misalignment (Vertical) **	±200	μm
Z misalignment (Longitudinal)	±1000	μm
Yaw misalignment	±10	mrad
Pitch misalignment	±10	mrad
Roll misalignment	±10	mrad

** with remote alignment