Short-Pulse X-Ray (SPX)

Cryomodule Design

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Jlab SPX Program Leader

APS-U Lehman Review
May 17-19, 2011

Outline:

- Scope of Work
- Requirements
- Cavity Design and Fabrication
  - Mark I
  - Mark II
- Cryomodule Design
  - Baseline Concept
  - Ring Test Cryostat
  - Helium Vessel Design
  - Tuner Design
  - Alignment Concept
  - Low Impedance Bellows
  - Cryogenic Heat Load Estimates

WBS – Scope of Work

R&D Phase:

- Develop a two cavity test cryostat for an APS ring test, October 2013
  - *Goal is to demonstrate crabbing in a stable operating configuration*
  - *Secondly, test design concepts for cavity, cavity alignment, HOM absorbers, cryogenic design in the operational and parked configuration*
    - Parked configuration is when cavities are detuned and off

Production Phase:

- Develop a cryomodule design for four cavity cryostat that meet APS operational requirements
- Fabricate, qualify and install 2 cryomodules in APS ring

The Team

- Project coordinators are John Mammosser (JLAB), Genfa Wu (ANL)

- **Task leaders have been assigned to each major component**
  - Helium Vessel: Katherine Wilson (JLAB)
  - Tuner: Joe Matalevich (JLAB)
  - Dampers: Geoff Waldschmidt (ANL)
  - Cavity: Haipeng Wang (JLAB) / Geoff Waldschmidt (ANL)
  - Cavity Alignment: Joshua Feingold (JLAB)
  - Cryomodule: Mark Wiseman (JLAB) / Joel Fuerst (ANL)

- Additional JLab Staff - R. A. Rimmer, P. Kneisel, G. Ciovati, G. Cheng, R. Geng, J. Henry, L. Turlington, C. Smith, R. Lasitor ,A. Burrill, T. Goodmen, L. King, S. Manning, I. Daniels, G. Slack, B. Clemens, K. Macha, D. Forehand, R. Overton, T. Harris, P. Kushnick, K. Worland, T. Bass, B. Carpenter, S. Castagnola, K. Davis, C. Dreyfuss, S. Dutton, B. Manus, B. Martin, A. Palczewski, M. Powers, T. Reilly

Performance Requirements:

Cavity:

Frequency deflecting mode – 2.815488 GHz (TM110)

Frequency LOM mode – 2.3 GHz

Deflecting Voltage – 0.5 MV

Operating temperature – 2K

Magnetic field at Voltage – 100mT

Q-value at Voltage - 1e9

Pdiss at Voltage - 7 Watts

Input coupling Qext – 2e6

Klystron power required - 10KW

HOM power (w/beam) – 492 W

LOM Power (w/beam) – 1800 W

Duty cycle – CW (8^{th} harmonic)

Beam current – 200mA

Pressure sensitivity – 9 Hz/Torr

- Cavity Q-value (Pdiss) will be most difficult parameter to achieve

- LOM/HOM Power handling is critical as well

Performance Requirements:

Cavity Alignment:

X-misalignment - <500 um

Y-misalignment - <100 um

Z –misalignment - <1000 um

Yaw – 10 mrad

Pitch – 10 mrad

Roll – 10 mrad

Shielded bellows typically do not have vertical (Y) compliance

- Alignment tolerances in y direction are beyond standard alignment techniques. Therefore active alignment is being pursued
- Roll is also a concern and will need development

Tuning Requirement:

Tuning range coarse - ± 200KHz

Tuning range fine - ± 25KHz

Fine tuning resolution – 40 Hz

Cavity stiffness – TBD

Fast detuning of cavity – 1ms

- Tuning resolution is finer then typical hardware used, piezo might serve as fine and coarse drive

Cryomodule Design Approach:

Where Possible Use existing Jlab cryostat design experience and concepts:

- Draw from Jlab cryomodule experience
- End loaded cryostat (SNS/Jlab Upgrade) style most likely
- Space frame if possible for cavity alignment and construction
- Cavity string assembly in clean room, hermetically sealed with end valves

Challenges:

- Frequency sensitivity of cavity requires high resolution tuner
- Alignment tolerances will require active alignment of cavities installed in cryostat
- Packaging is more difficult due to number of penetrations and waveguides
- Low Impedance bellows will be required

Ring Test Cryostat Approach:

- Ring test will be utilized to demonstrate stable crabbing while beam loaded and in the parked configuration
  - Alignment concepts must work for ring test
  - Fast detuning must be demonstrated
  - Need reasonable Q-value to maintain cryogenics operation in ring test configuration

- Jlab HTB cryostat will be used to save time and costs
  - Significant mods will be needed to vacuum shell

- Two cavity design are being pursued, Mark I and Mark II
  - Down select will be made to choose one design for the ring test
  - Prototype of both have been fabricated (some challenges here)
  - Mark I is qualified, Mark II is well under way to be qualified as well

Cryostat Safety:

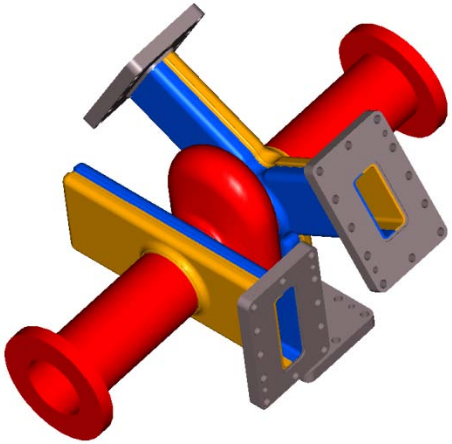
- ANL and Jlab safety requirements are the compatible 10CFR851

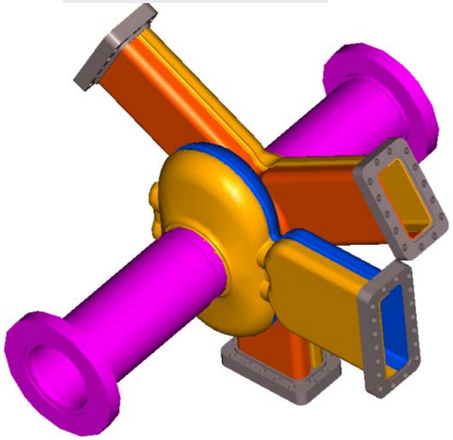
- Jlab will design to ASME pressure vessel code:

  ASME B&PV Code Section VIII requirements:
  - Equivalent level of protection (due to use of special materials)
  - Documented organizational peer review of design and calculations
  - Qualified personnel for inspections
  - Documentation, traceability and accountability maintained for pressure vessels

Cavity Designs:

- Two cavity designs being pursued
- Both have their benefits
- Down select planned for August 2011

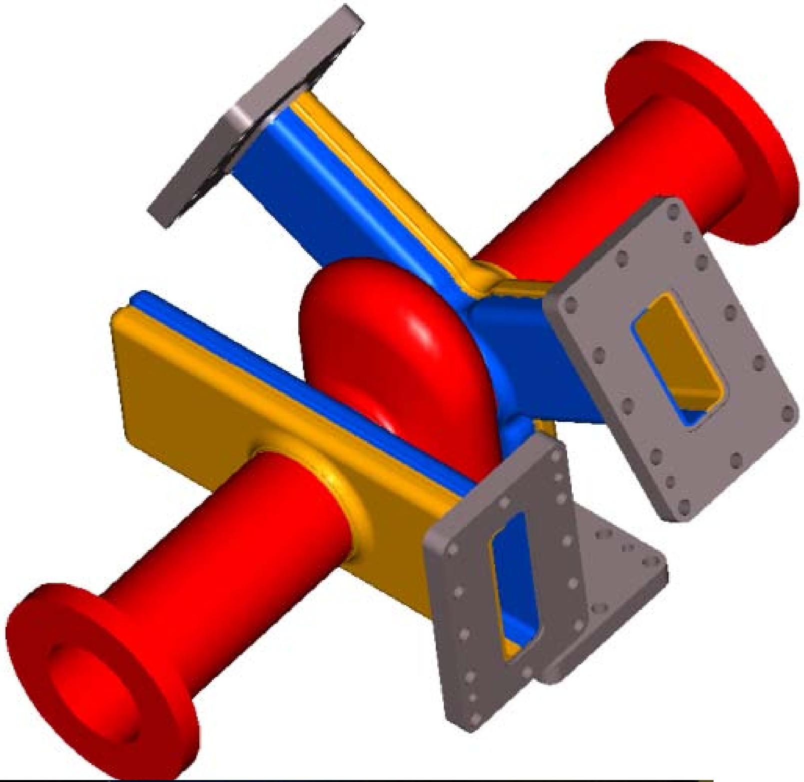




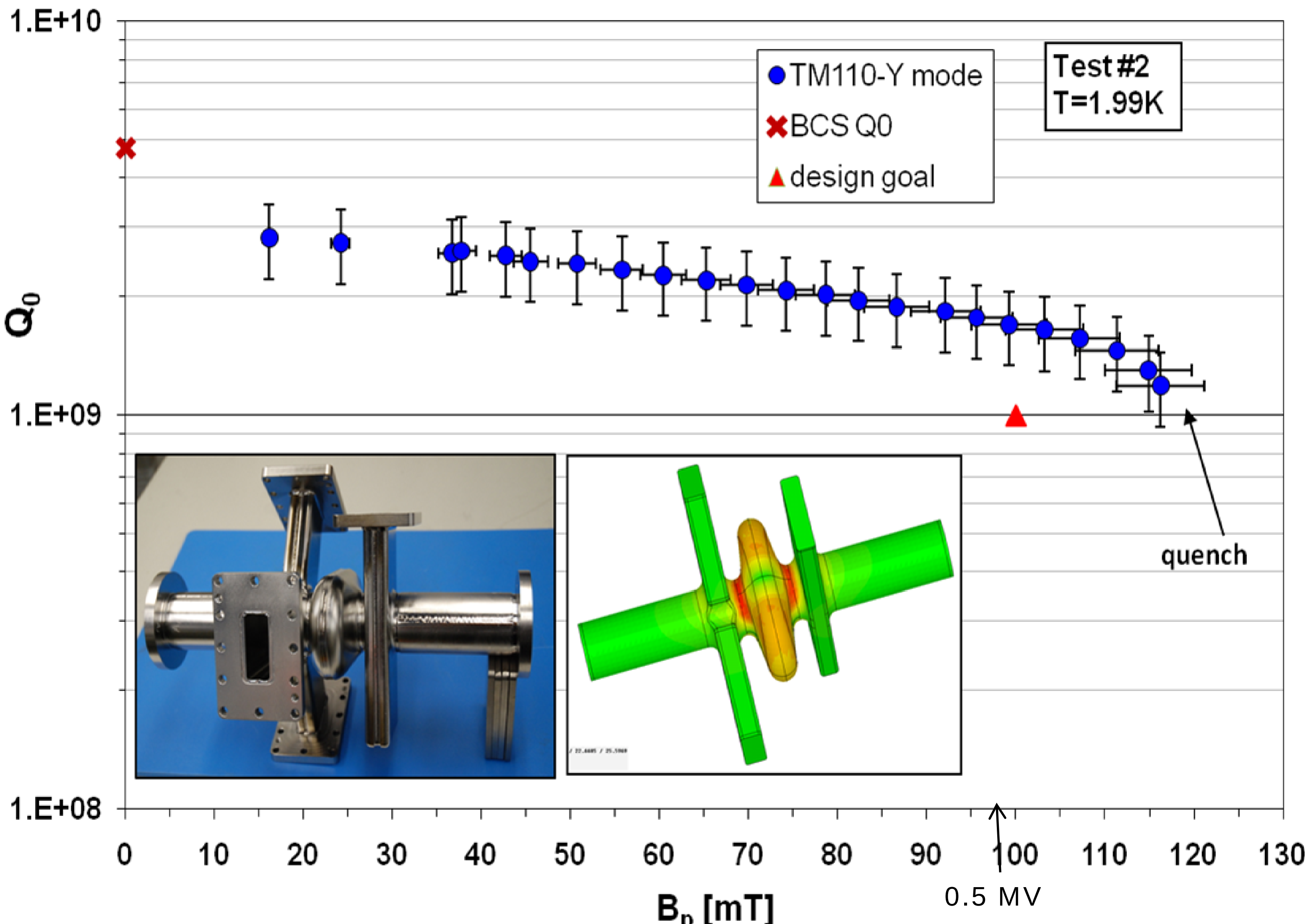
Cavity Comparison	MARK I	MARK II
Beam impedance margin	Meets Specs	Excellent
LOM Coupling	on beam pipe	on cavity cell
RF Kick Performance	same	same
Size		Compact
Induced HOM power	Meets Specs	Better

Mark I Cavity:

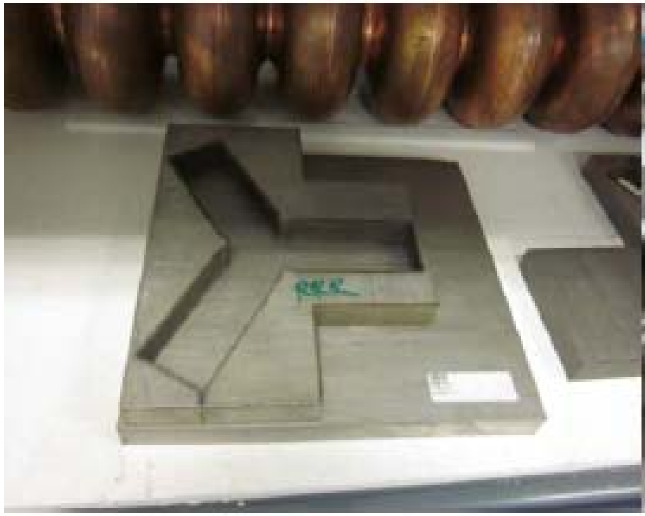
- Cavity was fabricated from sheet niobium with standard techniques
- The "Y" waveguide was fabricated from niobium stock due to the shape
  - Machining worked well



Mark I Prototype Crab Cavity (CC-B1 for SPX Project) Vertical Test at JLAB



Mark I Cavity Fabrication:



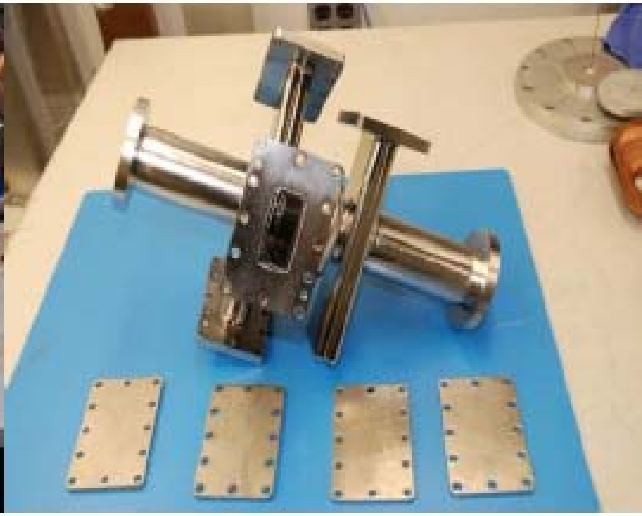
EDM cut Y Nb fine grain RRR>250 plate

CNC machine two halves and EBW

Survey on LOM WG pre-alignment

Finished Y waveguide group

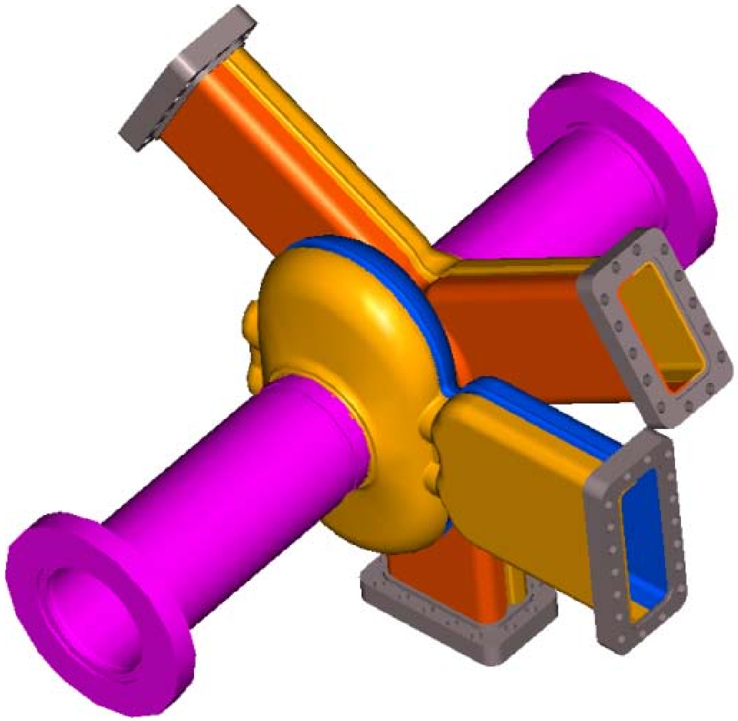
Finished two half groups before final equator EBW

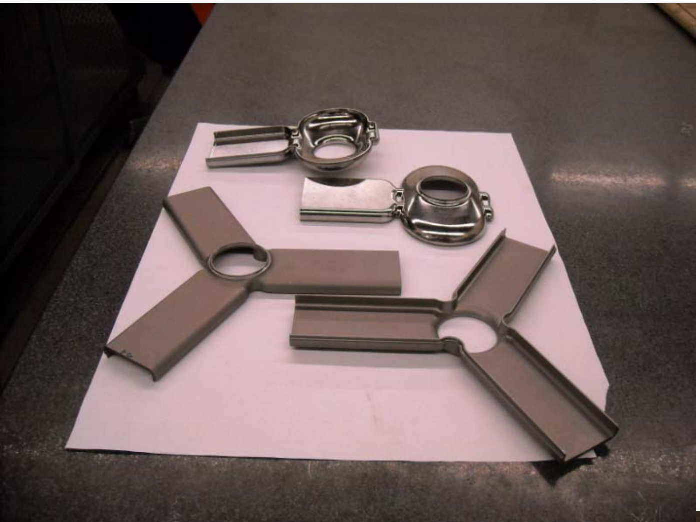


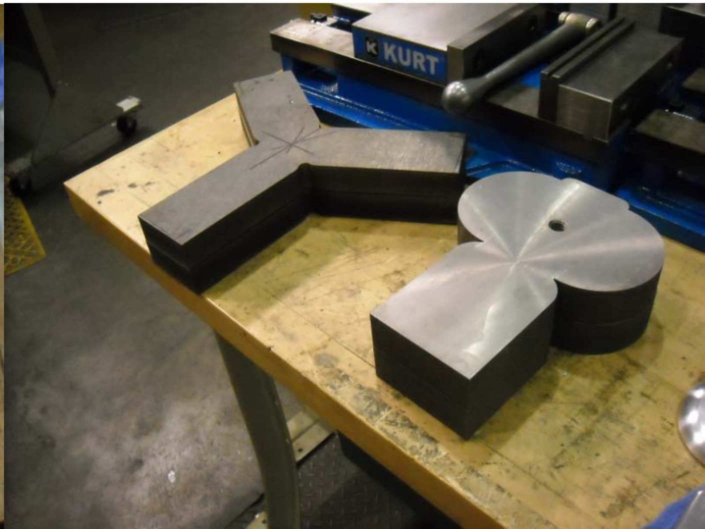
CCB1 cavity with Nb blank offs

Mark II Cavity

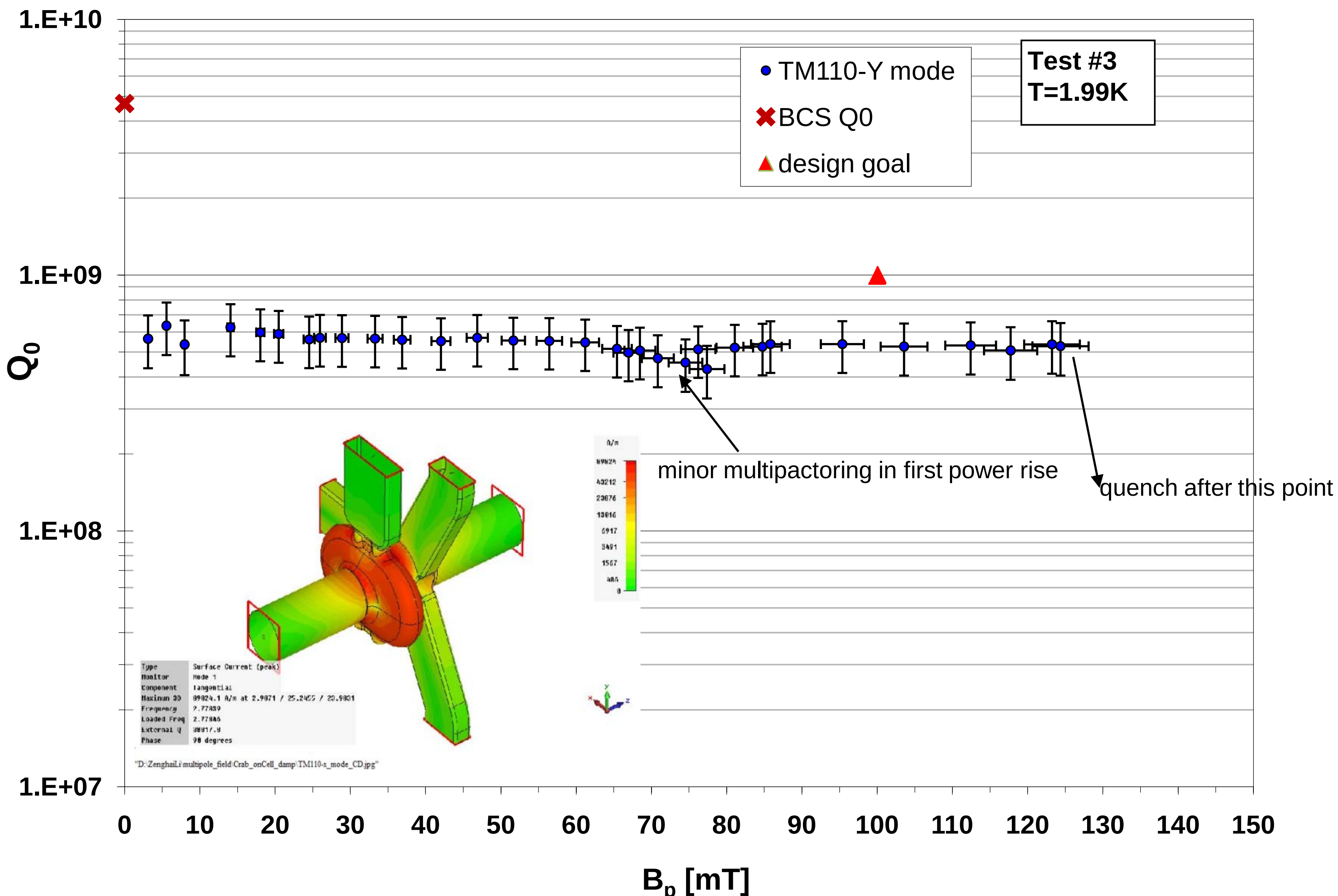
- Fabrication used bulk niobium for the cell and “Y” waveguide
  - Cell fabrication also worked well







Mark II Prototype Crab Cavity (CC-A2 for SPX Project) Vertical Test at JLab



Mark II Cavity Fabrication:


Cut fixture plate


machined fixture base


RRR>250 large grain Nb ingor


EDM wire cut Nb template


Machine outside surface


Machine inside surface with 30um unfinished


Milling tool head for last inner finish


Machine inner surface on the base


Finished first half with 4mm wall thickness


Match to other Al model half


Outside finish of first half


EDM wire cut Nb template for Y WG

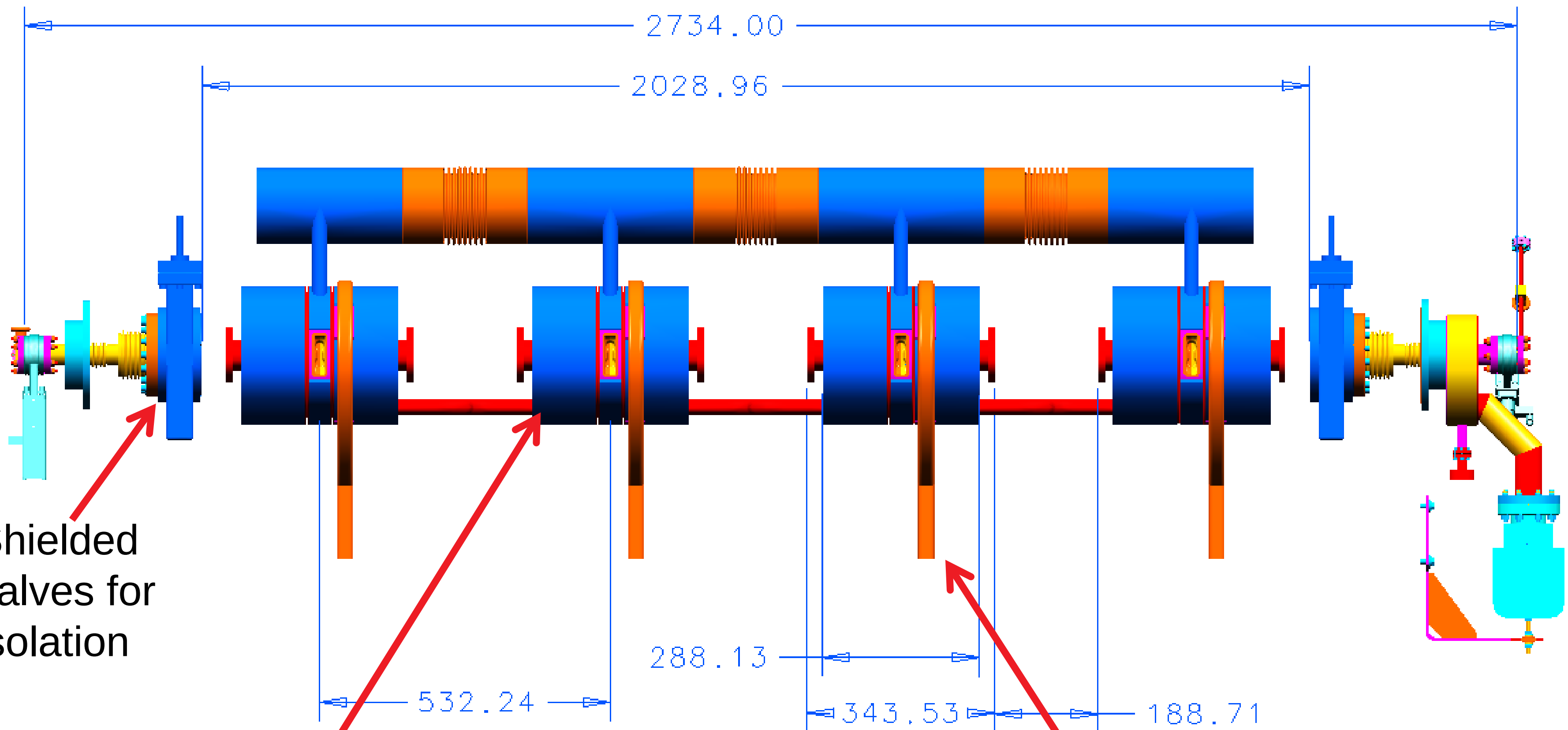
Cavity Processing and Testing:

Cryomodule Design:

- The four cavity cryostat design has been evolving as the details if the individual components have progressed.
  - Started with the cavity and the Jlab end loaded cryostat design
  - Helium vessel and tuner are well under way in the design effort
  - All hardware is evolving rapidly
    - *Cavity flange design was changed from indium seal to aluminum seal*
    - *All waveguides are inside helium vessel*
    - *Helium vessel will be titanium with a single bellows*
    - *HOM and LOM designs are progressing*
    - *Cavity alignment test stand fabricated (warm) and stretched wire measurements completed*

- Still a lot of work to do packaging all hardware and completing mechanical system analysis and design

Baseline Cryomodule Concept:

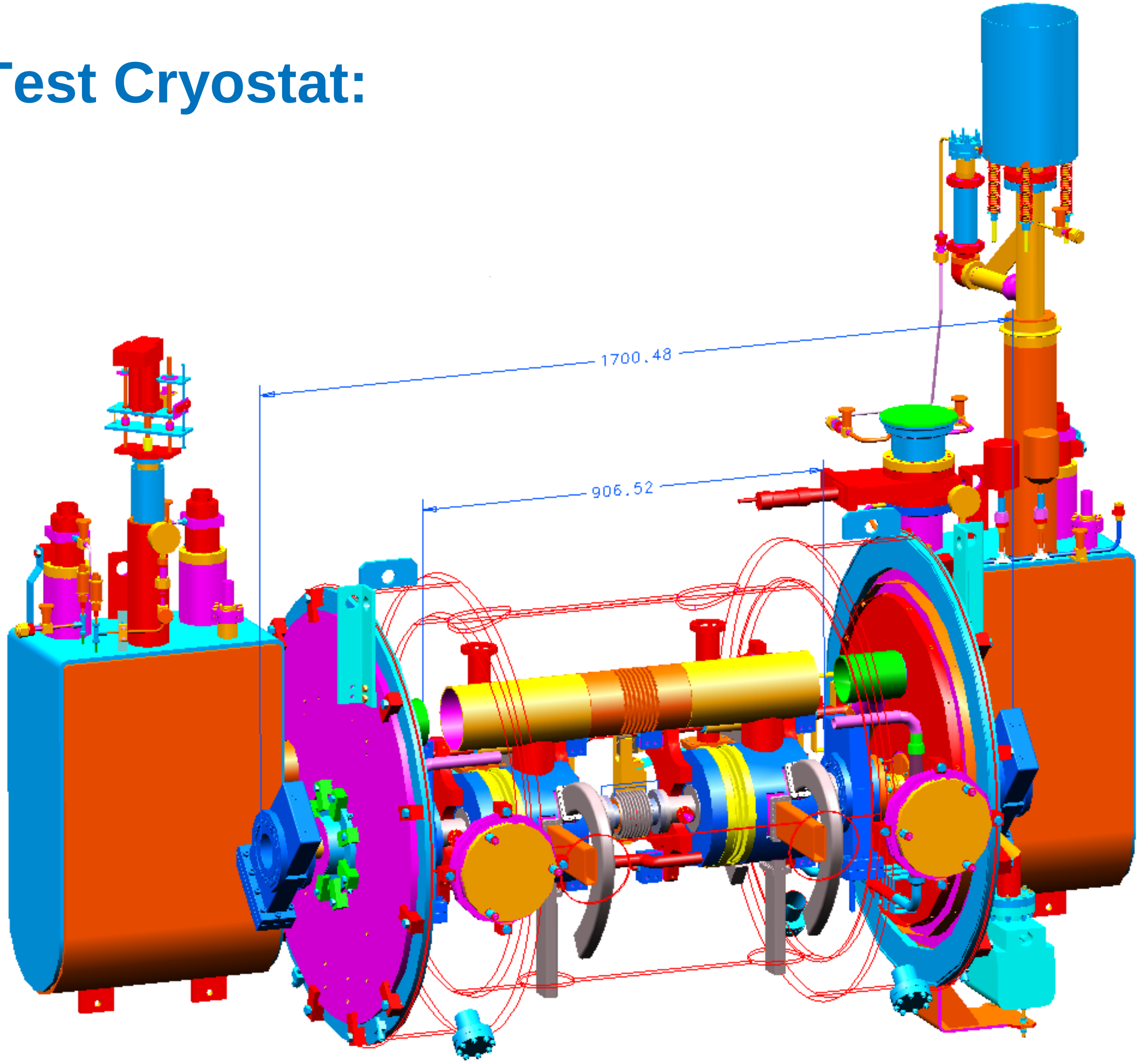


Shielded valves for isolation

4 cavity string, bellows in between

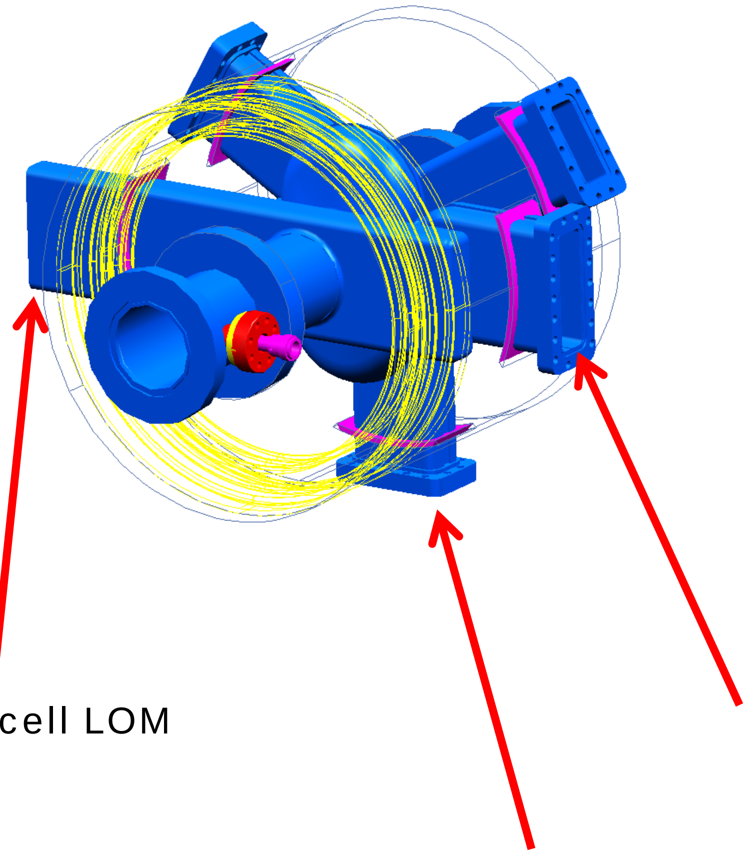
HOM waveguides terminate inside vacuum vessel

Ring Test Cryostat:



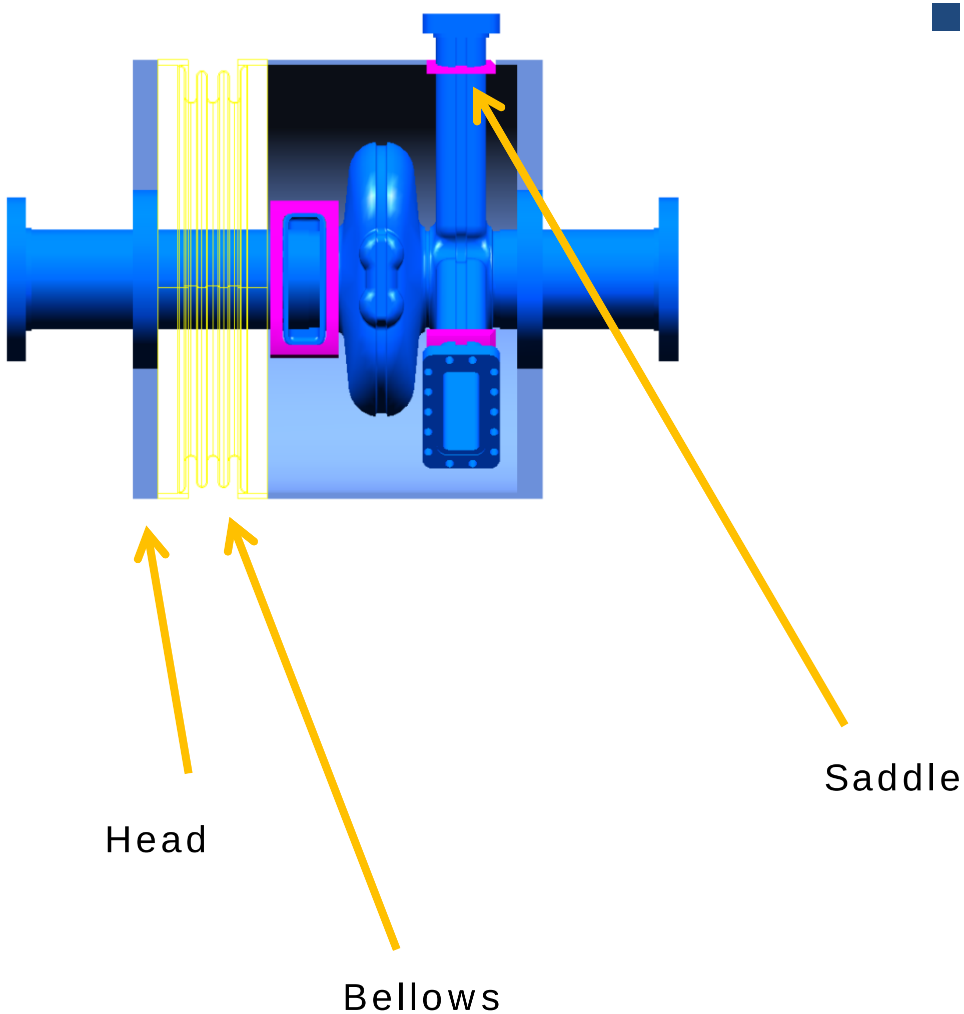
Helium Vessel Design Status:

- A universal helium vessel approach was taken for both cavity designs to save development time



This cavity model is both MARK I and MARK II designs which allowed for quick development of the concept

Helium Vessel Design:

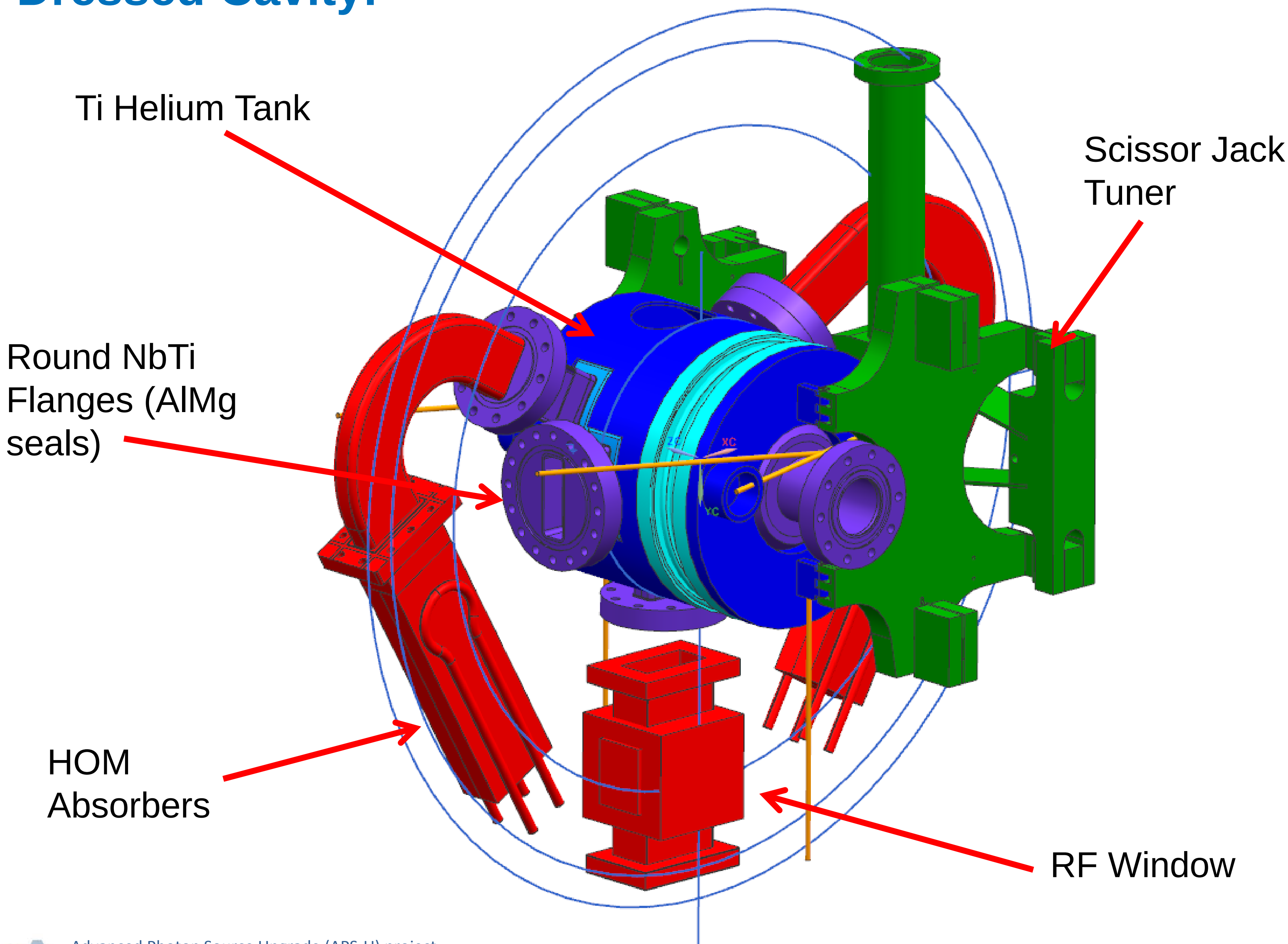


- **Basic concept incorporates waveguide into helium vessel**
  - Saddles on waveguide are welded to the helium vessel
  - Dish head on beam pipe forms end seals
  - Helium vessel will have one or two bellows (one bellows is shown here)
  - Design allows for either Titanium or SS (SS requires braze joints)

Helium Volume - 8.0 Liters

Vessel Helium Riser – ID 76.2 mm, 70 Watts

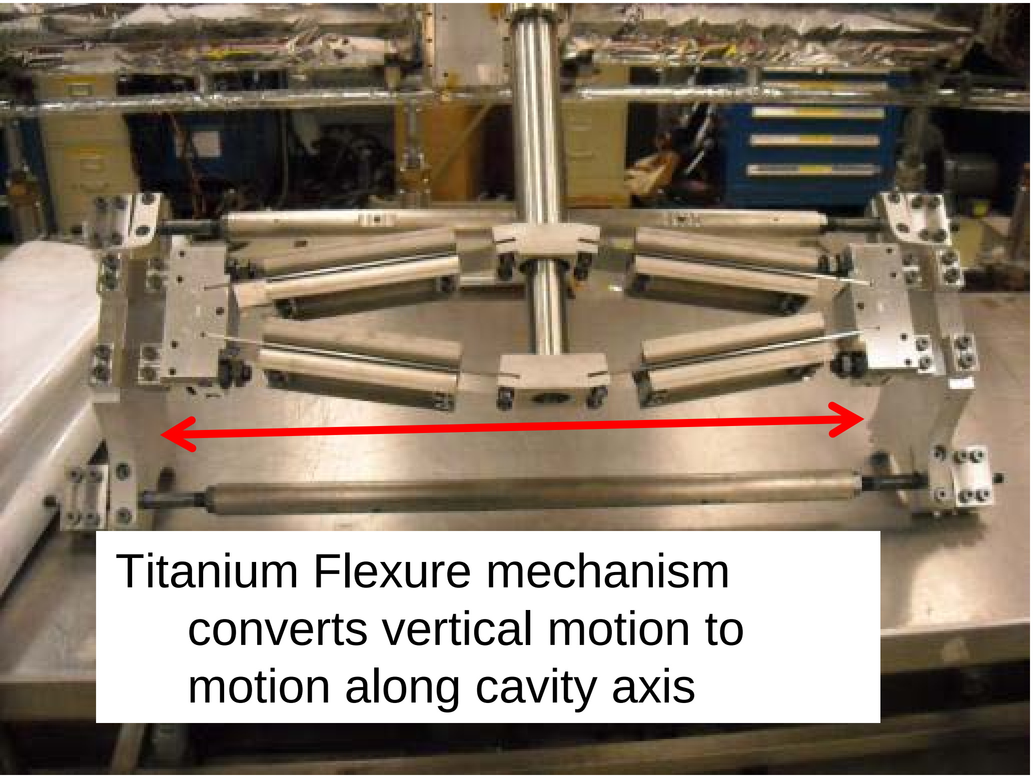
Dressed Cavity:



Tuner Design:

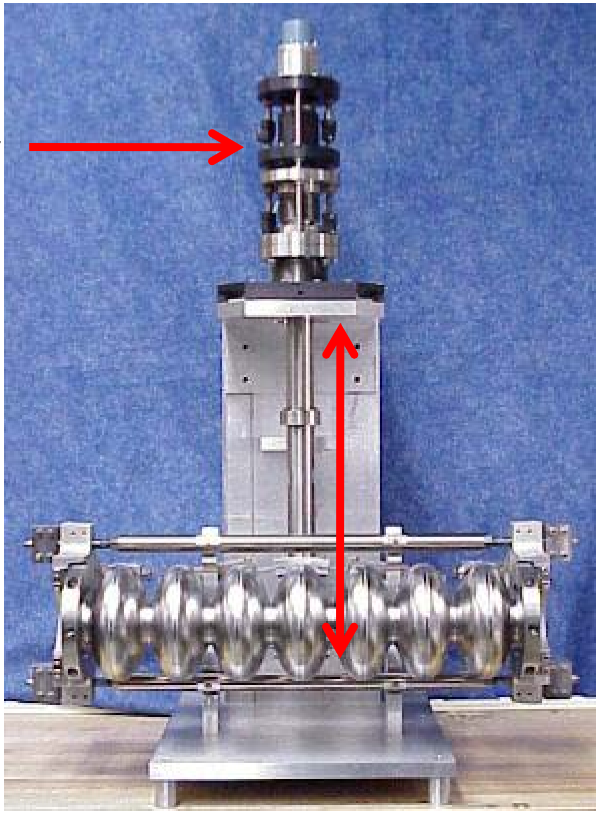
- **The Scissor jack tuner design was chosen due to the following factors:**
  - It capitalizes on Jlab experienced gained with the design and operational use
  - This design is very robust, few moving parts inside cryomodule, warm motor design
  - Warm Piezo incorporated in the design
  - Tuner floats , weight rides on cavity
  - Design works for both Mark I and Mark II
  - Good Field Stability

Jlab Upgrade Scissor Jack Tuner:



Titanium Flexure mechanism converts vertical motion to motion along cavity axis

Drive Components: Warm & easily accessible



Stepper motor, Harmonic Drive, Ball Screw, Piezo generate vertical motion

Upgrade Performance:

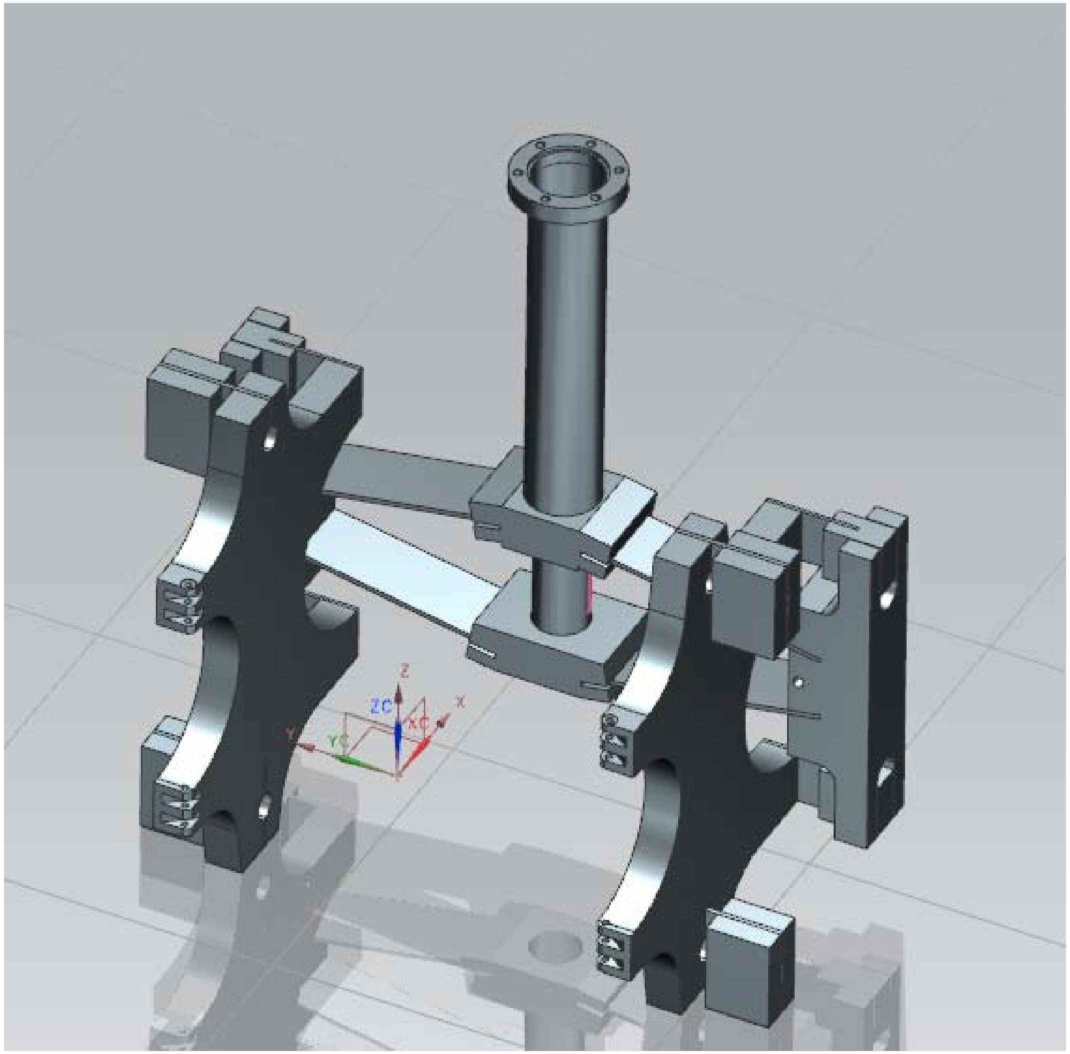
Coarse Range: +/- 200 kHz

Coarse Resolution: <2 Hz

Fine Range: > 550 Hz

Fine Resolution: <1Hz

Scissor Jack Crab Cavity Model:



- Preliminary concept scaled to single-cell crab cavity size
- Piezo and or Warm Motor
- Reliable and robust in operation

Scissor Jack Tuner:

- Mechanical Design Requirements
  - Compact size, must fit in 400mm
  - Tuning range ± 200kHz
  - Resolution 40Hz
- Challenge is tuning precision due to the increased frequency sensitivity of this cavity design
- Modeling of both cavities for optimal solution underway

Scissor Jack Tuner Comparison: (simulation & experiment)

APS Requirements	Mark I (3mm)	Mark II (4mm)	C100
Lorentz force detuning	15 Hz/(MV/m)^2	TBD	5 Hz/(MV/m)^2
Tuning sensitivity	3.81kHz/Lbf	3.14 kHz/Lbf	1.2 kHz/Lbf
Frequency sensitivity	8,844 kHz/mm	TBD	300kHz/mm
Pressure Sensitivity	40 Hz/Torr	9 Hz/Torr	232 Hz/Torr
Tuning Range	± 200 KHz	± 200 KHz	± 300 KHz
Cavity Linear Stiffness	1906 lbf/mm	TBD	260 Lbf/mm
Piezo Detuning Response	1ms	1ms	10 ms

x 29

Challenges are to increase tuner resolution over standard design and use piezo for fast detuning!!!

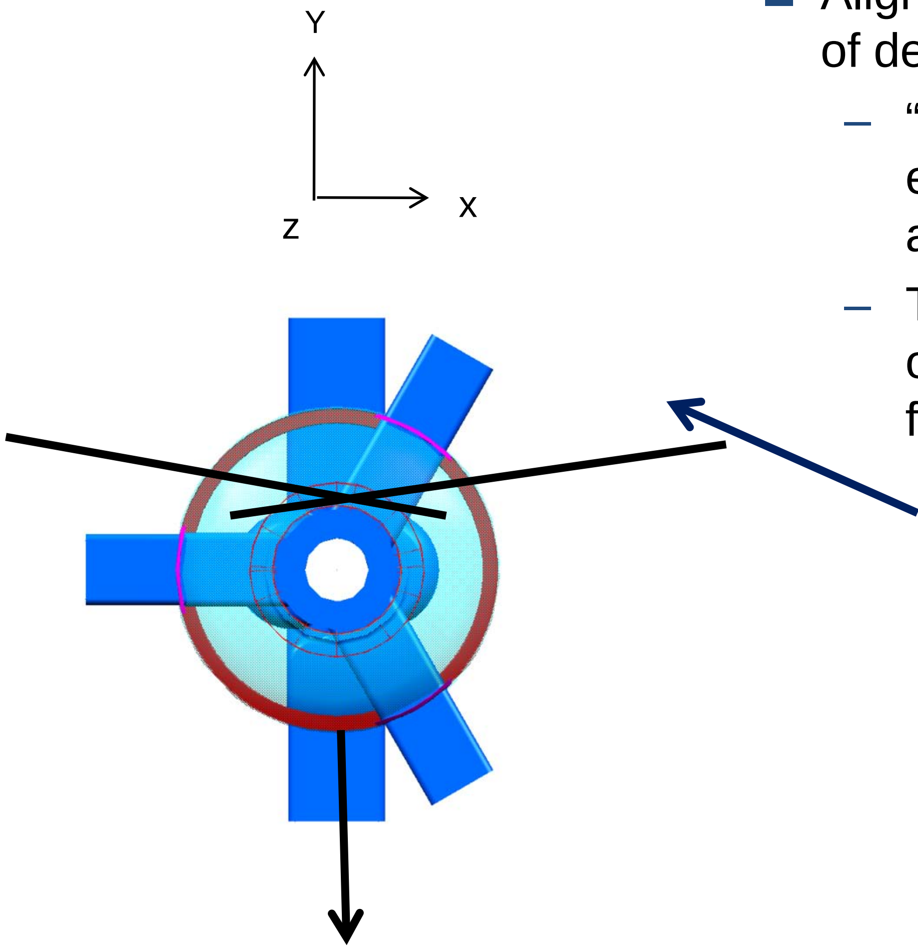
Options For Improving Tuner Resolution:

- Replacing ball screw - 5mm/rev → 2mm/rev
- Motor – 200 µsteps/rev → 800 µsteps/rev

One order of magnitude

- Modify the mechanical design to increase resolution
- Use Piezo instead of motor for coarse tuning

Alignment Concept:



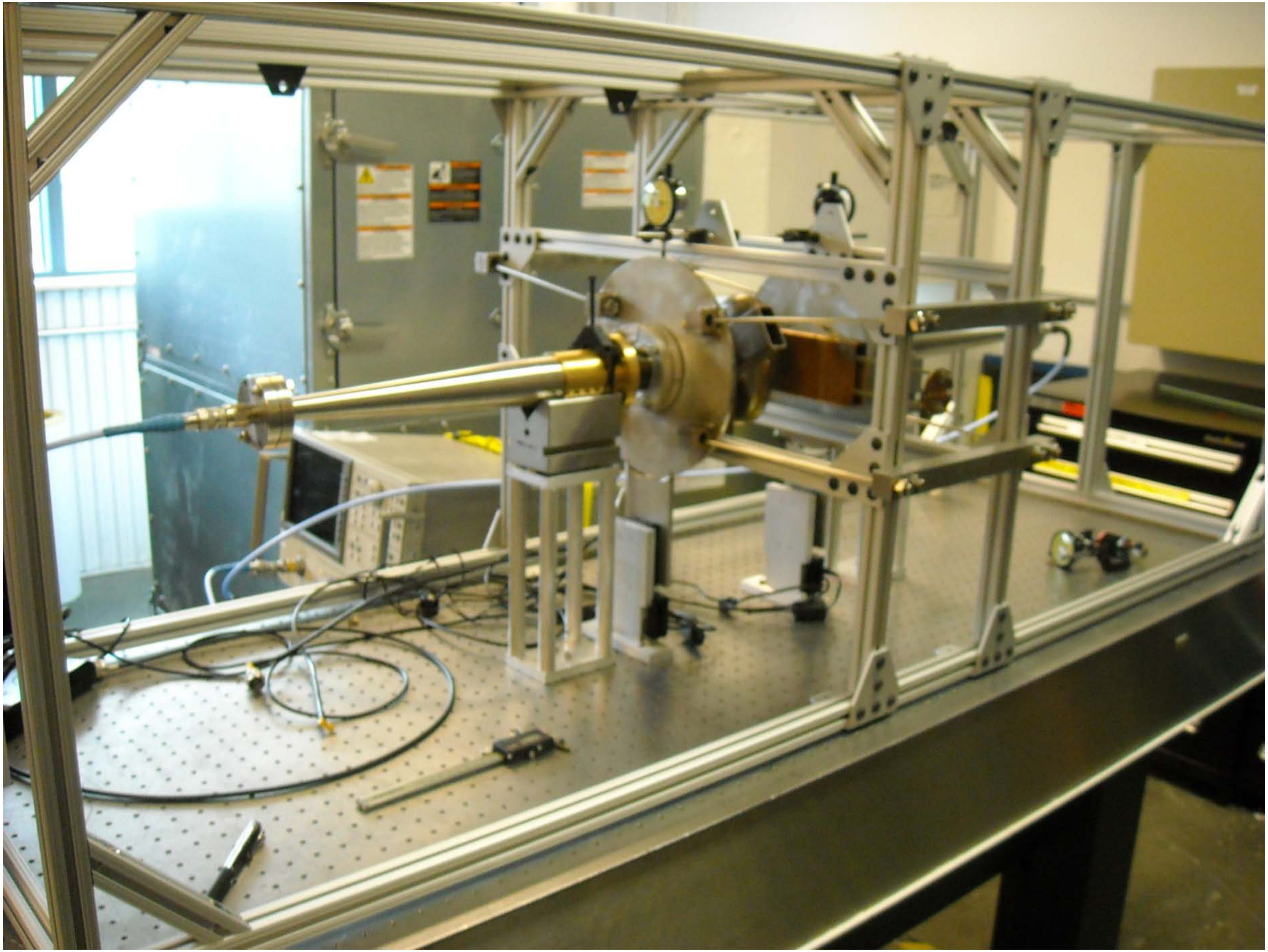
- Alignment concept is still in the early stages of development
  - "Y" requirement 100um alignment of electrical center is needed , active alignment will be required
  - Typical cryomodule alignment is on the order of 500um referenced to cavity flanges

Nitronic rods for fixed "X" direction

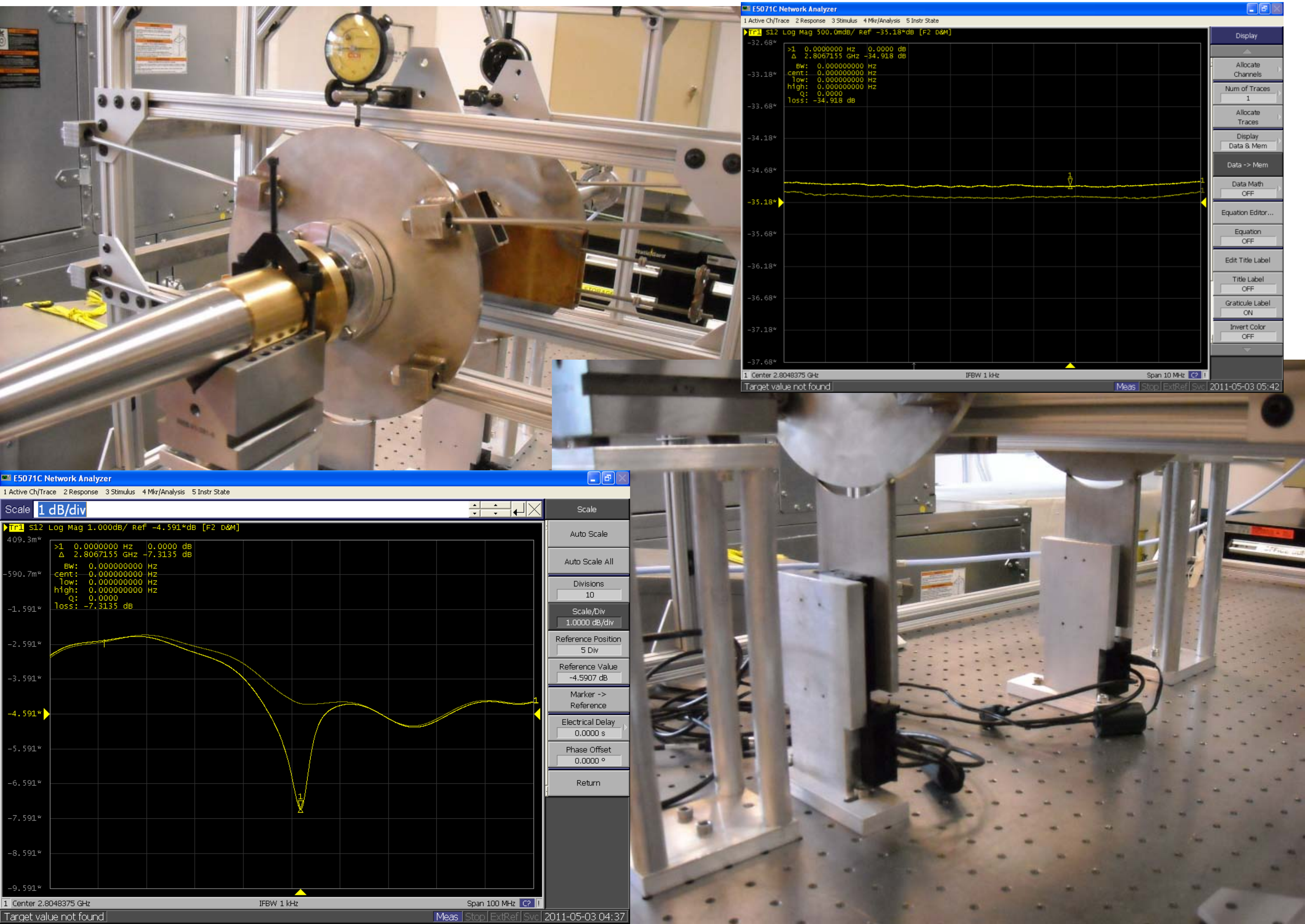
High precision actuators each end of cavity for vertical "Y" motion (1mm)

Alignment requirements	
X	<500um
Y	<100um
Z	<1000um
Yaw	10 mrad
Pitch	10 mrad
Roll	10 mrad

Mock Alignment Test Stand:



Mock Alignment Test Stand:



Preliminary Alignment Procedure:

- Setup stretched wire measurement on CMM
- Determine each cavities electrical center with RF (< 50um) X,Y
- Transfer electrical center datum to flanges (Fiducializing)
- Transfer cavity cell roll, pitch and yaw datum (Fiducializing)
- Complete helium vessel (possible transfer to helium vessel mounts)
- Align cavity datum to >100um accuracy in string (Vertical actuators set)
- Complete cryomodule assembly
- Check alignment through access ports
- Position cavity vertically with beam to reduce RF coupling

Areas of concern:

- Movement of cavities during cooldown, no easy way to check
- Repeatability after multiple cooldowns
- Alignment after shipping cryomodule, will need support hardware for shipping
- Cavity Roll specification maybe difficult

Alignment Concept Status:

- Overall alignment concept is developed

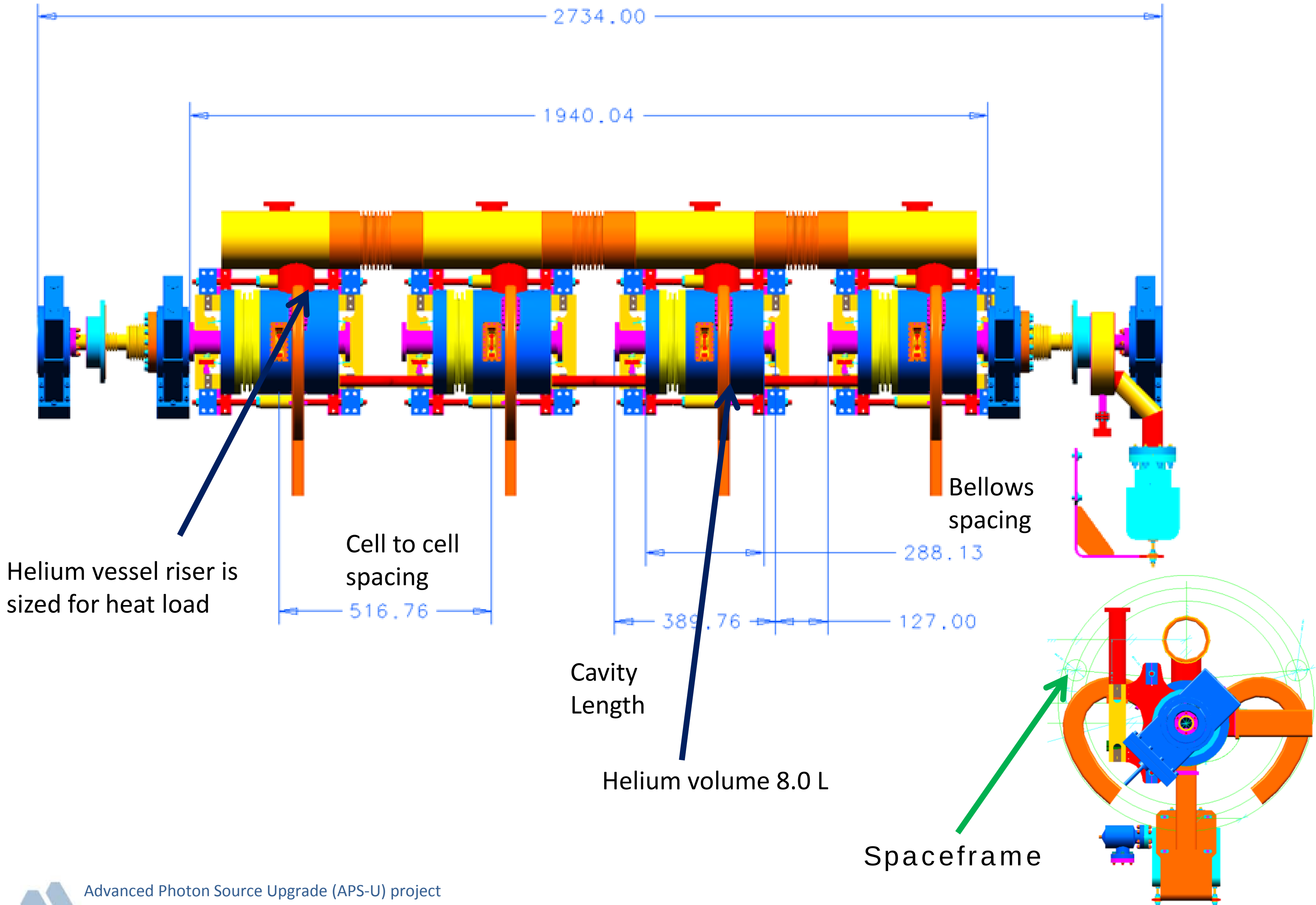
- Demonstration of concept is needed for all steps of the process

- Hardware design will depend on a number of factors:
  - Weight hardware (still in the design stages for most)
  - Stiffness and “Y” compliance of beam line bellows

- Hardware actuators with required precision are available

- There is some possibility active alignment is not needed just following outlined procedure

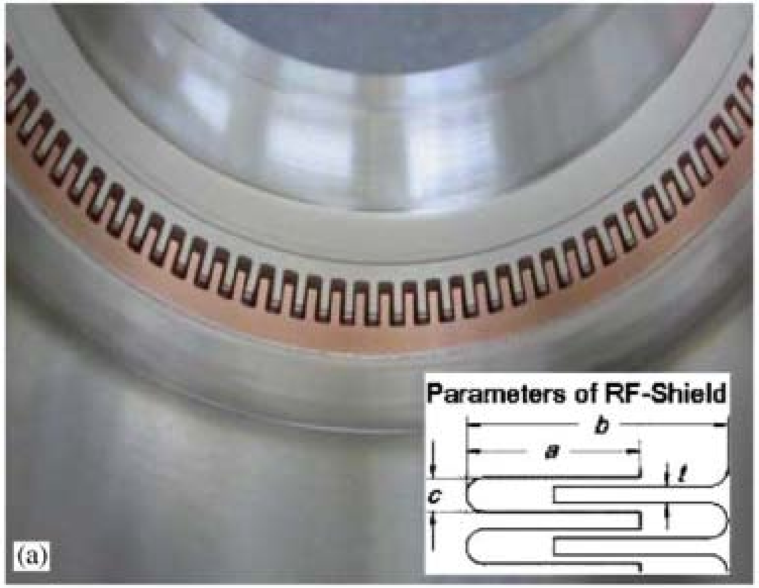
Cryomodule Layout:

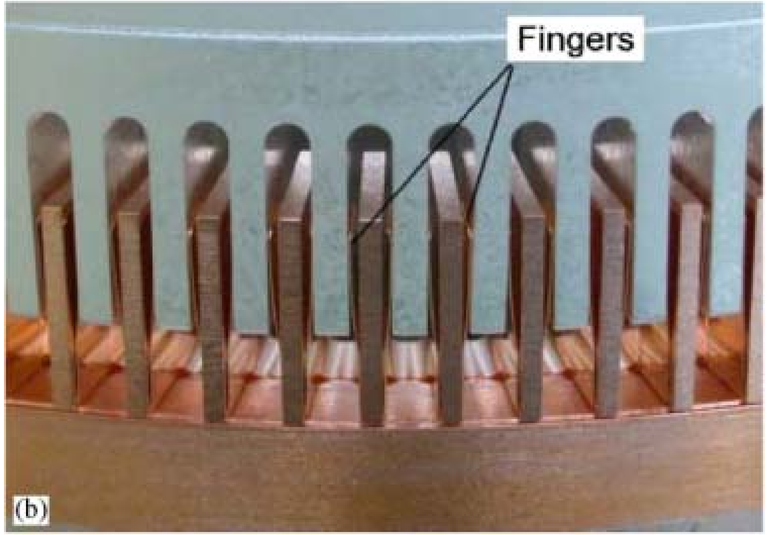


Low Impedance Bellows Options:

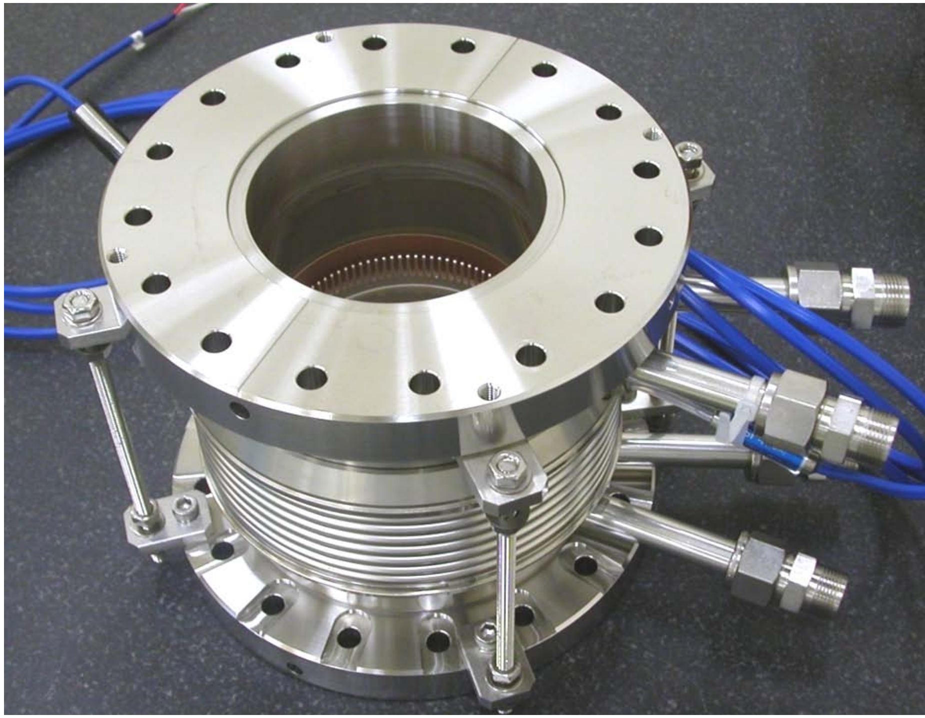
- Five bellows will be required for the 4 cavity cryomodule
  - Three interconnect bellows (between cavities)
  - Two warm to cold transition bellows (end cavities)
- Bellows must allow for thermal contraction of the string and active alignment of individual cavities
- Bellows Options
  - Full shielded design (KEK design)
  - Shallow convolution design (possibly cooled)
- Issues are vertical movement compliance and particulate generation

KEK Shielded Bellows Designs

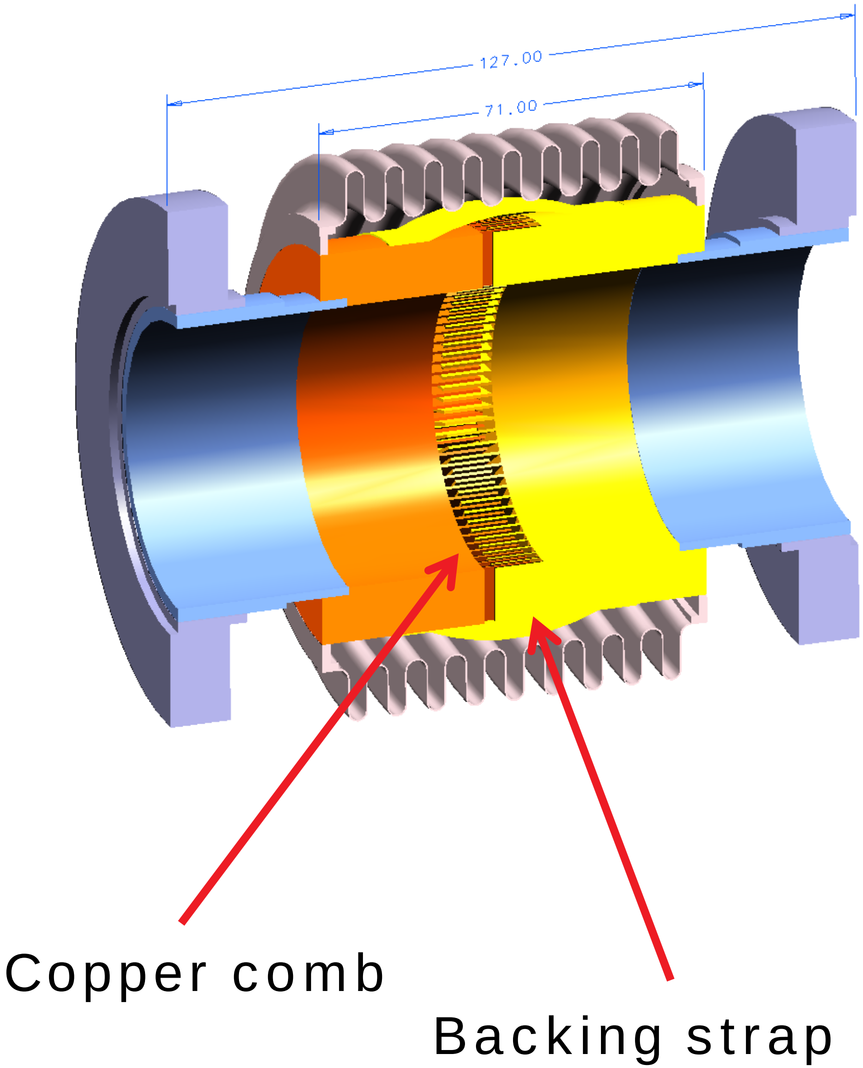




KEK Parameters
Ring current -1.5A
Bunch current 1.17mA
Bunch length 6mm



Shielded Bellows Concept:



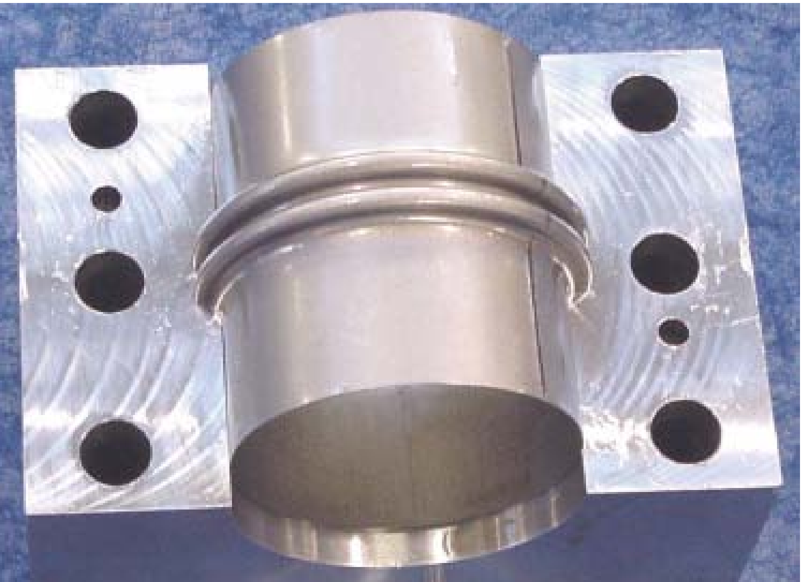
We scaled the KEK shielded bellows design to 52mm ID beam pipe

- Basic shielding principle – Interlocking comb type RF shield with shorting straps on back side

- Performance was good up to 1.2 A beam current
  - 1284 bunches
  - 6mm bunch length

Shielded or low impedance bellows (5)	**APS Requirements**
Thermal contraction	≈ 0.4 mm
Vertical movement	± 0.5 mm

Formed Bellows Option:



Spring constant =1.6 mm/kN

Formed Bellows (Jlab) may also work with a shallow low impedance convolution

DAφNE RF Shielded Bellows

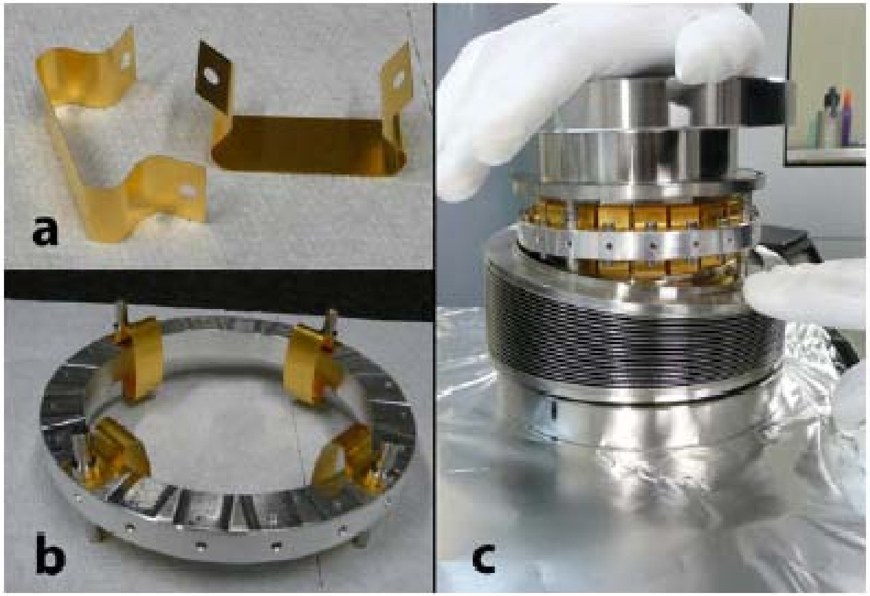
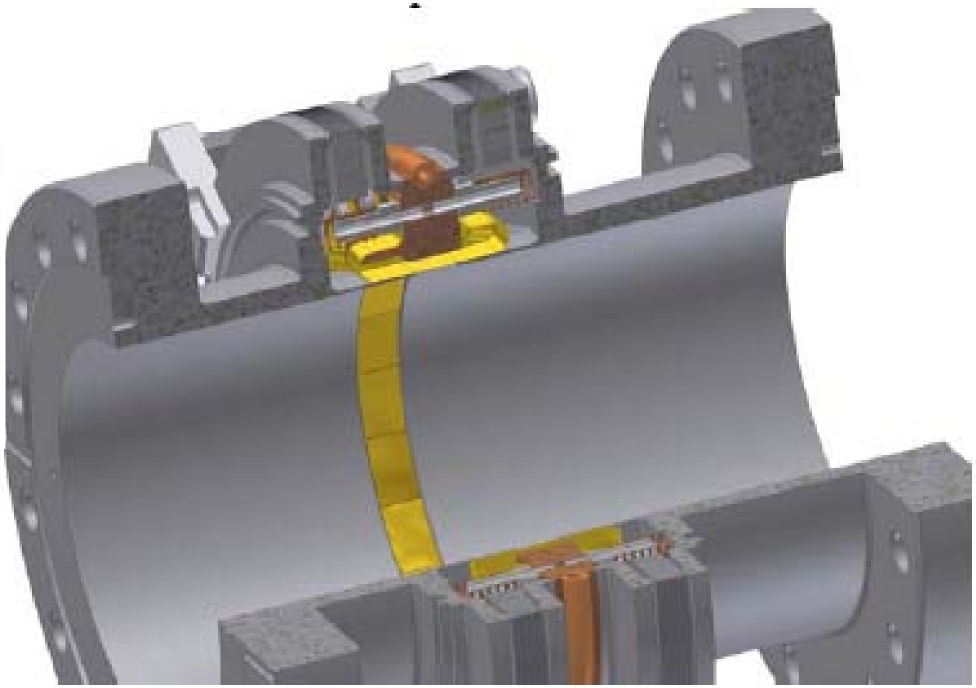


Figure 3: View of gold coated strip (a), supporting annular ring (b), RF shielded bellows assembly (c).

This design was used up to 1.9 Amps beam current

Meets out vertical compliance of ± 0.5mm



Question is how is the design on low particulate contamination!!!

Cryogenic Heat Load Estimates:

Estimate per cryomodule	2K		5k		Shield	
	Static (W)	Dynamic (W)	Static (W)	Dynamic (W)	Static (W)	Dynamic (W)
Cavity		28		0		0
HOM		0.5		5.1		16
LOM		0.5		12.8		40
FPC		0.5		12		24
Sub total	**10.0**	**29.5**	**5**	**29.9**	**180**	**80**
Total	**39.5**		**34.9**		**260**	

Thermal modeling is ongoing !

Major Challenges and Risks:

- **Cavity alignment requirements are challenging**
  - Active alignment will have to be demonstrated with beam loading

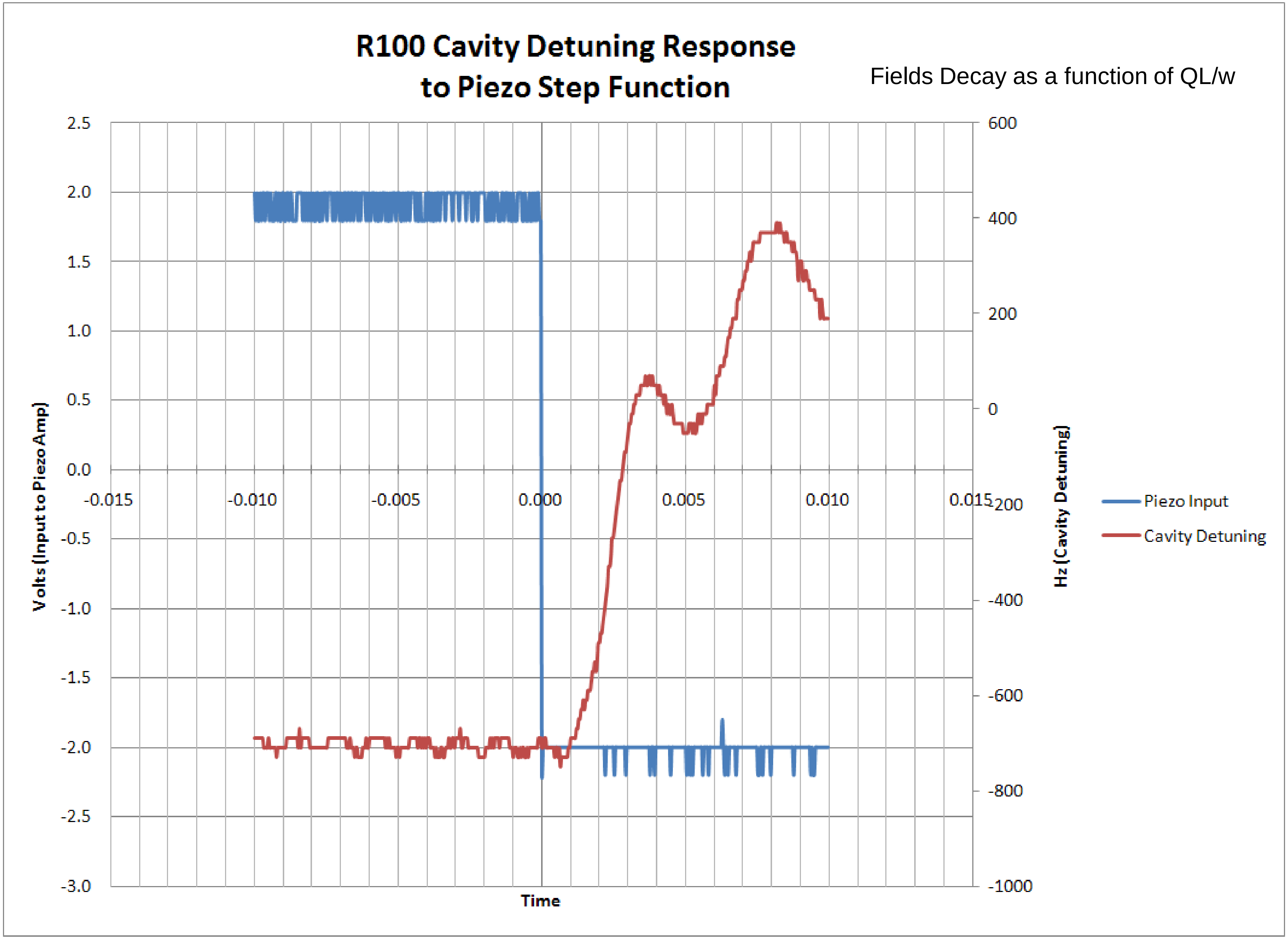
- **Packaging of components in cryomodule**
  - It is time consuming due to complexity
  - All component designs interact making packaging difficult (most designs still evolving)
  - Some hardware decisions not finalized
    - Bellows and valves
    - Spaceframe

Summary:

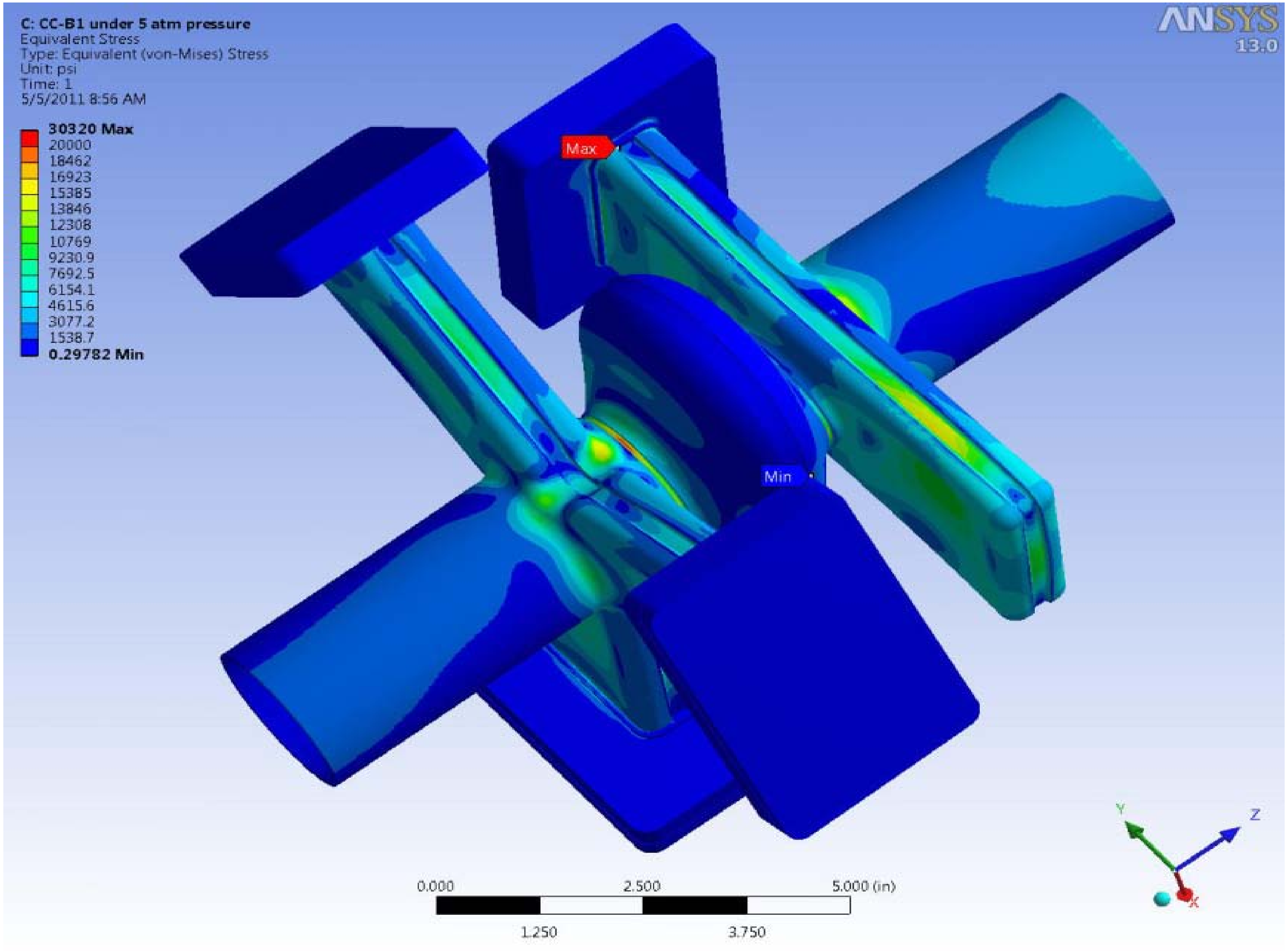
- Subcomponent design is well underway
  - Baseline cavity is qualified
  - Scissor jack tuner design underway
  - Packaging of cavity, helium vessel, tuner is underway
  - Mark II cavity fabrication completed for down select, testing underway
  - Concepts for active transverse alignment scheme are being evaluated, stretched wire measurements underway
  - Low-impedance bellows design underway
  - **Collaboration is working great !!!**

Backup Slides:

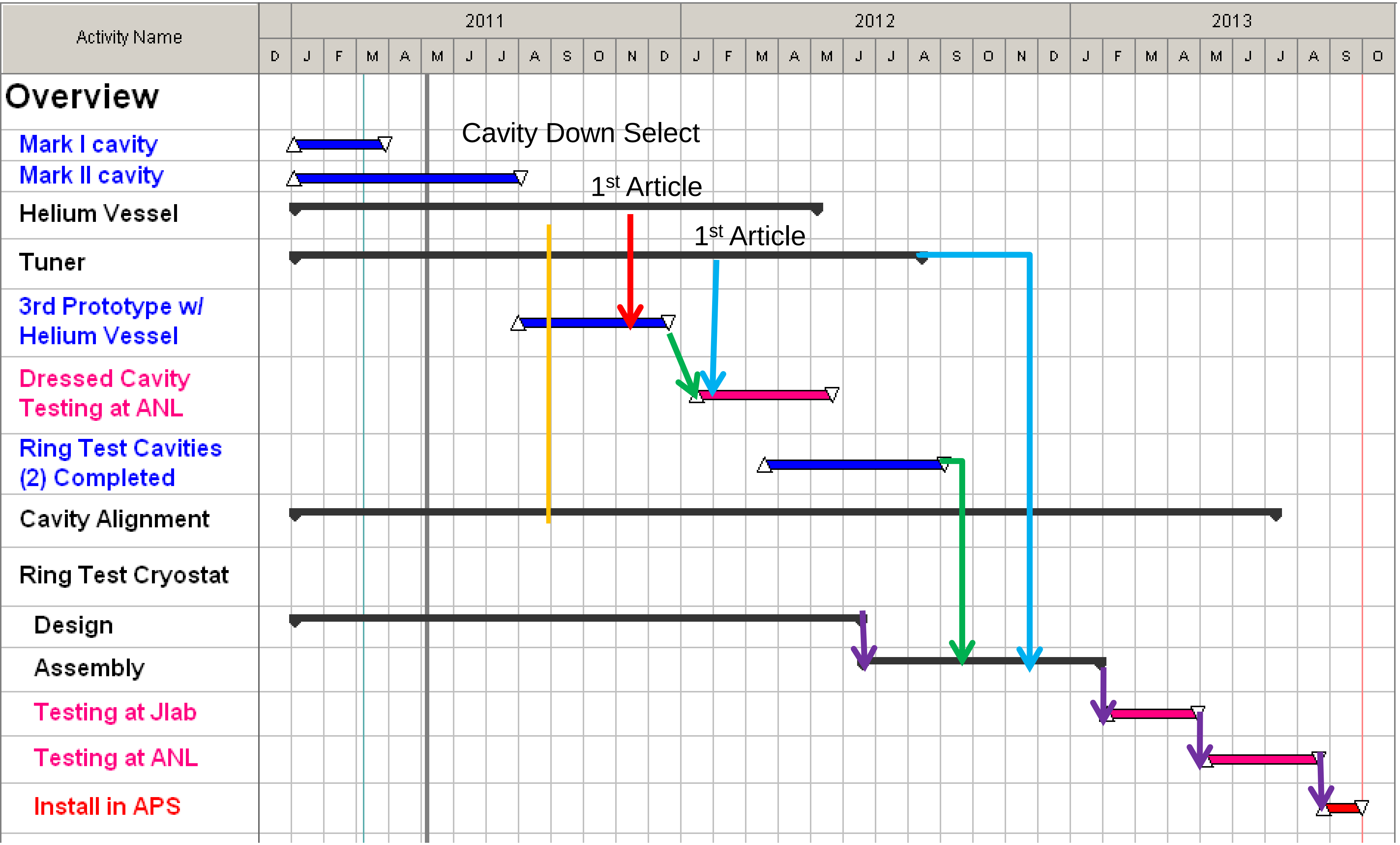
Fast Detuning with Piezo: R100 Cavity



Mechanical Stresses: Mark I @ 5atm



Project High Level Schedule:



Comparison to other cavity designs:

project name	APS-SPX	scaled KEK-B	scaled LHC HL-CC			
design name	Mark-I		EuCARD 4-rods	LARP-HWSR	Parrellel-bar	QWR crab
	squrashed elliptical	squrashed elliptical	optimized rod shape	squrashed spoke	elliptical curved bars	initial
design institute	JLab-ANL	KEK	Cockcroft-Lancaster-JLab	SLAC-AES	ODU-JLab	BNL
DFM frequency	2815.488	2815.488	2815.488	2815.488	2815.488	2815.488
(MHz)						
Rt/Q including TTF (Ohm)	35.8	46.2	953	215	262.6	850
Vt^2/(ωU)						
crabbing voltage Vt (MV)	0.51	0.43	0.68	0.73	0.88	0.55
at Bs=100mT						
peak surface Bs field/Vt	195.6	234.5	147.4	137.3	113.2	181.0
(mT/(MV)						
peak surface Es field/Vt	82	74.7	76.4	73.2	50.7	85.1
(1/m)						
geometry factor G	227.5	220	66.6	50	108.9	38.2
(Ohm)						
beam aperture dia. (mm)	50	18.1	11.9	11.9	11.9	2.86
aperture dia./wavelength	0.47	0.17	0.11	0.11	0.11	0.03
LOM Frequency (MHz)	2425	1792.2	2639.2	2358.0	no	no
Rt/Q*G (Ohm^2)	8144.5	10164.0	63469.8	10750.0	28600.4	32470.0
or Rt*Rs						

Cost Comparison Top vs End Loaded Cryostat:

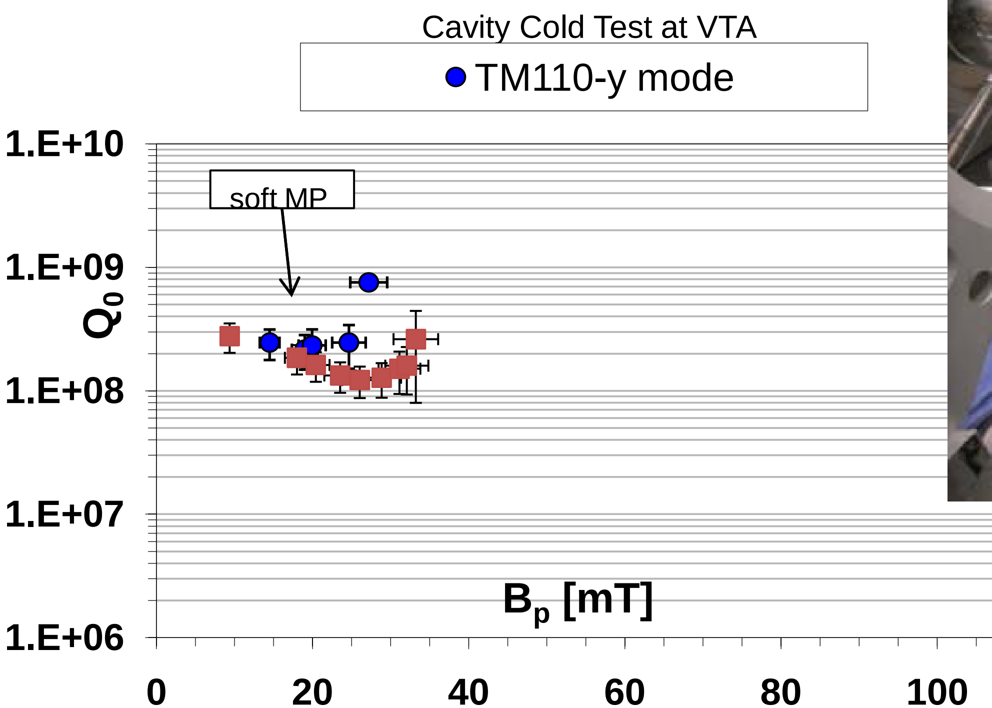
	Atlas - Box 2006	2010	Jlab end loaded 2010	
Cryomodule Cost Estimate	**Hardware + Labor**		**Hardware**	**Labor**
Cavity String	**(K$)**	**(K$)**	**(K$)**	**(K$)**
Cavity Fabrication	946.8	1046.4	664.0	83.5
Helium vessel hardware	91.3	100.9	67.1	24.1
Beamline valves/bellows	20.6	22.8	27.8	0.5
String Assembly			92.6	55.3
RF feedthroughs			86.2	44.3
HOM Dampers	7	7.7		
Helium header			32.0	4.2
Tuner	56.6	62.6	91.0	16.6
Alignment			69.4	17.4
Hardware			9.2	6.9
Labor	**125**	**138.2**		
Sub total	**1247.3**	**1378.5**	**1139.3**	**252.9**
Cryomodule Hardware				
Vacuum vessel	124	137.0	71.3	8.6
Cryogenic controls/valves	15	16.6		
Cryogenic piping	11.3	12.5		
Endcans			126.7	6.6
Thermal shield	35.0	38.6	44.7	6.2
Alignment frame /hardware	63.0	69.6	69.4	17.4
Magnetic shielding	7.1	7.9	24.3	5.9
Instrumentation (thermal diodes, heaters)			115.9	68.0
Thermal Strapping			95.8	26.9
Fast tuner	8	8.8		
MLI			3.2	3.9
RF Coupler /waveguide/ window	75.6	83.6	125.2	25.6
Module stands	6.6	7.3	16.6	0.3
Cryogenic U-tubes	10	11.1		
Misc			10.8	5.5
Labor	**125**	**138.2**		
Sub total	**480.6**	**531.2**	**703.9**	**175.1**
Total Cost	**1727.9**	**1909.7**	**1843.2**	**428.0**

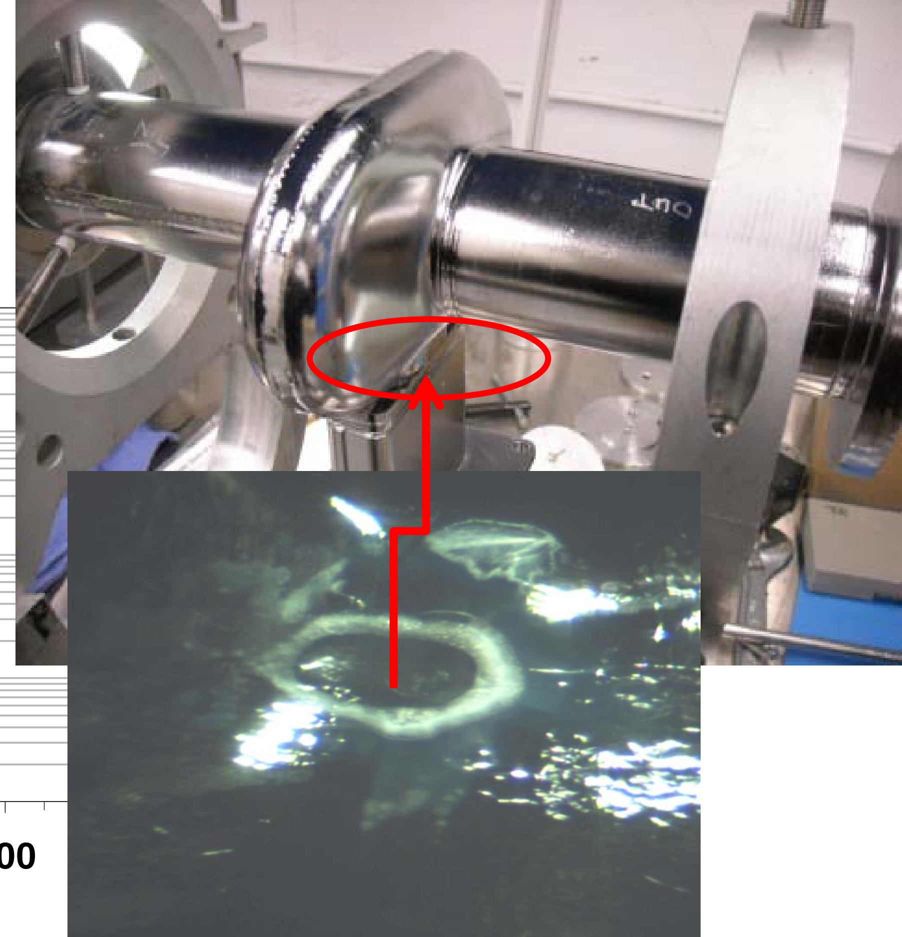
Summary	Total	Labor	Material
Jlab End Loaded	**2271.1**	**428.0**	**1843.2**
ANL Top Loaded	**1909.7**	**250.0**	**1659.7**
Diff	**361.4**	**178.0**	**183.5**

Cryomodule Cost Estimate:

SPX Cryomodule Cost Estimate (2- 4 cavity) **Cryomodule Part**	**Material Costs ($)**	**Labor Costs ($)**	**Total Cost ($)**
Beamline components (valves, ect)	444,527	7,774	452,301
Cavity fabrication	419,054	22,688	441,742
Niobium materials	244,933	60,819	305,752
Cavity string assembly	185,176	110,568	295,744
Endcans (supply and return))	380,069	19,732	399,800
Helium Headers	76,763	10,075	86,838
Hardware	18,433	13,870	32,303
Helium vessels	201,325	72,355	273,681
Instrumentation& assembly	86,198	40,532	126,729
MLI	6,469	7,833	14,302
Misc - Hardware and supplies	21,542	11,075	32,617
Magnetic shielding	97,072	23,658	120,730
Instrumentation	191,595	53,894	245,489
Spaceframe	97,181	24,410	121,591
Supports	66,576	1,050	67,625
Tuners	182,068	33,301	215,370
Top Hats	62,588	12,813	75,401
Thermal Shields	89,474	12,466	101,939
Vacuum vessels	285,094	34,343	319,437
CMProc Inst& Assembly	231,762	136,076	367,838
Acceptance testing (2 cycles)	39,980	599,900	639,880
Shipping/Installation	140,020	151,875	291,895
Alignment	239,680	90,100	329,780
Low Impedance Bellows	300,320	81,250	381,570
Project management	0	493,200	493,200
	4,107,898	**2,125,656**	**6,233,554**

Problems with Prototype Mark I:





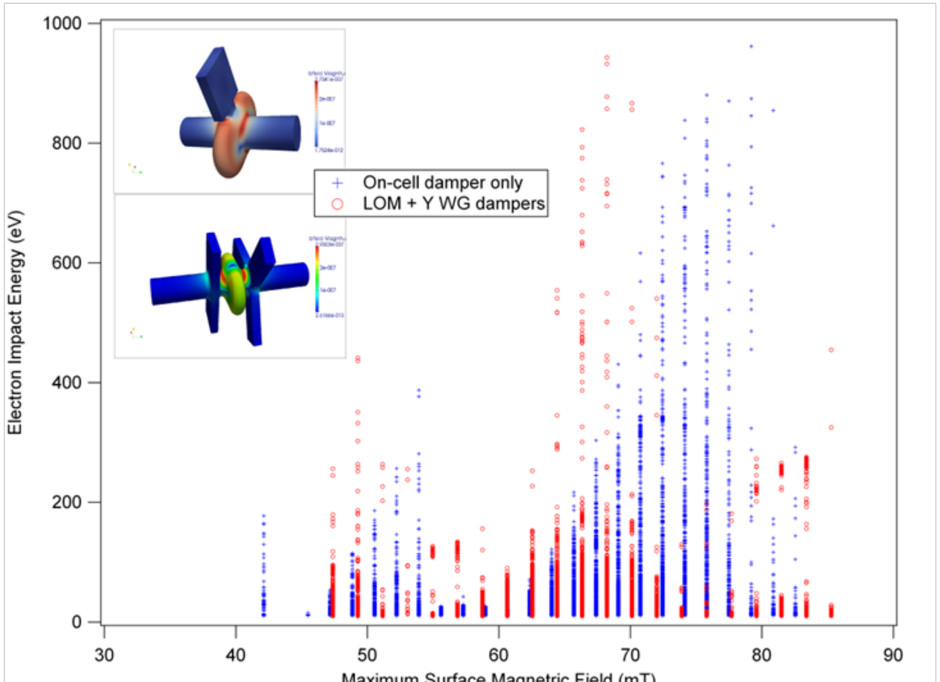
Poor Cavity Performance With Multiple Tests: Low Qo and Gradient

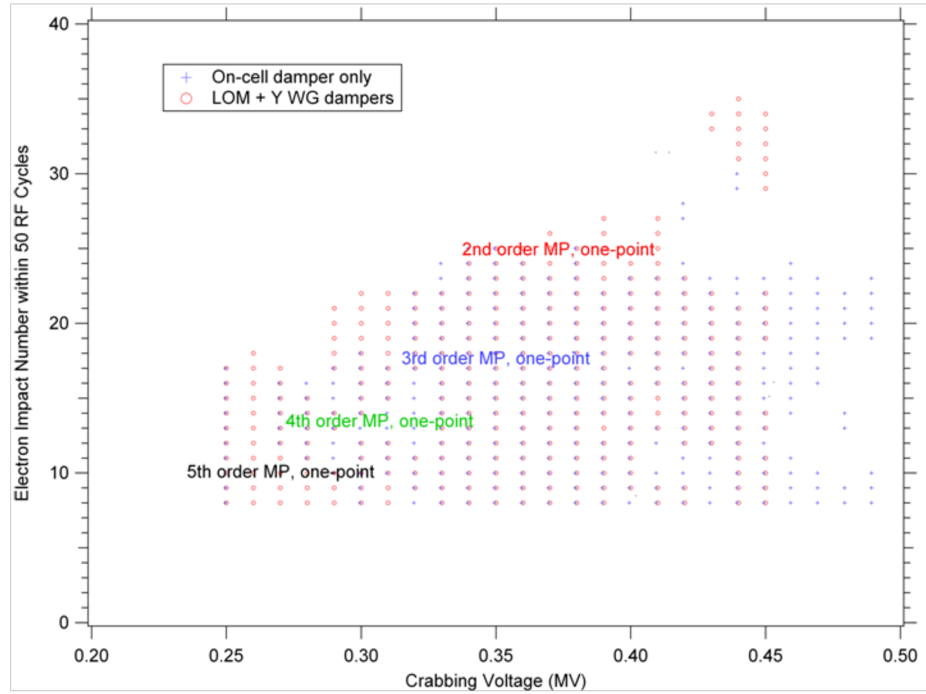
Multiple problems discovered:

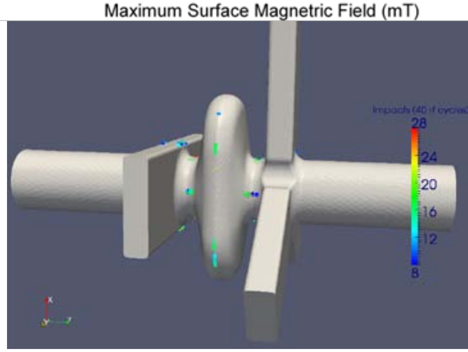
1) Weld crack opened up due to fabrication procedure (Trapped Acid at LOM waveguide)
2) Heavy grinding to smooth LOM / Iris welds
3) Input coupling errors, variable coupler erratic behavior
4) Multipacting
5) Indium Contamination

Multipactoring simulation and experiment confirmation

Simulations using SLAC ACD's Omega3P/Track3P by Geoff Waldschmidt







Locations of multipactors on based line cavity