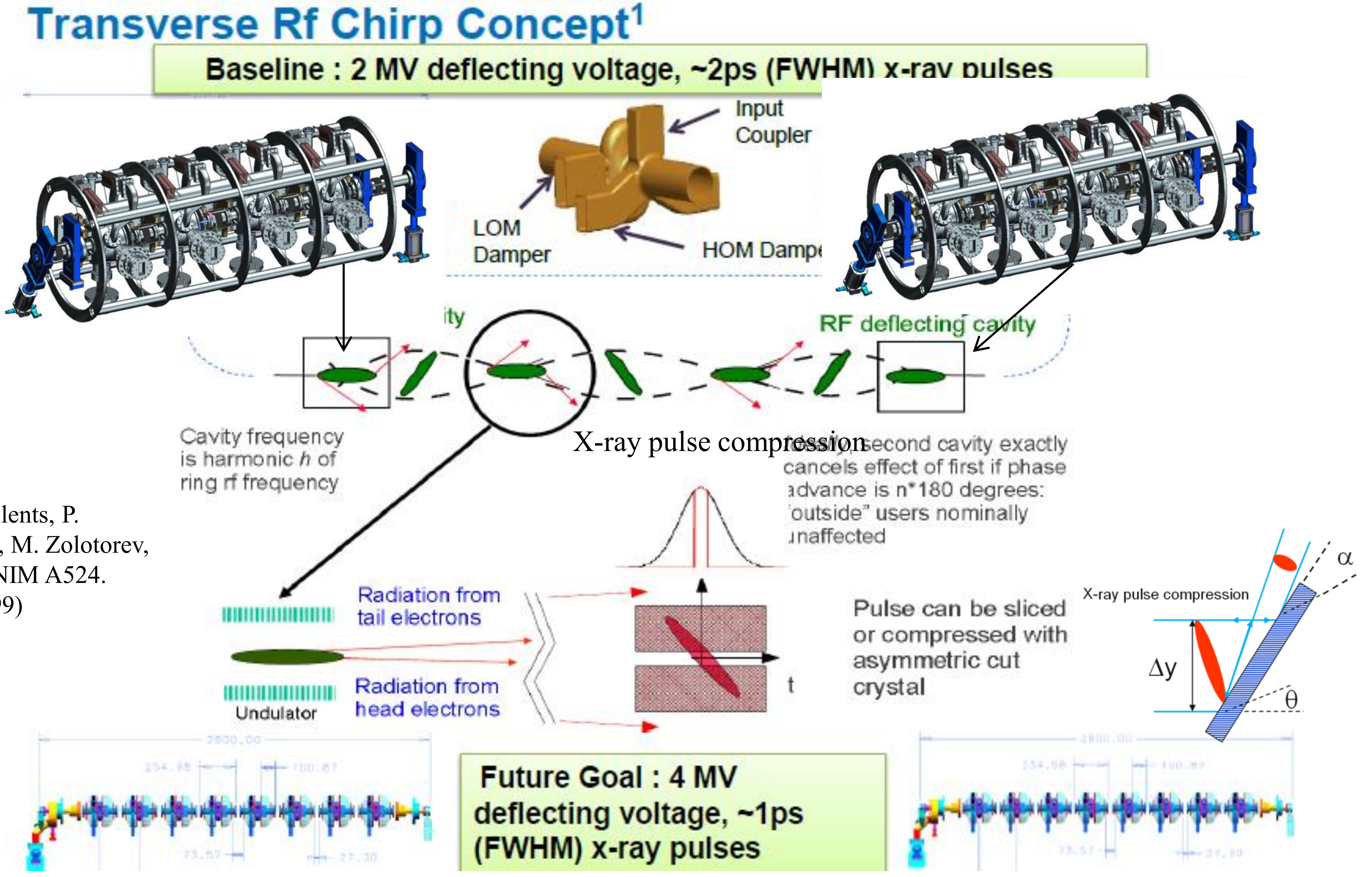
SPX Crab Cavity Development and Testing Result

Haipeng Wang

For the team of Short Pulse X-ray project at APS
from the
ANL-JLab-SLAC-LBNL-(Tsinghua-PKU)
Collaboration

SPX Project Baseline and Upgrade Plan



Transverse Rf Chirp Concept[1]

Baseline : 2 MV deflecting voltage, ~2ps (FWHM) x-ray pulses

Cavity frequency is harmonic *h* of ring rf frequency

X-ray pulse compression

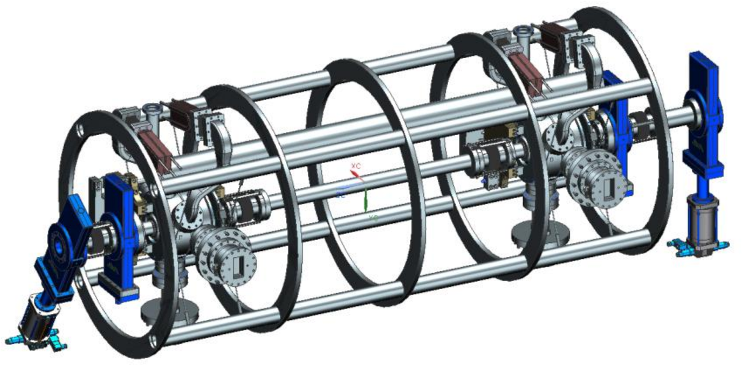
second cavity exactly cancels effect of first if phase dvance is n*180 degrees: outside” users nominally naffected

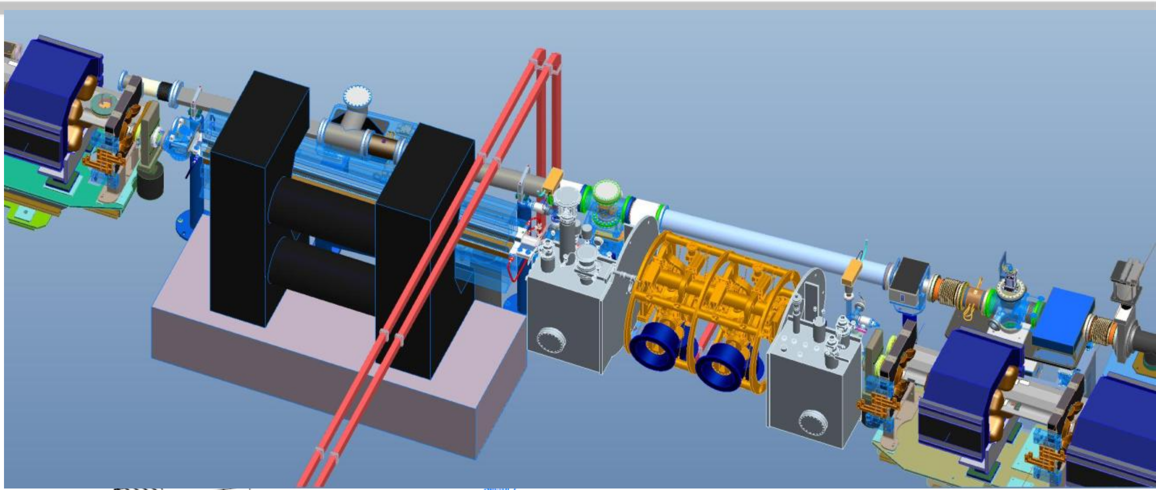
Pulse can be sliced or compressed with asymmetric cut crystal

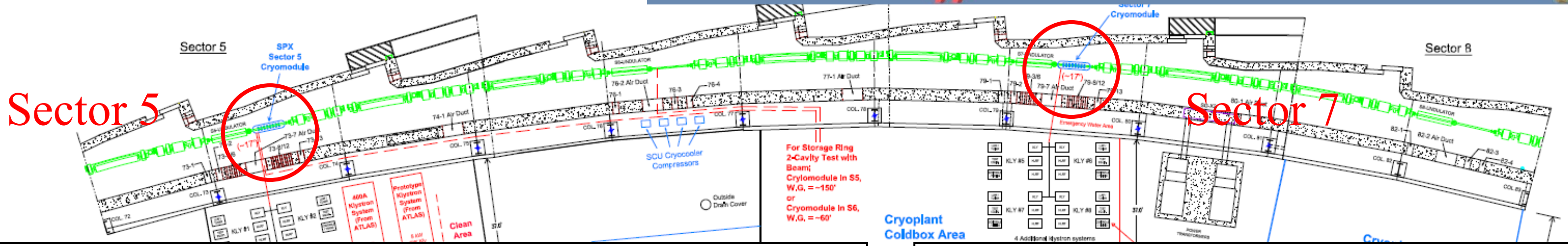
Future Goal : 4 MV deflecting voltage, ~1ps (FWHM) x-ray pulses

1: A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A524. 385, (1999)

SPX0 (R&D): beam test fully dressed 2-cavity Cryomodule in APS ring



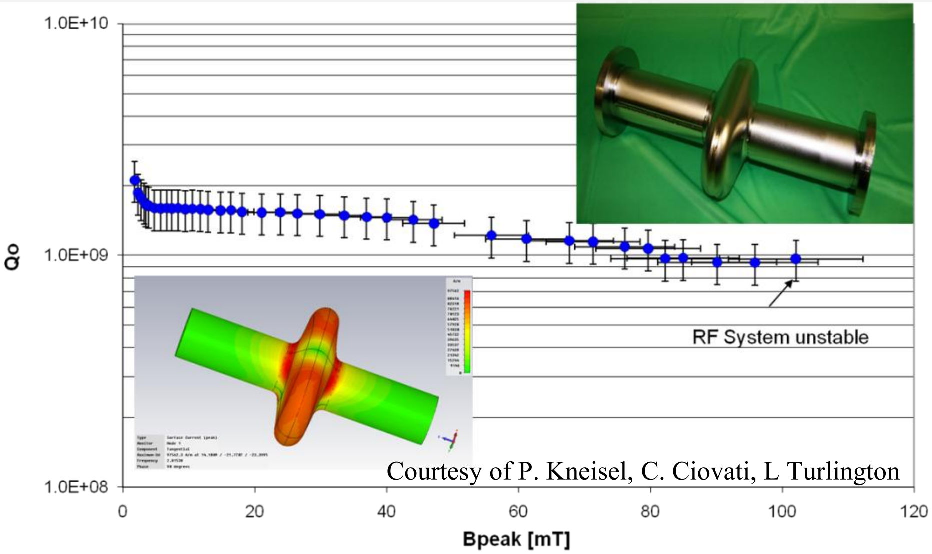




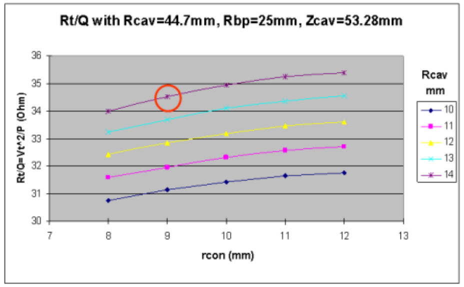
- **SPX0 will only be operated during the non-users periods**
- **Demonstrate SPX is transparent to storage ring operation with cavities detuned.**
- **Test and evaluate performance of deflecting cavities and RF components.**
- **Test design concepts for cavity, cavity/cryomodule alignment, LOM/HOM absorbers, damper design and cryogenics load**
- **Demonstrate cavity voltage regulation and control to required SPX tolerance.**
- **Demonstrate cavity differential phase control to required SPX tolerance.**
- **Demonstrate that fs-level synchronization (BW: 0.1 Hz – 1 MHz) can be achieved**
- **Opportunity for users to have a first look at short x-ray pulse**

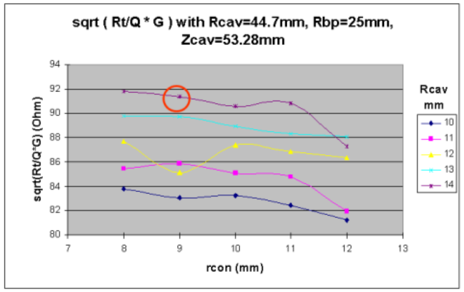
- Mitigate risks as much as possible before the construction phase
  - Effect of warm cavity (SPX0 will operate in batch fill mode only @ 2K LHe)
  - System shakedown (LLRF, HLRF, control, alignment, etc.)
  - Beam loading and rf power management
- Beam dynamics tests
  - Effects on lifetime and injection efficiency (nonlinear dynamics)
  - Orbit stability, beam behavior during cavity quench
  - Effects on single bunch accumulation limit (impedance)
- Diagnostics tests

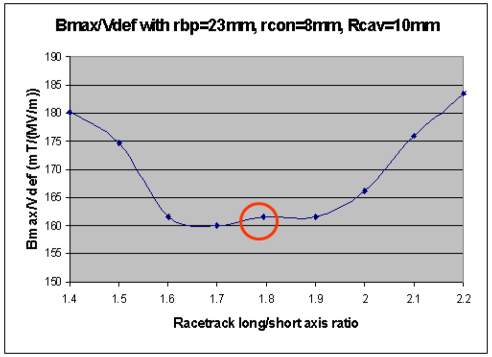
Early Prototypes and Design Optimizations in 2007-2008

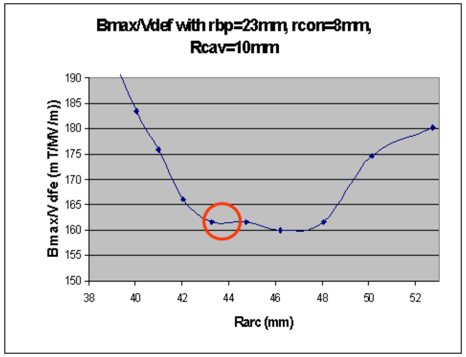


Courtesy of P. Kneisel, C. Ciovati, L Turlington





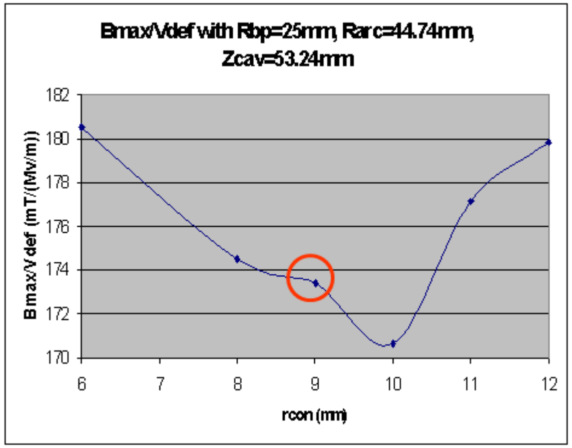


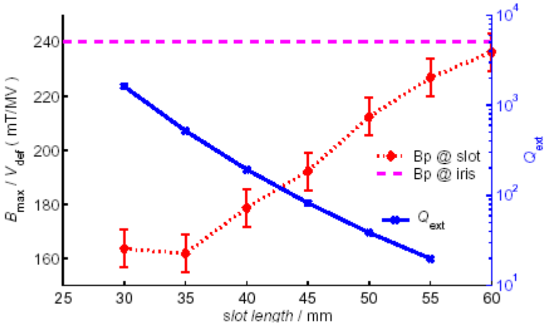


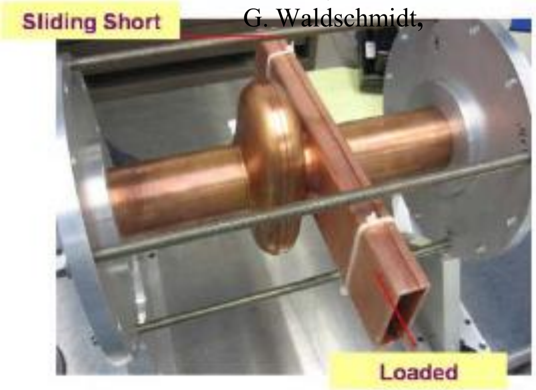
Courtesy of R. Rimmer

First CCA1 Cavity

Cavity shape optimization by CST, HFSS ANSYS
Courtesy of J. Shi and G. Waldschmidt,

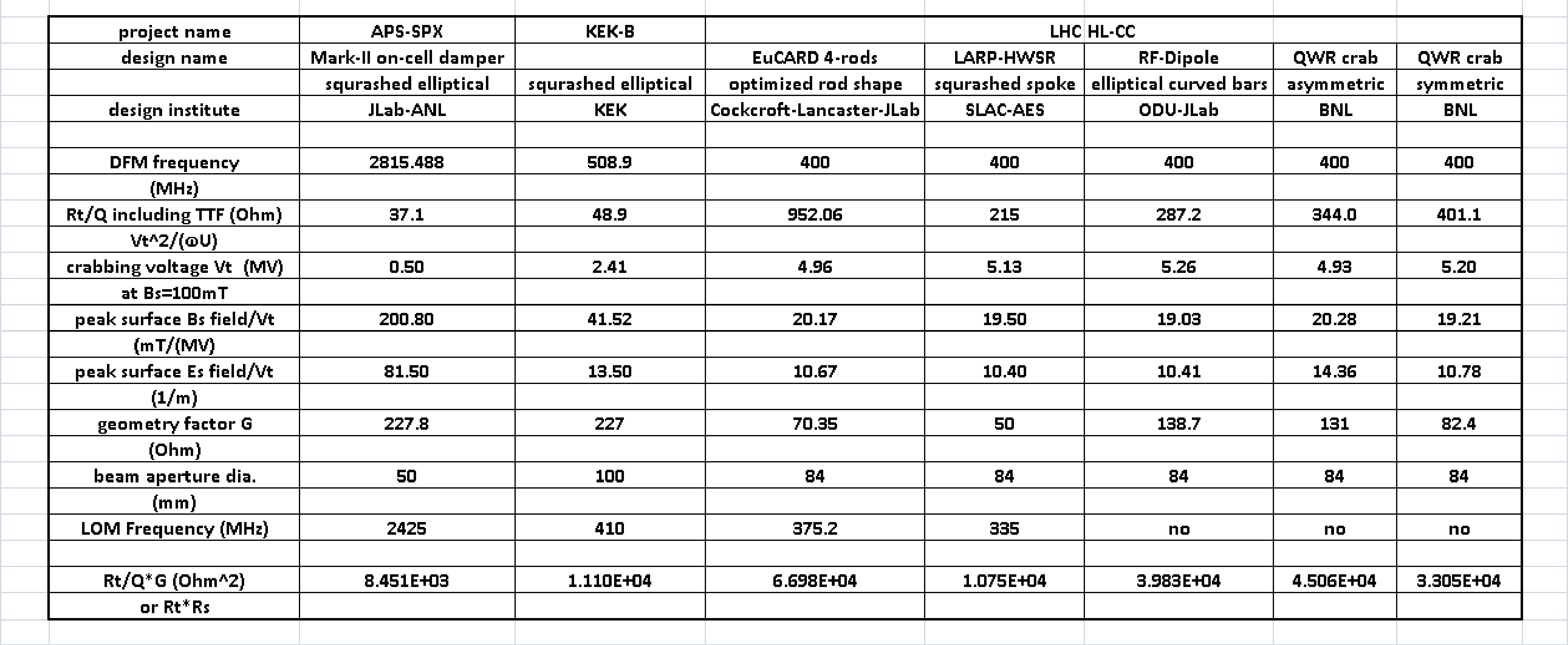






Design Comparison with Other Projects’ Crab Cavities

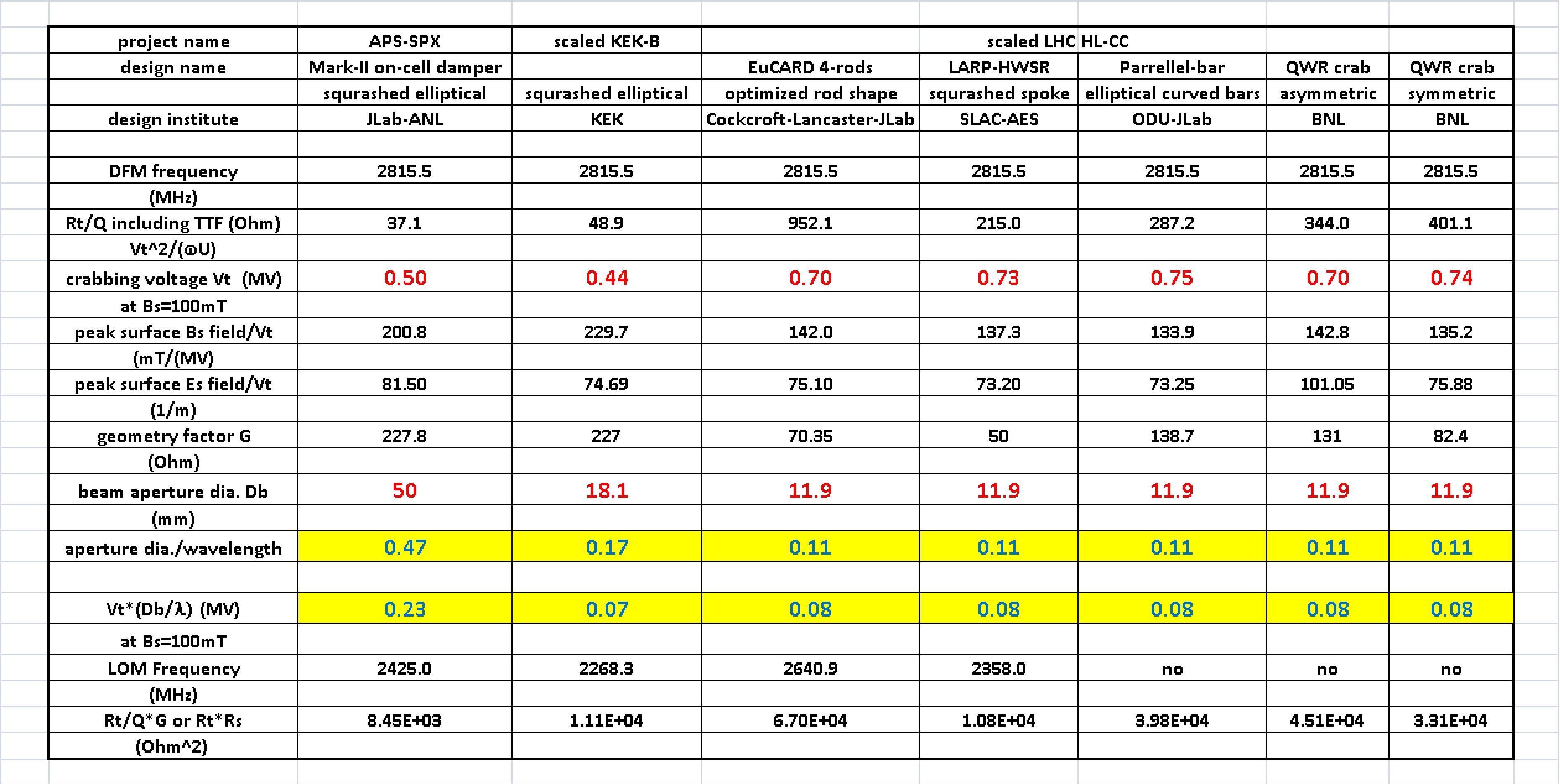
SPX cavity is frequency scaled up (2.815GHz , 8th harmonics of APS RF) of elliptical type from KEKB design. It requires high dV/dt and using part of RF curvature by the APS beam dynamics, much different from LHC-HL-CC compact designs.



project name	APS-SPX	KEK-B	LHC HL-CC				
design name	Mark-II on-cell damper		EuCARD 4-rods	LARP-HWSR	RF-Dipole	QWR crab	QWR crab
	squrashed elliptical	squrashed elliptical	optimized rod shape	squrashed spoke	elliptical curved bars	asymmetric	symmetric
design institute	JLab-ANL	KEK	Cockcroft-Lancaster-JLab	SLAC-AES	ODU-JLab	BNL	BNL
DFM frequency (MHz)	2815.488	508.9	400	400	400	400	400
Rt/Q including TTF (Ohm) Vt^2/(ωU)	37.1	48.9	952.06	215	287.2	344.0	401.1
crabbing voltage Vt (MV) at Bs=100mT	0.50	2.41	4.96	5.13	5.26	4.93	5.20
peak surface Bs field/Vt (mT/(MV)	200.80	41.52	20.17	19.50	19.03	20.28	19.21
peak surface Es field/Vt (1/m)	81.50	13.50	10.67	10.40	10.41	14.36	10.78
geometry factor G (Ohm)	227.8	227	70.35	50	138.7	131	82.4
beam aperture dia. (mm)	50	100	84	84	84	84	84
LOM Frequency (MHz)	2425	410	375.2	335	no	no	no
Rt/Q*G (Ohm^2) or Rt*Rs	8.451E+03	1.110E+04	6.698E+04	1.075E+04	3.983E+04	4.506E+04	3.305E+04

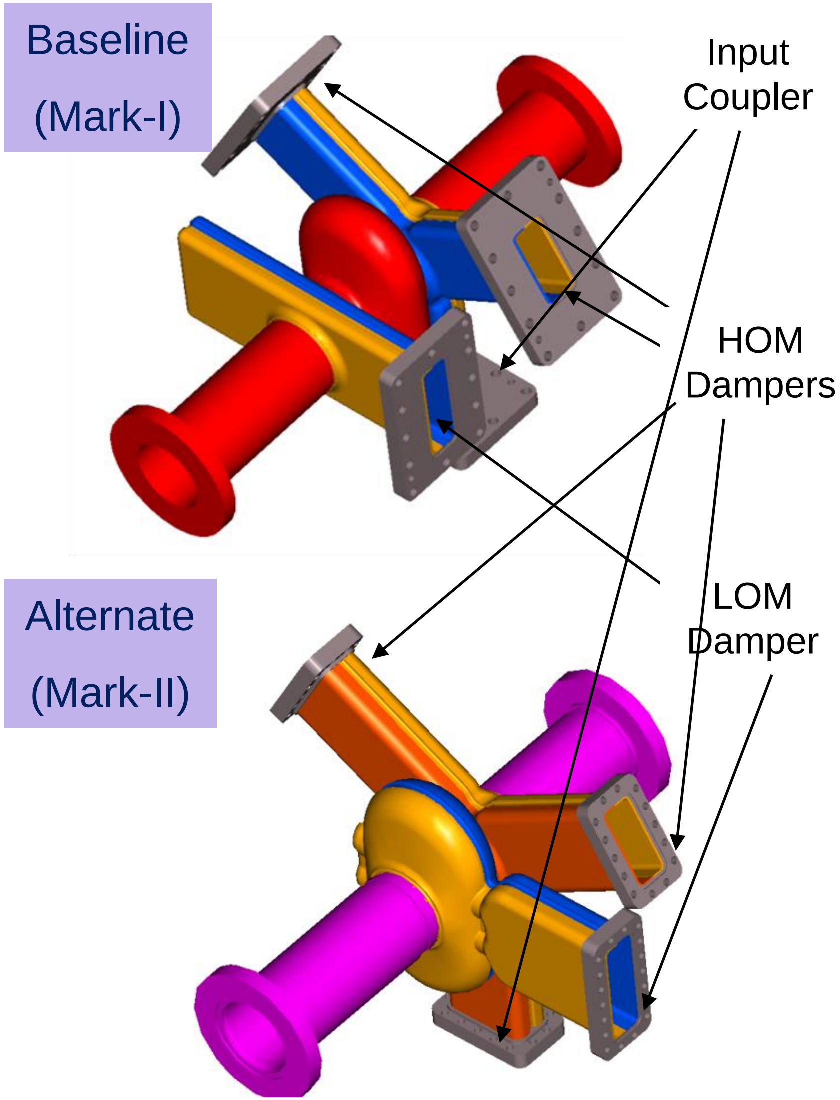
Design Comparison with Other Projects' Crab Cavities

Scale different designs to same frequency, but to compare beam apertures due to the HOM damping and beam emittance conservation requirement



project name	APS-SPX	scaled KEK-B	scaled LHC HL-CC				
design name	Mark-II on-cell damper		EuCARD 4-rods	LARP-HWSR	Parrellel-bar	QWR crab	QWR crab
	squrashed elliptical	squrashed elliptical	optimized rod shape	squrashed spoke	elliptical curved bars	asymmetric	symmetric
design institute	JLab-ANL	KEK	Cockcroft-Lancaster-JLab	SLAC-AES	ODU-JLab	BNL	BNL
DFM frequency (MHz)	2815.5	2815.5	2815.5	2815.5	2815.5	2815.5	2815.5
Rt/Q including TTF (Ohm) Vt^2/(ωU)	37.1	48.9	952.1	215.0	287.2	344.0	401.1
crabbing voltage Vt (MV) at Bs=100mT	0.50	0.44	0.70	0.73	0.75	0.70	0.74
peak surface Bs field/Vt (mT/(MV)	200.8	229.7	142.0	137.3	133.9	142.8	135.2
peak surface Es field/Vt (1/m)	81.50	74.69	75.10	73.20	73.25	101.05	75.88
geometry factor G (Ohm)	227.8	227	70.35	50	138.7	131	82.4
beam aperture dia. Db (mm)	50	18.1	11.9	11.9	11.9	11.9	11.9
aperture dia./wavelength	0.47	0.17	0.11	0.11	0.11	0.11	0.11
Vt*(Db/λ) (MV) at Bs=100mT	0.23	0.07	0.08	0.08	0.08	0.08	0.08
LOM Frequency (MHz)	2425.0	2268.3	2640.9	2358.0	no	no	no
Rt/Q*G or Rt*Rs (Ohm^2)	8.45E+03	1.11E+04	6.70E+04	1.08E+04	3.98E+04	4.51E+04	3.31E+04

Two Types of Bare Crab Cavity Designs for Down Selection in 2011



Baseline

(Mark-I)

Input Coupler

HOM Dampers

LOM Damper

Alternate

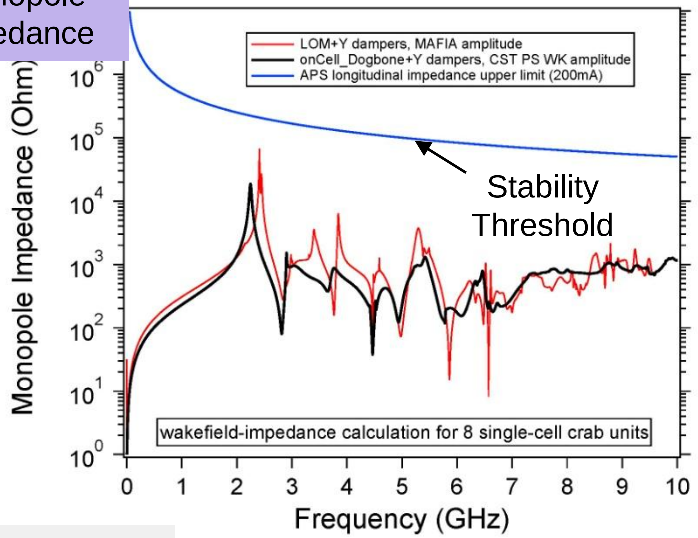
(Mark-II)

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

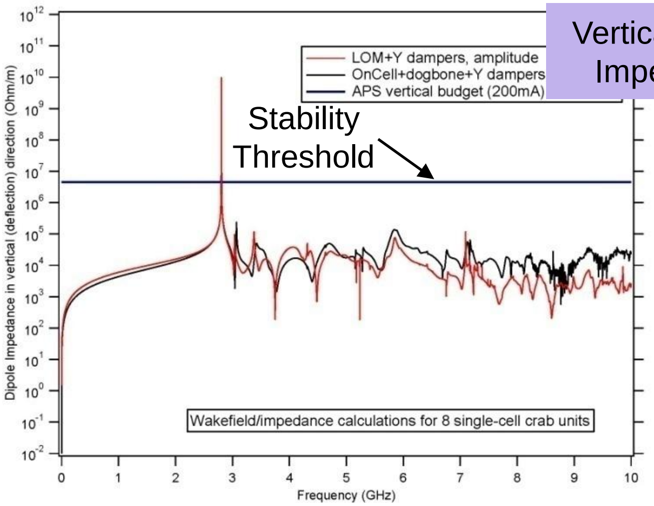
Alternate Cavity		
Rt/Q including TTF	37.1	Ω
Crabbing Voltage Vt at Bs=100mT	0.5	MV
Peak Surface Bs Field/Vt	200.8	mT/MV
Peak Surface Es Field/Vt	81.5	1/m
Geometry Factor	227.8	Ω
Material Thickness	4	mm Nb
LOM Coupler	1	On-cell

Longitudinal and Transverse Impedance*

Monopole Impedance



Vertical Dipole Impedance



Monopole Stability Threshold

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

Dipole Stability Threshold

$$R_t < 1.4\,M\Omega / m$$

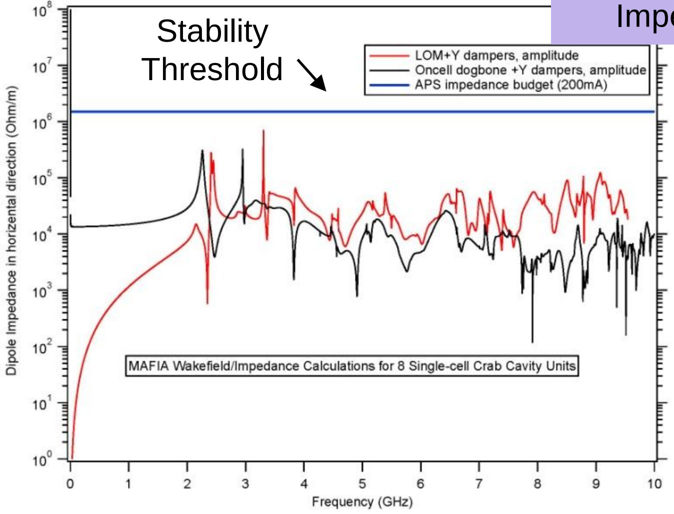
Horizontal dipole

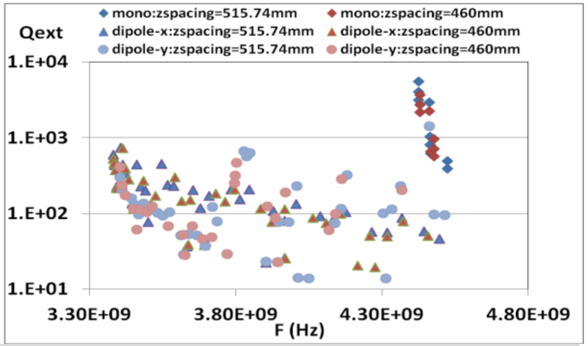
$$R_t < 3.9\,M\Omega / m$$

Vertical dipole

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

Horizontal Dipole Impedance

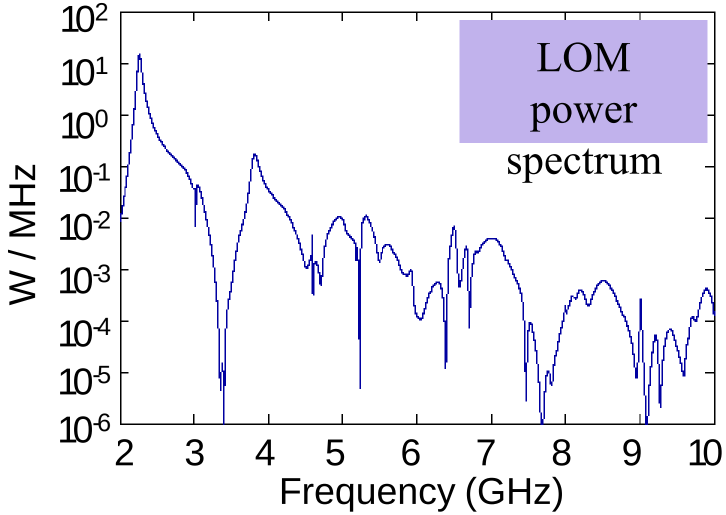




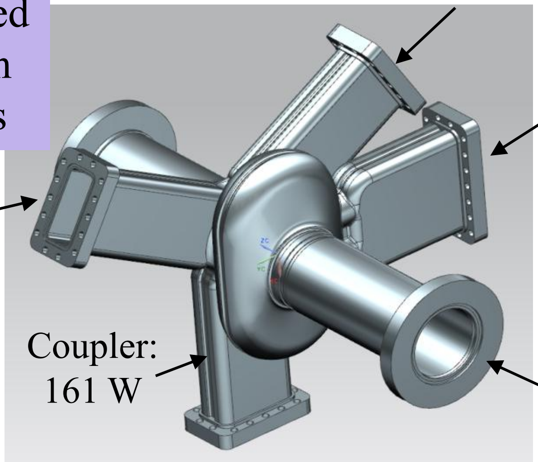
Trapped HOM in 4-cavity cryomodule
Omega3P simulation
IPAC 2012, WEPPC086
Courtesy of L. Xiao etc

LOM/HOM Induced Power

- Total LOM / HOM induced power is 1.8 kW for Mark-II cavity. Power is distributed through each of the waveguides.
- Design specifications for dampers: LOM = 2kW / HOM = 0.3 kW
- Waveguide damper design is based on PEP-II (10kW) and KEK (500W) operational dampers.
- LOM damper is challenging due to high-power (2kW), high frequency, and relatively narrowband, spectrum at 2.4GHz.


LOM power spectrum

HOM induced loss through cavity ports

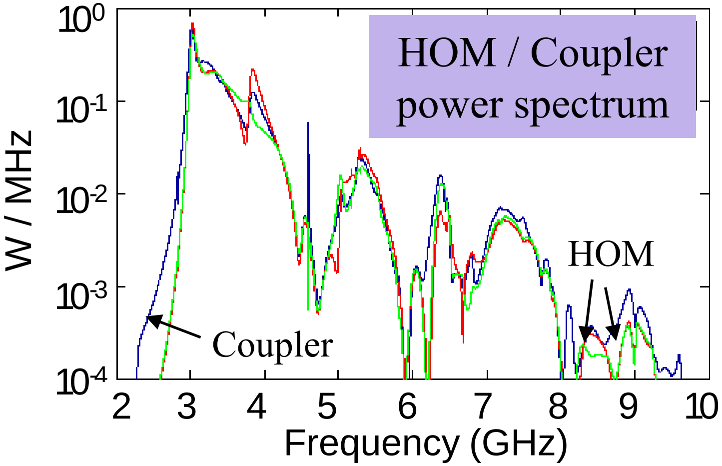

HOM 1: 165 W

LOM : 1.12 kW

HOM 2: 154 W

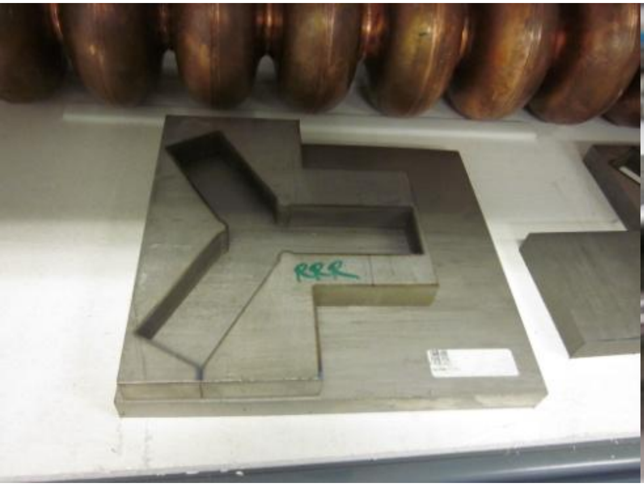
Coupler: 161 W

Beampipe: 6.1 W


HOM / Coupler power spectrum

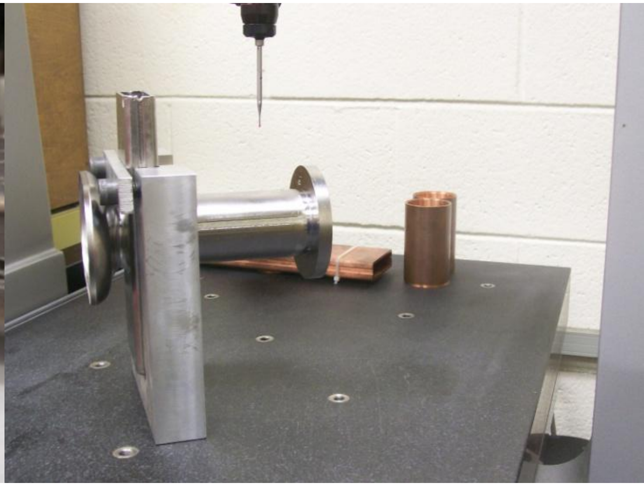
Power spectral density at cavity ports

Baseline CC-B1 Cavity Fabrication in 2010



EDM cut Y Nb fine grain RRR>250 plate

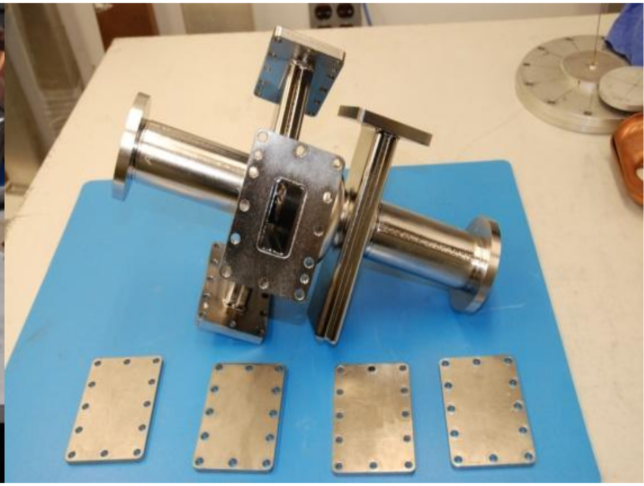
CNC machine two halves and EBW



Survey on LOM WG pre-alignment

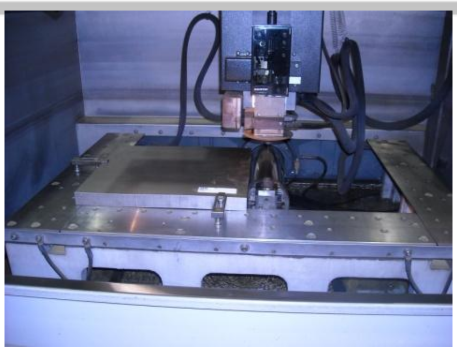
Finished Y waveguide group

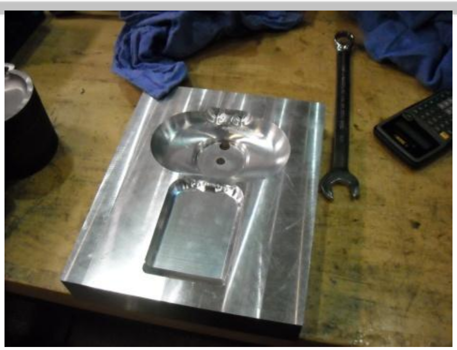
Finished two half groups before final equator EBW



CCB1 cavity with Nb blank offs

Fabrication of CC-A2 Cavity by CNC Machining

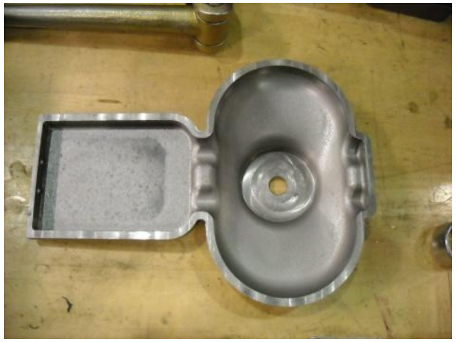

Cut fixture plate

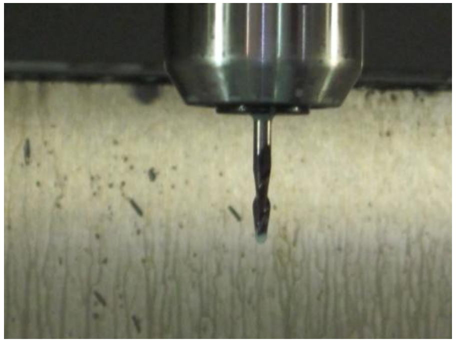

machined fixture base


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

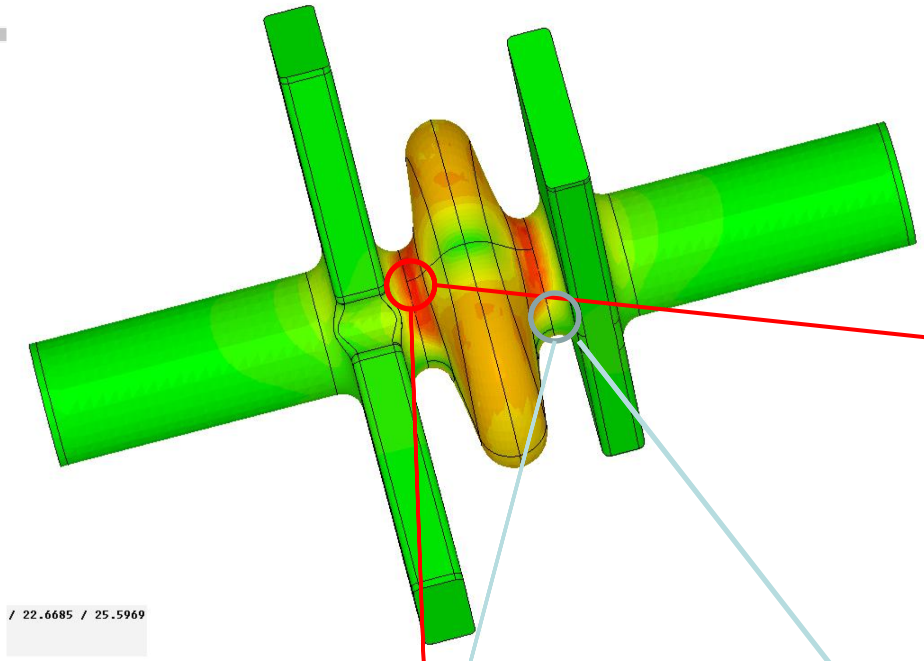

Finished first half with 4mm wall thickness

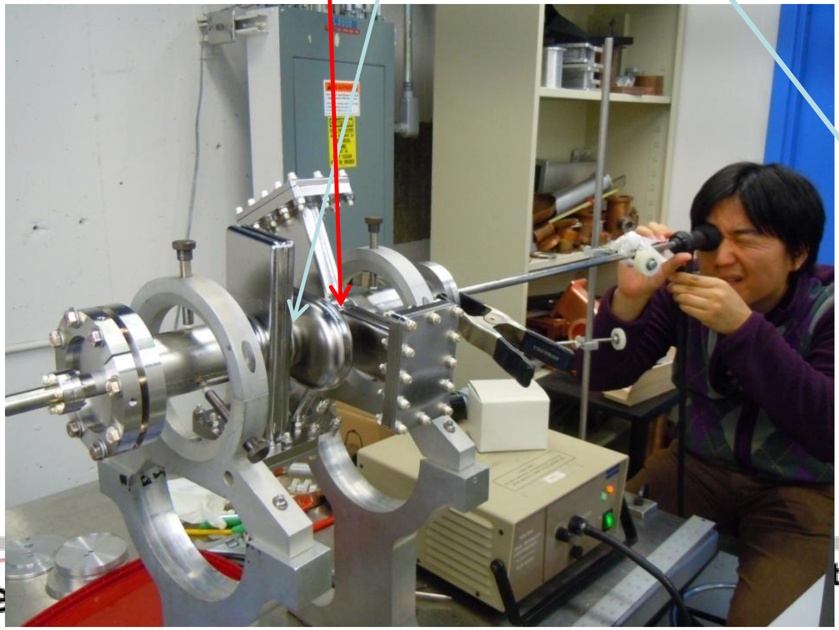

Match to other Al model half

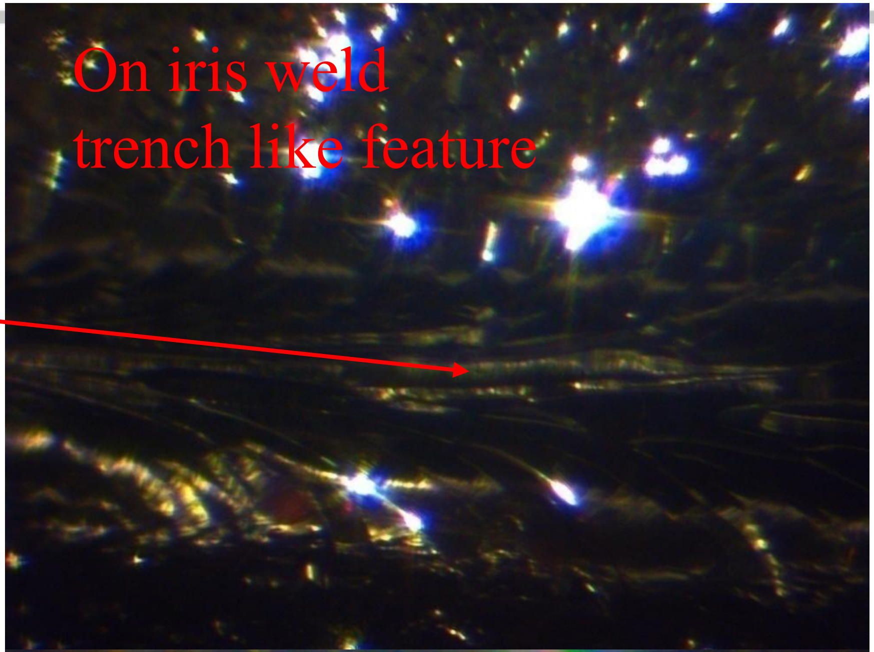

Outside finish of first half


EDM wire cut Nb template for Y WG

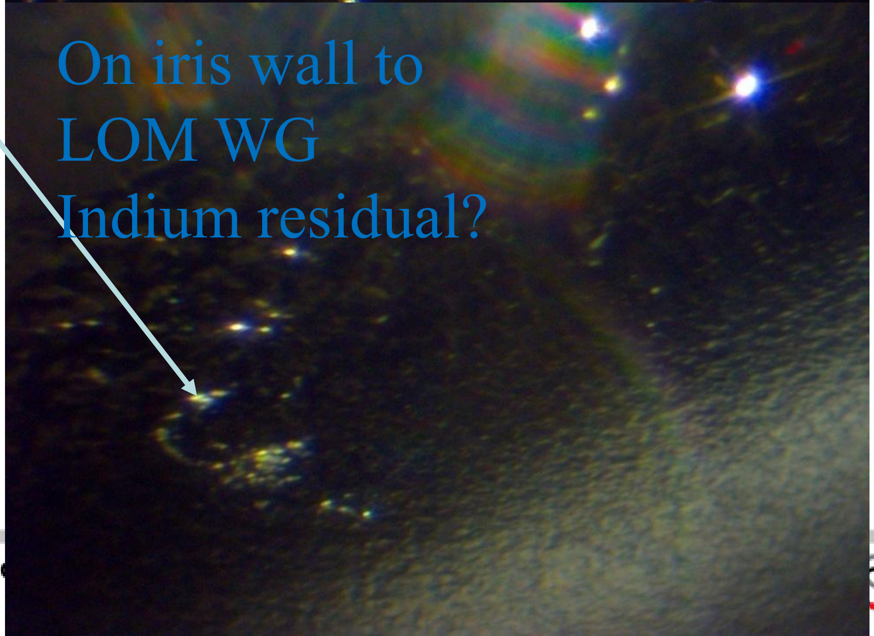
Cavity Surface Inspection by Bore Scope on Dec 07, 2010







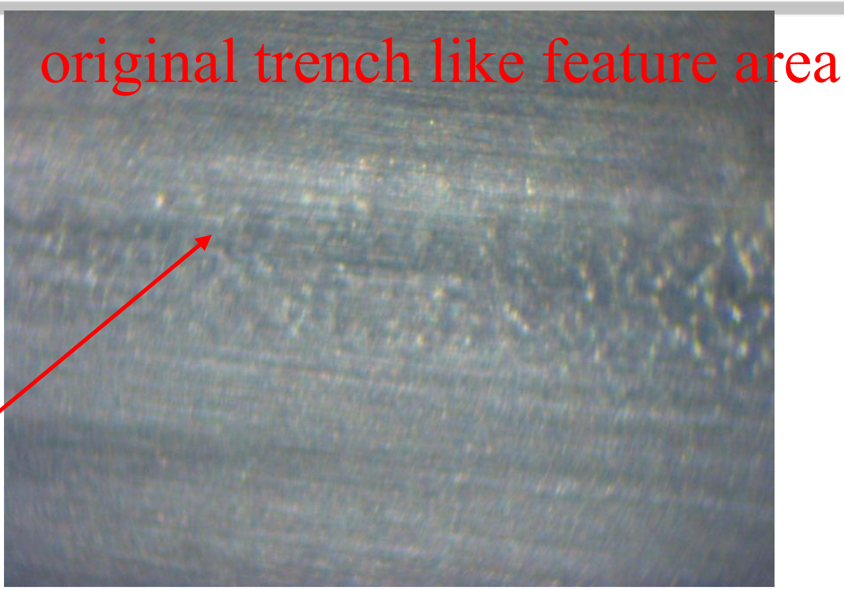
On iris weld
trench like feature

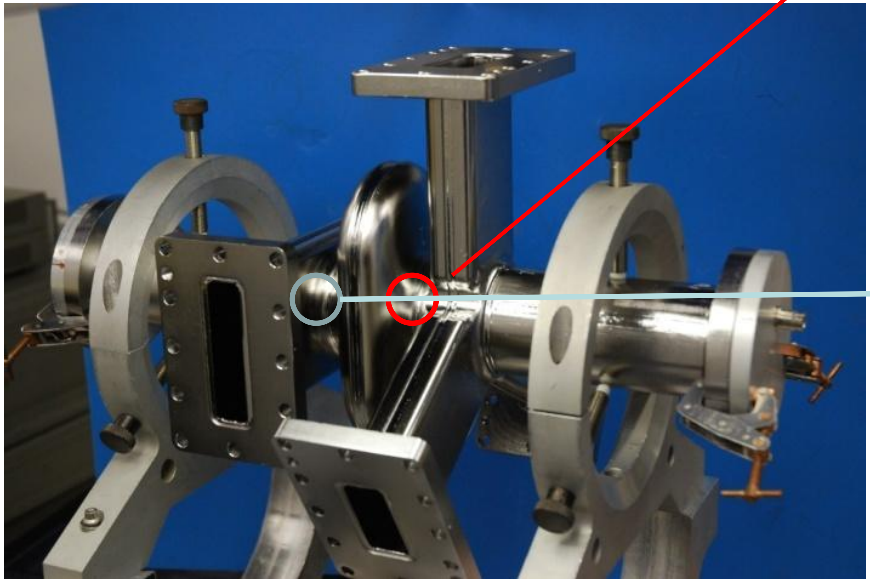


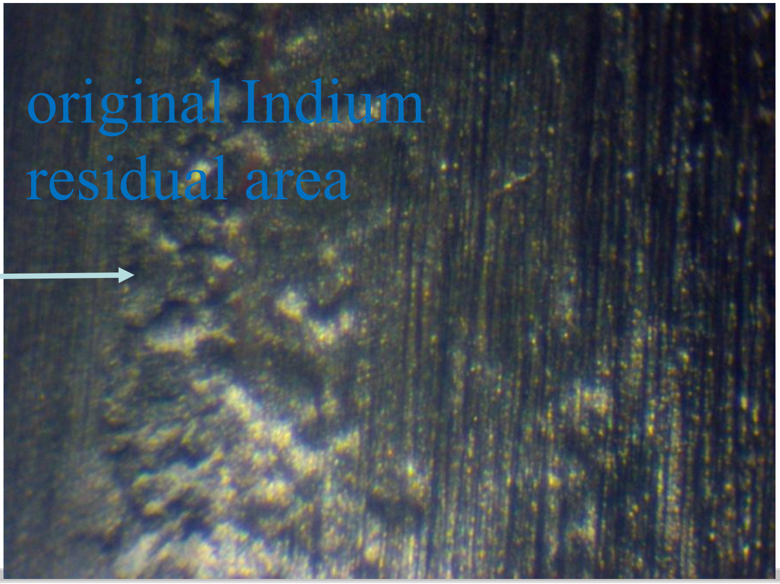
On iris wall to
LOM WG
Indium residual?

Cavity Surface Inspection and Treatment after Grinding and Hand Polishing

- Cavity was mechanically polished on the interior
- 80um BCP in the production cabinet
- Furnace treated at 600^{o}C for 10 hours
- Final BCP on bench 5um
- HPR ~1hr on R&D system
- Dry overnight in portable clean room class 10 area
- Final assembly and evacuation in class 100 room
- RF test at Dewar#4, 23 Torr He level 110cm



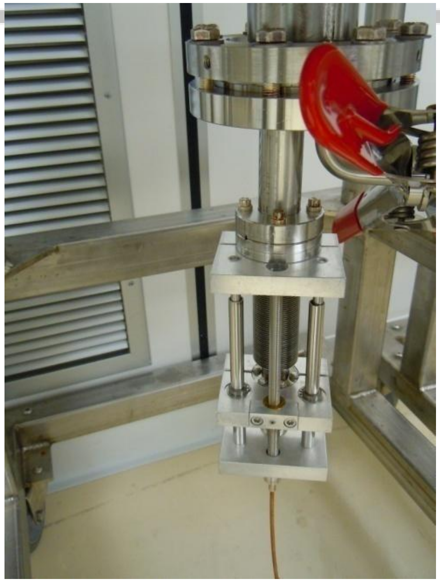




Surface Treatment and Clean Room Assembly of Baseline CCB1 Cavity

- 90+10um BCP, ΔT <10°C etching rate=1um/min to allow iris and equator removal the same amount
Inlet to outlet ΔT<1.5°C
- 600^{o}C for 4hrs bake
- Ultrasonic degrease
- HPR in R&D system ~ 1hr
- Dried in class 10 for several hrs
- Assembly in class 10
- Attached to test stand in class 100
- First assembly got a leak on pumping port after a few days
the cavity got reassembled. The indium seal on the pumping flange got clean with dry N2 blow and plugging beam pipe.
- variable coupling was set up
- <5e-10 mBar at 2K
- Liquid Helium Level in 128cm at the test start.

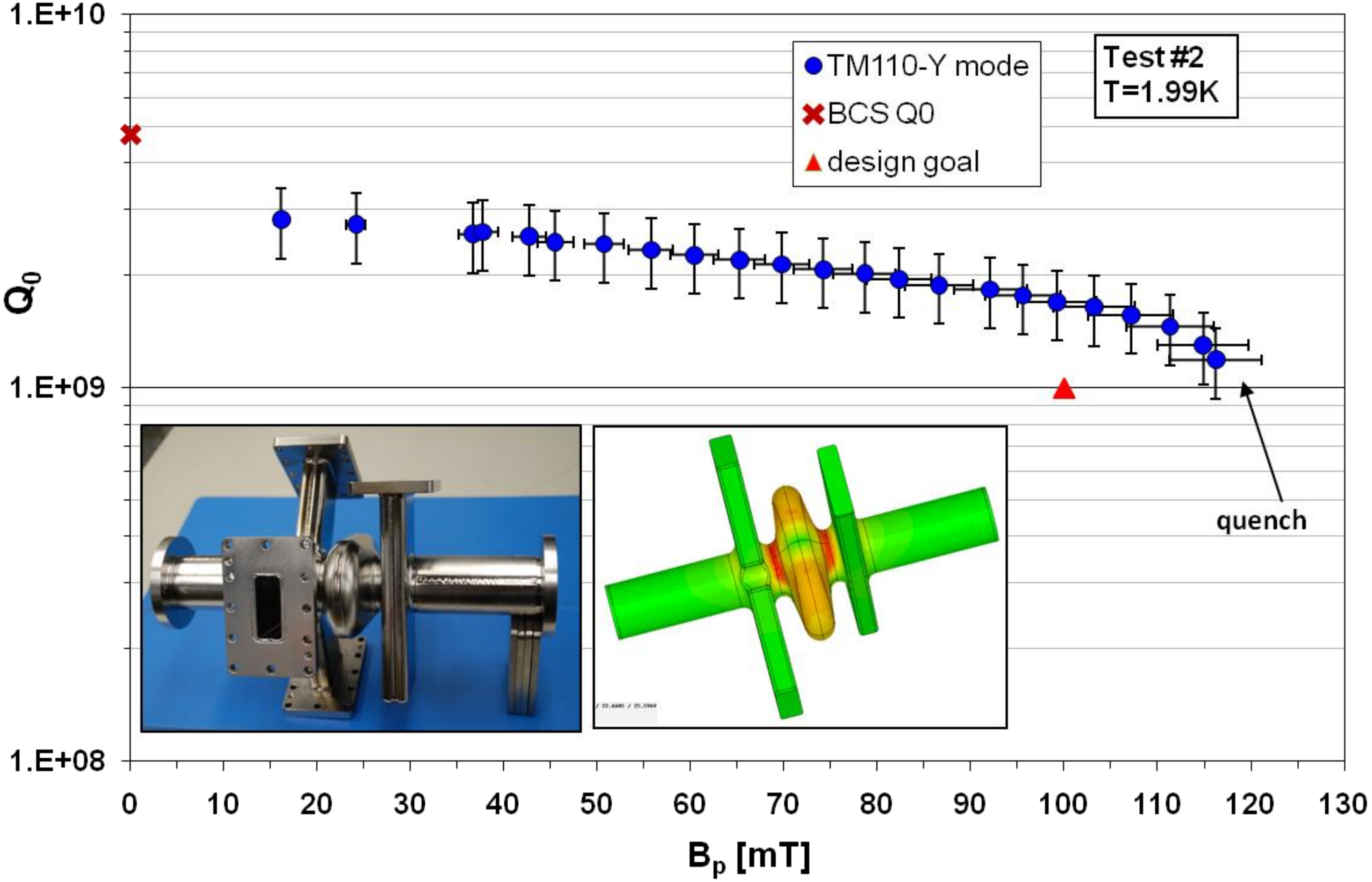



The Baseline Cavity CCB1was Qualified 3 Times at JLab/ANL

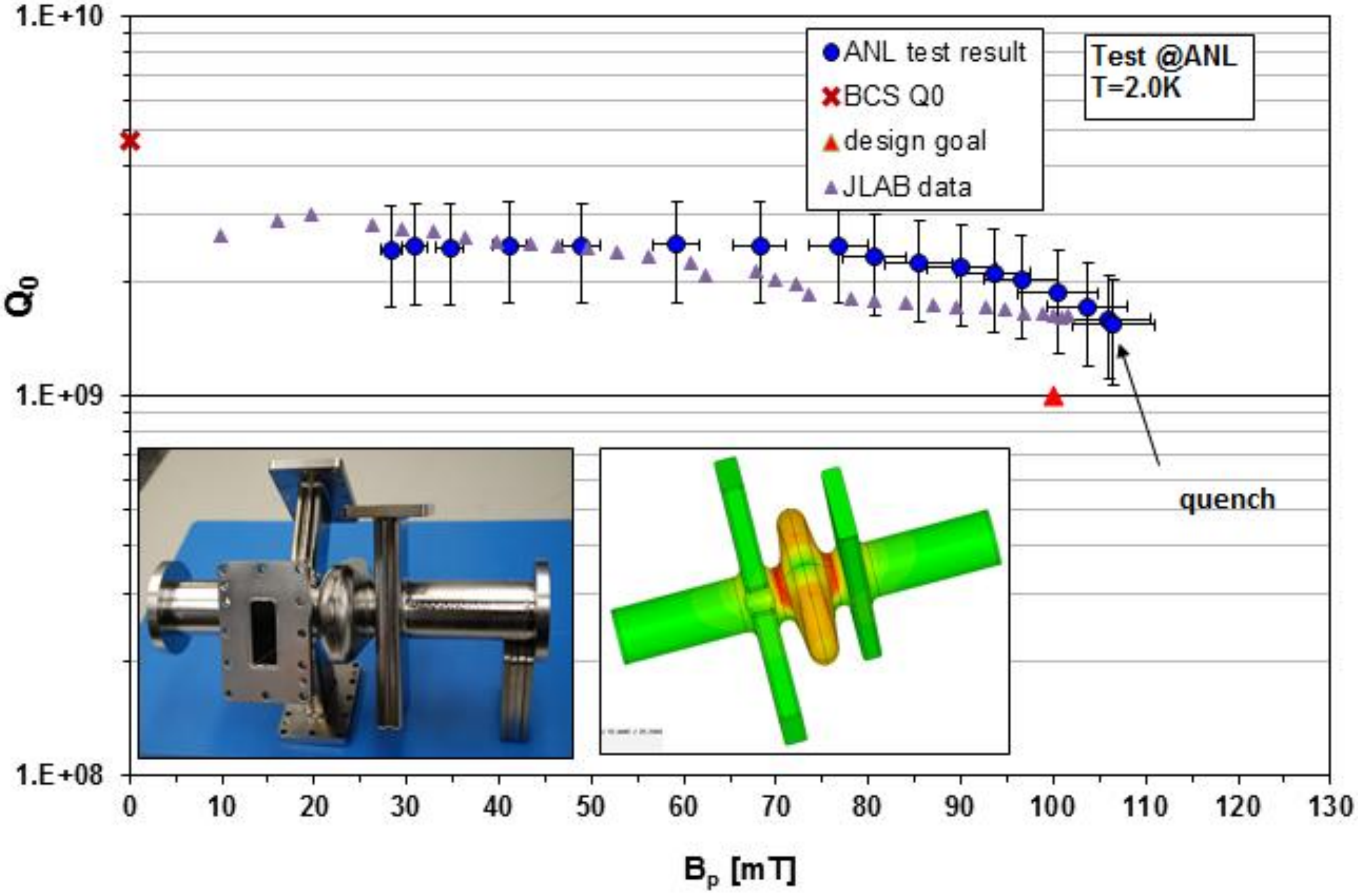
"Baseline" Prototype Crab Cavity (CC-B1 for SPX Project) Vertical Test at JLab

Test data: Feb. 11, 2011



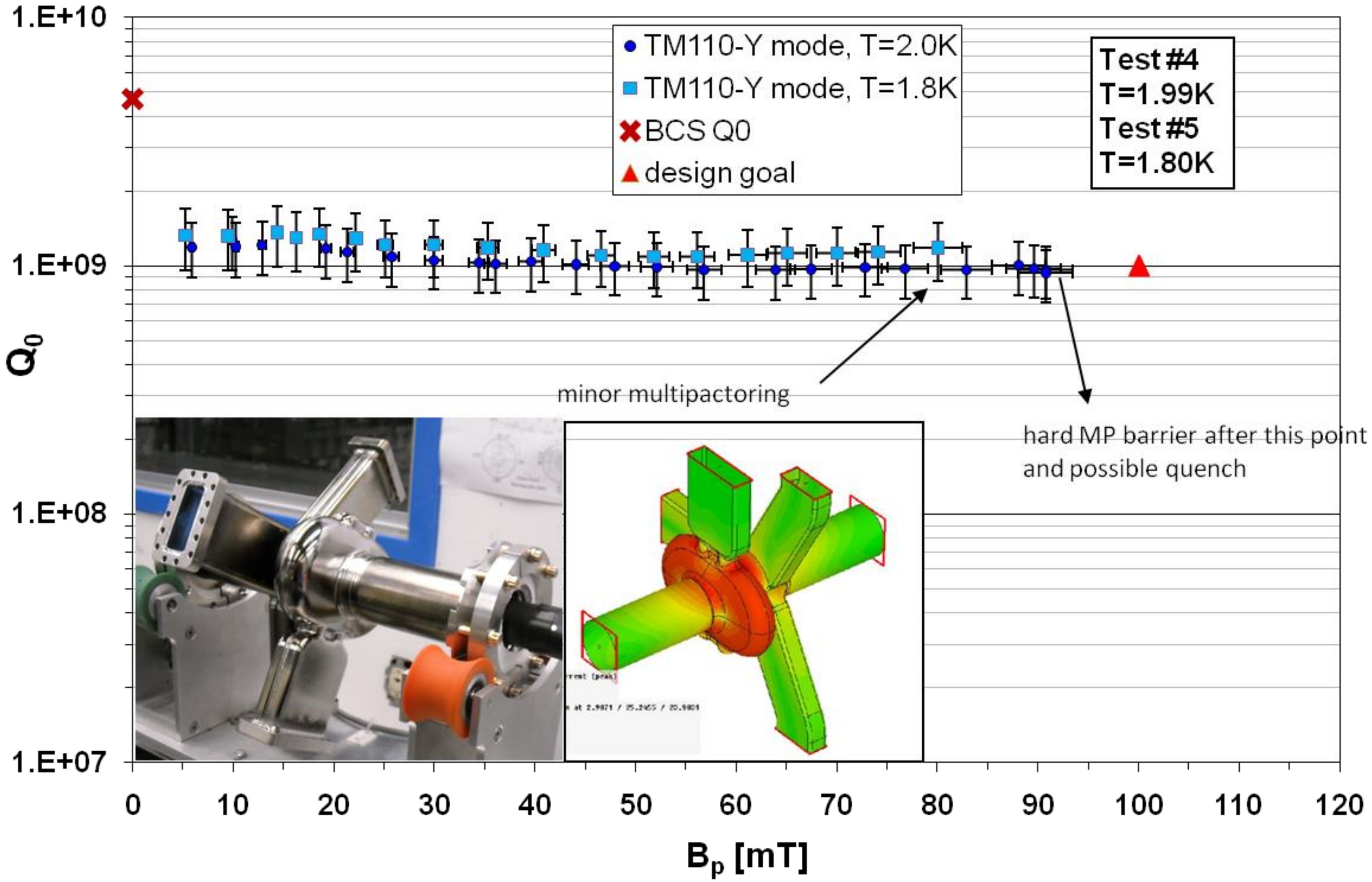
The Baseline Cavity CCB1was Qualified 3 Times at JLab/ANL

Mark-I Cavity (CC-B1 for SPX Project) Vertical Test at ANL 12/20/2011



Test Results for CC-A2 Cavity on August 13-16, 2011

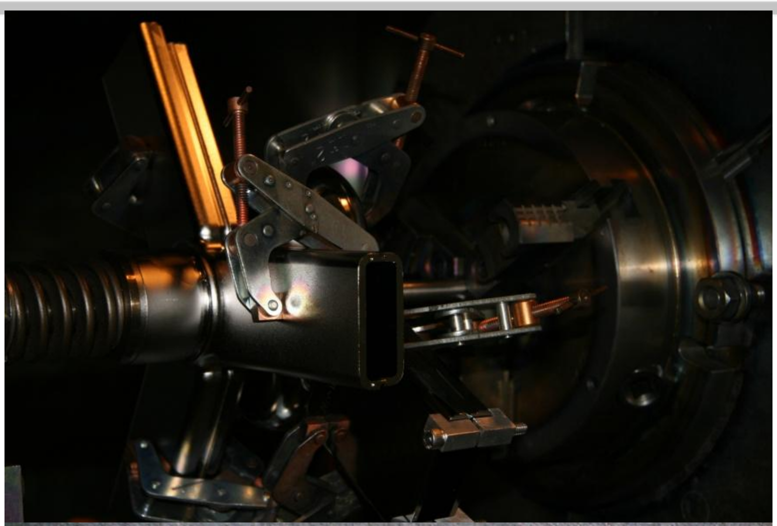
"Alternate" Prototype Crab Cavity (CC-A2 for SPX Project) Vertical Test at JLab

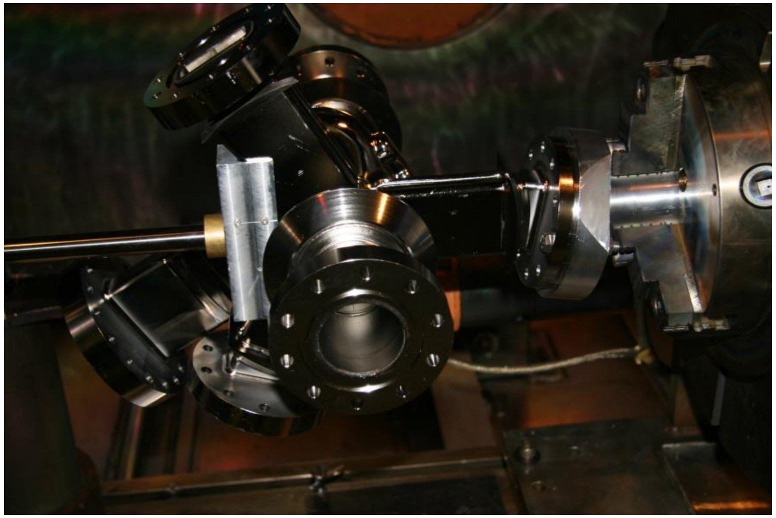


minor multipactoring

hard MP barrier after this point and possible quench

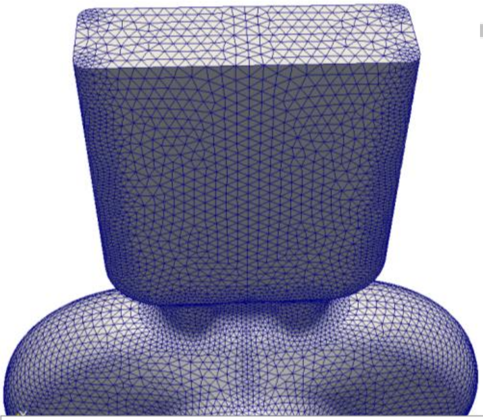
CCA3 production cavities (3) EBW fabrication





Courtesy of B. Clemens and G. Slack

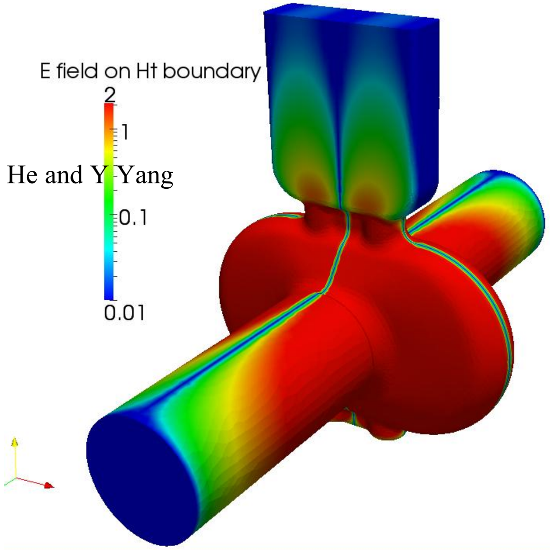
Dipole field leaks from LOM WG to NbTi blank caused a low Q problem



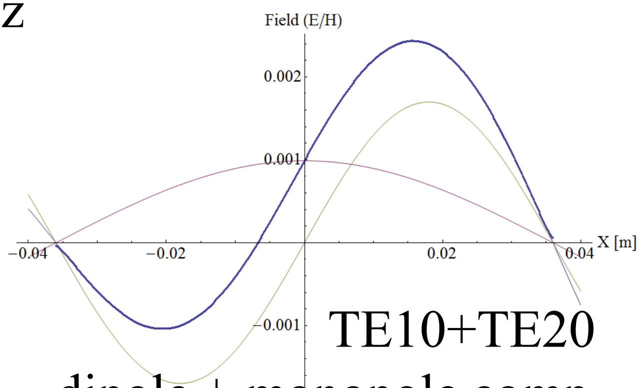
$F_{TE10\ cutoff}<F_{LOM}<F_{DFM}<F_{TE20cutoff}$

2078MHz<2425<2815<4156MHz

Port field on asymmetric meshing

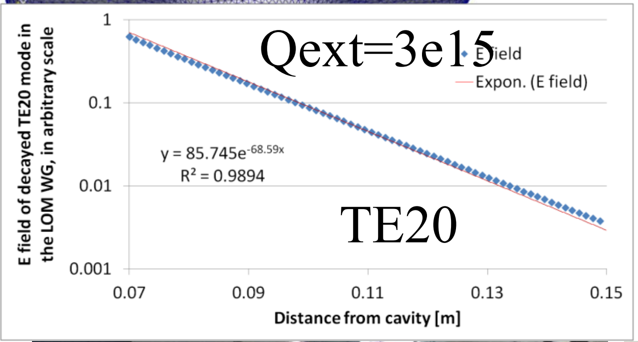


Courtesy of F. He and Y Yang



TE10+TE20

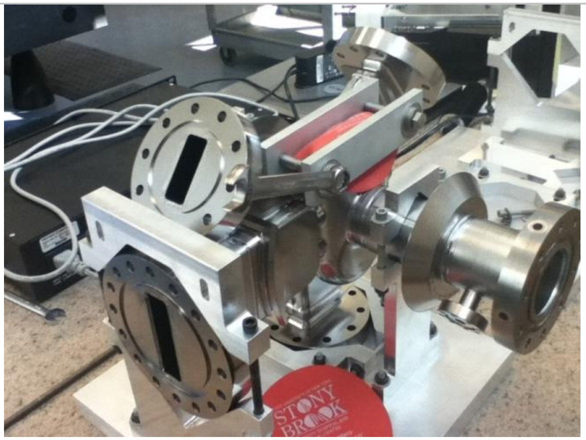
dipole + monopole comp.

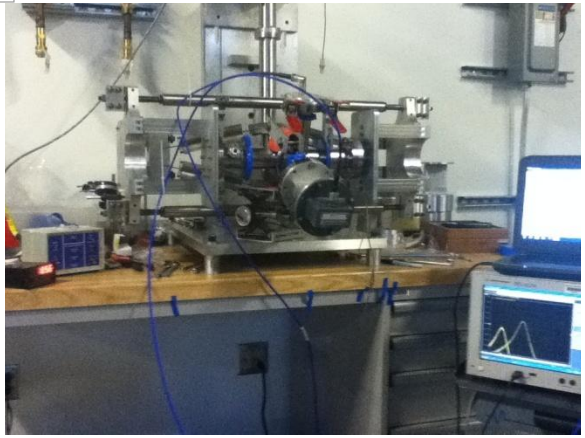


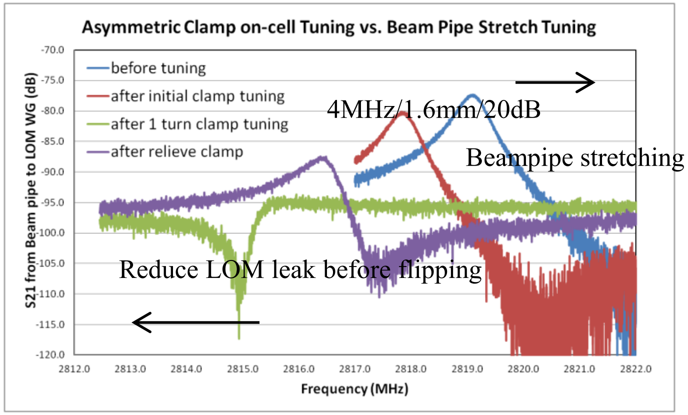
Qext=3e15

TE20

Tuning to symmetry of dipole field also corrects electric center of the crabbing field





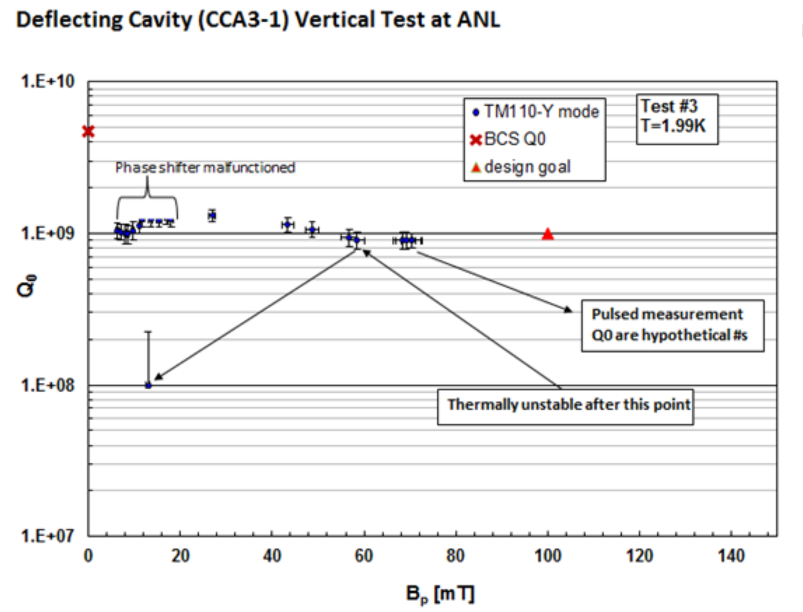


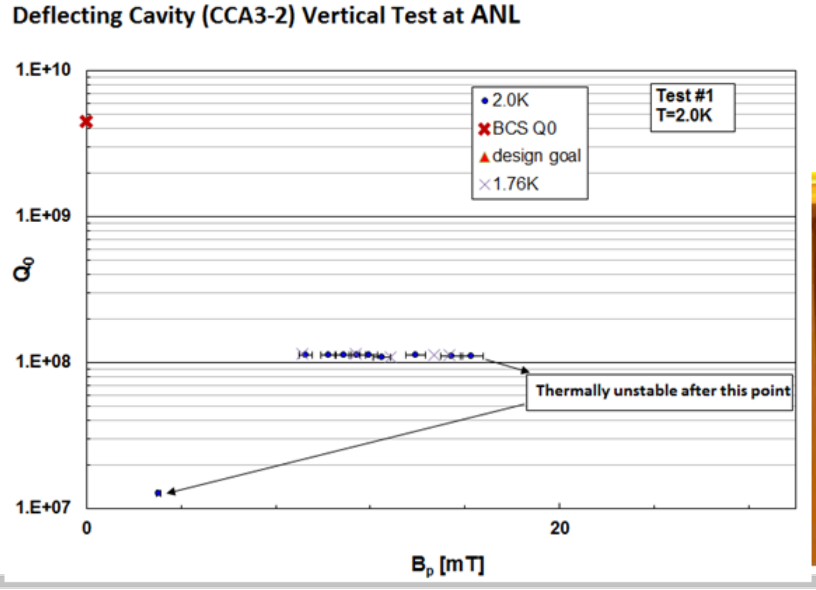
4MHz/1.6mm/20dB

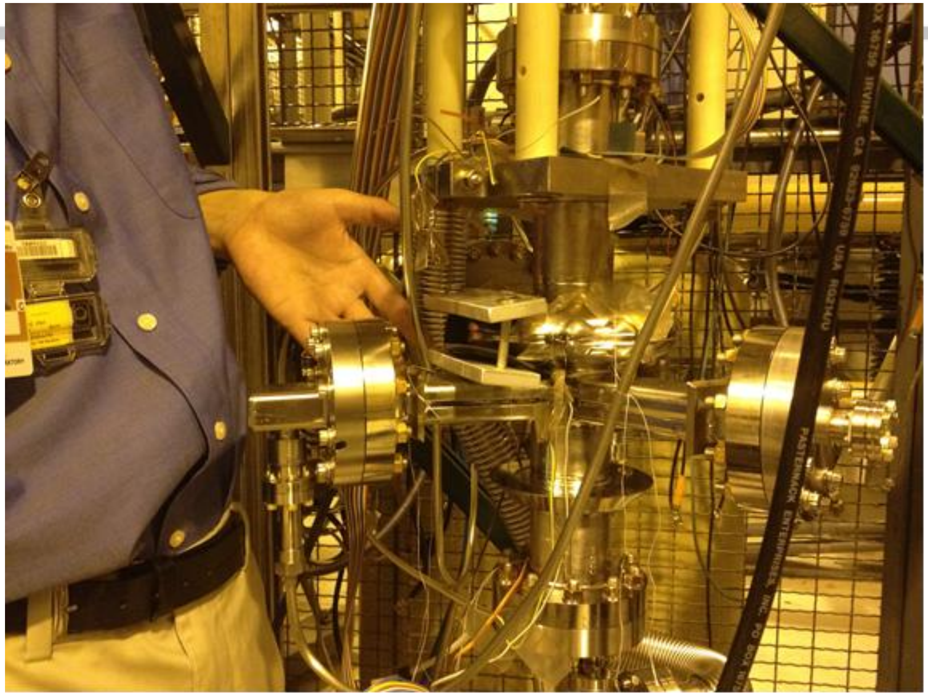
Beampipe stretching

Reduce LOM leak before flipping

First Production Cavity Vertical Test and Lessons Learned

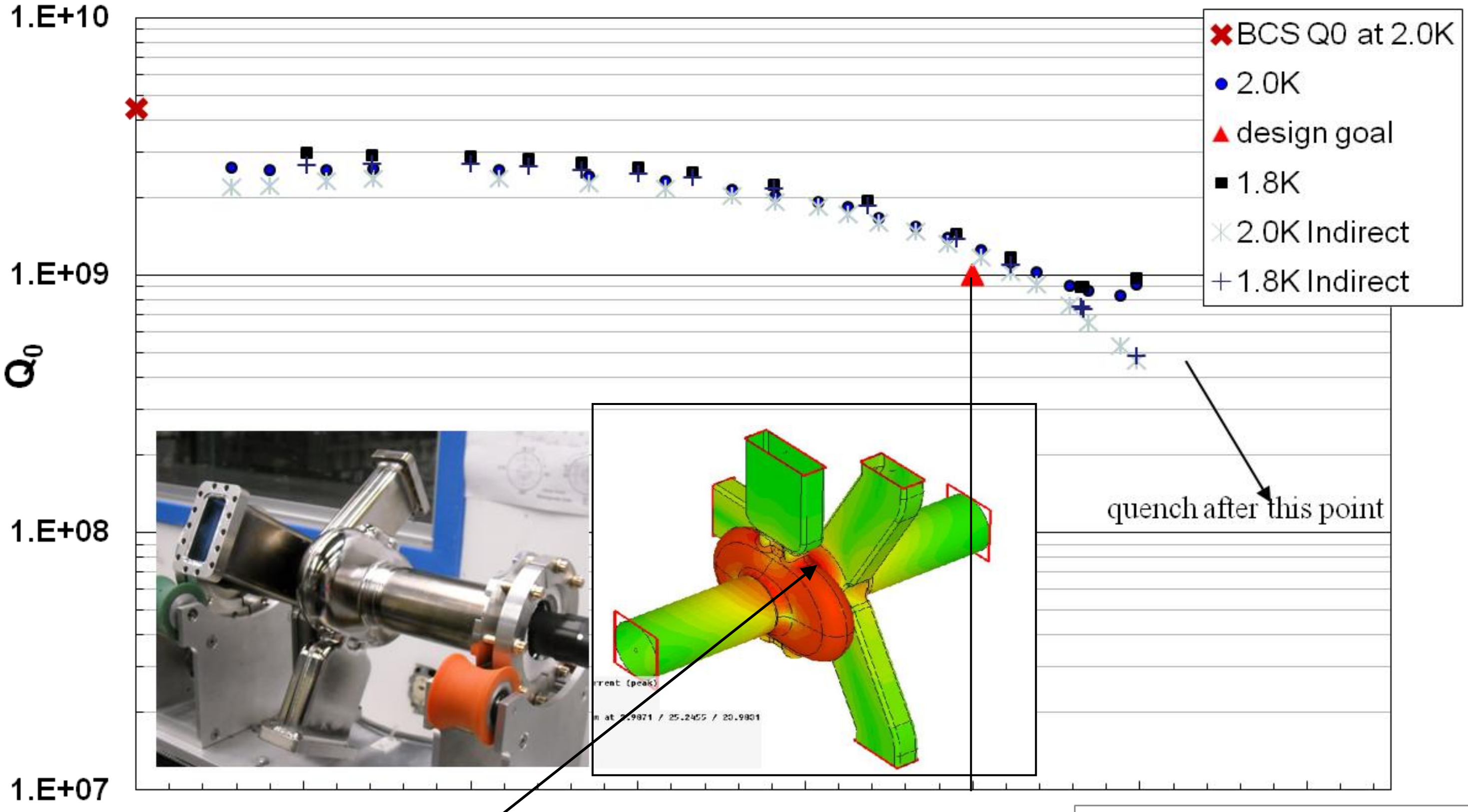

Deflecting Cavity (CCA3-1) Vertical Test at ANL

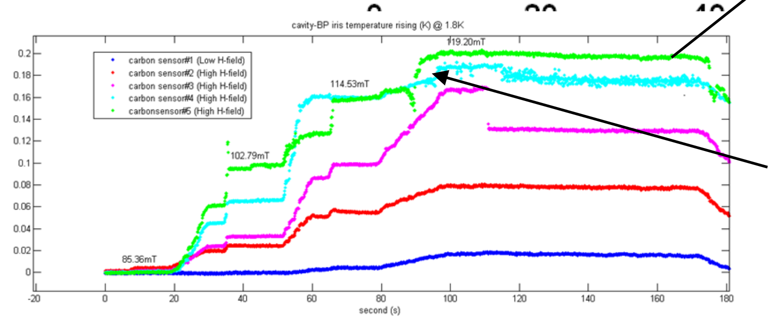

Deflecting Cavity (CCA3-2) Vertical Test at ANL



Courtesy of G. Wu, J. Holzbauer, Y. Yang

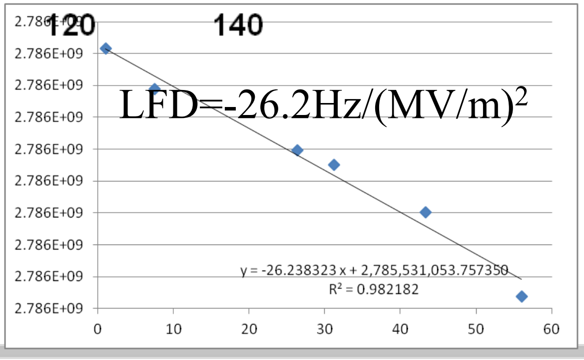
Mark-II type cavity first time passed QA spec after tuning the dipole field





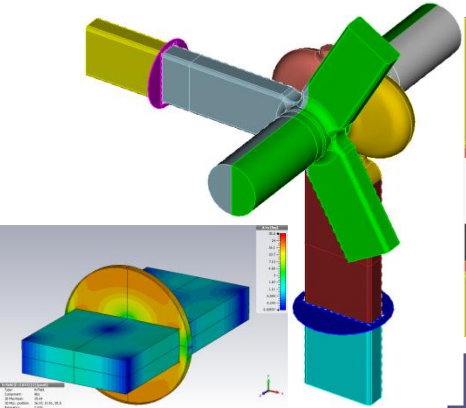
AT 1.8K test, the average detected temperature rising around 119mT is 140mK while in 89mT the average rising is only 15mK.

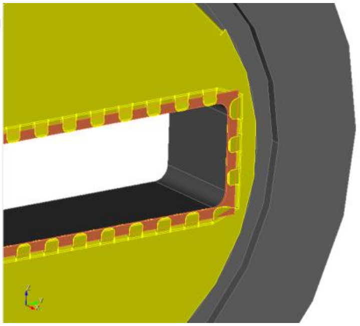
Courtesy of G. Wu, J. Holzbauer, Y. Yang

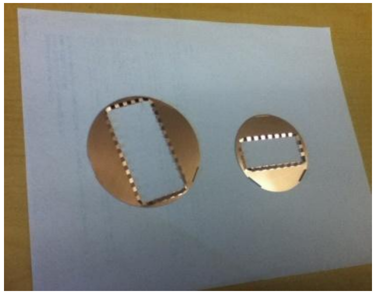


LFD=-26.2Hz/(MV/m)^2

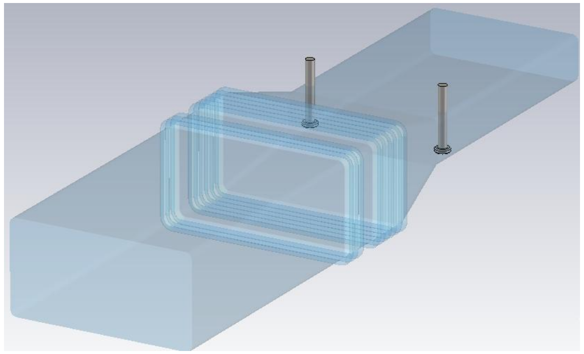
Design to block RF leaks from cavity to LOM WG and AlMg seals

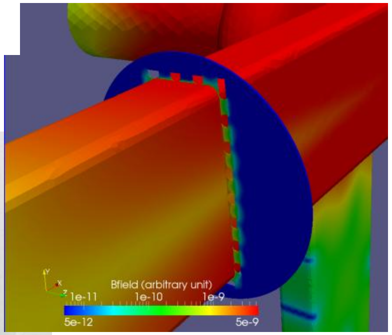


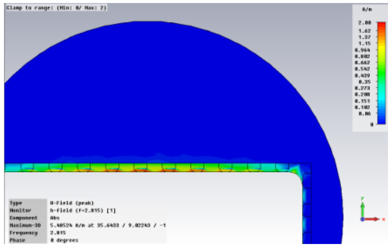




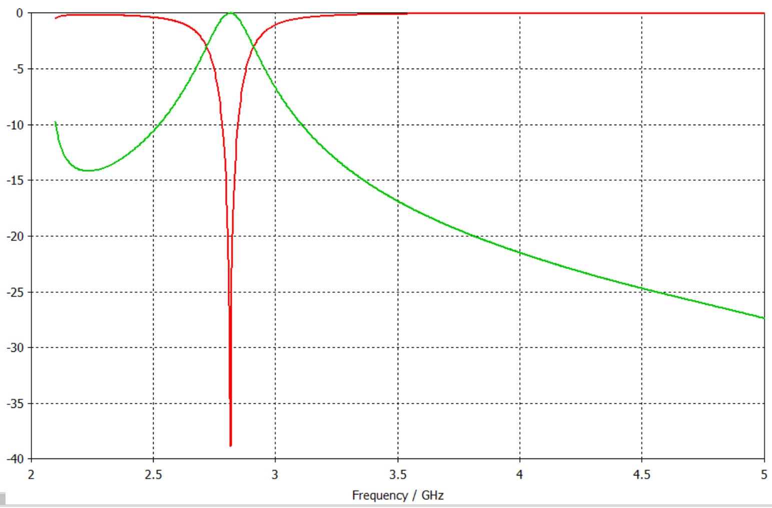
Double screws notch filter on NC (SC?) waveguide

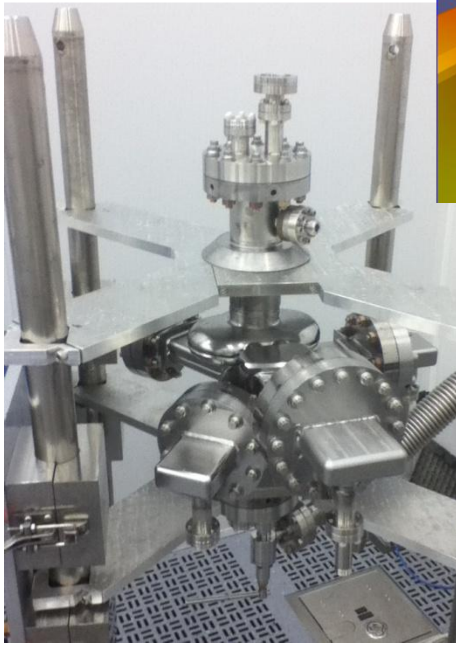






Courtesy of F. He, G. Waldismidt and Y. Yang





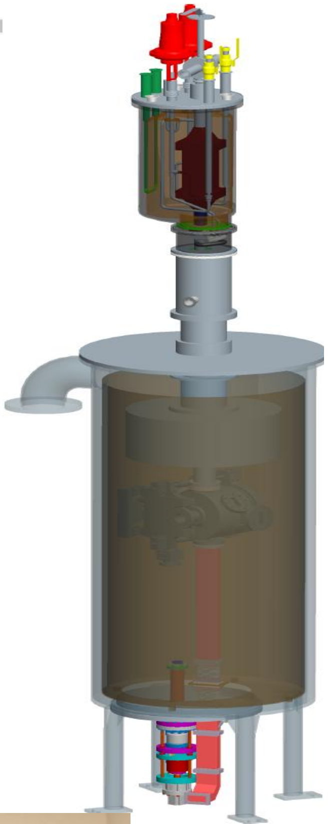
DPC shielding Q (with top-hat)	**4E11**
LOM shielding Q (with top-hat)	**1.3E13**
LOM shielding Q (port matched)	**$Q_{e\text{-}LOM}$ * 1.1E6**

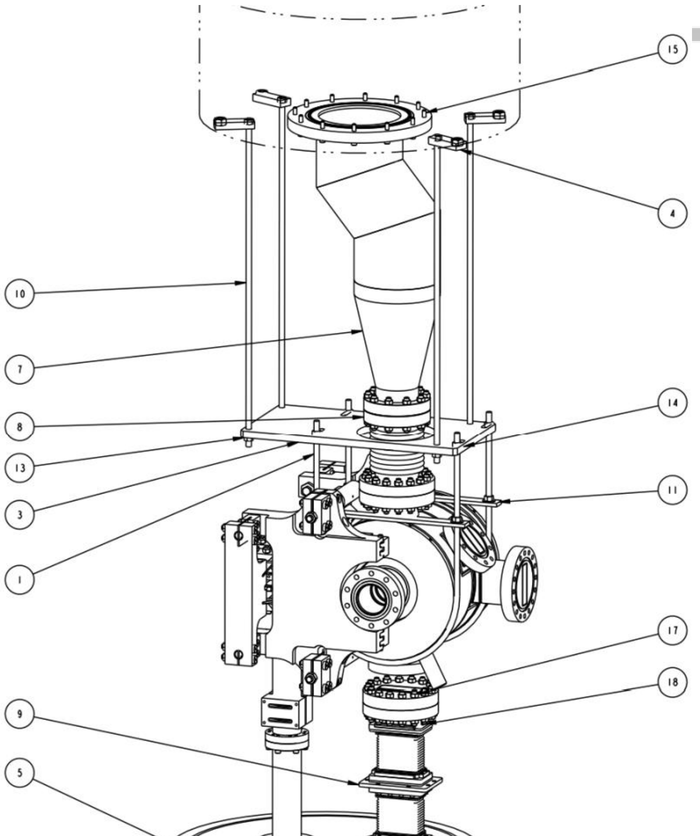
CCA3-3 cavity with RF gaskets will be VT tested at ATLAS this week.

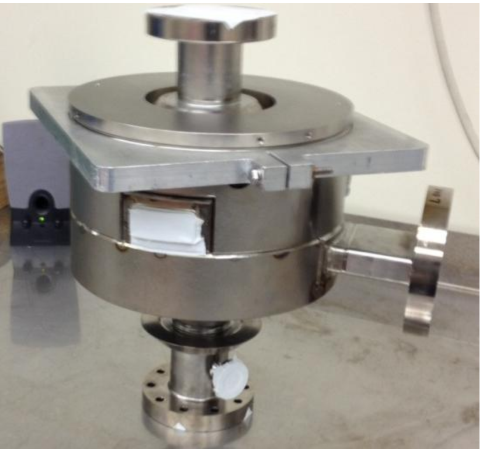
Recent Progress toward horizontal test with tuner to be done in Nov.

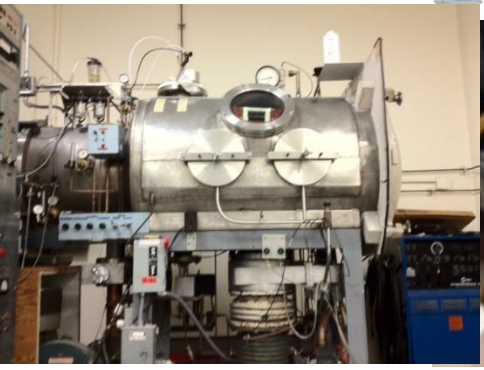
Horizontal cavity test
- No LOM/HOM loads but
- with windows & WG bellows
- Fully dressed tuner
- 5kW amplifier
- 50W cooling@2K
- Analog and digital LLRF
- Ti helium vessel and bellows

is being welded at ORNL.



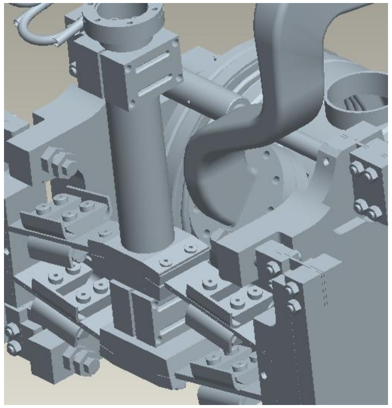


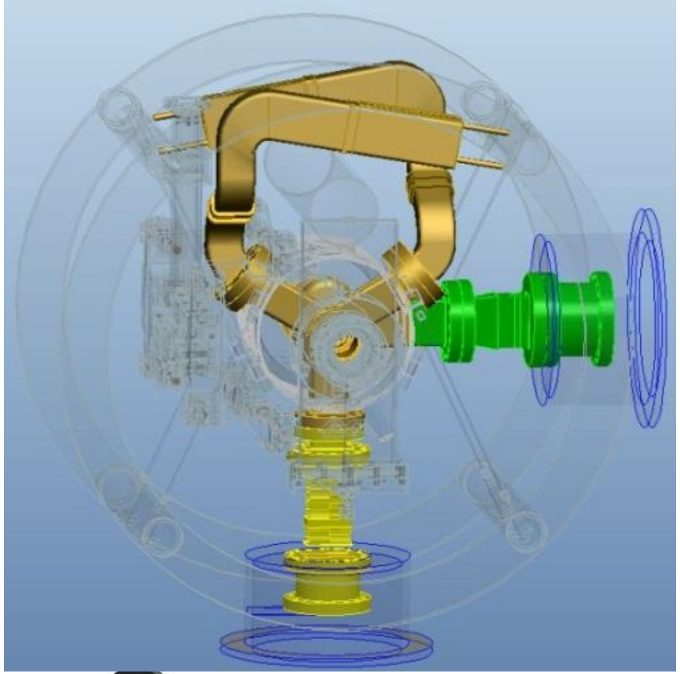


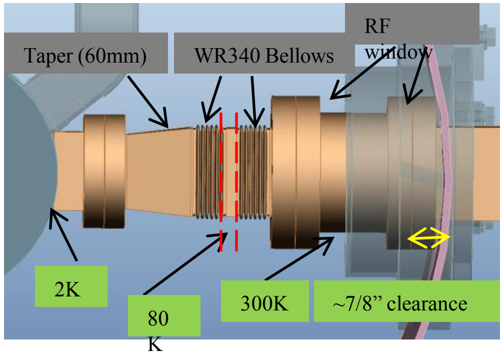


Courtesy of G. Wu, J. Mammosser and B. Stillwell

Cryomodule Engineering Design (SPX0)







Taper (60mm)

WR340 Bellows

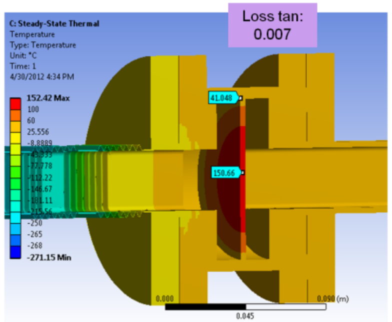
RF window

2K

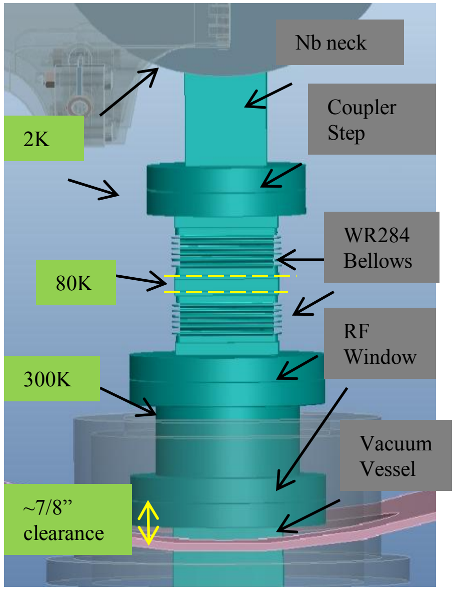
80 K

300K

~7/8" clearance



Loss tan: 0.007



Nb neck

Coupler Step

2K

WR284 Bellows

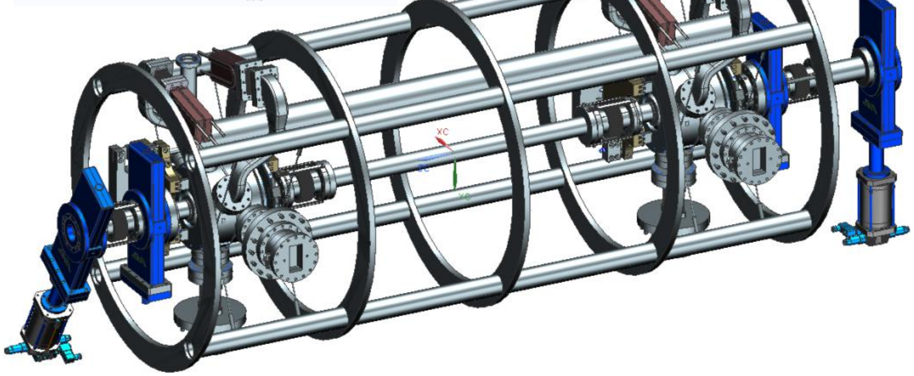
80K

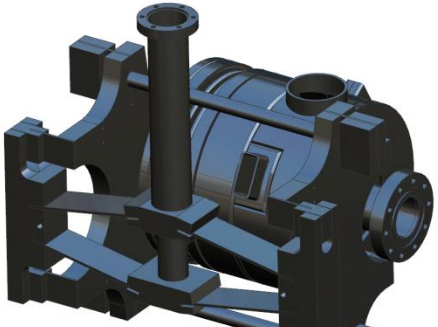
RF Window

300K

Vacuum Vessel

~7/8" clearance





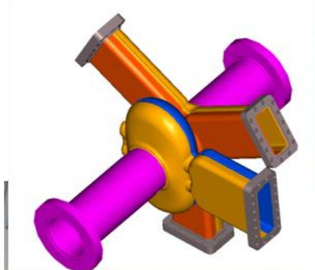
Tuner

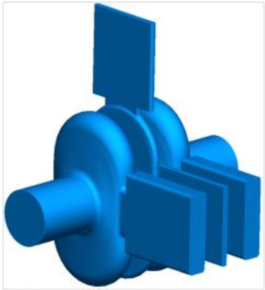
Summary

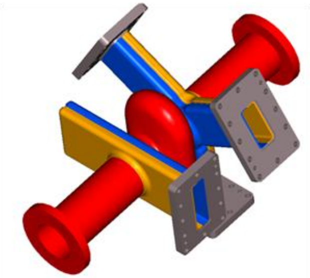
- SPX(0) project has been successfully gone through critical R&D phase. Crab cavity design, prototype, down selection, vertical test result have demonstrated successfully the frontier SRF technology application for both high gradient and high current accelerator application.
- The recent test result shows a major milestone achievement and to be ready for the CD2 review next month.
- Horizontal test will be the next milestone toward to the SPX0 cryomodule development.
- Engineering analysis and design are in good progress in all technical details.
- SPX is a challenging, exciting and collaborating project for producing short pulse x-rays for future science at APS.

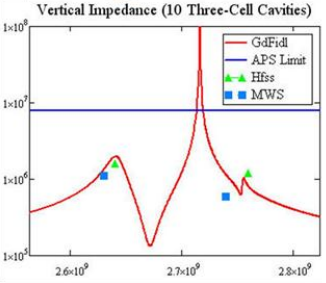
Backup Slides

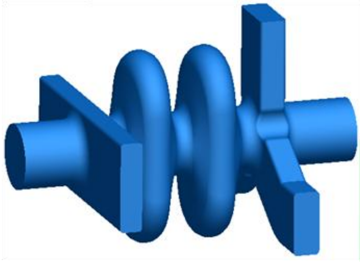
Why Was SRF Crab Cavity Design not Multi-cell?

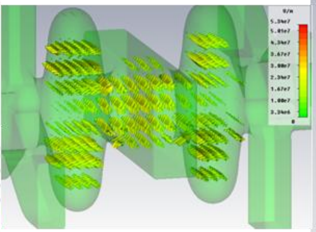


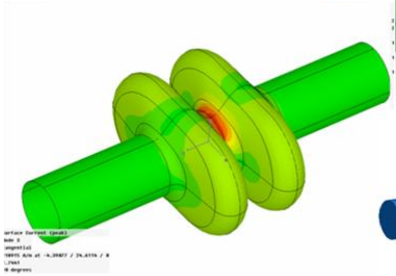


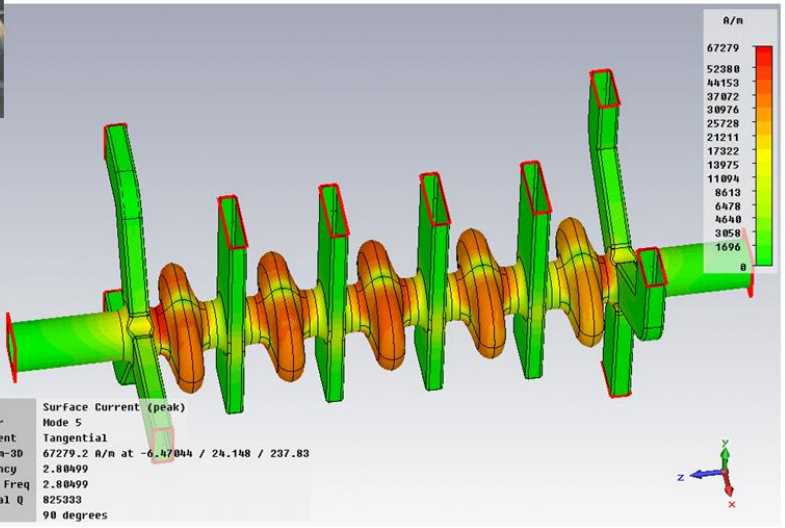








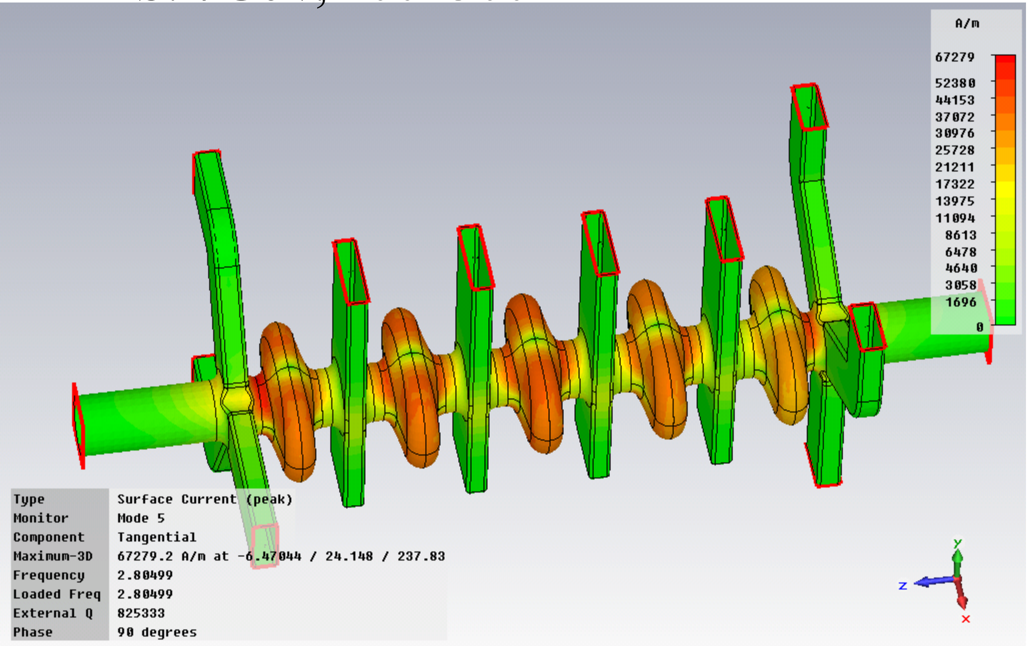




```
Type           Surface Current (peak)
Monitor        Mode 5
Component      Tangential
Maximum-3D     67279.2 A/m at -6.47044 / 24.148 / 237.83
Frequency      2.80499
Loaded Freq    2.80499
External Q     825333
Phase          90 degrees
```

TM110-y Same Pass-band Modes in a 5-cell APS Crab Cavity

APS: 7GeV, 100~300 mA



Type Surface Current (peak)
Monitor Mode 5
Component Tangential
Maximum-3D 67279.2 A/m at -6.47044 / 24.148 / 237.83
Frequency 2.80499
Loaded Freq 2.80499
External Q 825333
Phase 90 degrees

Scaled Frequency	Scaled External Q-factor	Rt/Q
GHz	for a flat 0-mode Hx field	Ohm, at y=1cm offaxis distance
2.794523	1.69E+07	0.02
2.799700	2.96E+06	0.20
2.806271	9.21E+05	0.90
2.811808	5.29E+05	3.04
2.815488	8.07E+05	185.99

Hi Bob,

Sang-ho Kim from SNS ("HOM power in elliptical superconducting cavities for ...") referenced a Cornell study that showed the standard deviation of the HOM frequencies to be sigma=0.00109 * |fn - fo|, where fn is HOM and fo is the tuned operating mode. If you take Haipeng's values

2.794523GHz and 2.815488GHz, respectively, this gives you sigma=22.85kHz. But how accurate this is, and how applicable to dipole mode cavities, I don't know. On the other hand, I talked with Louis again and the actual frequency control that is required is 135kHz (i.e., frev/2).]

Geoff

Robert Rimmer wrote:

Hi Geoff,

I presume that the SPM frequencies would tune very similarly to the operating mode so it might be worth thinking about how they track. We would keep the operating mode very stable in frequency with the active tuners, so the SPM's might stay put too? A bigger problem may be that they might be different from one cavity to another because of manufacturing variations. In other words controlling their absolute frequency might be harder than keeping them stable. On the other hand their offset from the operating mode should be determined only by the cell to cell coupling. I wonder how repeatable that might be?

Bob.

On May 18, 2010, at 7:03 PM, Geoff Waldschmidt wrote:

Hi Haipeng,

The Physics group looked at the multi-cell design and found that it would be difficult to implement. From the impedance criteria that we've been using, it wouldn't work - which we already know. But, in order to park it between dangerous sidebands, the SPM frequencies would need to be controlled to within 50kHz which would appear to be very difficult. As far as I can tell, it doesn't look possible. Do you have any further questions that I should ask?

Geoff

Subject: HOM too stong

Date: Tue, 18 May 2010 16:59:37 -0500

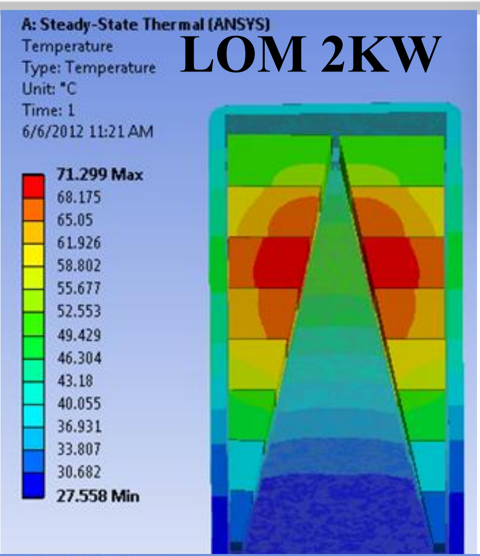
From: Louis Emery <lemery@aps.anl.gov>

The limit on the Rt quantity that we use is 7.9 MOhm/m. This is specified in my OAG-TN-2007-023, and other documents that Y. Chae wrote. Converting your (R/Q)' quantity to Rt gives me 47 MOhn/m, which is 6 times too large. I ran the instability code to see what growth rates the 47 MOhn/m HOM produces, and I got 6 times too high growth rate. I did this for 24 singlets. I didn't do hybrid mode yet, but sine the Q's are so high, I think the results would be the same. (For the normal conducting cavities of 3 years ago, a Q of 10000 would actually decay some during one turn). I didn't do a randomization of frequencies, which "could" help. But in that calculation I would have to include the other HOMs, and add three more cavities. If you think you could reduce the Q by say 20, then I could try that with the full-blown calculation. It may be marginal.

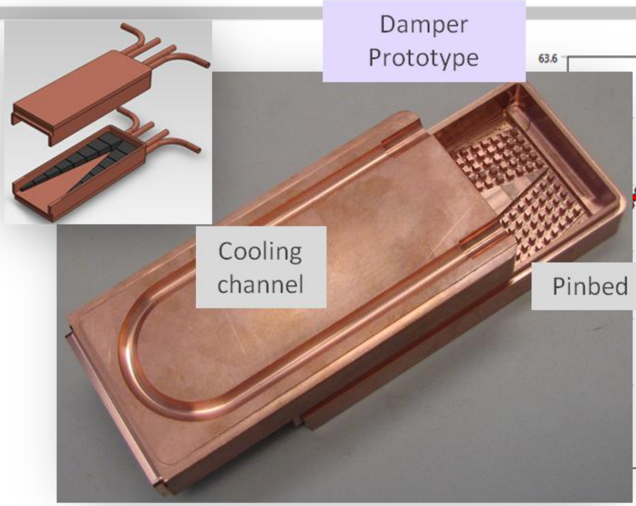
Louis Emery

- One of multi-cell cavity design choices for APS crab cryomodule.
- Are the same pass-band modes (SAMs) with given loaded Qs and Rt/Qs allowed in the APS for a 200mA stable beam operation with different filling patterns?
- If not, what their frequency spectrum and loaded Qs could be allowed for a stable beam operation?

LOM/HOM RF-thermal Simulation on Waveguide SiC Dampers



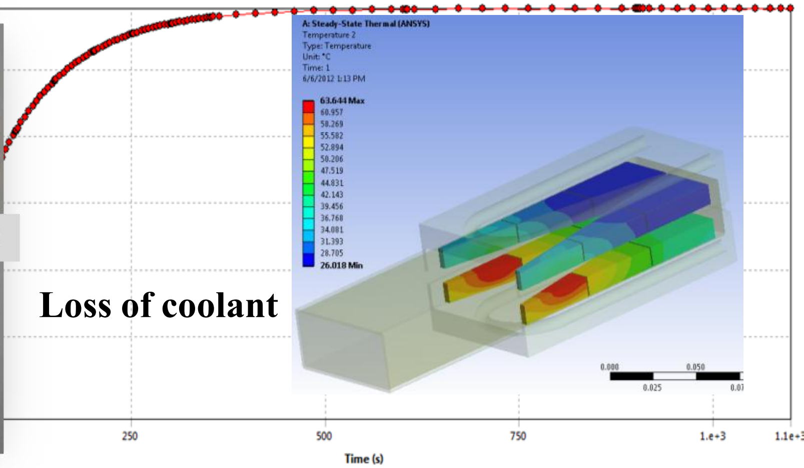
LOM 2KW



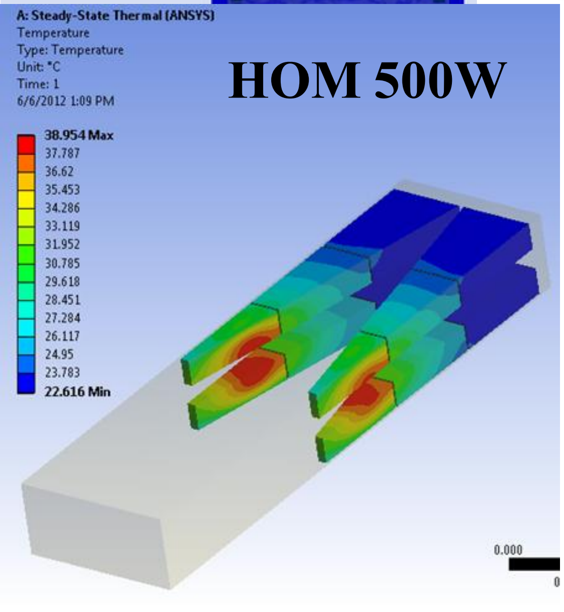
Damper Prototype

Cooling channel

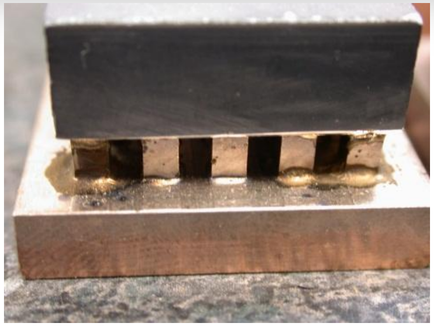
Pinbed

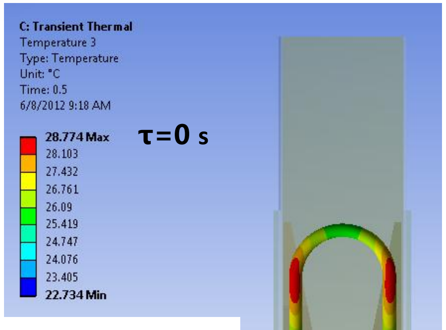


Loss of coolant

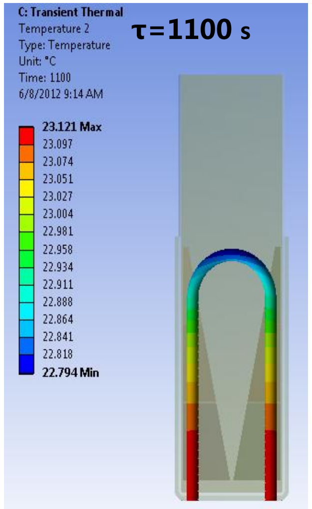


HOM 500W

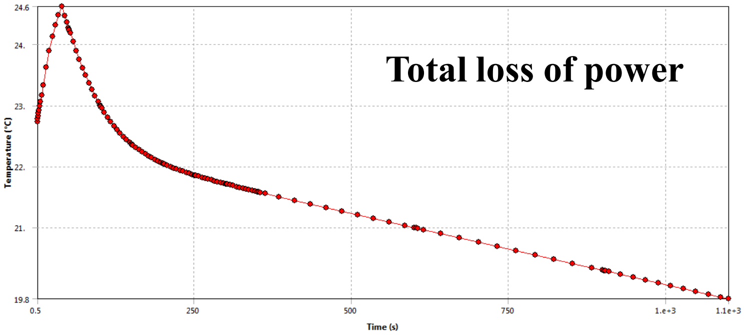




τ=0 s



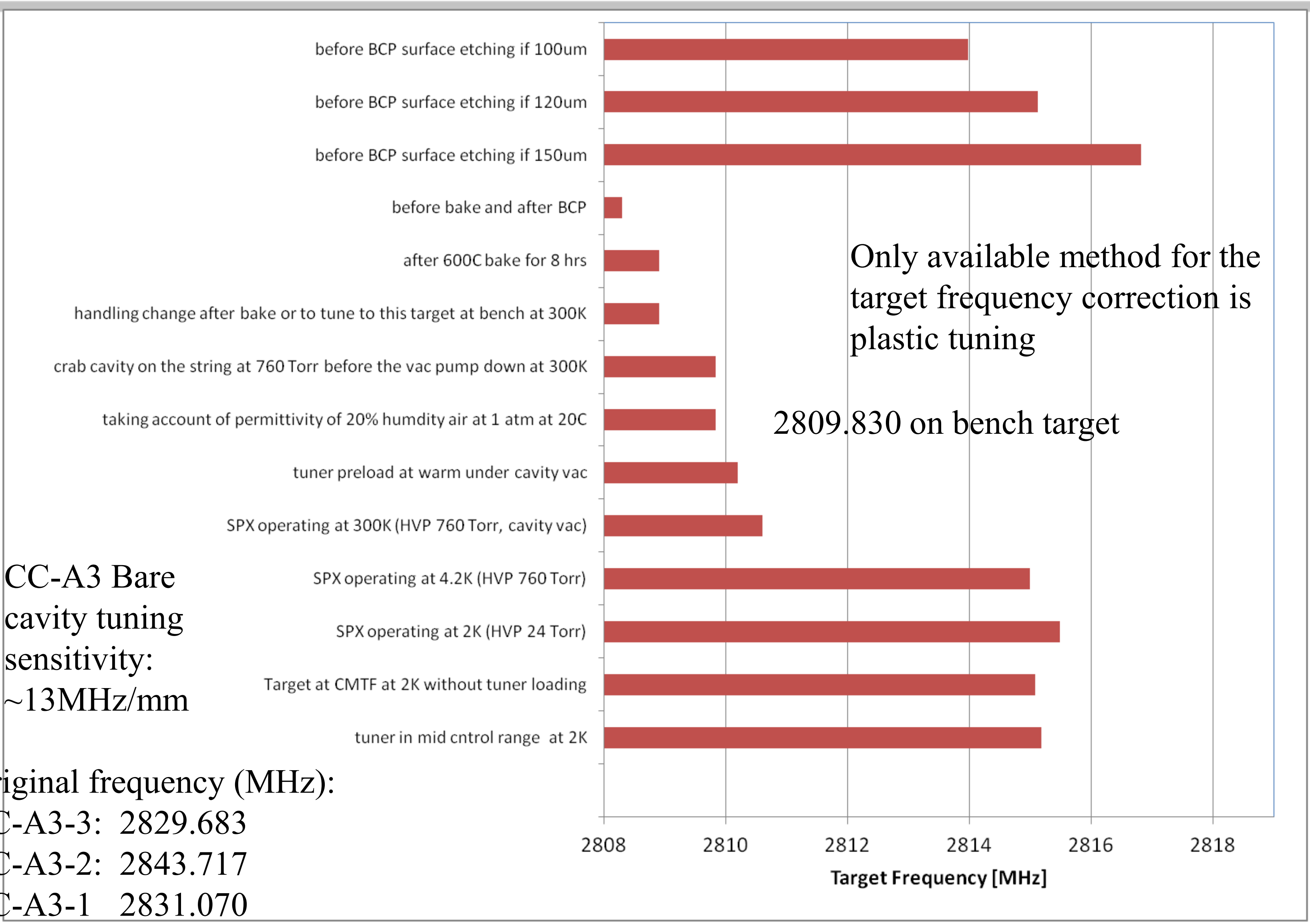
τ=1100 s



Total loss of power

Courtesy of G. Waldschmidt and
B. Brajuskovic

Frequency Recipe of CCA3 Cavity Design Based on CC-B1 CCA1-A2 Prototypes



Only available method for the target frequency correction is plastic tuning

2809.830 on bench target

CC-A3 Bare cavity tuning sensitivity: ~13MHz/mm

Original frequency (MHz):
CC-A3-3: 2829.683
CC-A3-2: 2843.717
CC-A3-1 2831.070

SPX Tuner Design Status:Tuner Resolution

		12Gev Upgrade C100 Style Cavity	**SPX** CC-A3 3.5mm wall	**SPX** CC-A3 3.5mm wall
Cavity Related Info				
Tuning Sensitivity*	**Hz / um**	310	8900	8900
Stiffness*	**N / um**	1.2	23.0	23.0
Deflection required for 1 MHz frequency shift	**um**	3226	112	112
Force required for 1 MHz frequency shift	**N**	3871	2584	2584
Tuner Related Info				
Stepper Motor Resolution	**Steps/rev**	200	200	800
Harmonic Drive Ratio		100	100	100
Ball Screw Pitch	**mm/rev**	5	5	2
Resolution from Stepper**				
full step	**Hz / increment**	13.6	390.4	39.0
half step	**Hz / increment**	6.8	195.2	19.5
quarter step	**Hz / increment**	3.4	97.6	9.8
Resolution from Piezo				
Piezo resolution (drive axis)	**nm**	0.13	0.33	0.33
Piezo resolution (cavity axis)	**Hz**	0.01	0.52	0.52

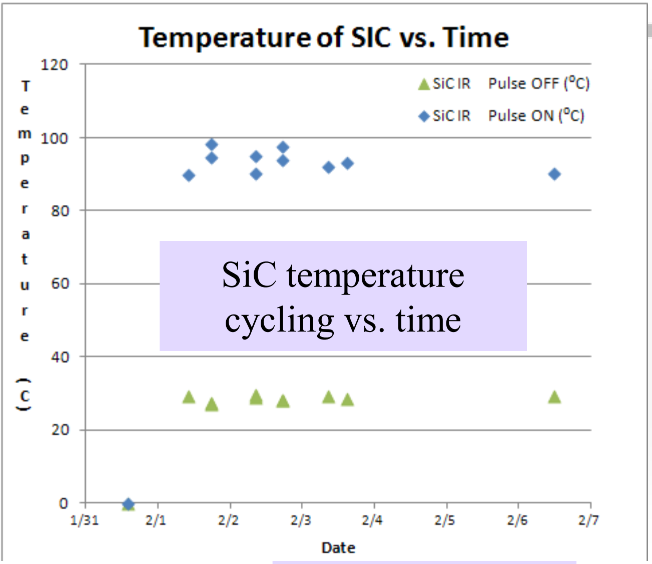
Design Specifications

- Coarse Tuning Range:
  - 400 kHz
- Tuning Resolution:
  - 40Hz

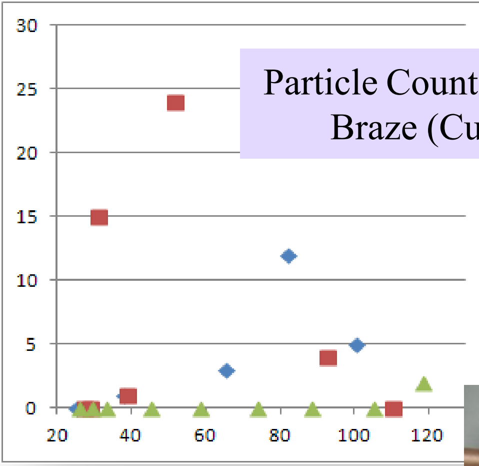
* - SPX numbers taken from J. Liu FEA

** - 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.

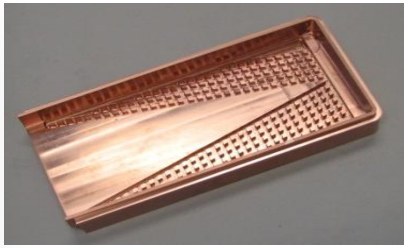
LOM/HOM Loads Sample Tests and Production Fabrication

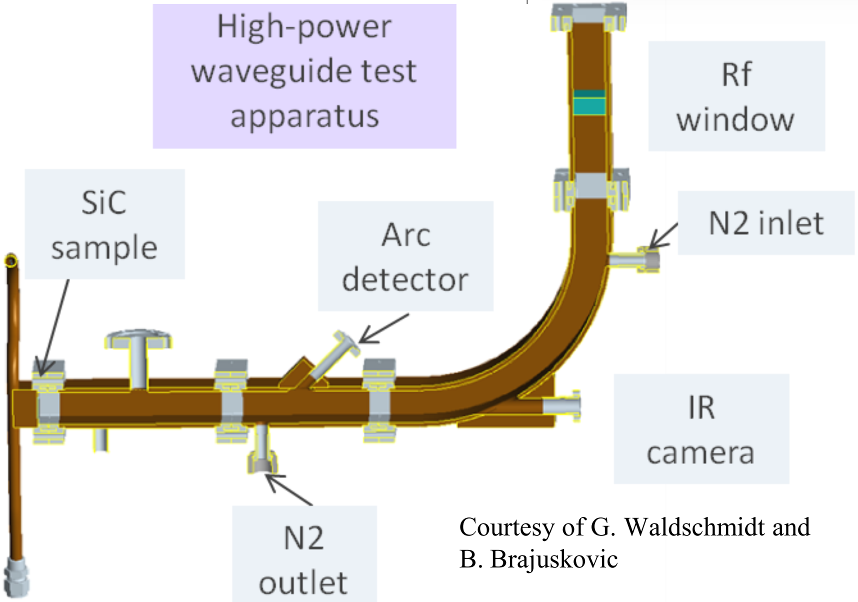


SiC temperature cycling vs. time



Particle Count vs. Temp: SiC + Braze (Cusil / Incusil)



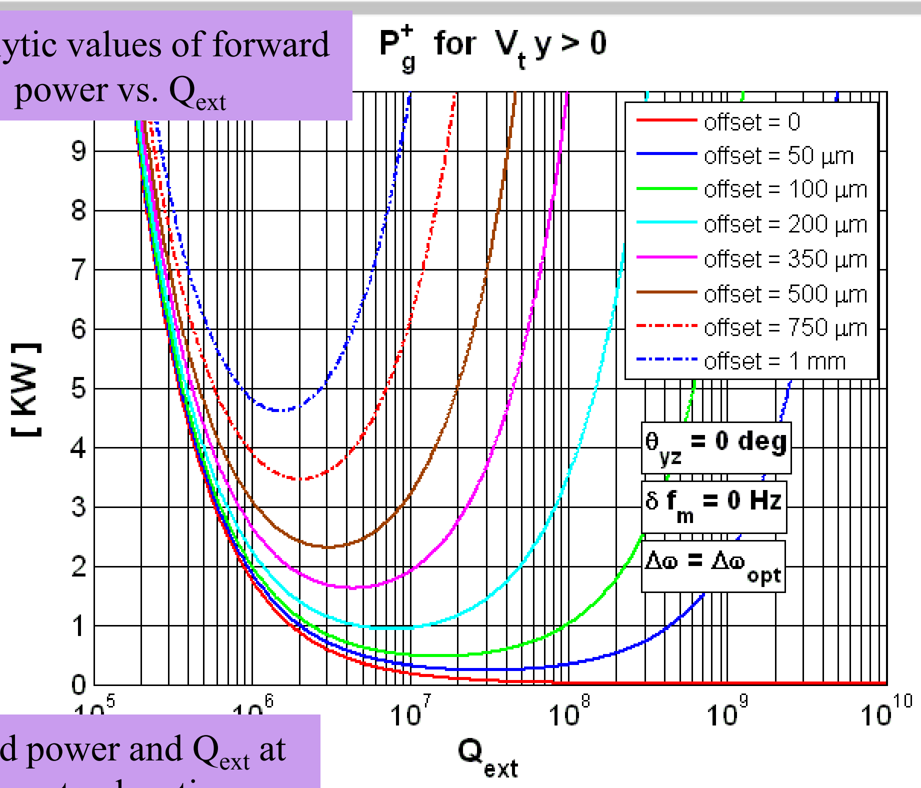


High-power waveguide test apparatus

Courtesy of G. Waldschmidt and B. Brajuskovic

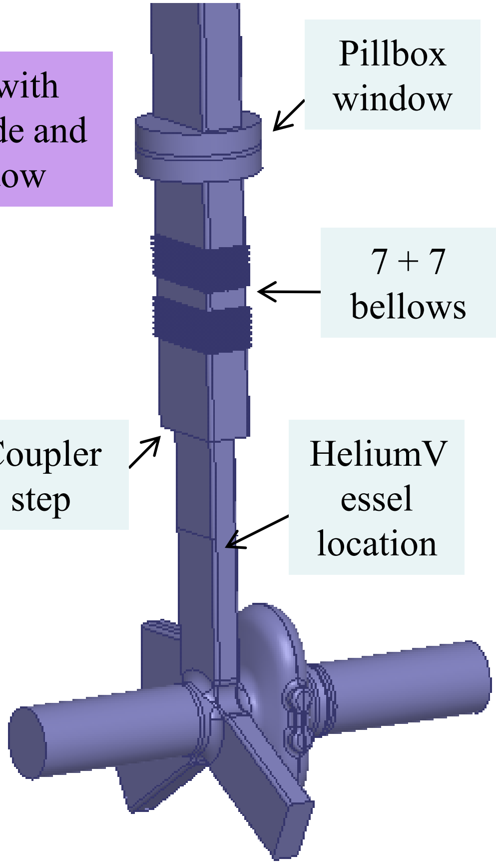
Input Power Coupler Design Opertimization

*Analytic values of forward power vs. Q_{ext}



- $Q_{ext} \sim 1*10^6$ which locates the coupler step at 219 mm from cavity center-line.

SPX cavity with FPC waveguide and single window



Pillbox window

7 + 7 bellows

Coupler step

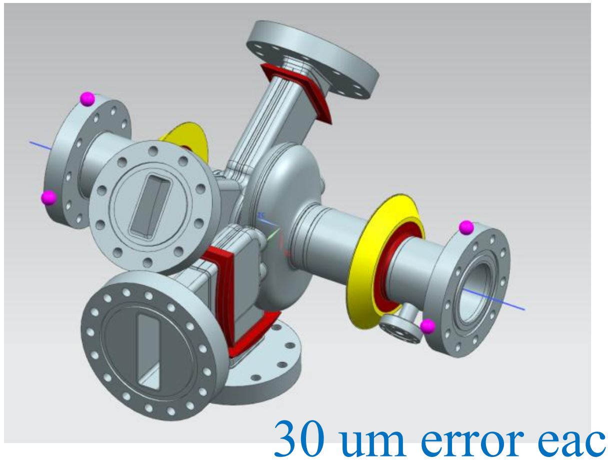
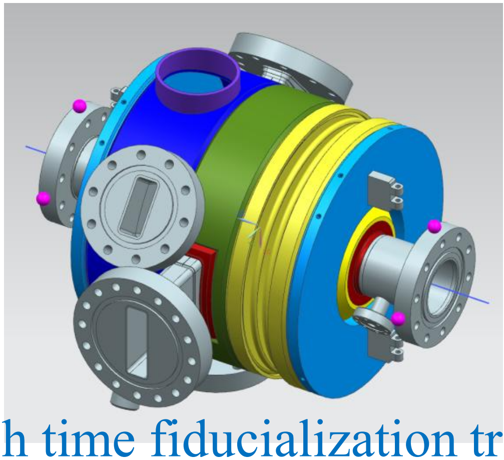
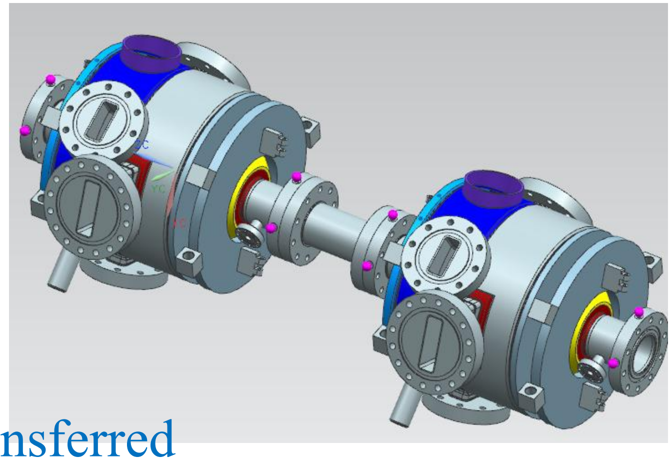
HeliumVessel location

Forward power and Q_{ext} at various step locations (simulation results)

Step (mm)	Freq (GHz)	P_{fwd} (kW)	Q_{ext} (No Round)
209	2.815	2.41	6.95E+05
219	2.815	1.82	9.14E+05
229	2.815	1.36	1.23E+06

*Plot courtesy of T. Berenc

SPX0 Crab Cavities Alignment Requirement and Plan

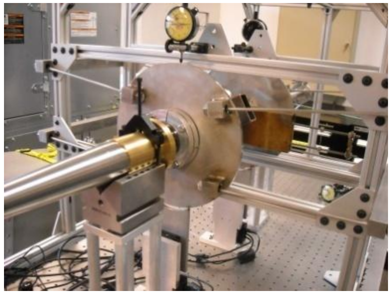
30 um error each time fiducialization transferred

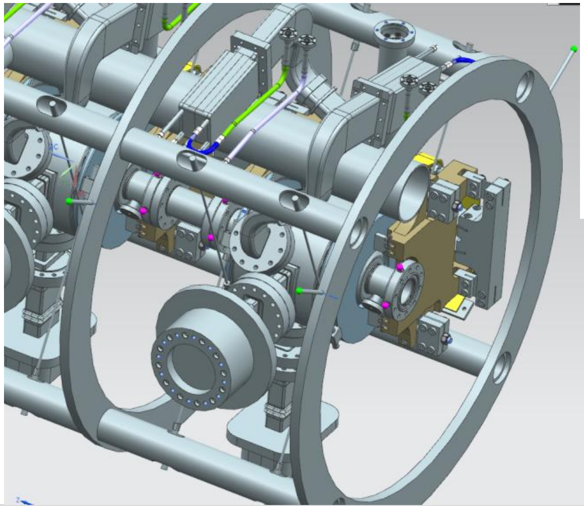
Wires stretching using TM110-y mode

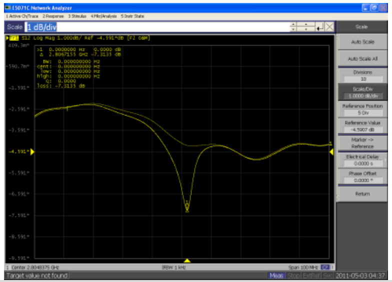
Table 7: Alignment requirements for SPX0 cavities (full range).

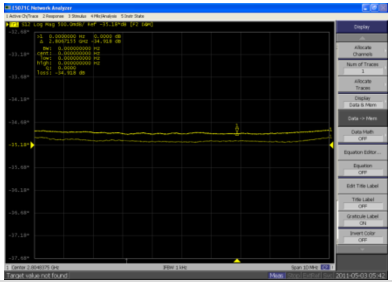
	Cryomodule alignment	Cavity inside cryomodule
ΔX	±500 μm	±500 μm
ΔY	±200 μm	±200 μm
ΔZ	±1000 μm	±1000 μm
Yaw	±10 mrad	±10 mrad
Pitch	±10 mrad	±10 mrad
Roll	±10 mrad	±10 mrad

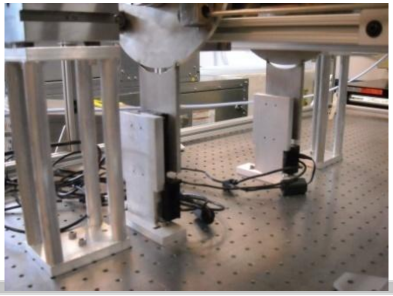
Courtesy of J. Mammoser and J. Feigol







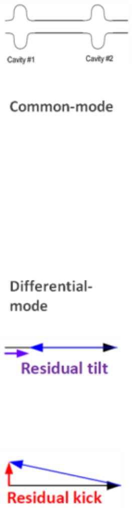




HL-RF and LL-RF systems for SPX0: requirement and design layouts

Cross-phase operation on zero crossing

	RMS Value	Bandwidth	Driving requirement
Common-mode voltage variation	< 7%	0.1Hz – 271 kHz	Keep beam emittance variation distinguishable from differential voltage effect for SPX0
Common-mode phase variation	< 5 deg < 18 deg	0.1 Hz – 1 kHz 1kHz – 271 kHz	Keep global orbit motion distinguishable from differential phase for SPX0 Keep rms emittance variation distinguishable from differential phase for SPX0
Differential –mode voltage variation	< 1% < 0.77%	0.1 Hz – 1 kHz 1 kHz – 271 kHz	Check voltage regulation required for SPX: keep rms emittance variation outside SPX under 10% of nominal 35 pm Check voltage regulation required for SPX: effective emittance growth under 1.5 pm for SPX
Differential-mode phase variation	< 0.077 deg < 0.28 deg	0.1 Hz – 1 kHz 1 kHz – 271 kHz	Check phase regulation required for SPX: keep global rms orbit motion under 10% for beam size/divergence for SPX Check phase regulation required for SPX; keep emittance growth outside of SPX under 10% of nominal 35 pm



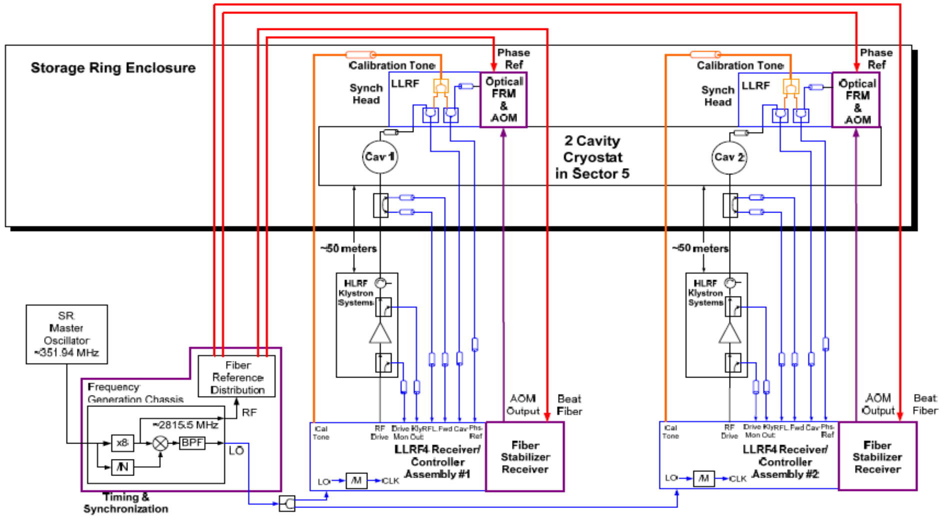
In-phase operation on zero crossing

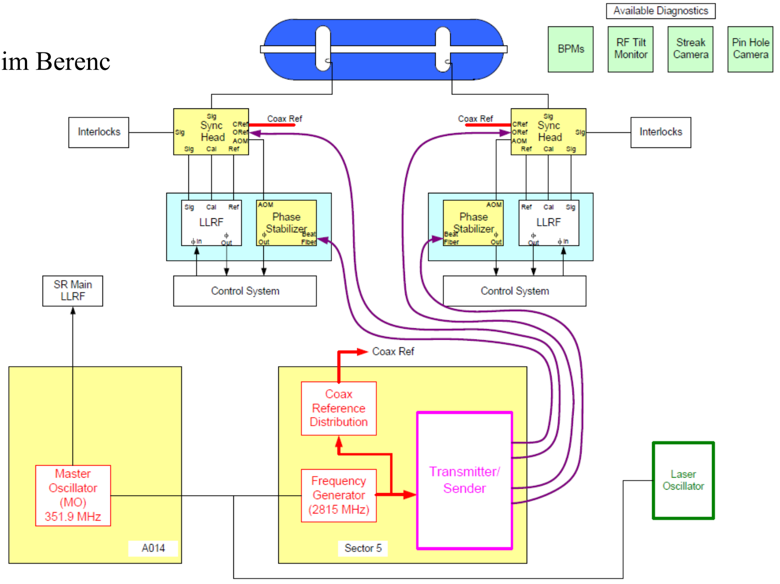
	RMS Value	Bandwidth	Driving requirement
Common-mode voltage variation	< 6.9%	0.1Hz – 271 kHz	Keep beam emittance variation under 10%
Common-mode phase variation	< 2.5 deg < 3.6 deg	0.1 Hz – 60Hz 60 Hz – 271 kHz	Be able to control arrival time jitter Be able to control effective pulse duration increase
Differential –mode voltage variation	< 10%	0.1 Hz – 271 kHz	
Differential-mode phase variation	< 10.7 deg	0.1 Hz – 1 kHz	Keep rms beam motion under 10% of beam size/divergence

Cross-phase operation on crest

	RMS Value	Bandwidth	Driving requirement
Common-mode voltage variation	< 5%	0.1Hz – 1 kHz	Confirm SPX differential voltage requirement
Common-mode phase variation	< 7.2 deg	0.1 Hz – 1 kHz	Confirm SPX cavities voltage requirement
Differential –mode voltage variation	< 1% < 0.77%	0.1 Hz – 1 kHz 1 kHz – 271 kHz	Confirm SPX requirement Confirm SPX requirement
Differential-mode phase variation	< 2.3 deg	0.1 Hz – 1 kHz	Confirm SPX voltage requirement

Courtesy of Tim Berenc





LLRF System Bench Test for SPX0

Residual Phase Noise Test Set (measure noise between cavity emulators)

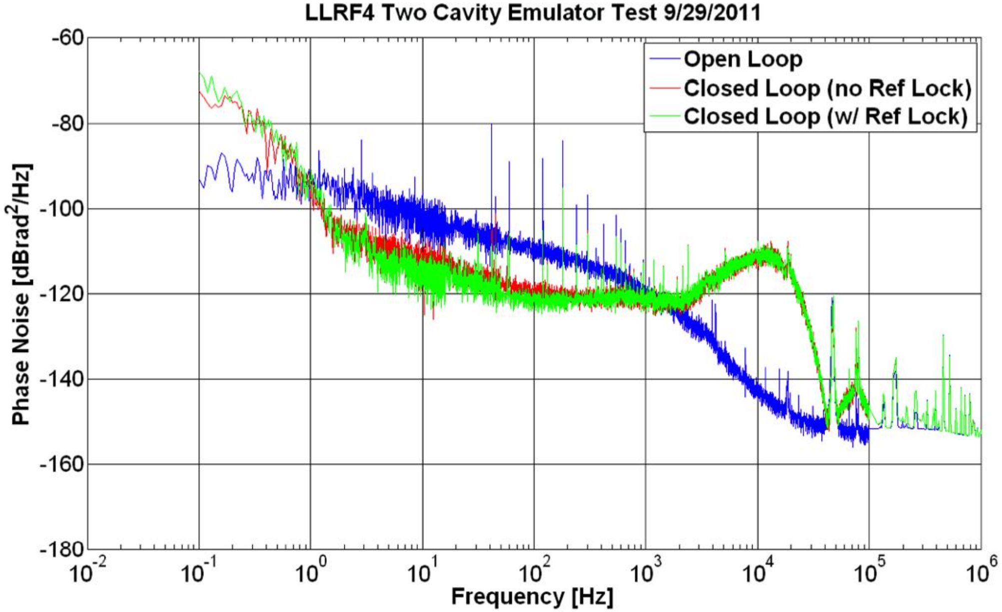
Cavity Emulators #1 and #2

LLRF Receiver #1

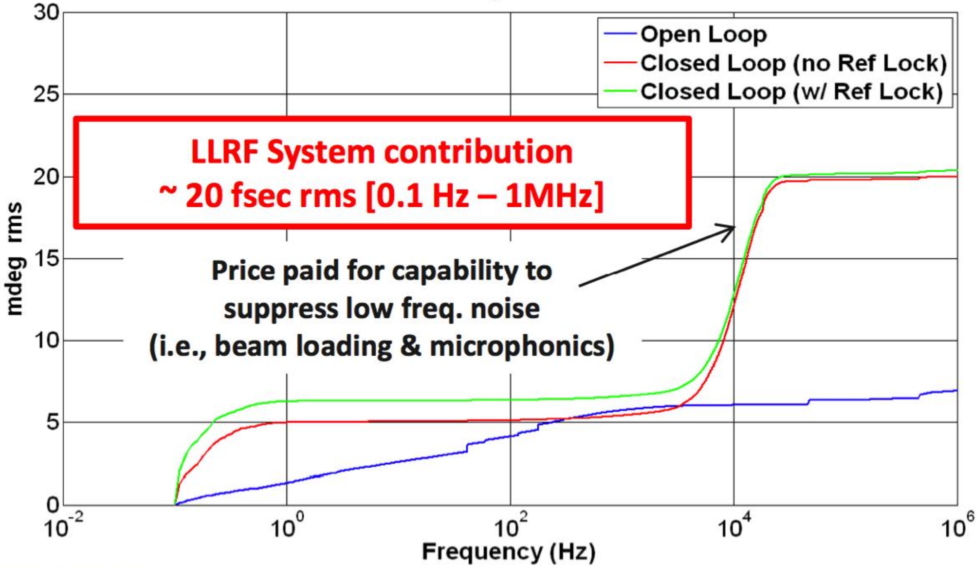
Freq. Generation Chassis

LLRF Receiver #2

Courtesy of Tim Berenc



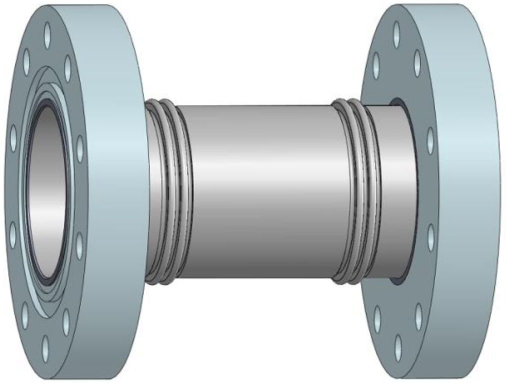
LLRF4 Two Cavity Emulator Test 9/29/2011

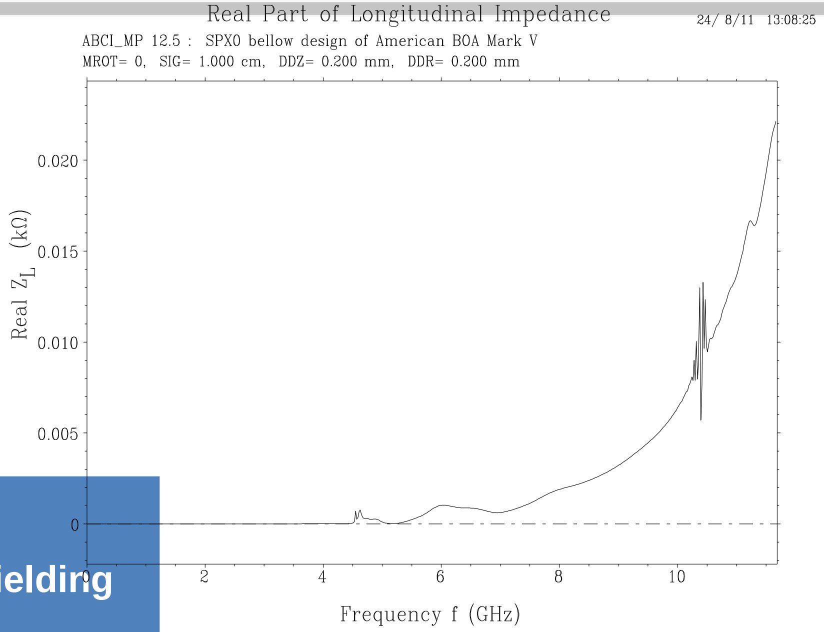


LLRF System contribution
~ 20 fsec rms [0.1 Hz – 1MHz]

Price paid for capability to suppress low freq. noise (i.e., beam loading & microphonics)

Low Impedance Unshielded Bellows



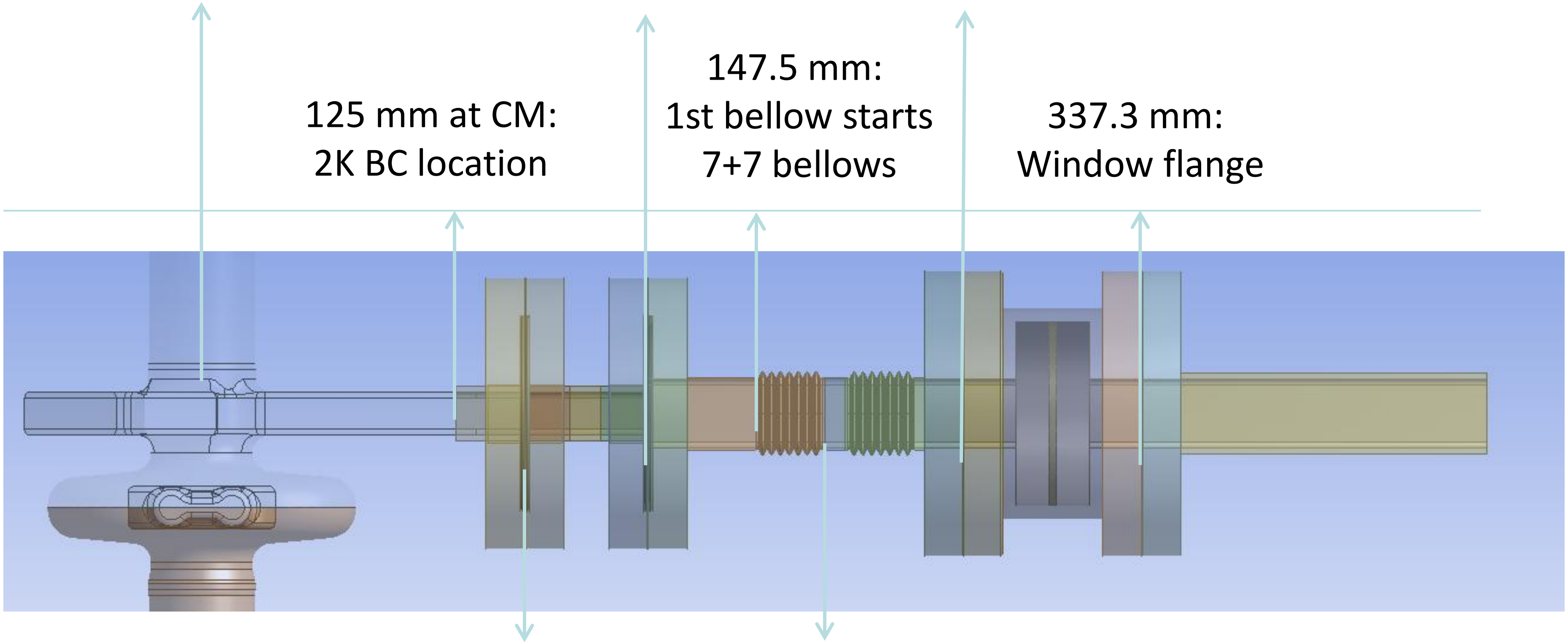


Bellows	Bunch length [mm]	Nominal loss factor K_{loss} [mV/pC]	Shielding
APS	3	64	Yes
SOLEIL	3	20	Yes
SPEAR3	3	67	Yes
NSLS-II	3	18	Yes
American BOA IV	3	455	No
American BOA IV	10	1.517	No

Materials: Copper plated Stainless Steel or Phosphor copper alloy

Courtesy of G. Wu

FPC Geometry Layout



Center line

220.8 mm:
Spool piece ends

249.6 mm:
Pillbox Window

147.5 mm:
1st bellow starts
7+7 bellows

125 mm at CM:
2K BC location

337.3 mm:
Window flange

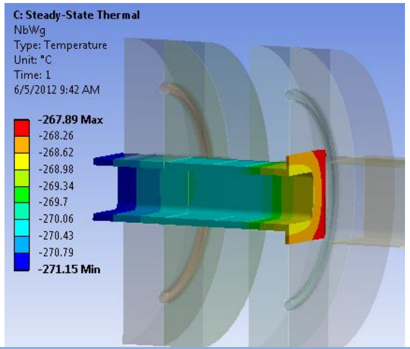
162.8 mm:
Spool piece starts

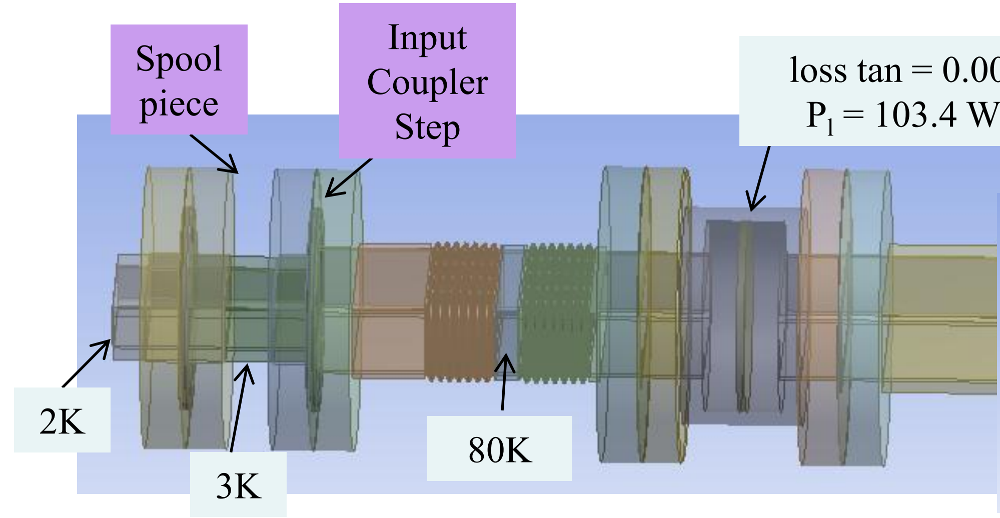
180.2 mm:
11mm wide
80K location

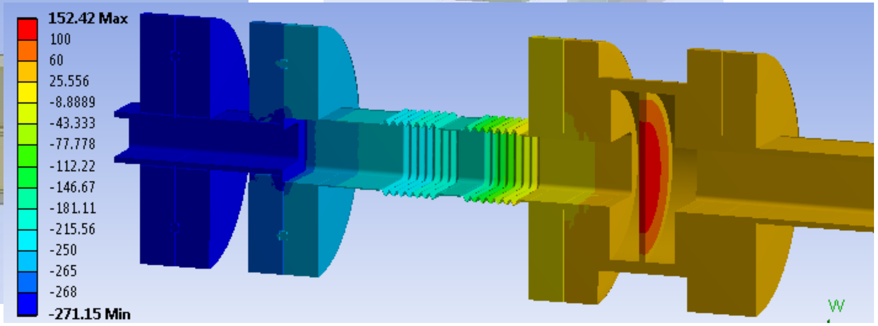
Courtesy of G. Waldschmidt and J. Liu

FPC Thermal Analysis

- Spool piece added to extend Nb waveguide – reduce heat load due to cavity evanescent field.
- Bellows consists of a 7 + 7 convolution pattern with 80K thermal strap.
- NbTi flange to Nb weld joint contact included.





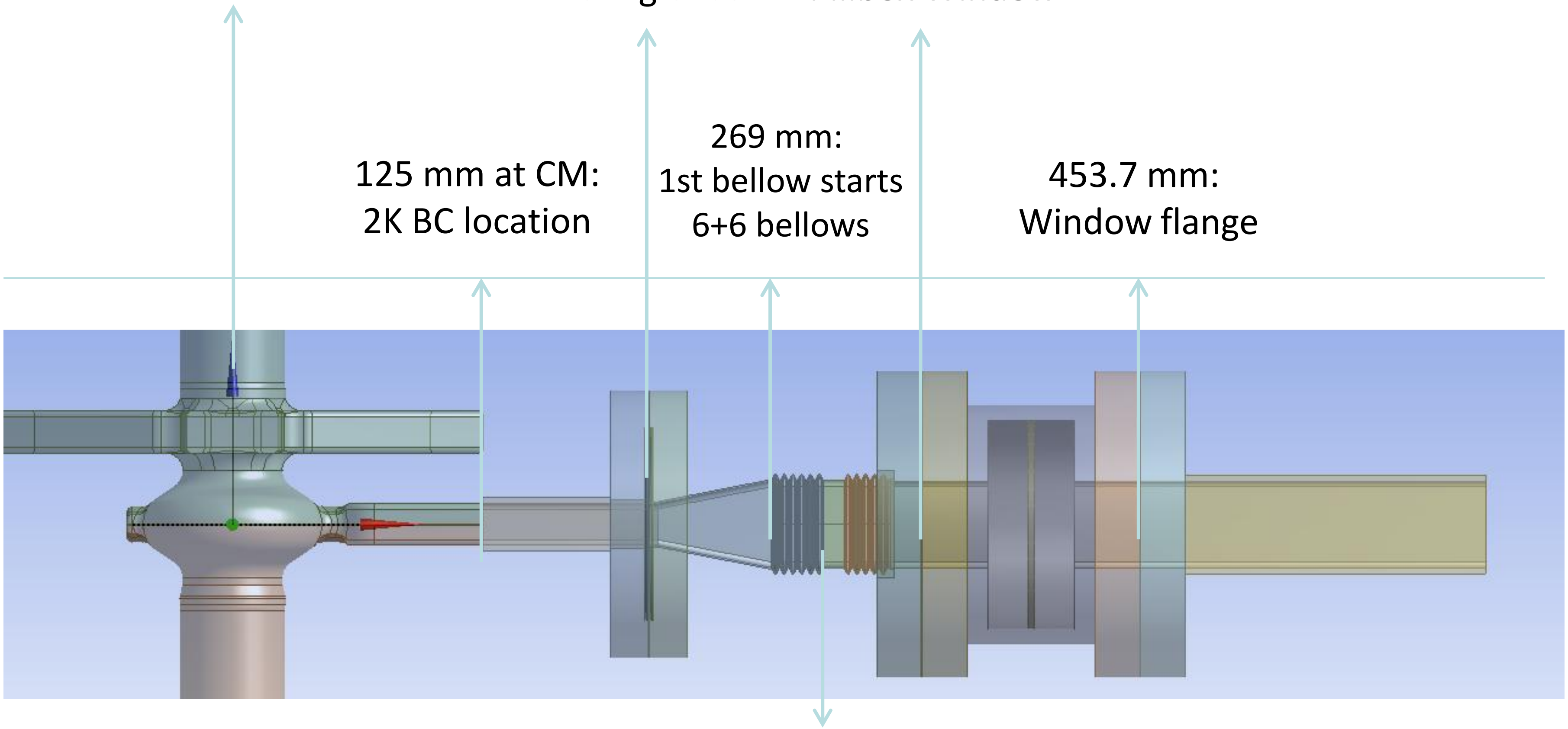


Thermal analysis with 0.5 MV deflecting voltage

RF Power (W)	Loss Tan	RF Window (W)	Cu Plating (um)	2K (W)	3K (W)	80K (W)	300K (W)
STATIC	---	---	10	-0.13	-1.01	-3.74	4.88
5.97 (Dynamic)	0.007	103.4	10	-0.23	-1.38	-4.18	-103.55

Courtesy of G. Waldschmidt and J. Liu

LOM Geometry Layout



Center line

207.9 mm:
Nb Wg ends

344.6 mm:
Pillbox Window

125 mm at CM:
2K BC location

269 mm:
1st bellow starts
6+6 bellows

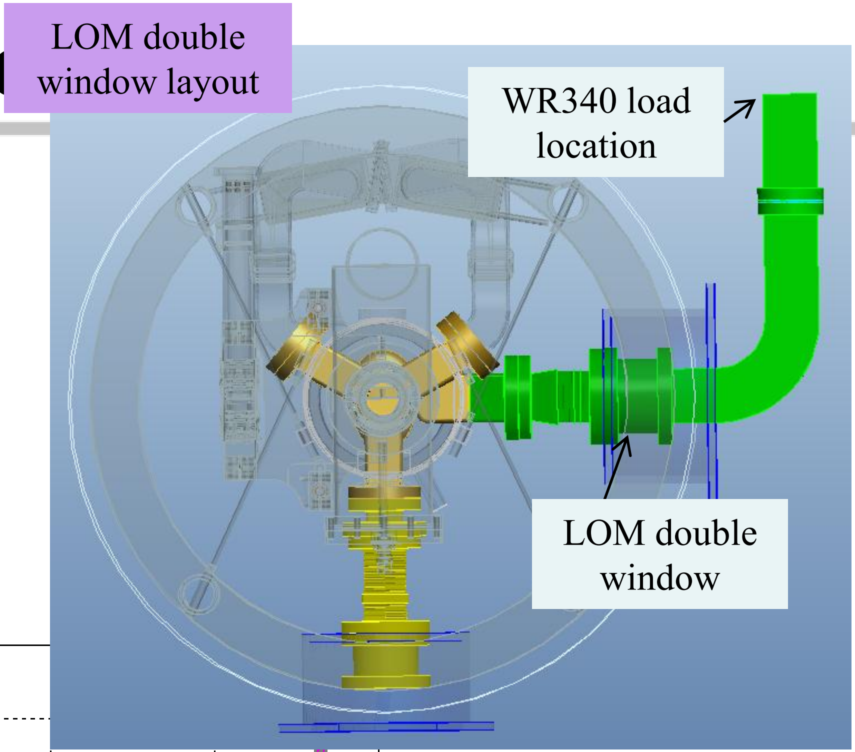
453.7 mm:
Window flange

295.4 mm:
10mm wide
80K location

Courtesy of G. Waldschmidt and J. Liu

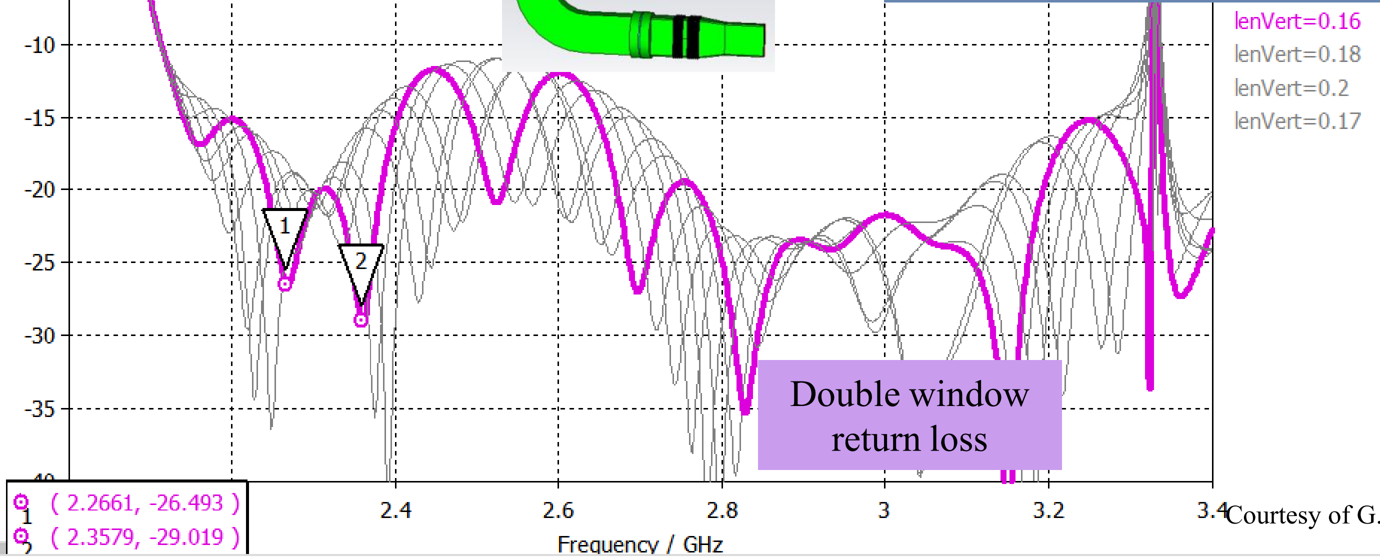
LOM Doubl

- Double window separation was optimized for ~2.2 – 2.4 GHz and are relatively broadband from 2.2 – 4 GHz.
- LOM double window terminates in an out-of-vacuum WR340 rf load.
- Prototype windows are currently being tested at CML.


LOM double window layout

WR340 load location

LOM double window



Double window return loss

Courtesy of G. Waldschmidt and J. Liu

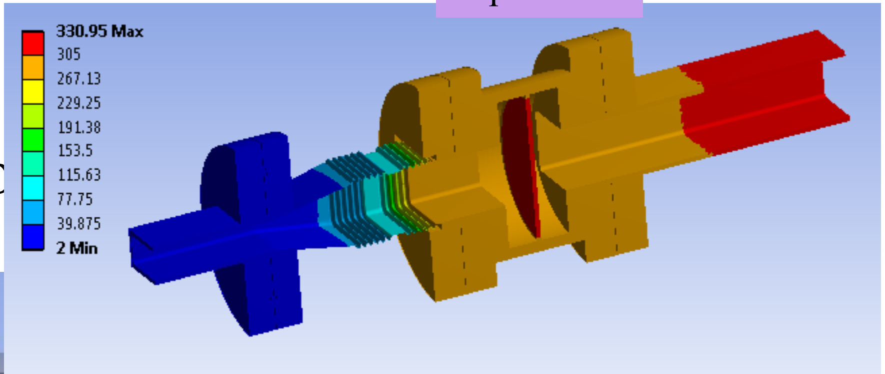
LOM Thermal Analysis

Thermal analysis

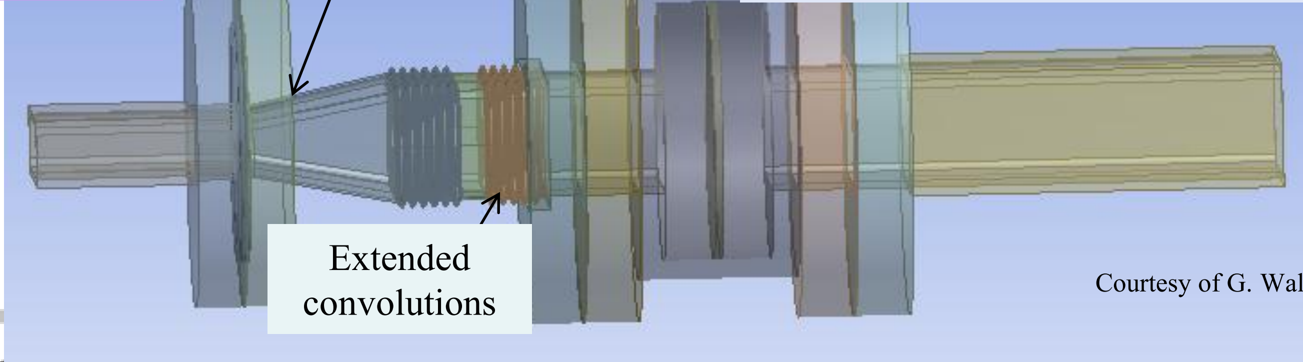
Input power (kW)	Cu Plating (um)	Loss Tan	Window losses (W)	RF Surf losses (W)	2K (W)	80K (W)	300K (W)
STATIC	10	---	---	---	-1.36	-7.09	8.46
2	10	0.007	21.3	2.81	-1.57	-7.28	-15.30

- Taper was extended into SS cavity flange to improve broadband rf performance.
- Convolutions were extended into flan duce 80K

Thermal profile



LOM waveguide geometry


Extended taper

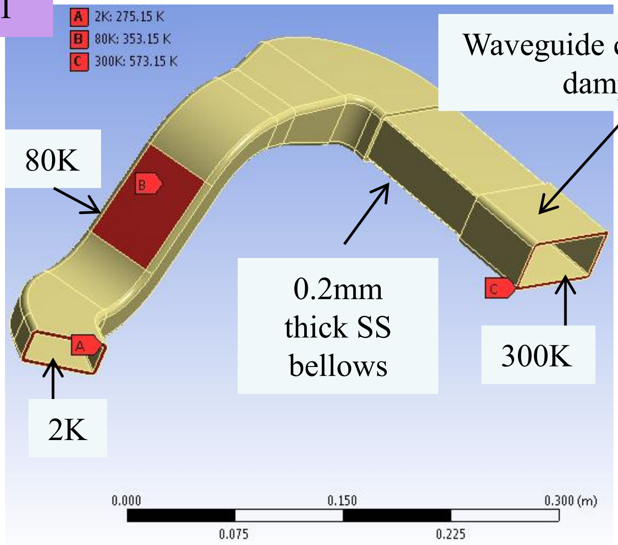
Extended convolutions

Courtesy of G. Waldschmidt and J. Liu

HOM Waveguide Static Heat Load*

SS waveguide (3.18 mm thick) - no copper plating

Case 1



Waveguide connects to damper

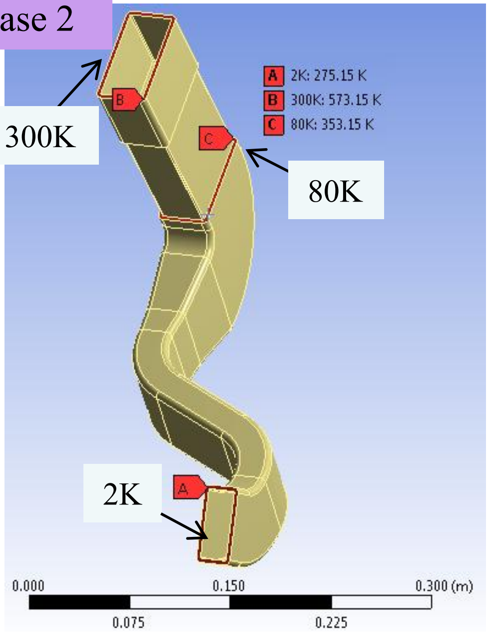
80K

0.2mm thick SS bellows

300K

2K

Case 2



300K

80K

2K

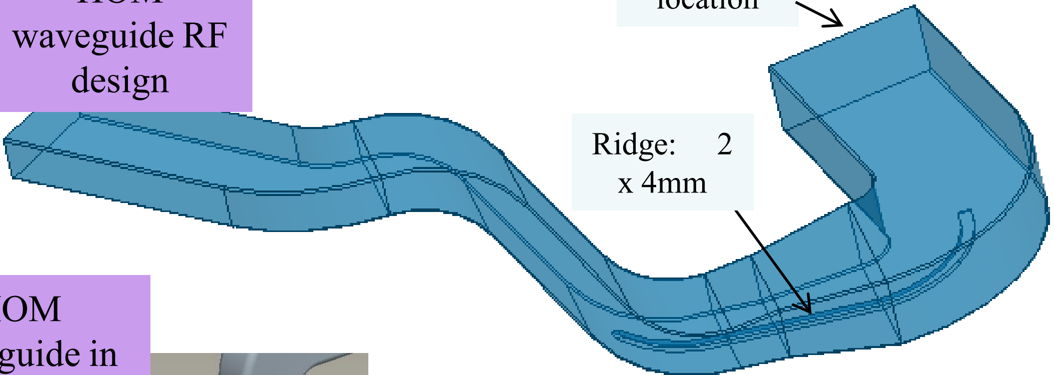
Heat load estimation per HOM waveguide

Heat Flow	Case 1 static	Case 2 static	Targeted static	Expected dynamic	Estimated Total
2K (W)	-1.2	-0.41811	< -1.0	< -1.3	<2.3
80K (W)	0.2	-0.73	< -5	< -5	<10
300K (W)	1.0	1.14	N/A	N/A	N/A

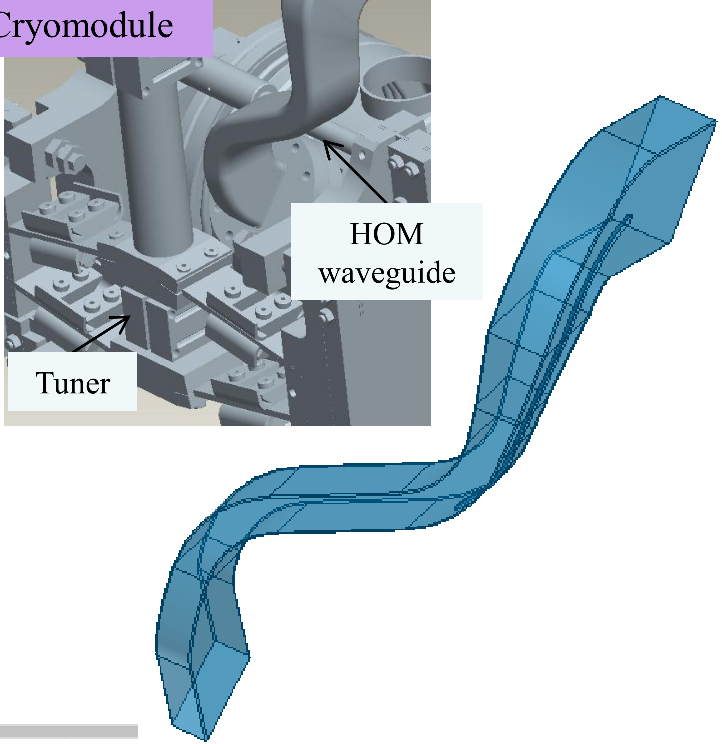
*Courtesy of J. Liu

HOM Waveguide RF Performance*

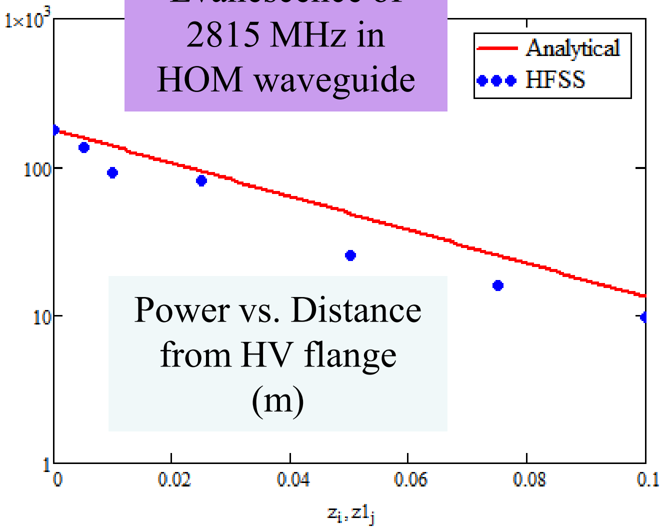
HOM waveguide RF design



HOM waveguide in Cryomodule

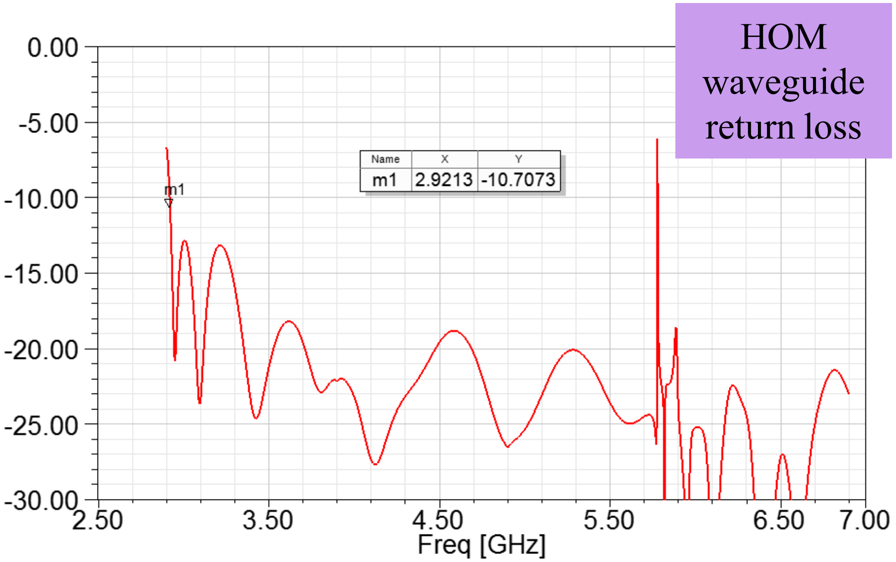


Evanescence of 2815 MHz in HOM waveguide



Power vs. Distance from HV flange (m)

HOM waveguide return loss



*Design courtesy of J. Holzbauer

HOM Dynamic Heat Load (Archive Results)

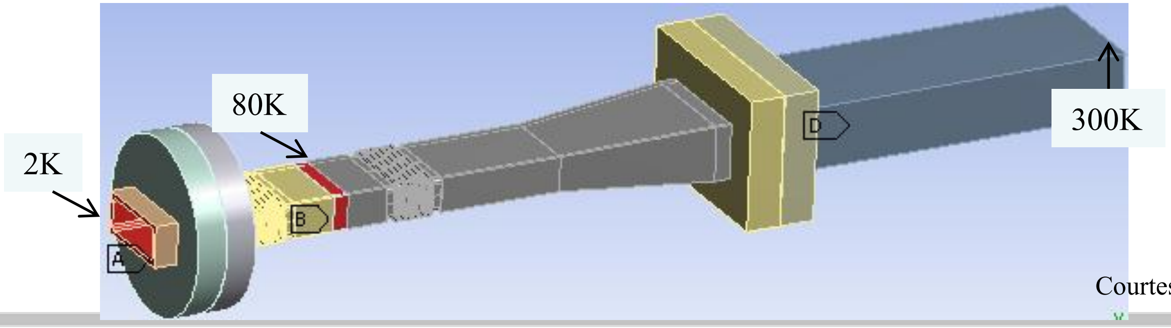
Results to be used only as an estimation of dynamic loading

- Dynamic loading
  - Cavity evanescent field at 0.5 MV deflecting volt
  - 500W traveling wave at 2.8 GHz
- Simplified geometry without ridge
- Custom bellows will be not be included in the actual SPX geometry.

Thermal analysis with 0.5 MV deflecting voltage

Traveling wave dynamic losses contribute ~0.1 W to 2K

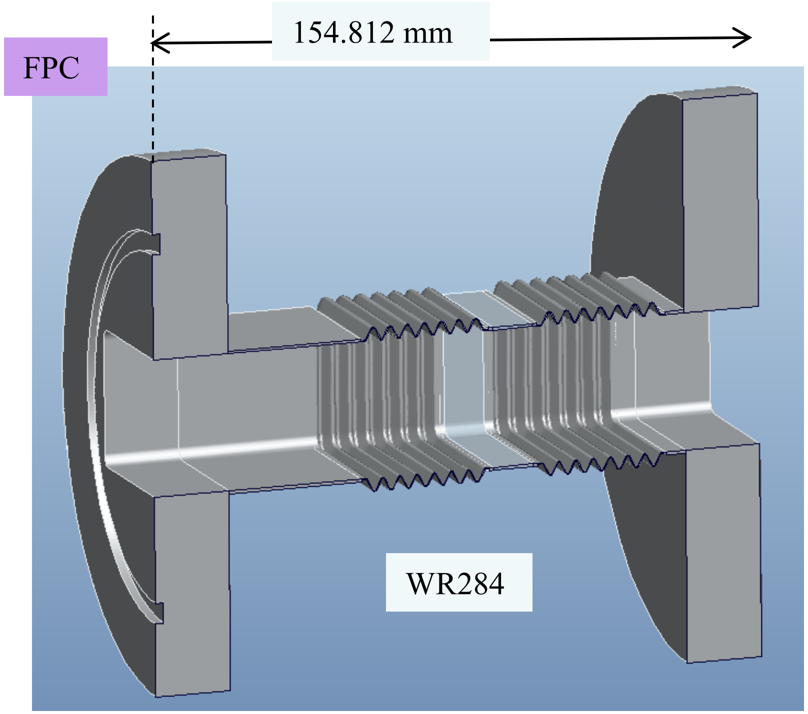
Case	RF Load (W)	Nb Neck (mm)	Cu Plating (um)	2K (W)	80K (W)	300K (W)
STATIC	---	15	10	-0.86	-0.37	1.23
Evanescent (no traveling)	2.03	15	10	-2.07	-1.09	1.12

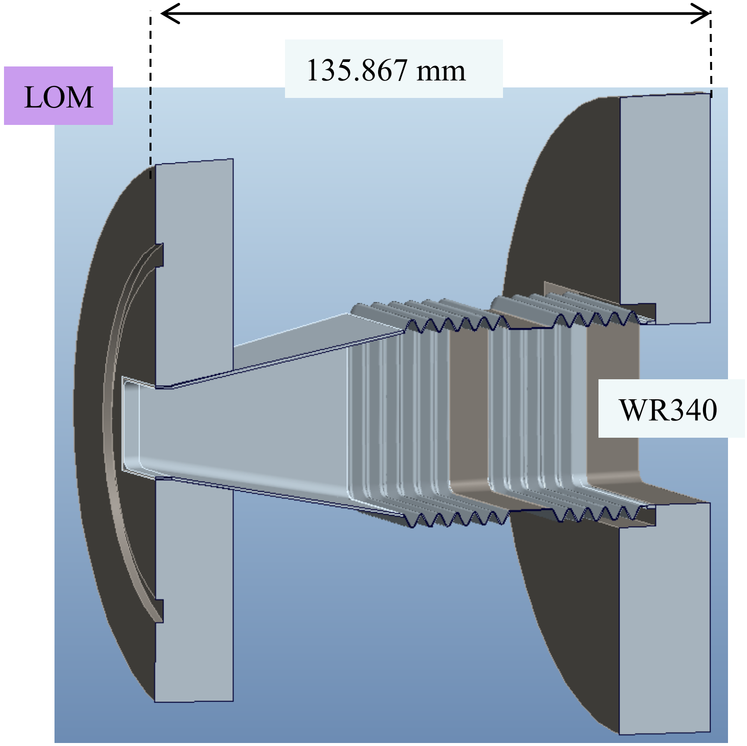


Courtesy of G. Waldschmidt and J. Liu

Bellows: FPC / LOM

- Location of FPC bellows convolutions was optimized for rf performance
- LOM bellows utilizes taper in cavity flange for improved broadband performance and cuts additional convolutions into the rf window flange to reduce 80K heat load.

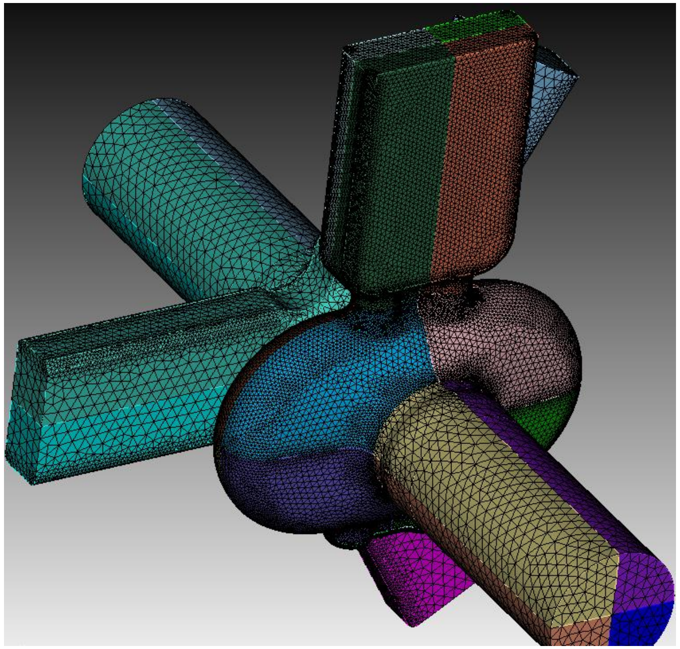




Courtesy of G. Waldschmidt and J. Liu

Effect of Waveguide "Y" Group to LOM Leaking

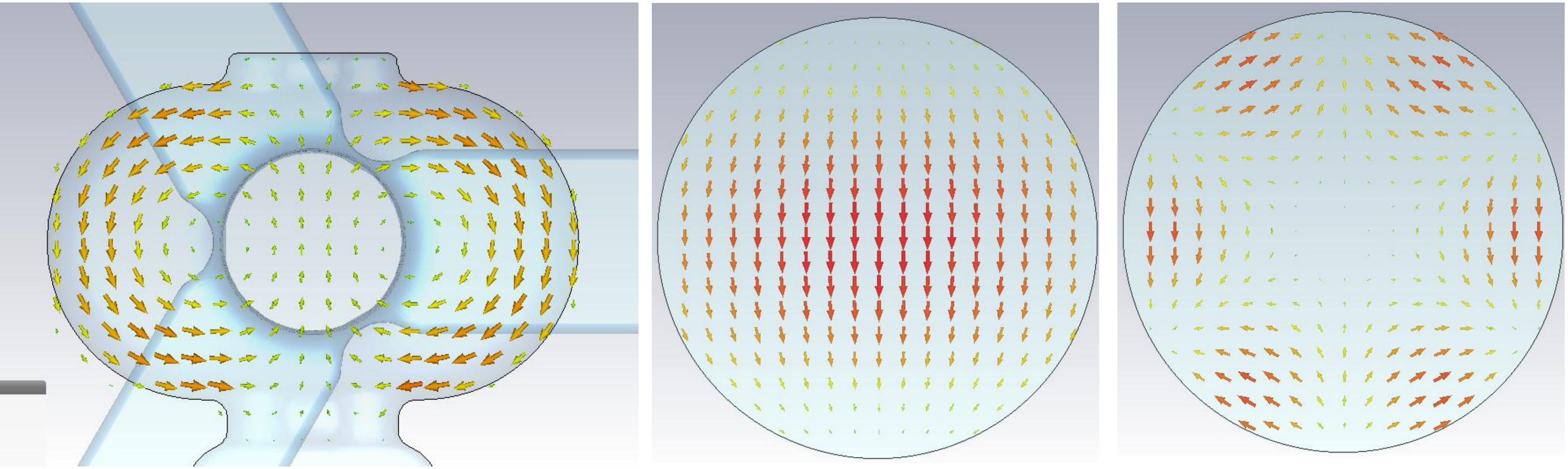
Original Model	M:/ANLcrab/JimHenry/cavity/CC-A3/CC-A3 cavity for Geoff 31jan12MOD10FEB.stp
Meshing	Tet10, 330k – 813k mesh cells
Frequency	2.829GHz
More descriptions	Fully symmetric mesh: cavity mesh mirrored by X/Y/Z plane, LOM WG by X/Z plane, Y-group by Y plane.
Conclusions	Calculated Qe of TE10 in LOM WG is **9.4e6**, and it is induced by monopole mode excited by the reflection from Y-group.



Courtesy of F. He

How monopole mode be excited (1)

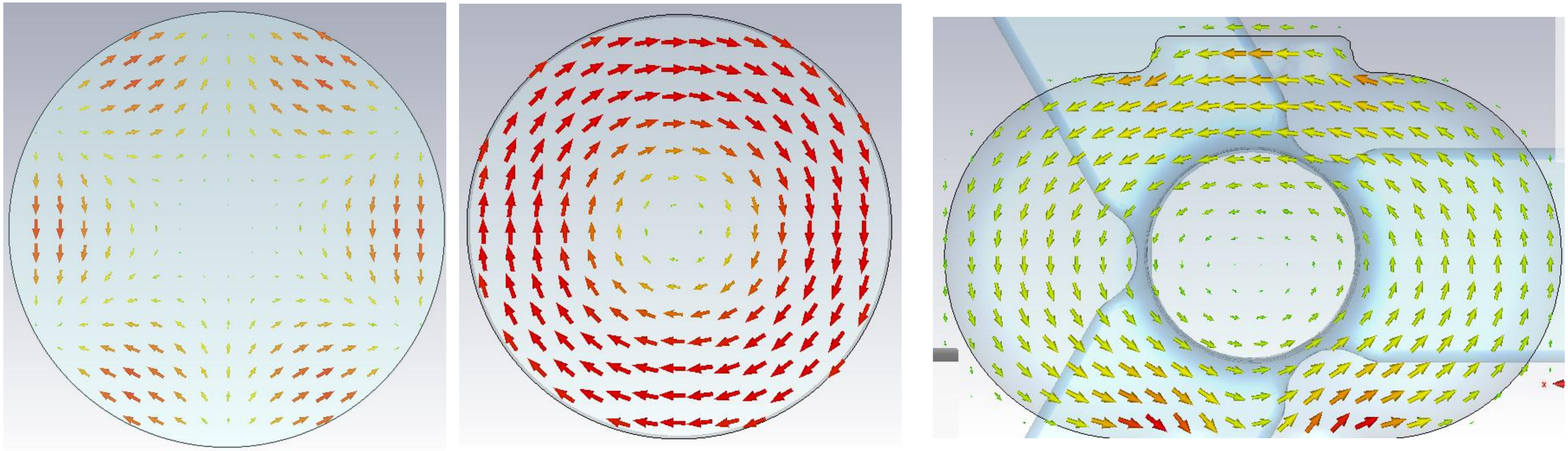
- Various modes in the beam pipe (circular WG) can be exited by the cavity, including dipole of TE11, and Hexapole of TE31
- Below illustrate B field of cavity, TE11, and TE31



Courtesy of F. He

How monopole mode be excited (2)

- The TE31 in beam pipe excites TE10 in Y-group, and the reflection excites TM01 in beam pipe, which in turn excites monopole mode in cavity
- Below is B field of TE31, TM01 and monopole in cavity



Courtesy of F. He