# Deflecting Cavity Developments for APS

J. Mammosser, H. Wang, R. Rimmer, J. Henry, K. Wilson, P. Dhakal, A. Nassiri, J. Kerby, J. Holzbauer, G. Wu, J. Fuerst,, G. Waldschmidt, Y. Yang, Z. Li, F. He

ATLAS, Cornell University, ORNL,FNAL

# Background:

- **Jlab and ANL started a collaboration in mid 2010 to develop the cavity and cryostat designs for a Short Pulse X-Ray (SPX), in plans for the upgrade to the APS ring.**
  - Tasks were shared between the laboratories for an integrated design!!

- **The SPX concept consists of two sets of deflecting cavities to be located in straight sections of the APS ring.**

- **The first set of cavities chirp the beam adding a correlation between electron longitudinal position and transverse momentum**

The X-Rays produced will also have this correlation!

# Background:

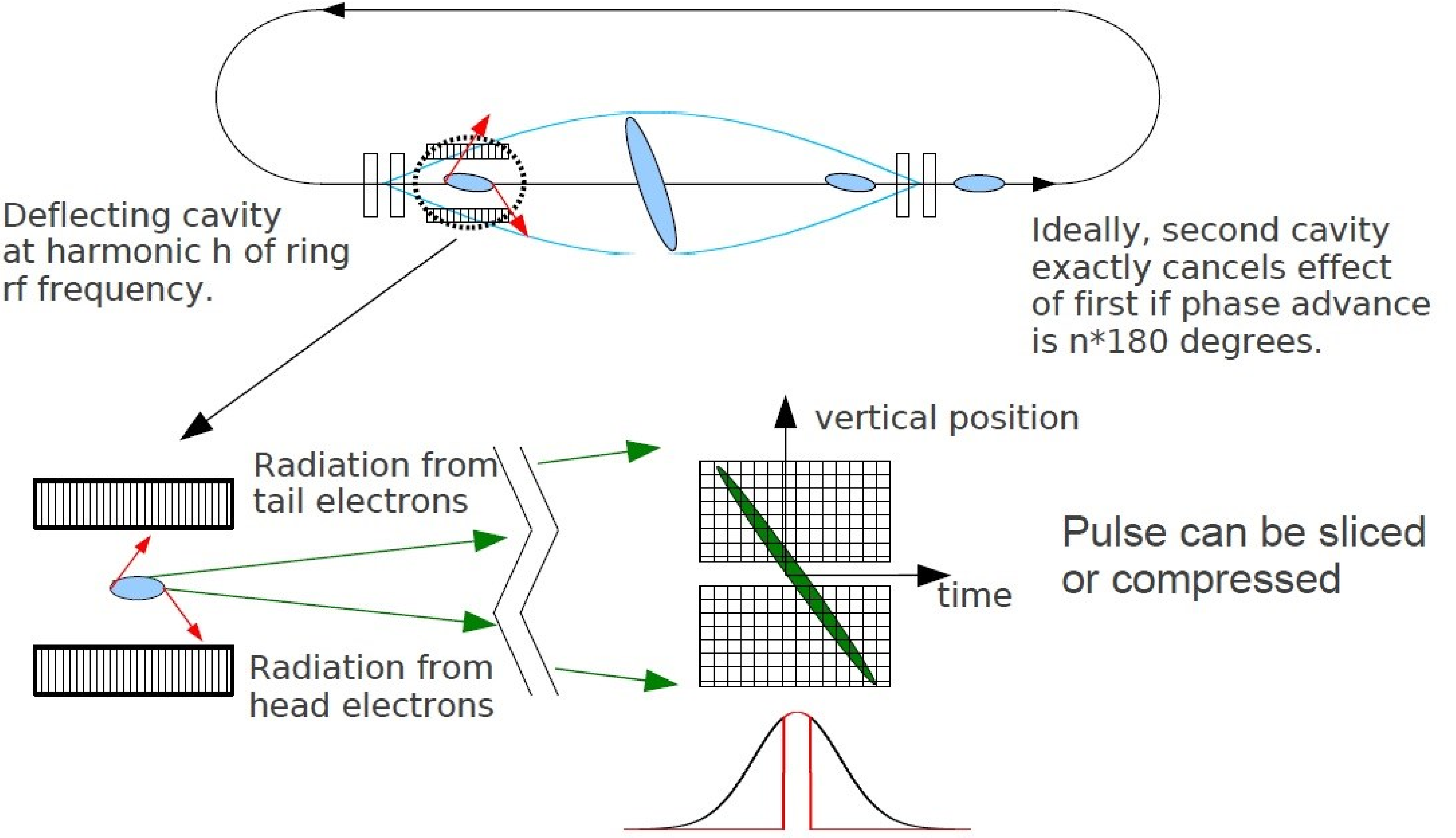
- X-Rays can then be put through transverse slits to produce pulses that are 1-2% of those currently available to users.

- The second set of cavities are located a multiple of 180 degrees of phase advance and allow the beam to be unchirped, removing all the effects of the first cavities

  – If done correctly, SPX experiments can be carried out in a few sectors of the ring without affecting the rest of the users around the ring

- The focus was on the demonstration of the technology with development of cavity, ancillary systems and a cryostat for a in-ring test

# SPX Concept:




[1]A. Zholents et al., NIM A 425, 385 (1999).

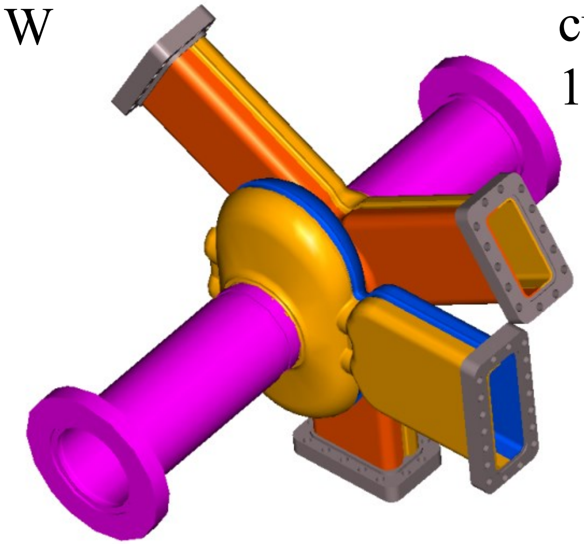
# Cavity Design:

- Deflecting cavity is a flattened oval shape that operates in the TM110 mode, 4 cavities would be required in each sector
- A lower order mode (LOM) must be damped, TM010
  - Up to 860 W
- HOM power of 150W or more would have to be damped
- Overall size was compressed to meet thermal design constraints and space in the ring constraints

| Cavity Design | Parameters | Units |
|---|---|---|
| Frequency of Deflecting Mode | 2815.488 | MHz |
| Duty Cycle | CW ($8^{th}$ harmonic) | |
| Geometry Factor | 227.8 | Ω |
| Active Length | 53.24 | mm |
| R/Q | 37.1 | Ω |
| Cavity Overall Length | 389.76 | mm |
| Cavity Deflecting Voltage | 0.5 | MV |
| APS Beam Current | 150 | mA |
| Beam Pipe Aperture | 52 | mm |
| Cavity Iris Aperture | 50 | mm |
| Peak E-field (Ep) | 40.8 | MV/m |
| Peak B-field vertical test | 105 | mT |
| Alignment Cavity to Cavity | Electrical Center | |
| X-Alignment | ± 500 | µm |
| Y-Alignment | ±200 | µm |
| Z-Alignment | ±1000 | µm |
| Yaw misalignment | ±10 | mrad |
| Pitch misalignment | ±10 | mrad |
| Roll misalignment | ±10 | mrad |

# Cavity Design:

- “Y” Endgroup with FPC and two HOM waveguides
- **LOM waveguide on-cell, coupled via a dog bone iris**
- **Cell flattened oval with matching dog-bone short**
- Beam-pipe located field probe

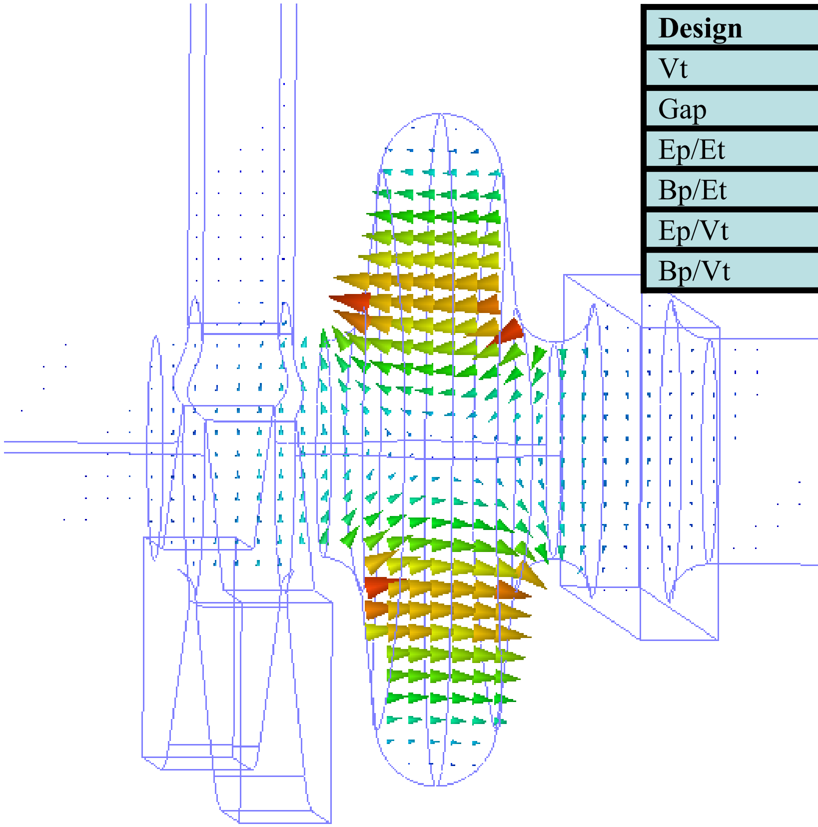



Beam Induced RF Power

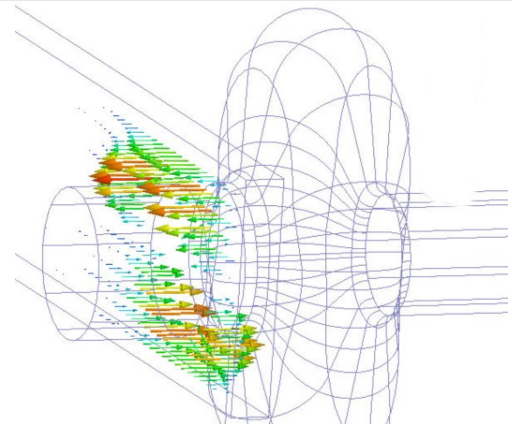
We knew from the start this would be a challenging design !!

# Cavity Fields

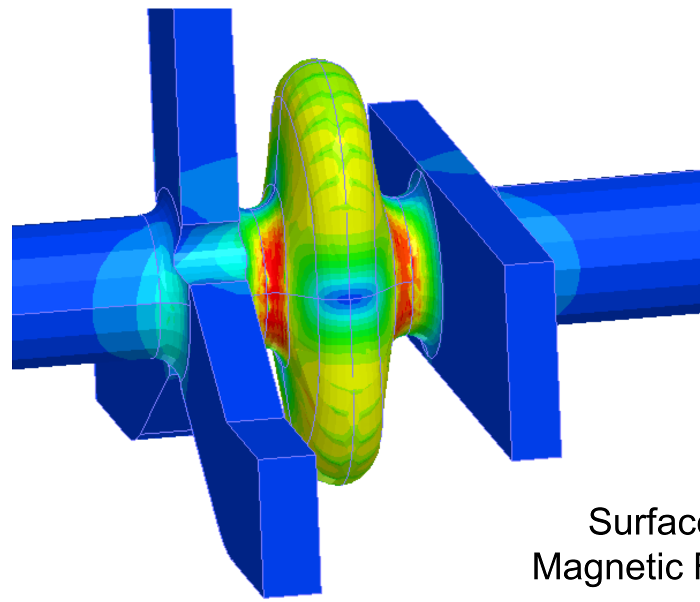
| Design | Parameters |
| --- | --- |
| Vt | 0.5 MV |
| Gap | 0.0532 m |
| Ep/Et | 4.4 |
| Bp/Et | 11.34 mT/MV/m |
| Ep/Vt | 82.65 1/m |
| Bp/Vt | 2130 mT/MV |



Electric Field Vector



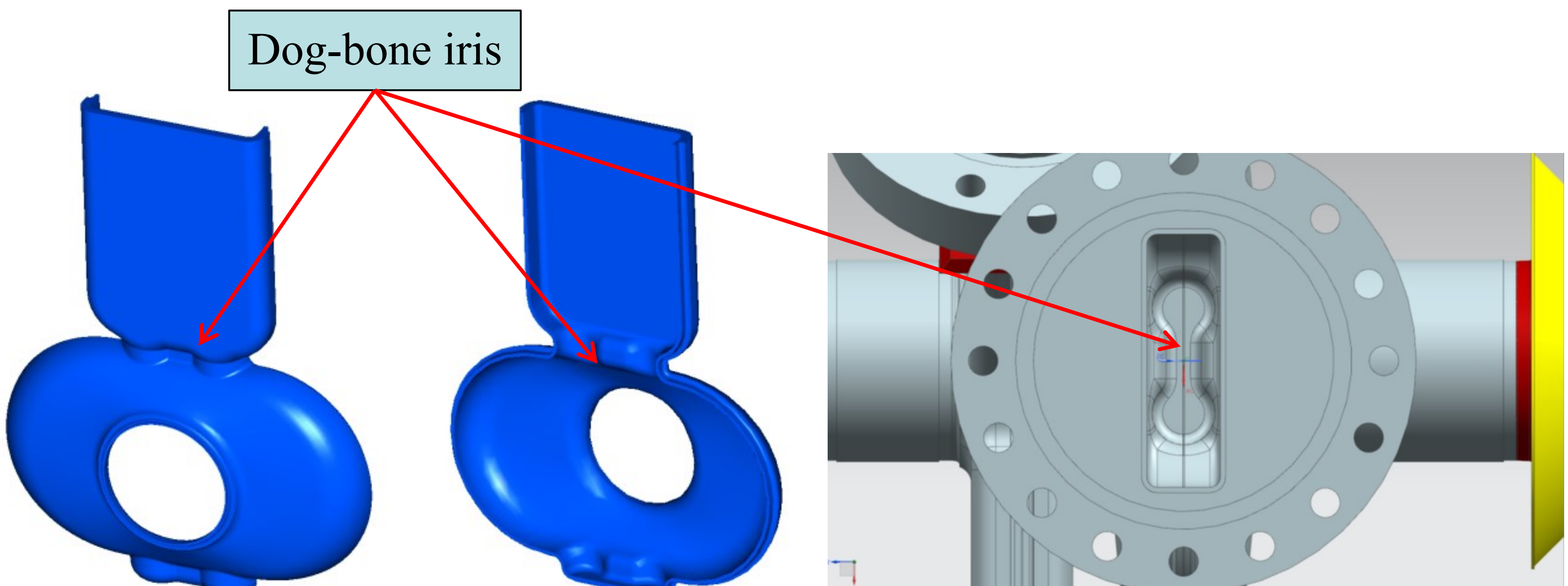
$TE_{20}$ coupling mode to LOM damper waveguide



Surface Magnetic Field

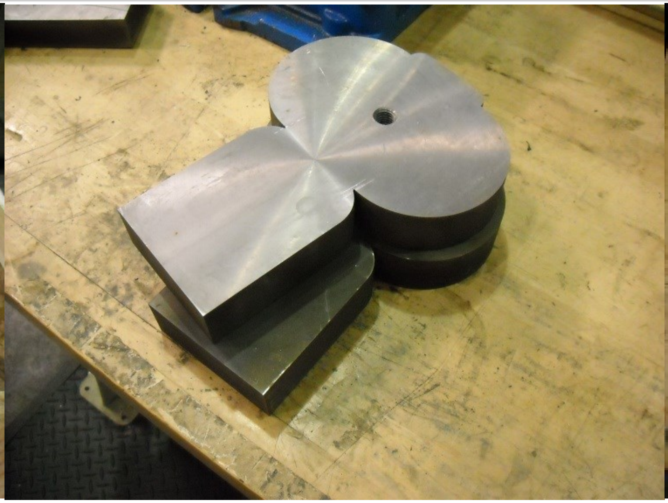
# Cavity Fabrication:

- We decided to machine these components from bulk niobium material due to these factors:
  - The complicated shape of the dog-bone iris and "Y" waveguide did not lend itself well to deep drawing
  - The sensitivity of the tuning and asymmetry effects of the cell and dog-bone on the LOM tuning




How do you weld the equator?

# Cavity Fabrication Steps: Ingot Material

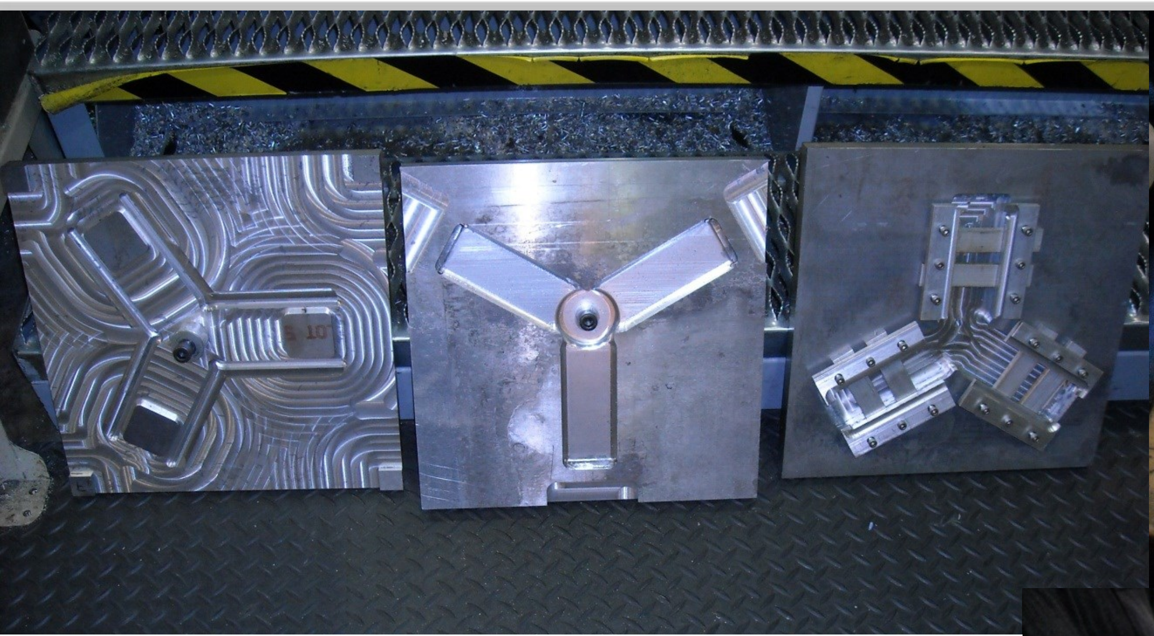



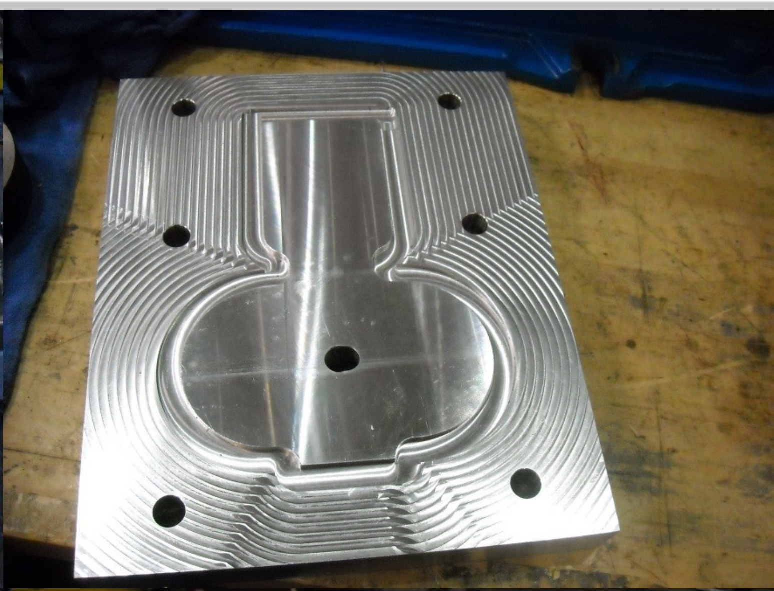

Fabrication started from purchased Nb ingot, RRR ~ 125

Vendors were:
CBMM
Niowave

Wire EDM was used to cut initial shapes for cell and waveguide

# Cavity Fabrication Steps: Tooling

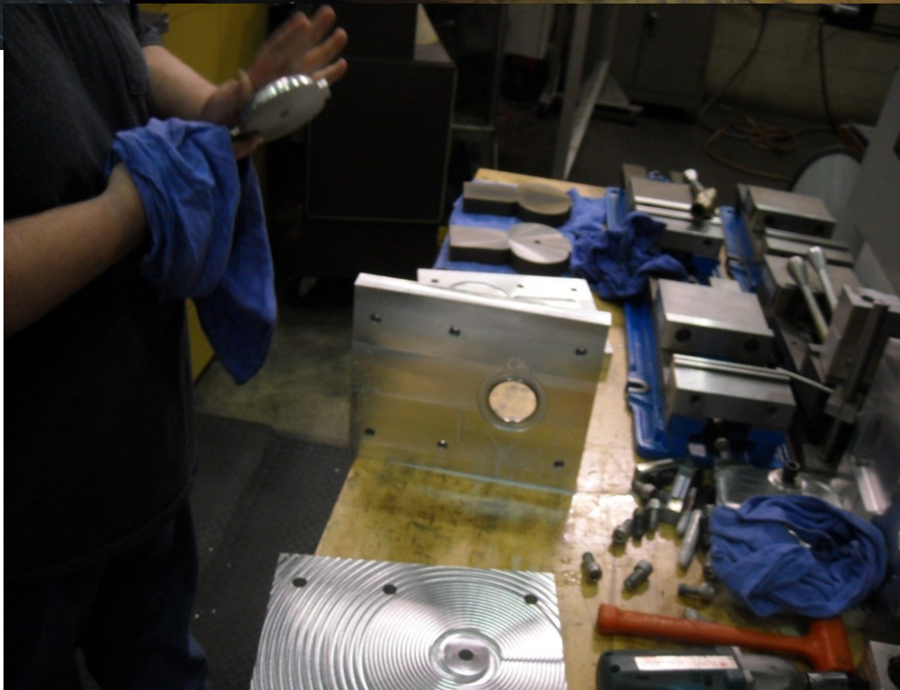




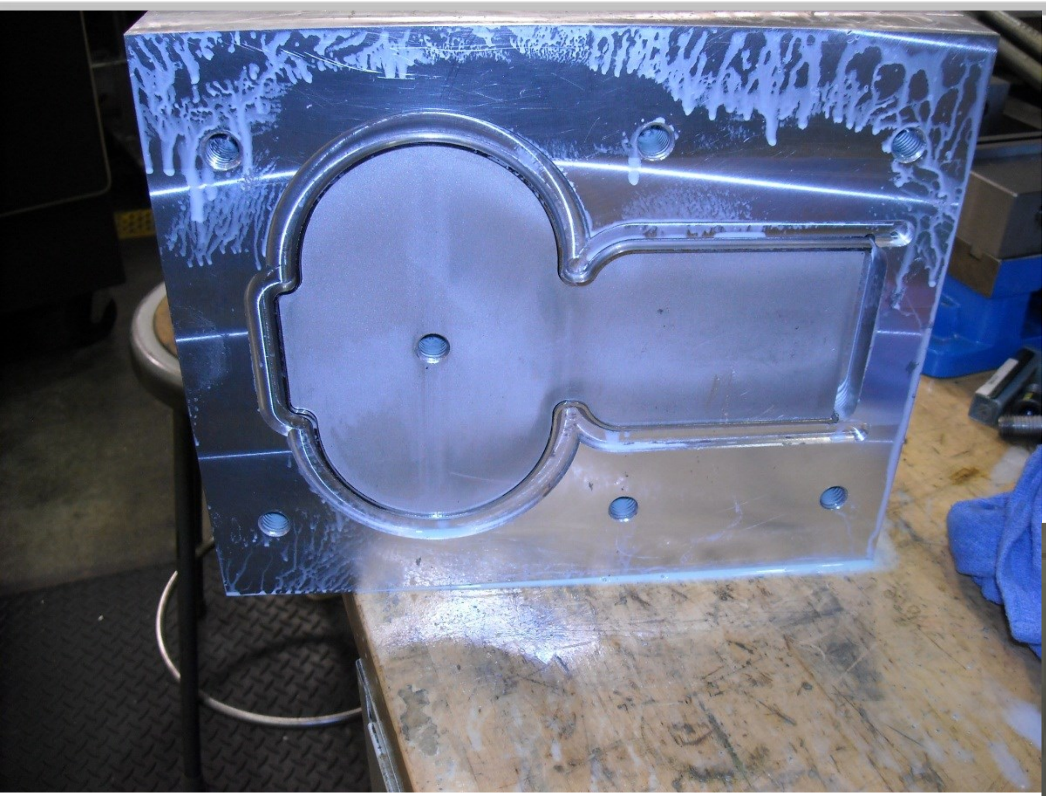
3- Tooling was fabricated for holding components for inside and outside machining and weld step trimming

4- **CAD 3D program loaded to machine tool**

5- Aluminum first article cell was machined to develop program and measure achievable tolerances



# Cavity Fabrication: Milling

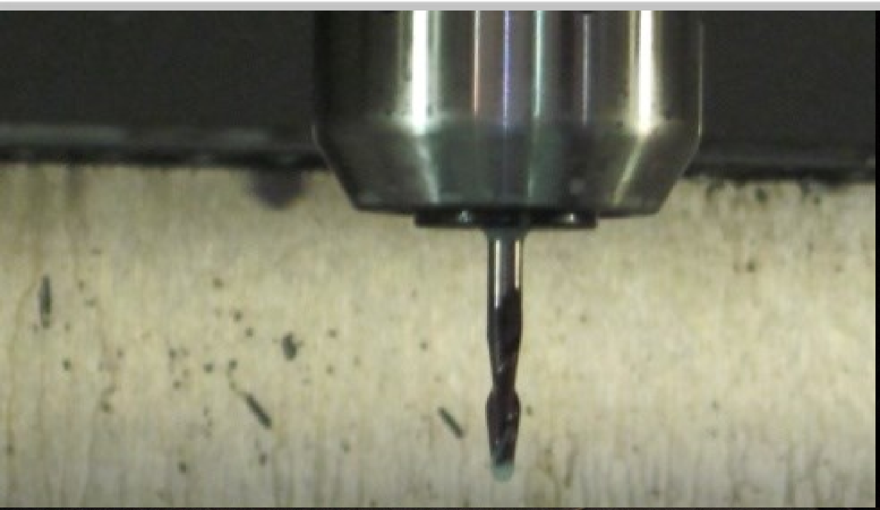


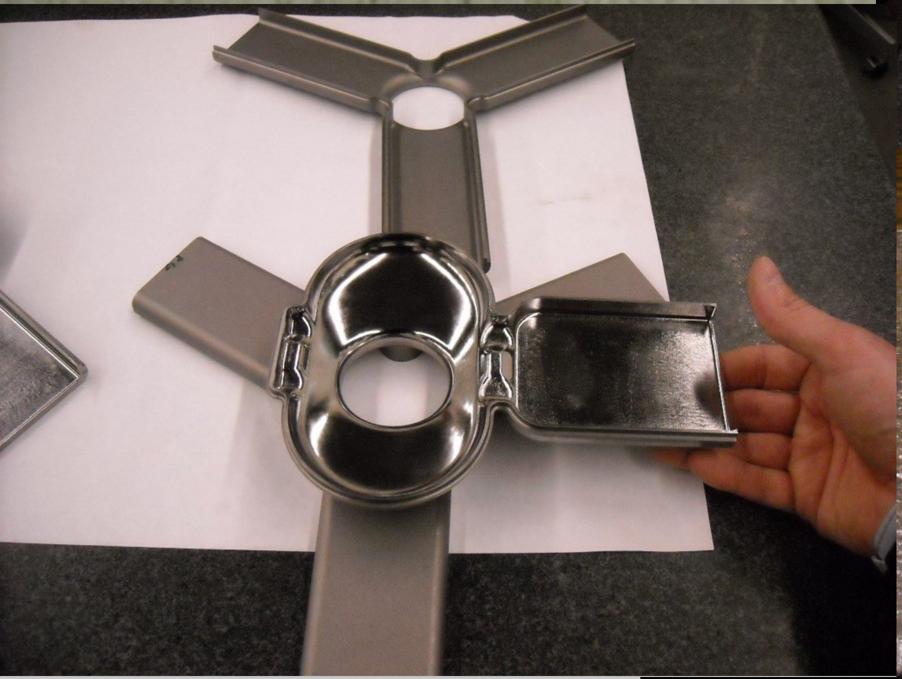
6 – Cavity machining for all subcomponents

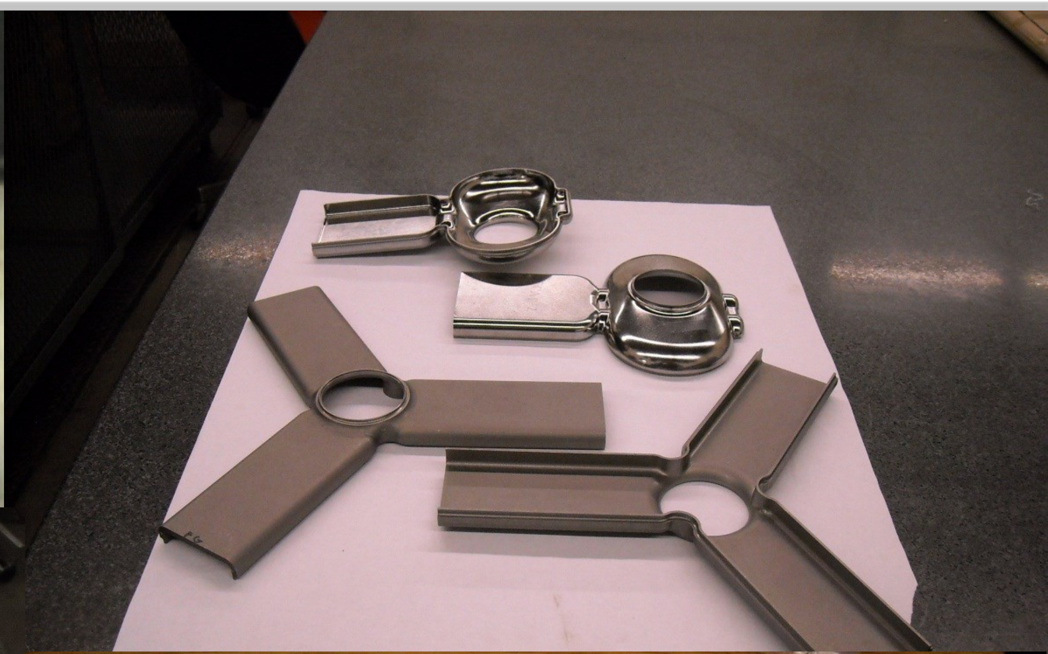
Outside machining fixture

Inside machining fixture

# Cavity Fabrication: Milling

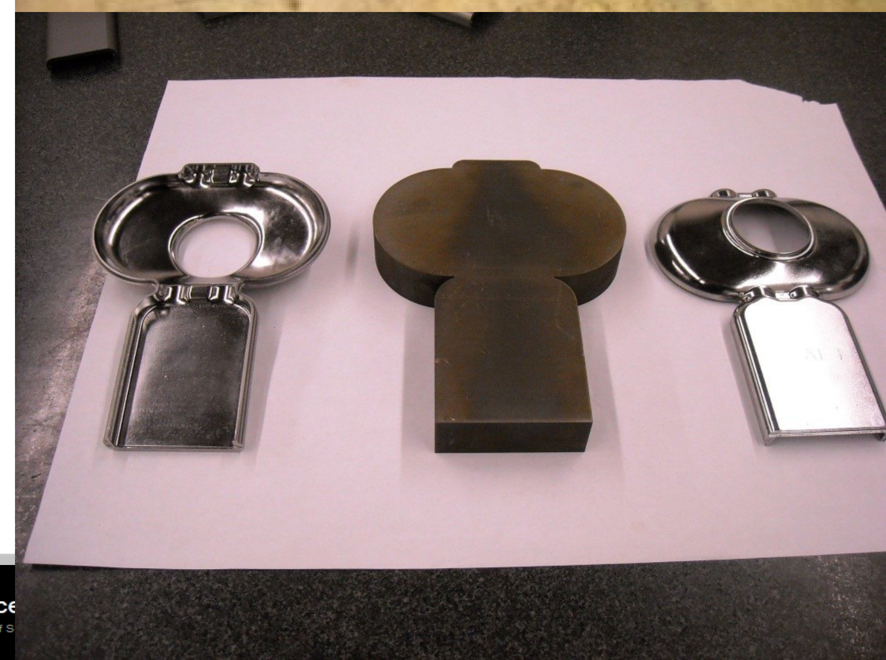






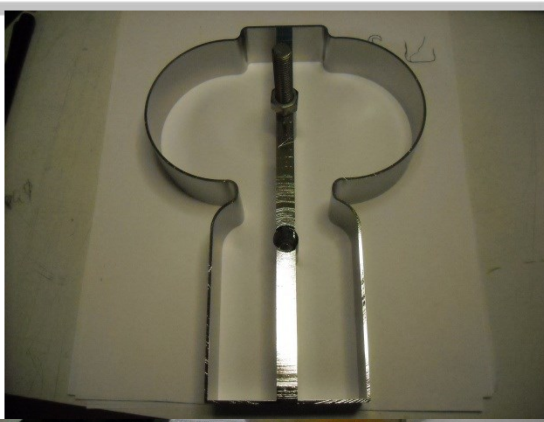
# Cavity Fabrication: Milling

- The process was repeatable and accurate with in ±0.5 mills
- Surface finish was good due to large grain material +BCP
- Machining time was 24 hours per cell, all milling was performed in an automated way
  - Running through to the next day, attended only for changing tooling and occasional observation



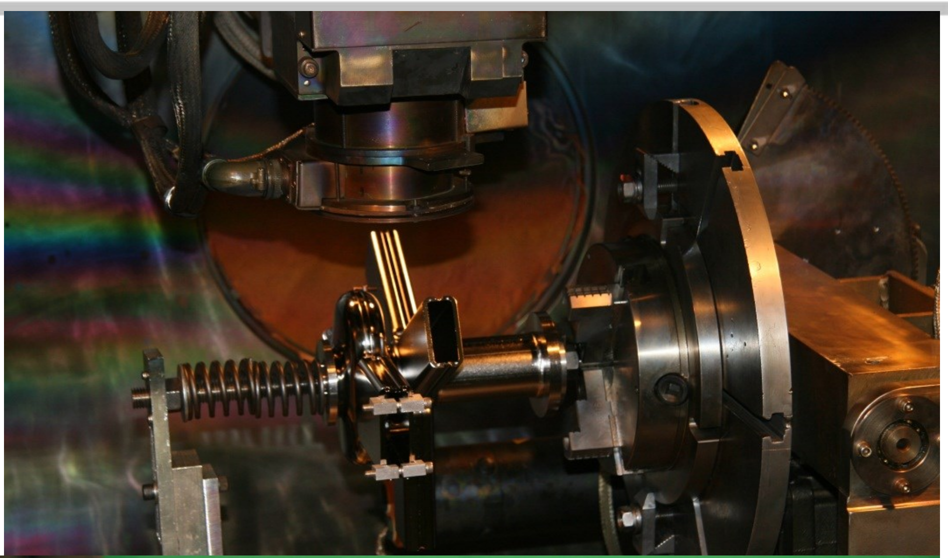
# Cavity Fabrication: EB Welding

- In order to develop weld parameters, tooling was fabricated for the equator weld
  - 2 axis programming would be required
- Test runs were performed on template to develop parameters and give confidence
- Cavity welding began



# Cavity Fabrication: EBW

- Weld map was identified and the equator weld was performed in one pass
- Cavity welding was rushed due to facility shutdown for SRF building upgrades (8 mo.)
  - This led to the decision to weld on the flanges one at this stage and would allow testing of the cavities during the facility downtime

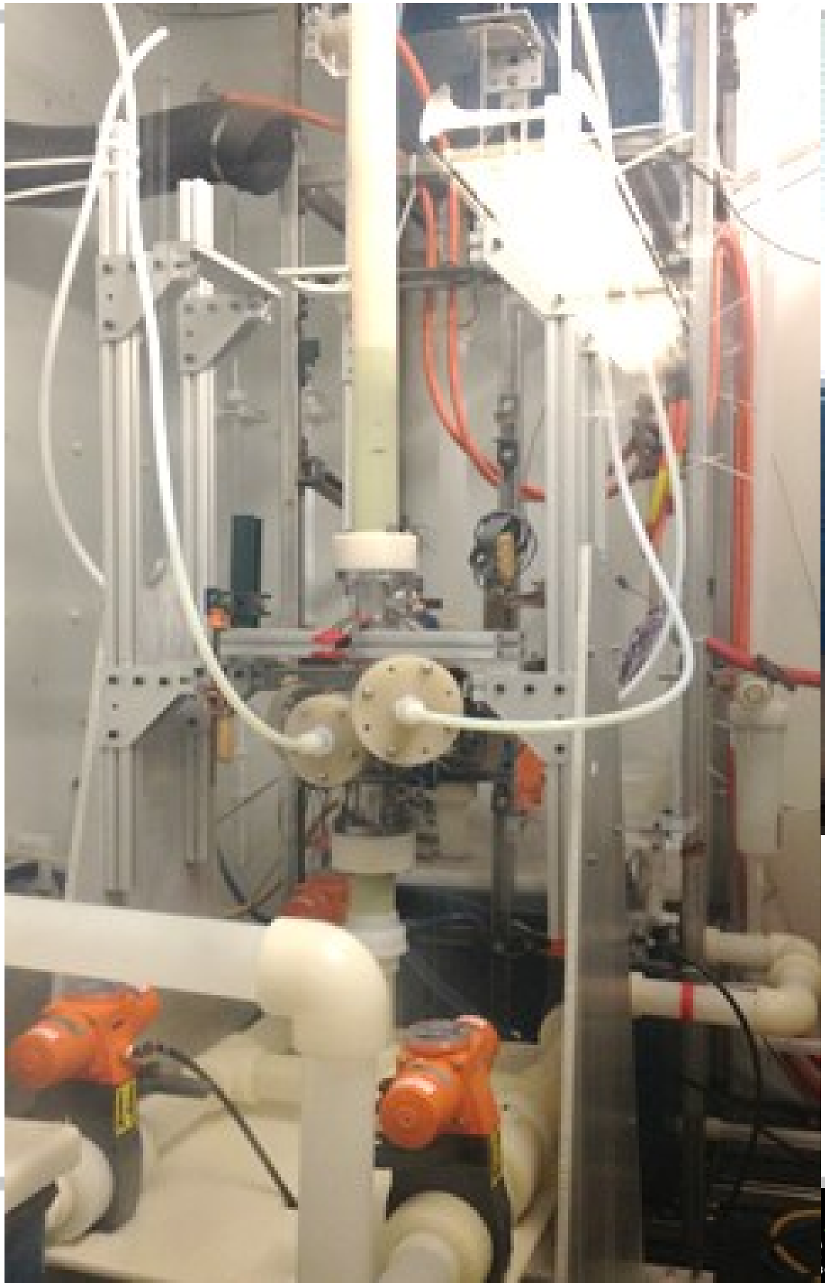


# Cavity Fabrication Completed

Four Demonstration Cavities Completed:
CCA2, CCA3-1,CCA3-2, CCA3-3

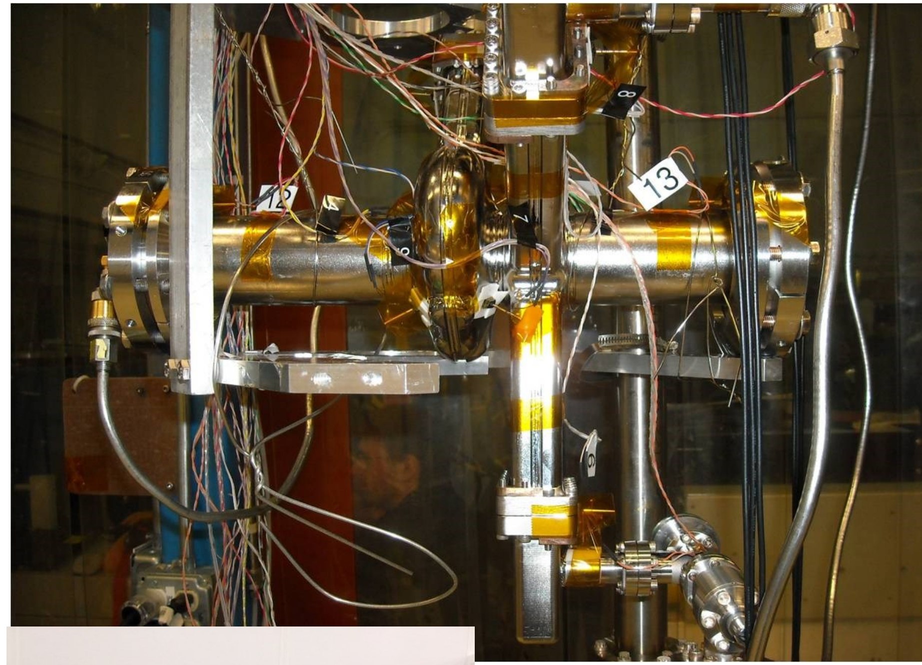
- CCA3-1 and CCA3-2 shown here

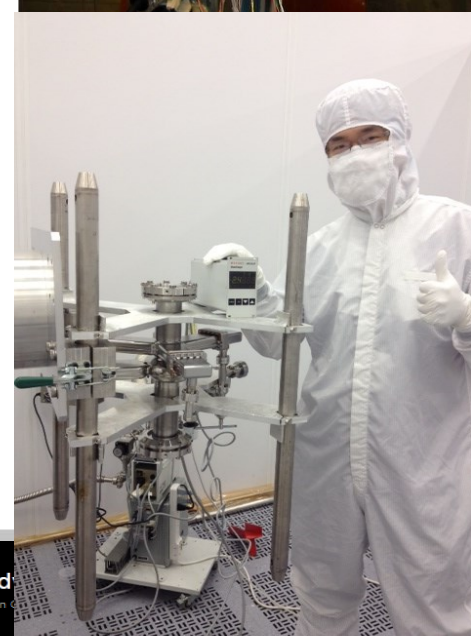
# Cornell -Chemistry and Inspection



# Vertical Qualification Tests:

- Cavity testing started with CCA2 and progressed to CCA3 cavities
- Processing procedure:
  - RF tuning
  - Degreasing
  - BCP  wet bench
  - HPR 1 Hr
  - Dry over night in cleanroom
  - Assembly, evacuation and leak test, isolate vacuum
  - Insertion into stand
  - Dewar insertion and cool down



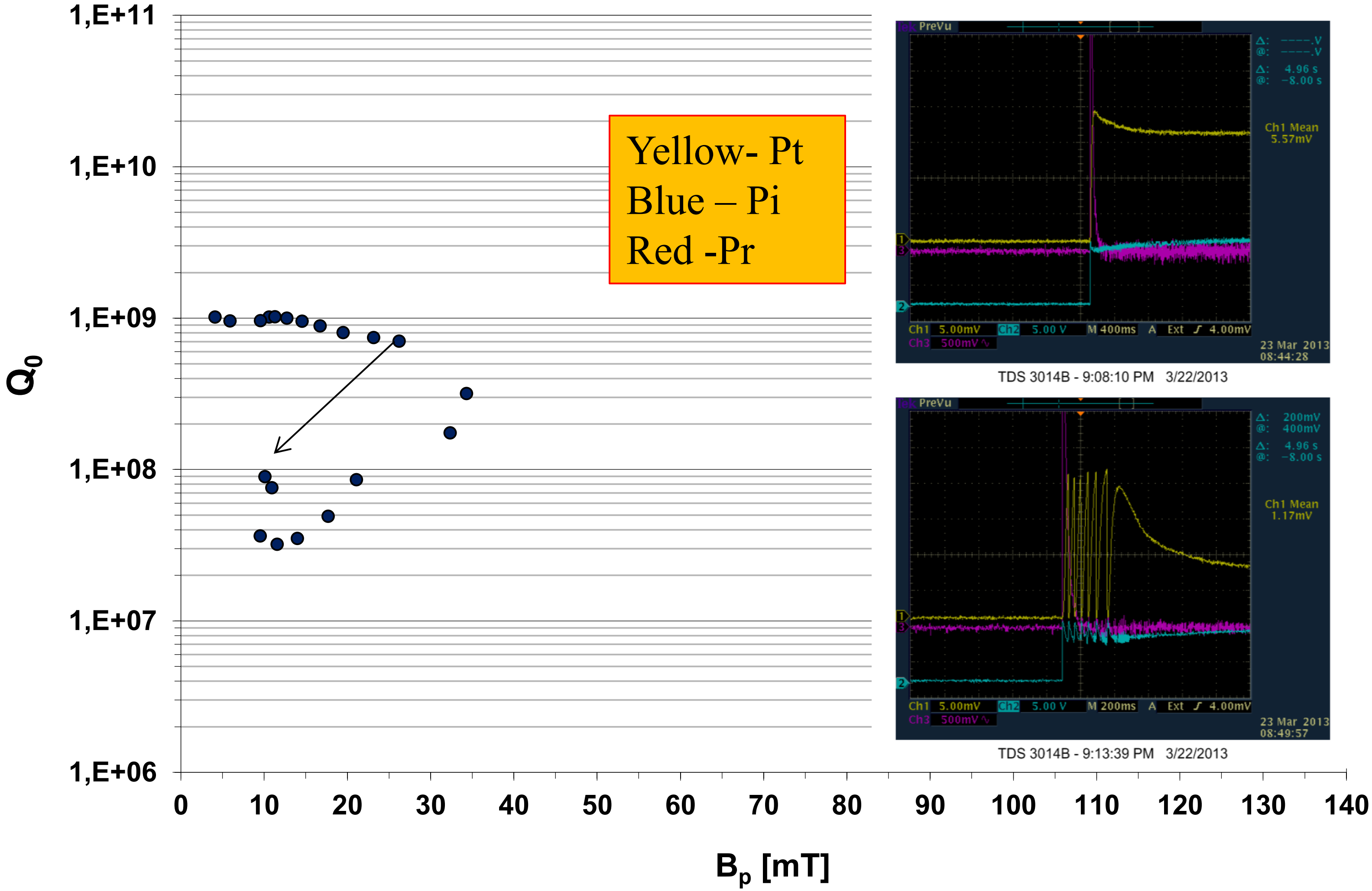


# Vertical Testing:

- Early cavity test showed:
  - Low Q-values
  - Thermal Heating
  - Q0-switching
  - Early quenches

- The cavity performances were not repeatable and an occasional good test occurred making it difficult to analyze

# CCA3-3 for SPX-0, Vertical Test at JLab on March 22, 2013



# What We Learned From This Effort:

1. The deflecting mode was coupling power out the LOM waveguide and was very sensitive to chemistry, handling and frequency tuning

**Tuning and tracking of the LOM coupling was required to reduce risk of heating and MP**

2. Small features on the niobium dog-bone equator weld were very important to reduce early quench

**EBW repairs to the Dog-bone region were necessary to remove features and reduce early breakdowns**

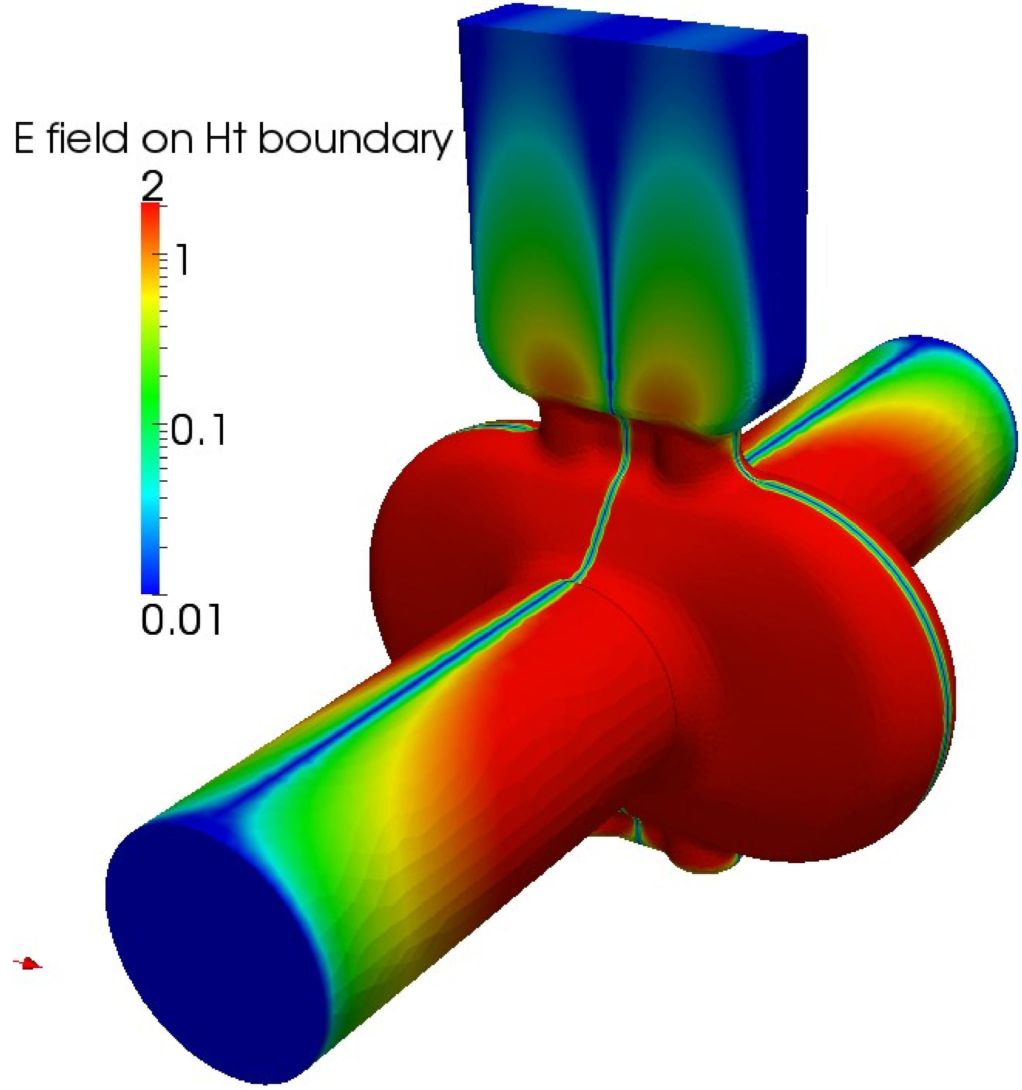
3. Multipacting at the dog-bone region was enhanced due the small features and vacuum conditions

**Repairs to Dog-bone surfaces, active pumping on cavities and RF processing at quench improved performances past specifications**

# Simulations – Omega3P

With symmetric fields coupling of the LOM could be small Qext >10^8

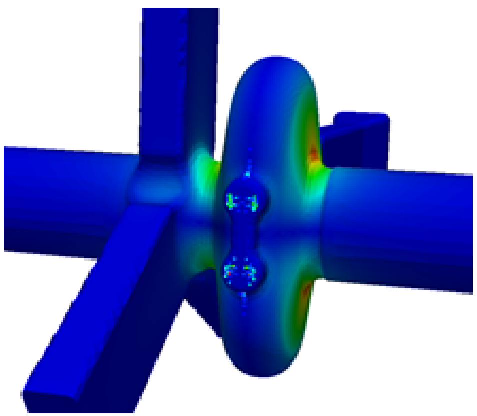
Small deformation could lead to Qext -10^5



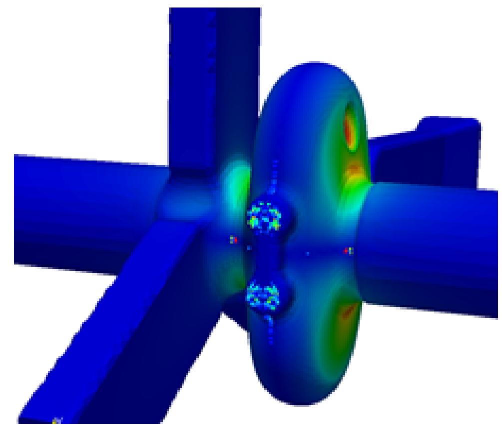
# SLAC MP simulations at Dog-bone

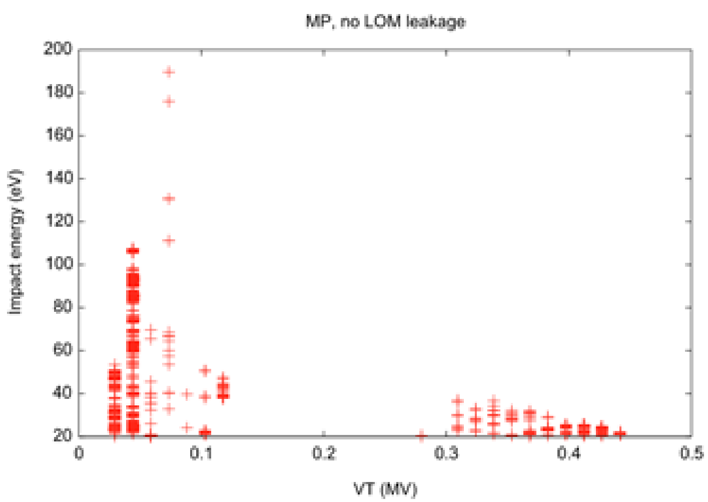
## MP in the Symmetrizing Stub

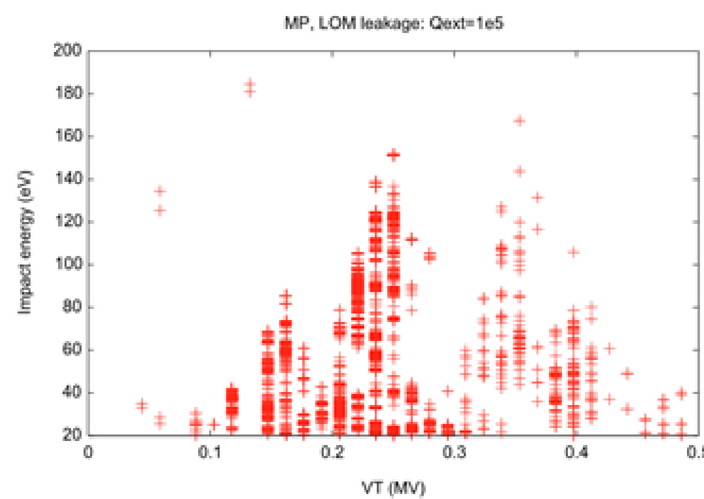
No leakage

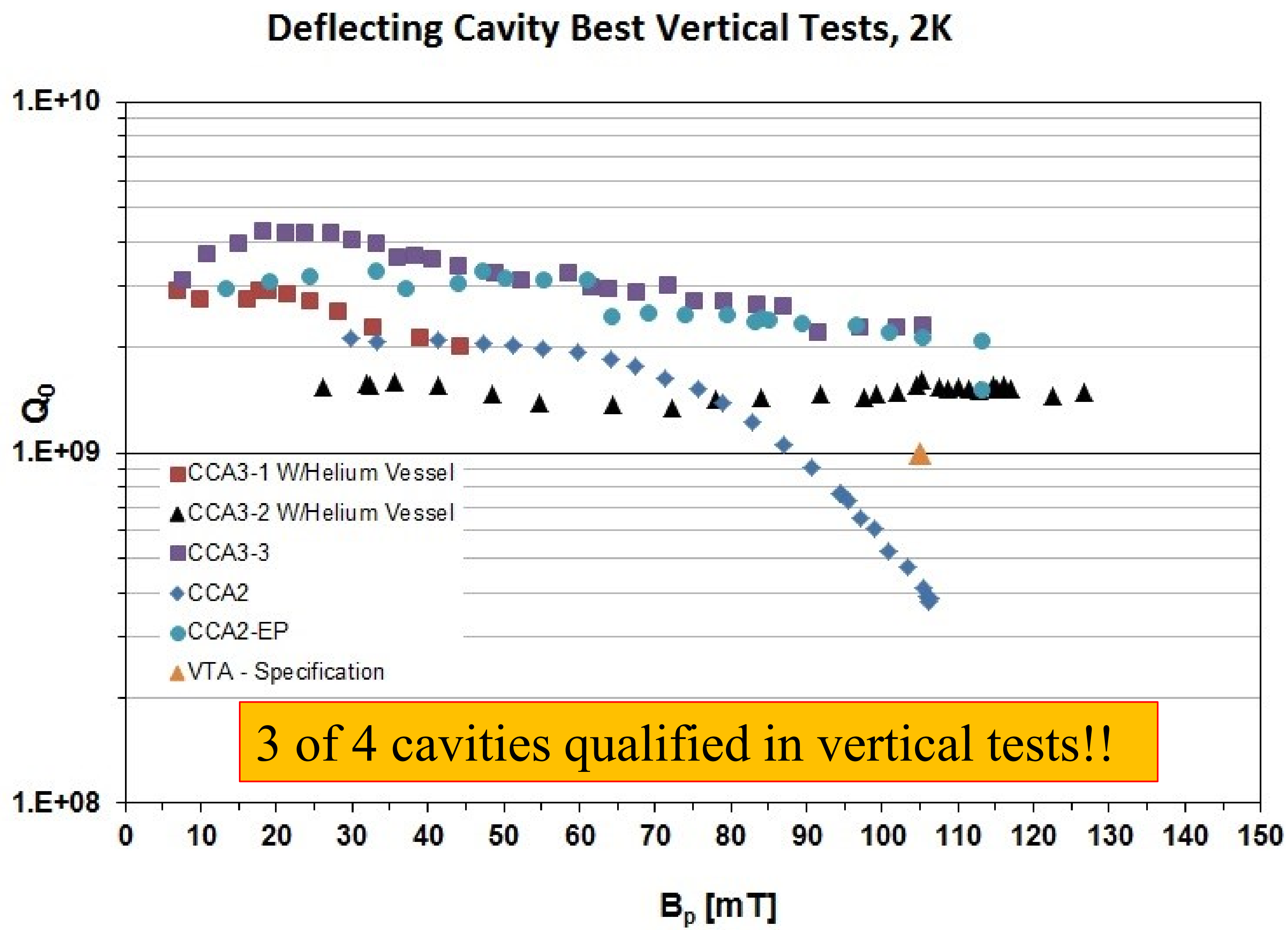


With leakage: Qext=1e5

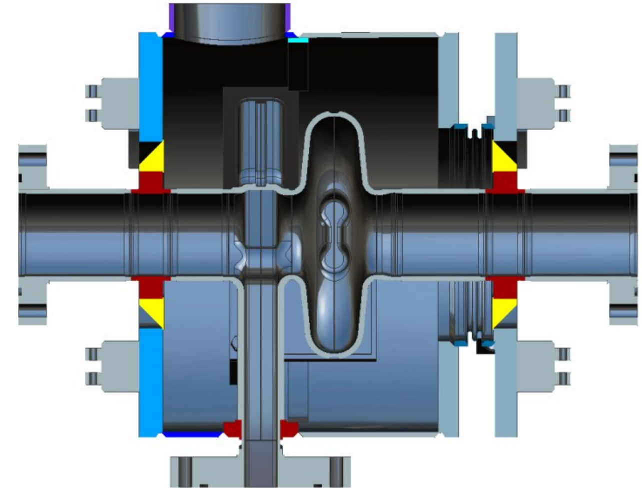




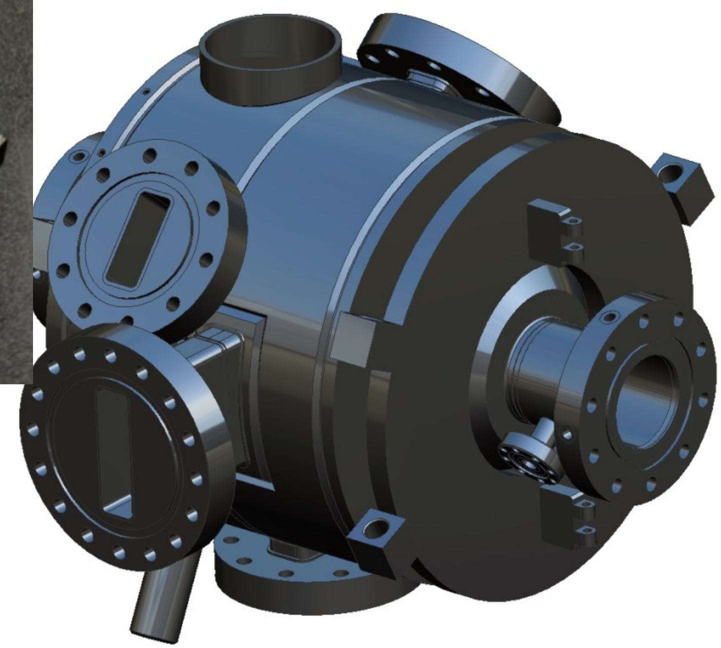

Deflecting Cavity Best Vertical Tests, 2K
1.E+10
1.E+09
1.E+08
Q0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Bp [mT]
CCA3-1 W/Helium Vessel
CCA3-2 W/Helium Vessel
CCA3-3
CCA2
CCA2-EP
VTA - Specification
3 of 4 cavities qualified in vertical tests!!

# Helium Vessel Development:



- A Titanium helium vessel was chosen for the deflecting cavity due to its frequency sensitivity, 10MHz/mm

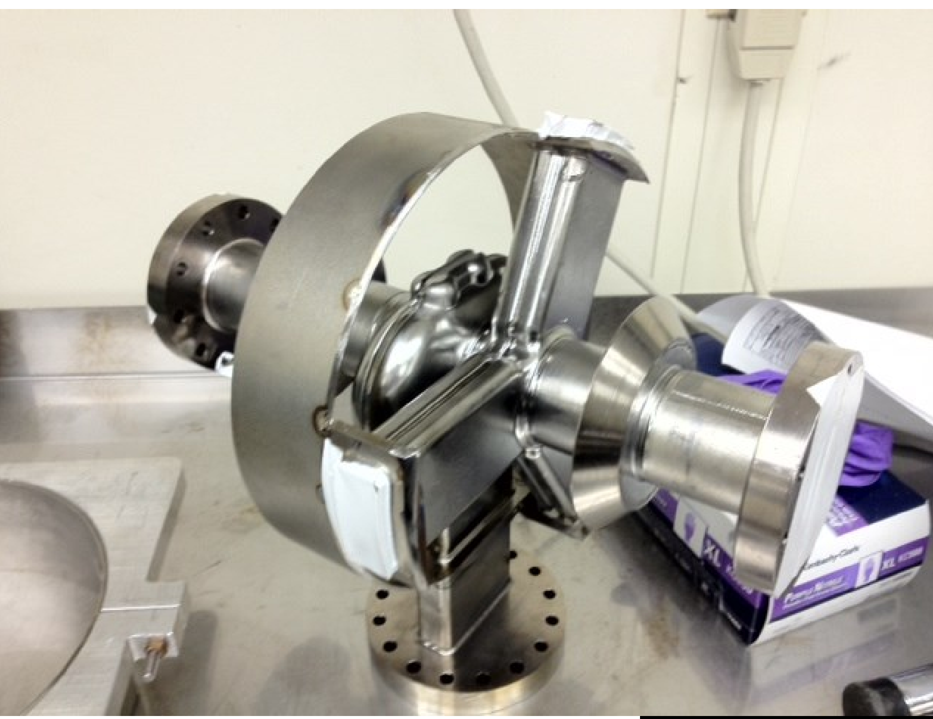
- Vessel design was patched together due to the number of waveguides and space constraints
  - Waveguide lengths were defined by the thermal design
  - Increase the volume of liquid (10 liters)

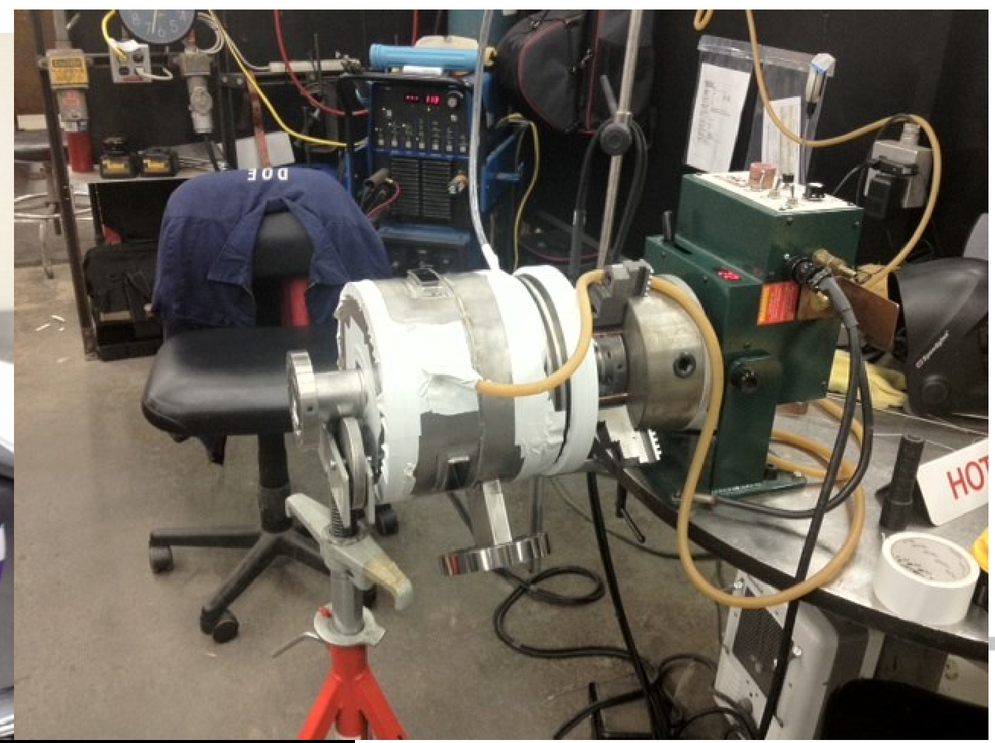


8 body welds

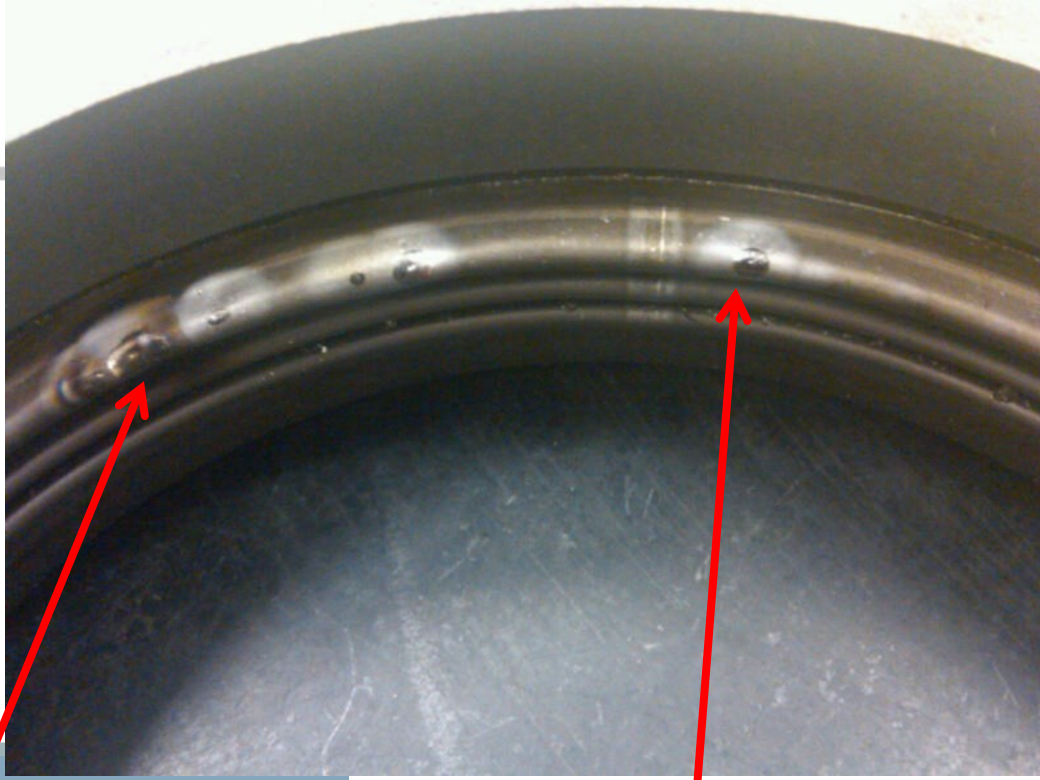
# Titanium Welding Problems:

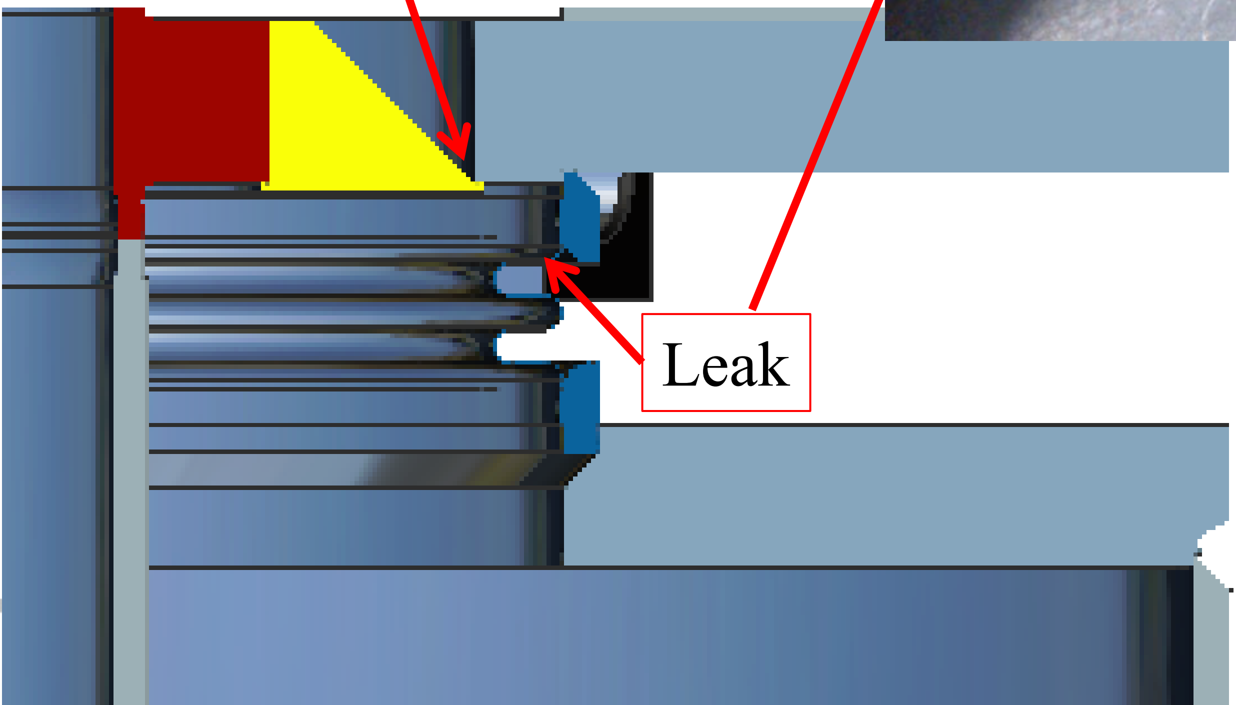
1. First attempt at welding under flanges failed due to limited access which lead to inadequate gas shielding (CCA3-1)
2. Flanges were removed and cavity was welded at ORNL for quick recovery of the cavity
3. Weld arc damaged helium vessel bellows (CCA3-2)





# Helium Vessel Bellows Leak





# CCA3-2

√ Helium Vessel Welding Complete and Leak Tight

√ Preparation for Vertical Test

√ Cavity was qualified for next horizontal test at ANL

# Horizontal Testing Preparation:

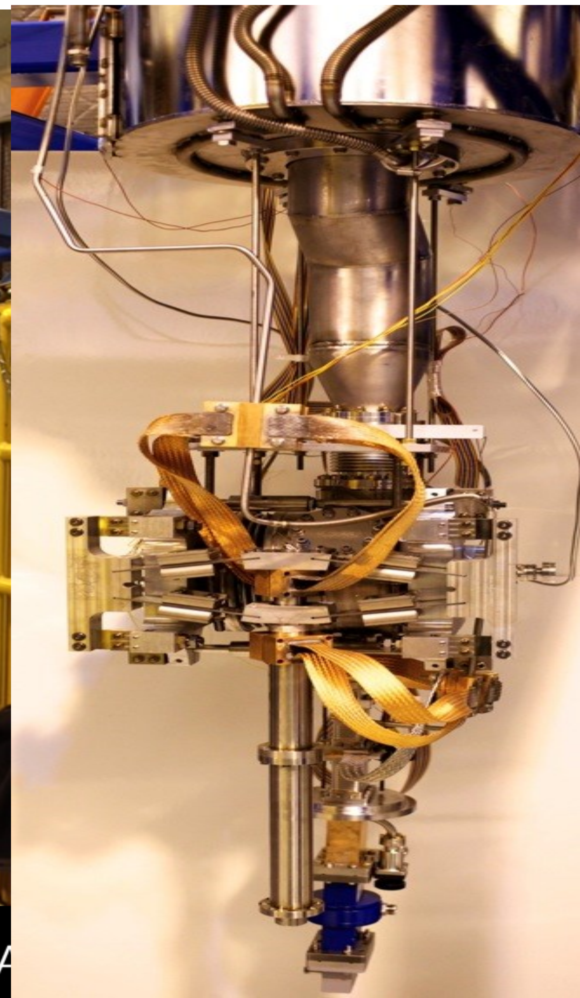
- CCA3-1 was processed and assembled for the horizontal test
  - Waveguide and window were then assembled to the cavity
  - Cavity was mounted in a transportation frame in the cleanroom



# Pictures from Horizontal testing at ATLAS

Tuner Installation

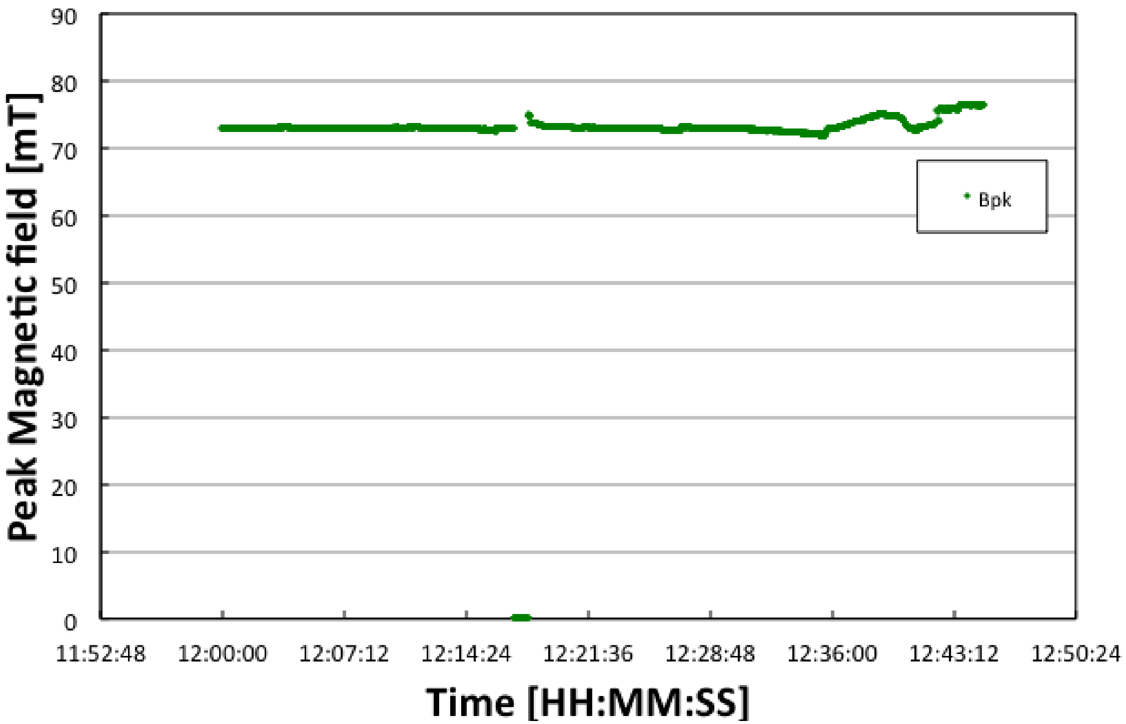
Cavity Mounted on Insert

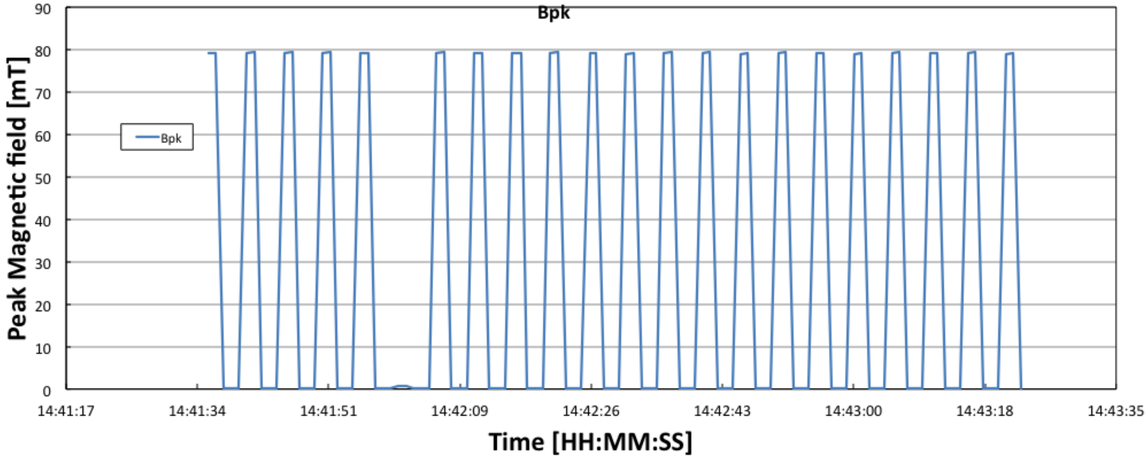


Transfer of Insert to Dewar

# Horizontal Test Results:

- CCA3-1 was ran CW over a period of two days
- Tuner and LLRF system was operated and limitations identified
- Software scripts were developed to capture critical data



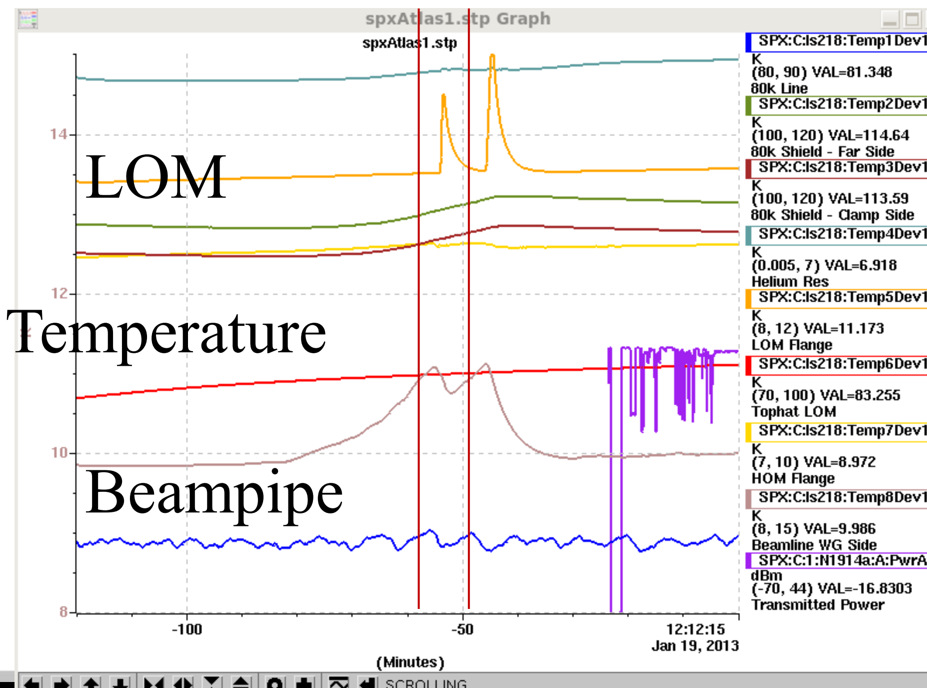
# HCT Cavity Performance

75mT Stable Performance

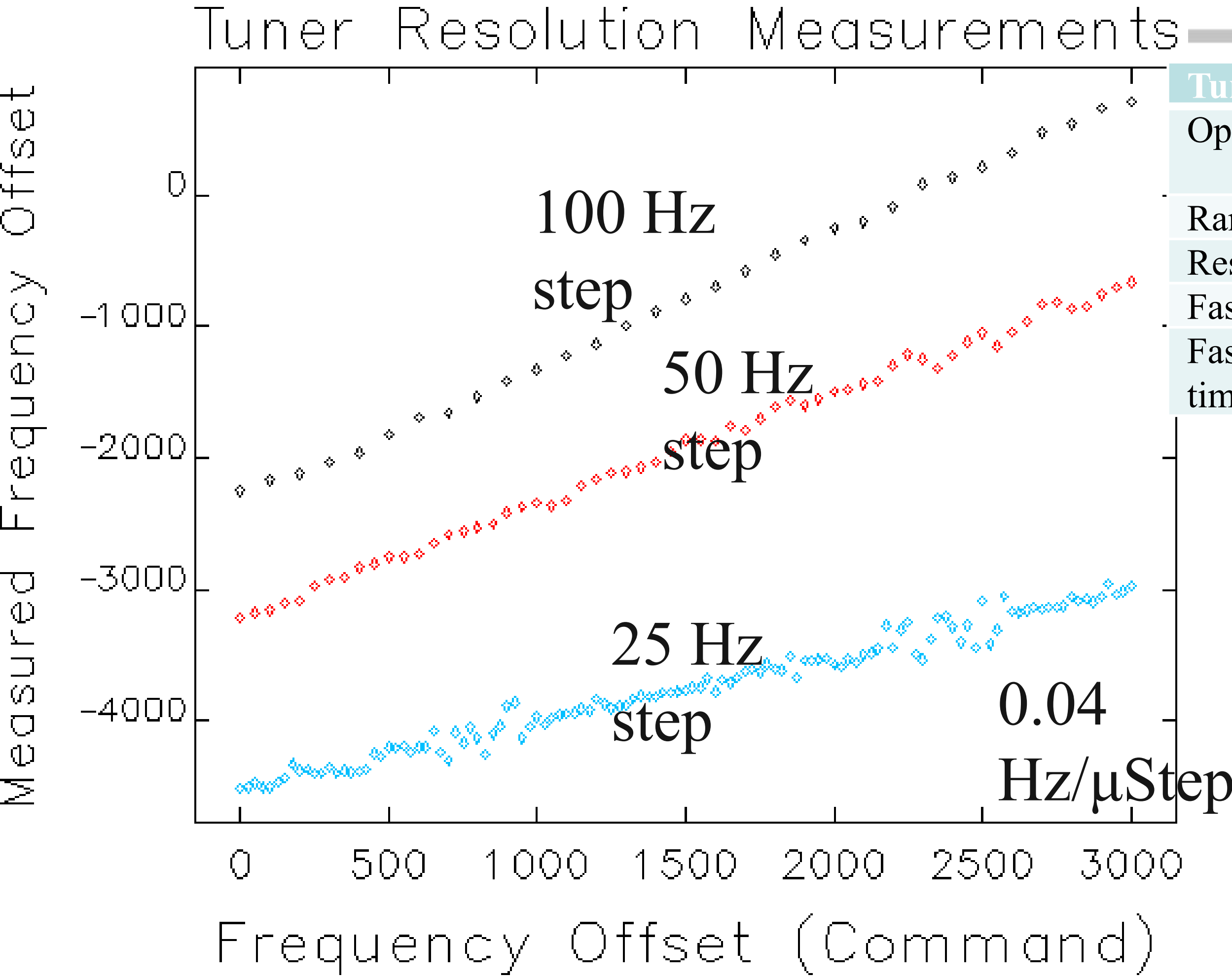
- Stable operation for over an hour at just below Q-Drop limit
- All sensors thermally stable
- No conditioning improvement
- No indication of multipacting

LOM Thermal Limitation

- Clear evidence of LOM heating upon Q-Drop
- Possible Magnetic Quench on NbTi top hat



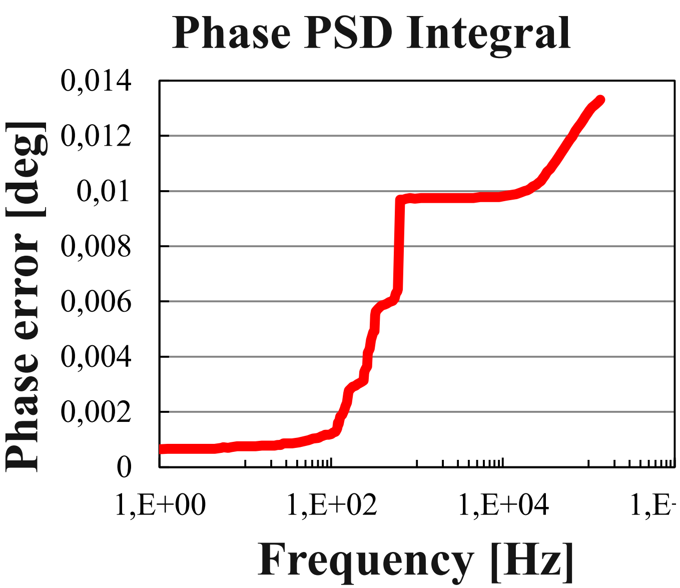
# Good Tuner Linearity

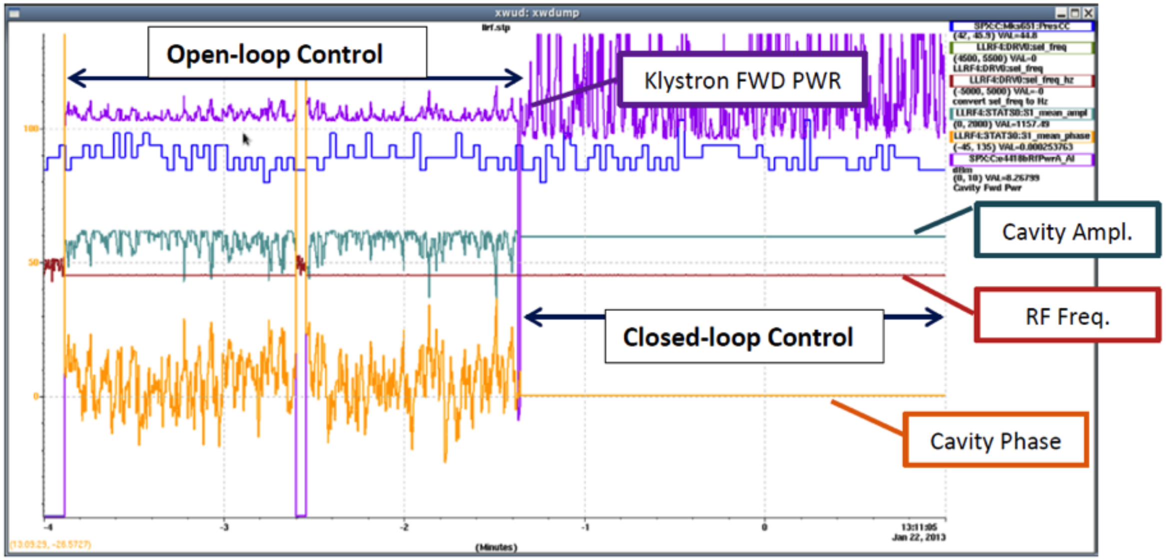



| Tuner Specification | Value | Unit |
|---|---|---|
| Operating frequency | 2815.48 6 | MHz |
| Range | ±200 | kHz |
| Resolution | ≤40 | Hz |
| Fast detuning | 3 | KHz |
| Fast detuning response time | ≤1 | ms |

Cavity frequency showed standard deviation of 250Hz (1kHz pp) due to microphonics and pressure variation. When averaged, 25Hz step showed good linearity

# Digital LLRF Control



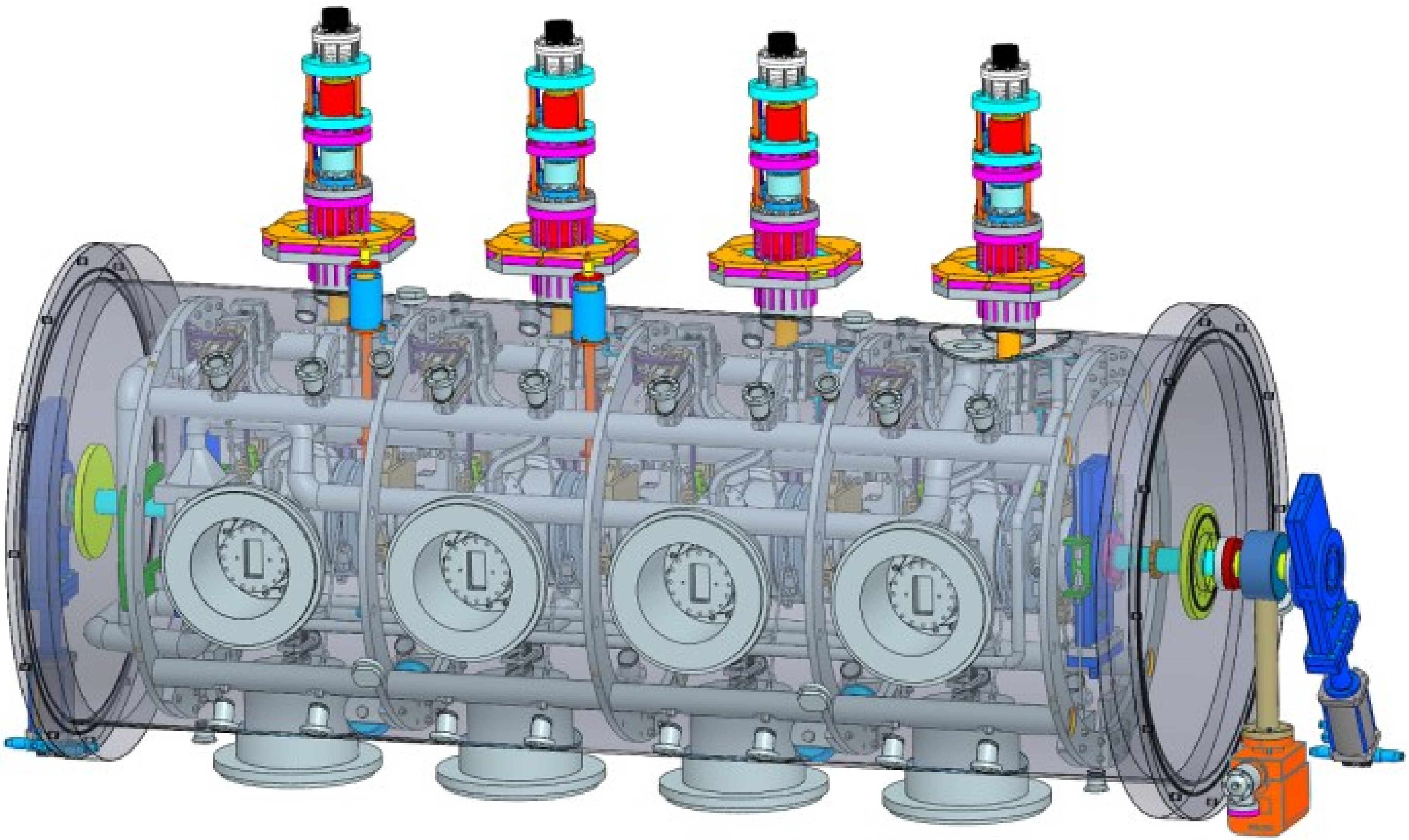




**The closed-loop control performance of SPX LLRF cavity field controller at ~ 10w RF power level with presence of significant microphonics in SRF.**

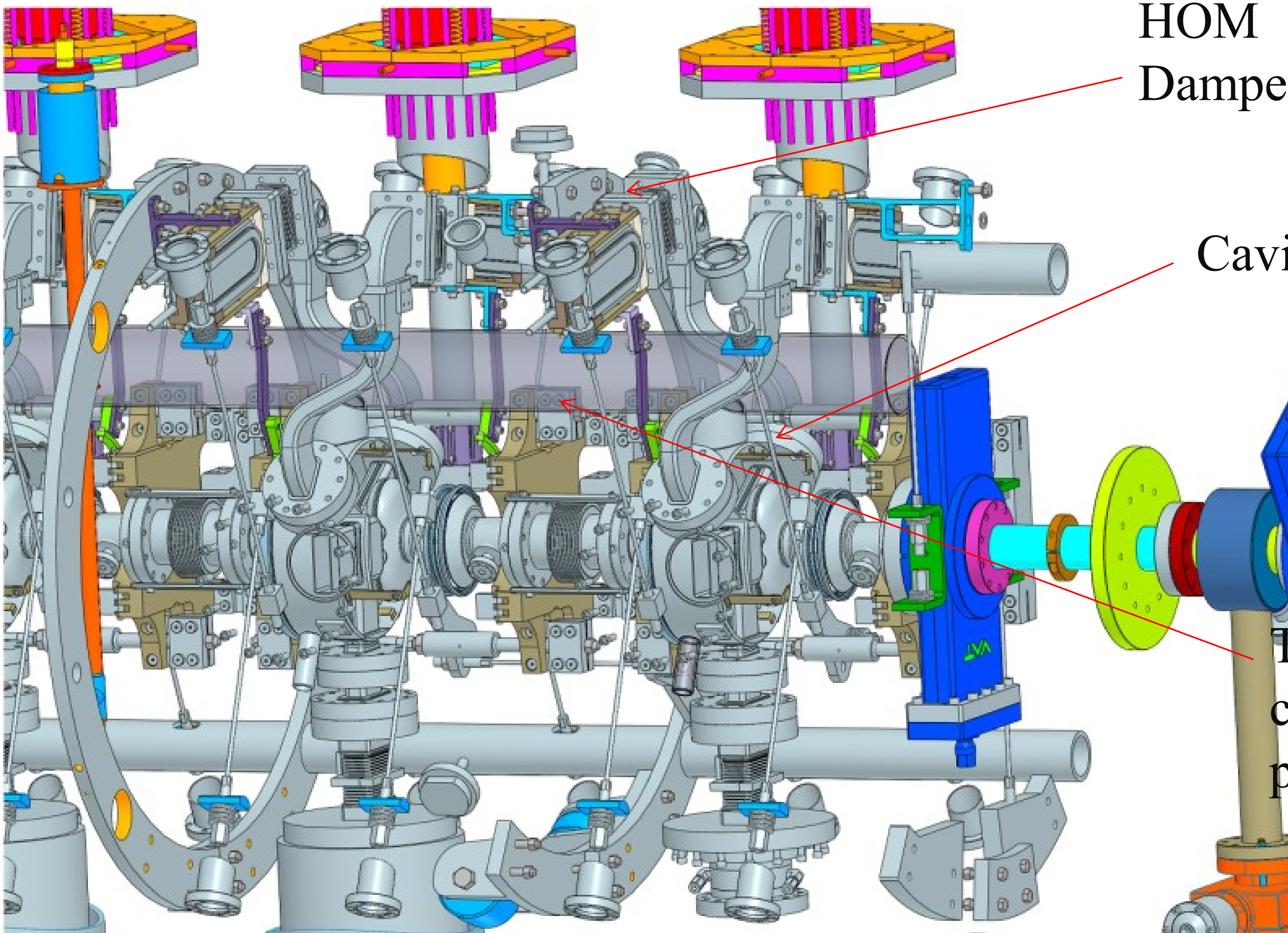
Closed-loop measurements indicate that the integrated phase error is less than 10 mdeg in the bandwidth of 1Hz to ~ 10 kHz and under 20 mdeg up to 135 kHz

Courtesy of H. Ma, T. Berenc and L. Doolittle

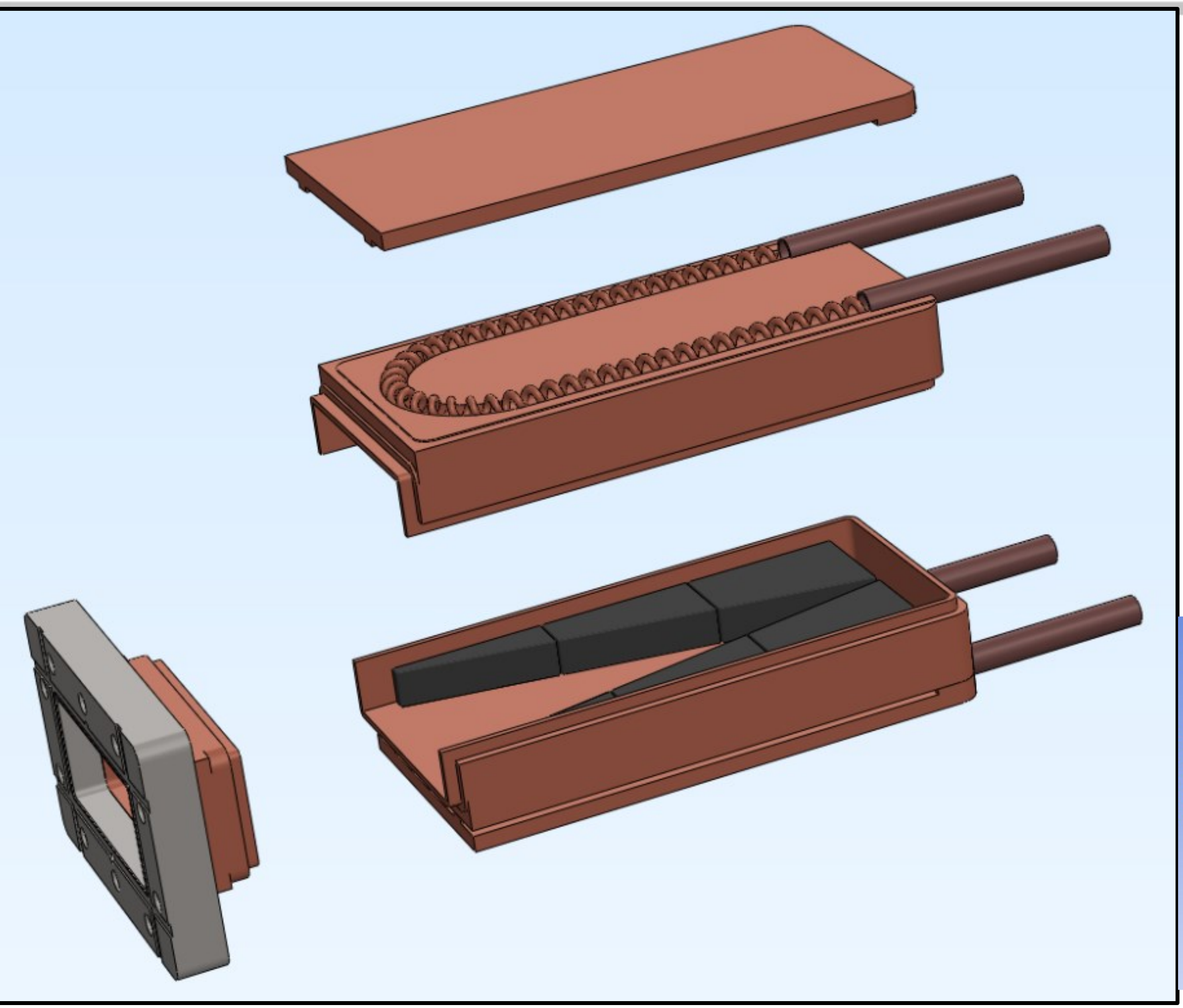
# Cryomodule Design:

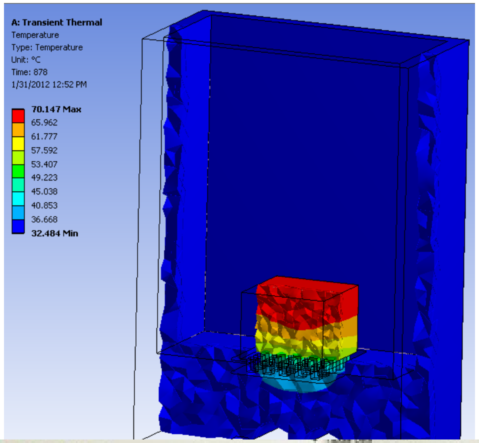


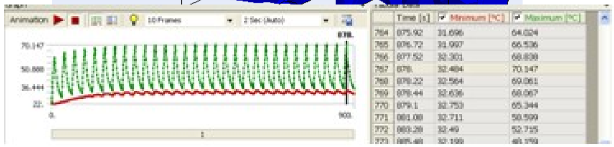
# SPX Cryomodule Concept -packaging

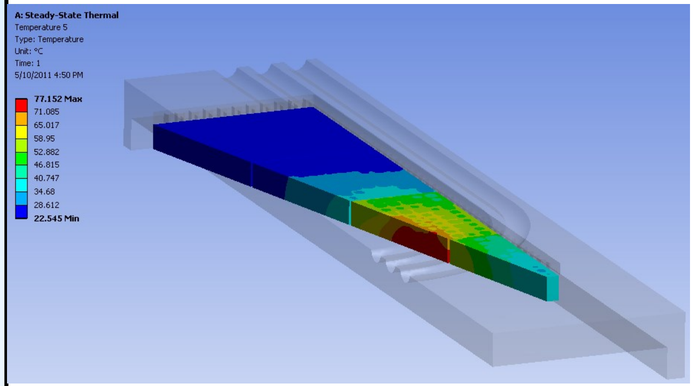


# HOM Load Design:







# Conclusion:

- Four superconducting deflecting cavities were designed, fabricated and tested for ANL's SPX project (CCA2,CCA3-1, CCA3-2, CCA3-3)
- Three of the four cavities meet gradient and Q0 specifications
- Cavity fabrication from large grain ingot material was successful
- Many technical problems were encountered and overcome for this challenging cavity and helium vessel design.
- **The collaboration between ANL and Jlab was very successful, sharing technical expertise and facilities**
  - **Special thanks to ATLAS, Cornell, FNAL and ORNL staff for their support and expertise**