

# RF Power Coupler, Slow Tuner and Solenoid for PXIE 162.5 MHz HWR Cryomodule

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Physics Division

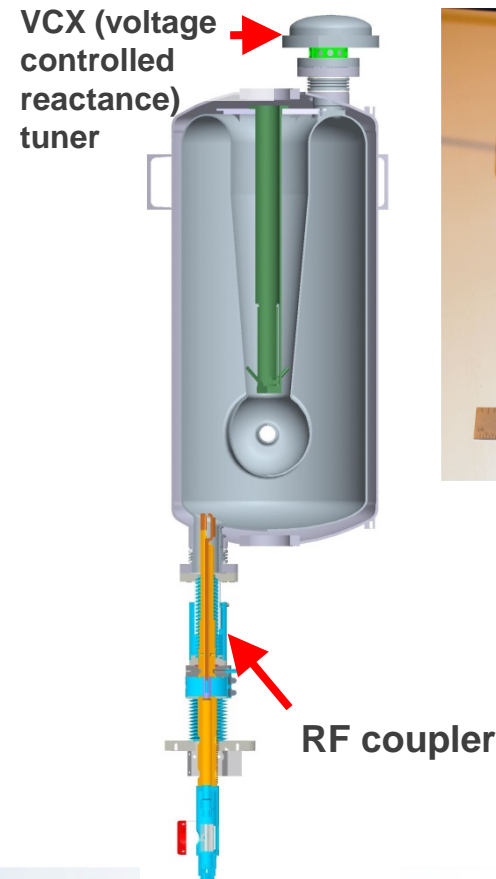
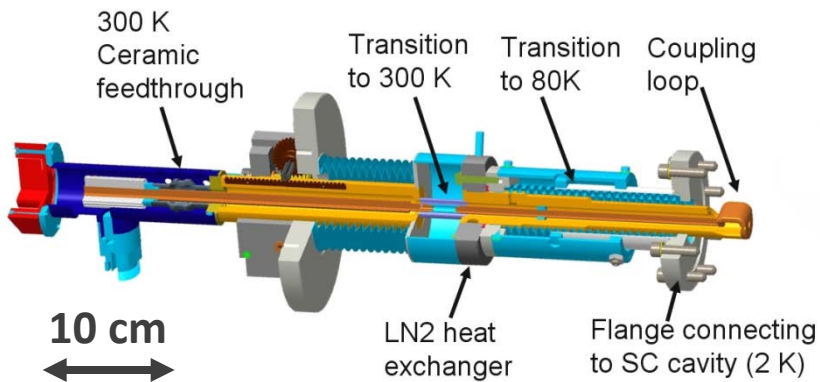
October 15, 2013

# Power Coupler Background



# RF Power Coupler for 2009 ATLAS Upgrade

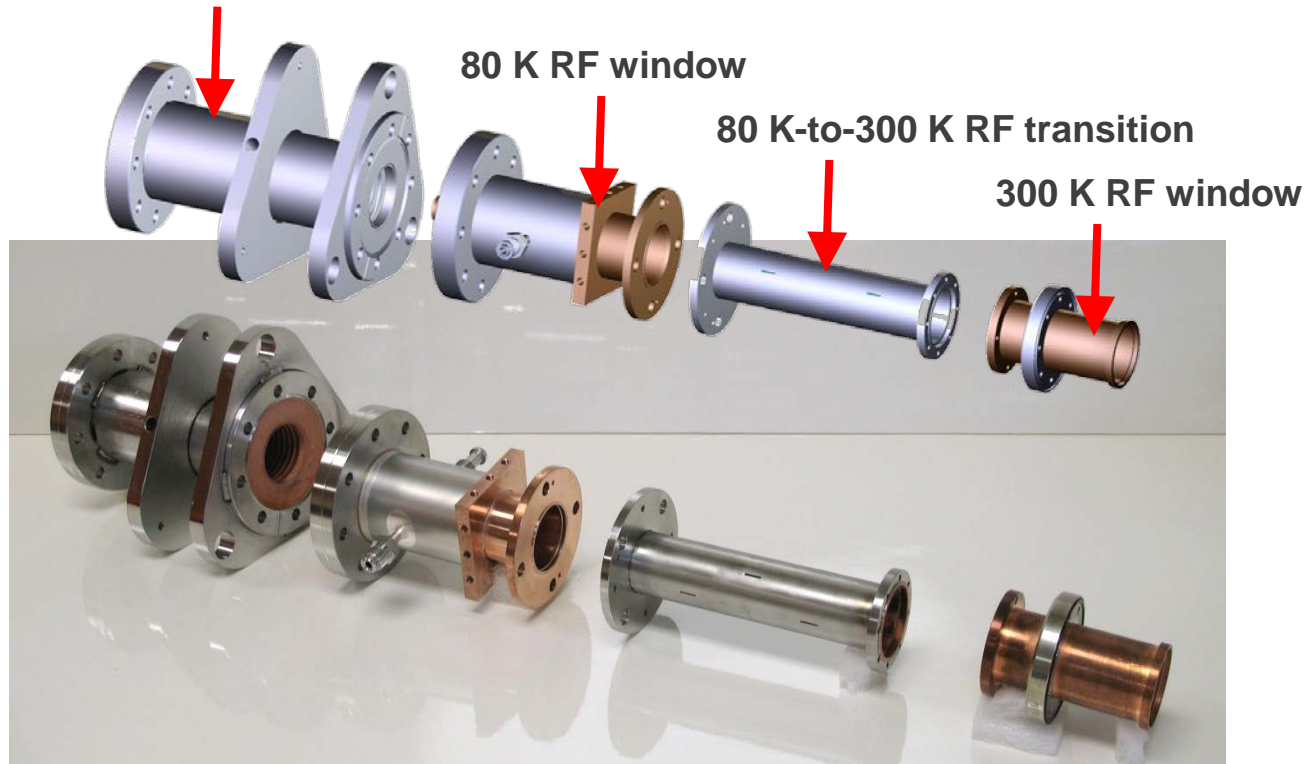
- Single room temperature RF window and vacuum break
  - Hermetically seals the clean cavity string assembly
  - Entire ½-meter assembly was installed in the clean room
- Center conductor cooled by direct contact with outer conductor
- Used with VCX so requires low power handling (~few hundred Watts)



# RF Power Coupler for 2013 ATLAS Upgrade

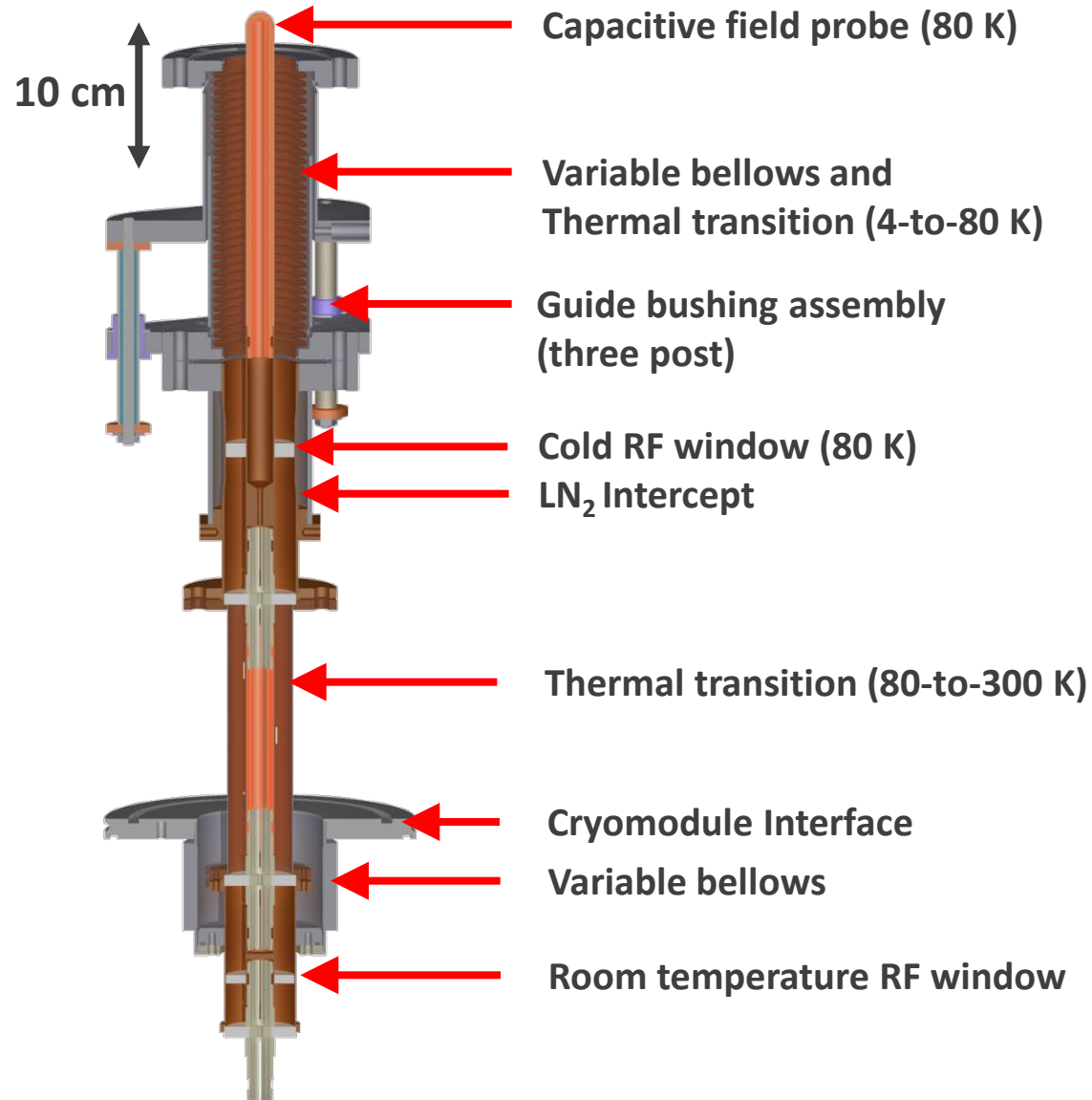
- Capacitive, co-axial, 50  $\Omega$
- Relatively large 40 mm outer conductor
  - 40 mm coax suitable for room temperature operation with no active cooling at this power and frequency
- Separate coupler functions into 4 main subcomponents

**4 K-to-80 K, 7 cm variable bellows**



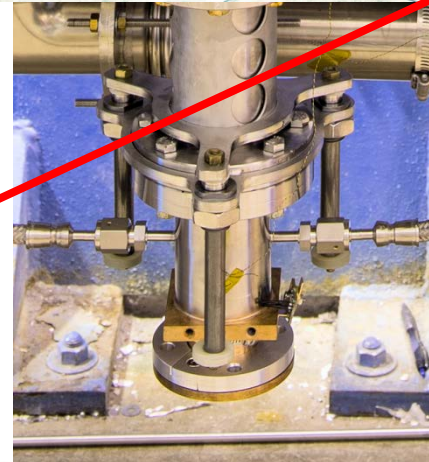
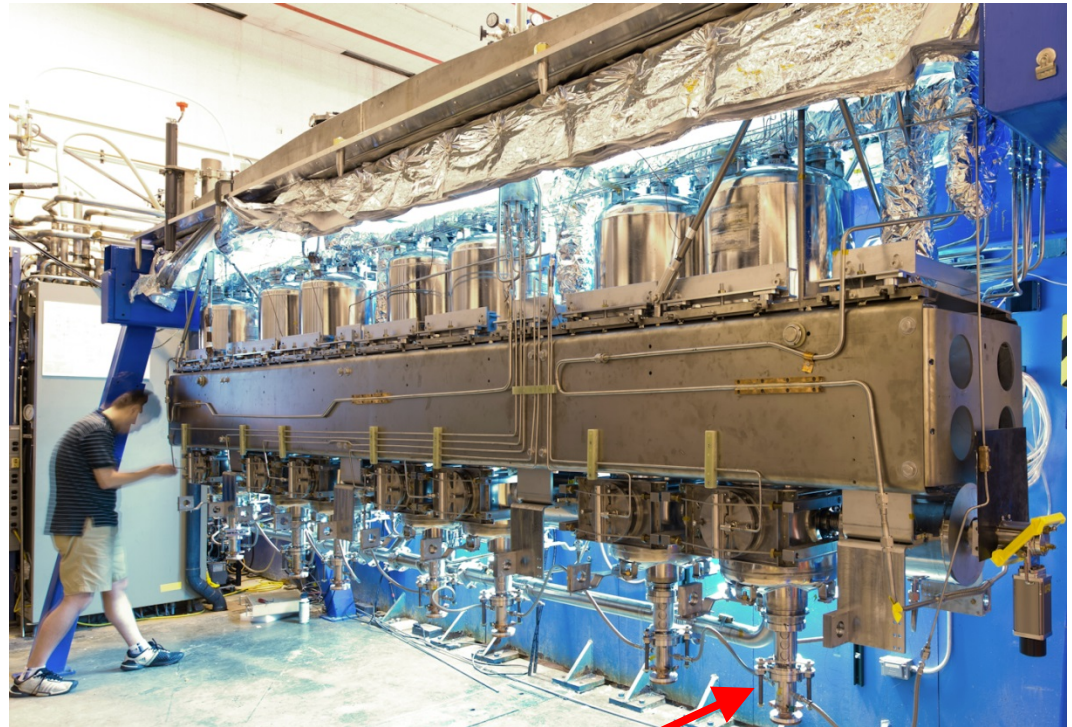
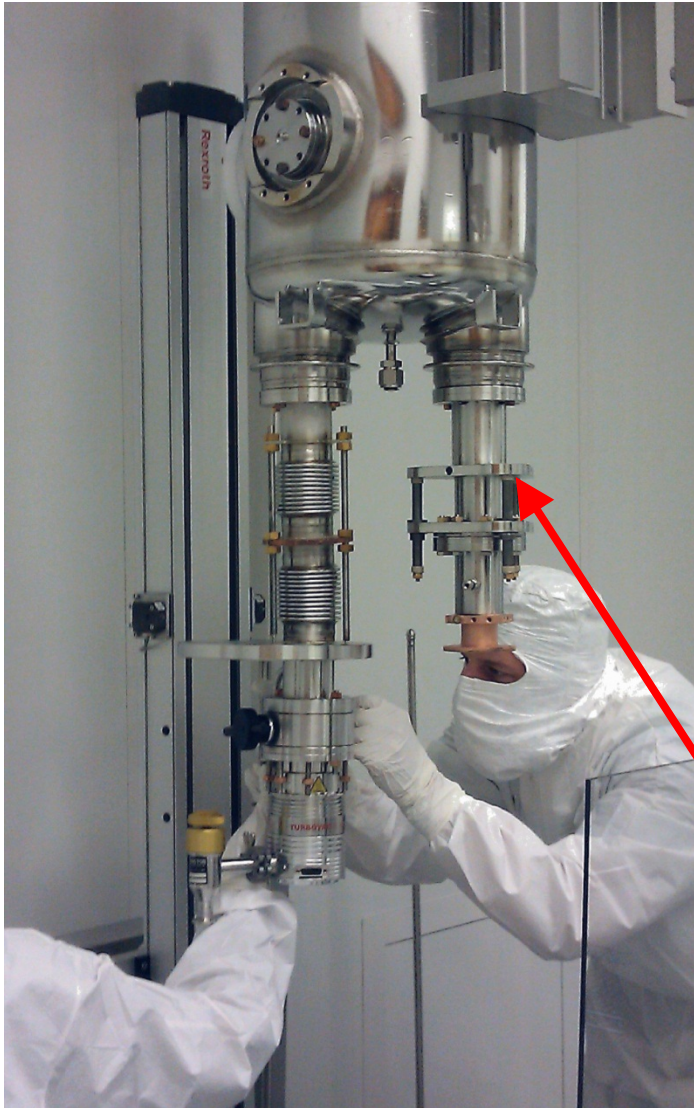
# Features of Recent ANL Designed Couplers (PXIE, ATLAS, MSU/FRIB, SARAF)

- 3 mm (thick) wall OFHC copper capacitive field probe conduction cooled to  $\sim 80$  K through cold ceramic window
  - No room temperature surfaces looking into the cavity
- 150 micron (thin) wall stainless bellows with 15 microns copper plating
  - Variable motion to adjust  $Q_{\text{EXT}}$  (60 dB in this case, 20 dB for PXIE)
  - Can match RF power into cavity multipactor barriers
  - Accurate cavity  $Q_0$  measurements
- Compact clean assembly due to use of a 2<sup>nd</sup> room temperature RF window and removable room temperature thermal transition



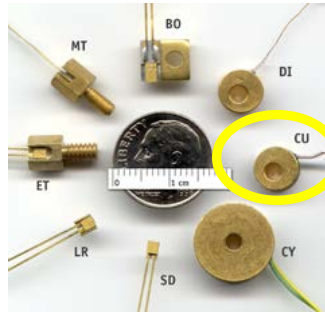


# Power Coupler on 2013 Cavity & Cryomodule Assemblies



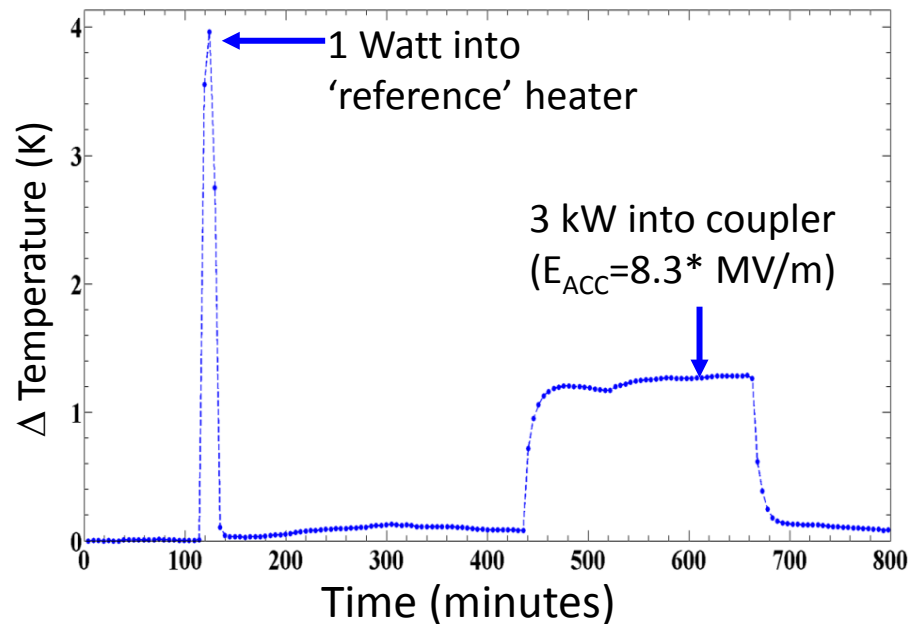
**Cold window  
& bellows  
assembly**

# Heating for Two Different Cavity/Coupler Pairs as Measured at the 4 Kelvin Cavity Flange

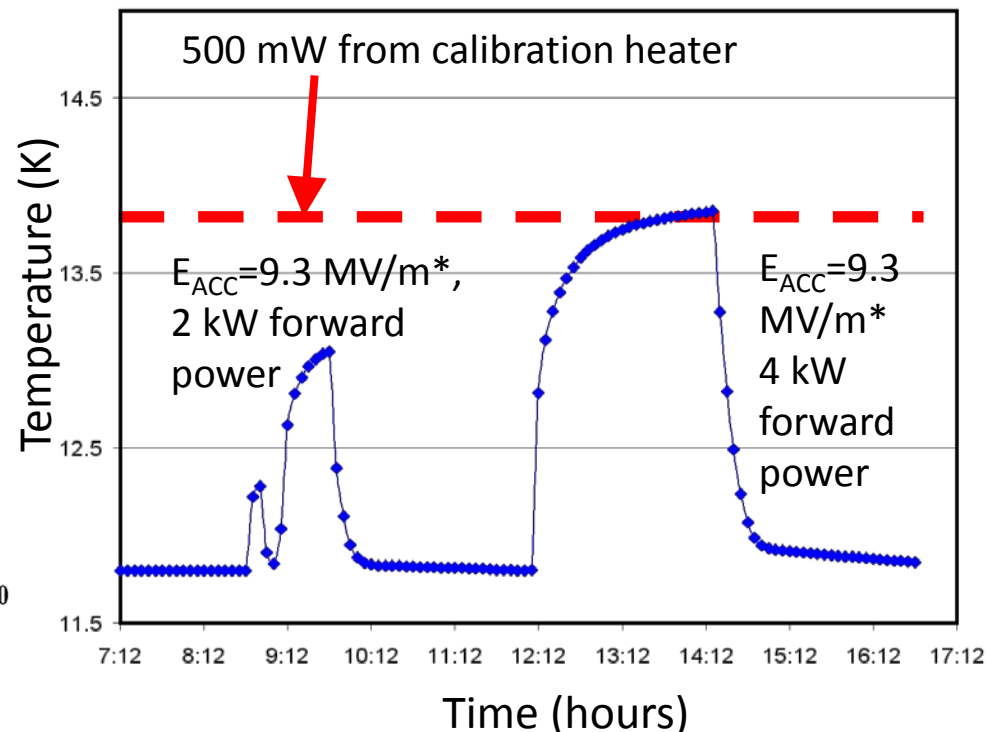


Measurements using LakeShore Si Diodes (CU bobin-style), mounted fixed with stainless hose clamps and Indium

Relative sensitivity in ANL testing +/- 2 mK below 10 K



\* $E_{ACC}=8.3$  MV/m is planned ATLAS field level ( $I_{eff}=\beta\lambda$ )



\* $E_{ACC}=9.3$  MV/m is ~10% above planned ATLAS field level

# PXIE HWR Coupler





# Basic Considerations for a New Power Coupler

## 1. Power handling capability

- Starting point was existing ATLAS coupler, 4 kW at 72 MHz (full reflection, overcoupled/weakly coupled)
- PXIE, 10 kW full reflection at 162.5 MHz

## 2. Little/No adverse impact on cavity RF performance

- Cleanliness
- Static/dynamic heat losses to He

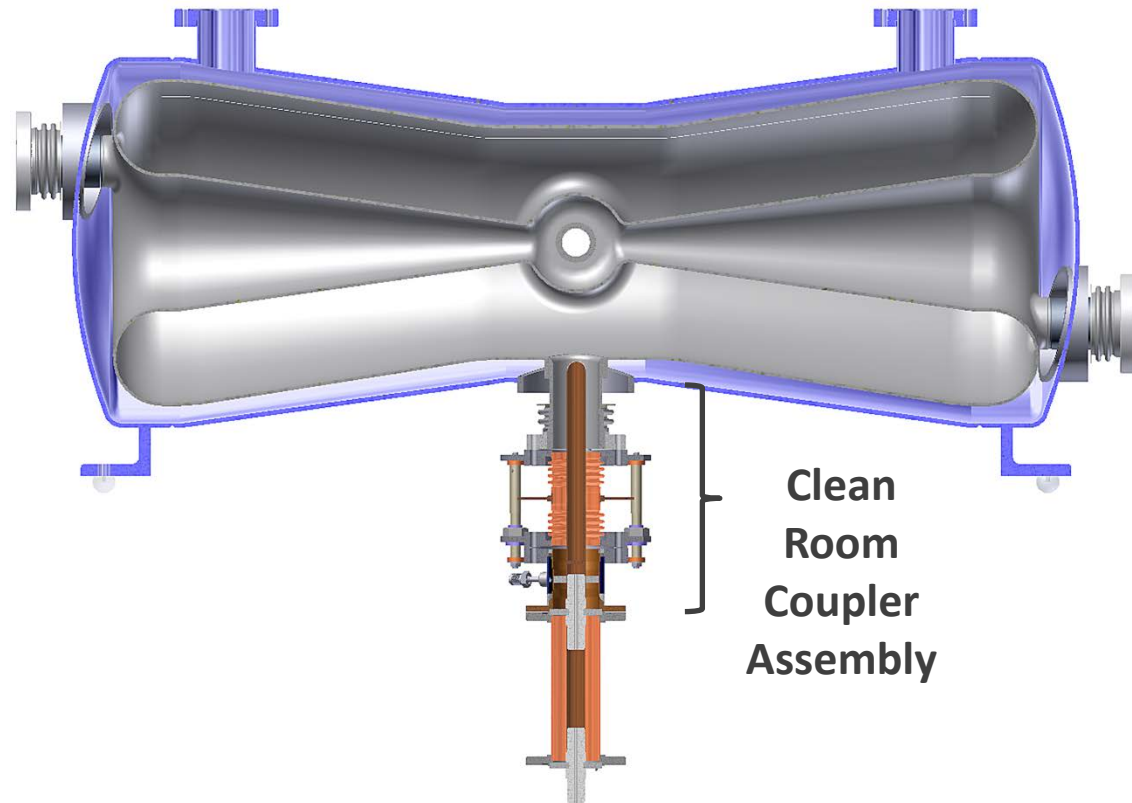
## 3. Suitability for various operating modes

- Low-to-high beam current, overcoupled on resonance, unmatched
- Primary method of phase stabilization
- RF conditioning of cavity multipacting, high-power pulse conditioning



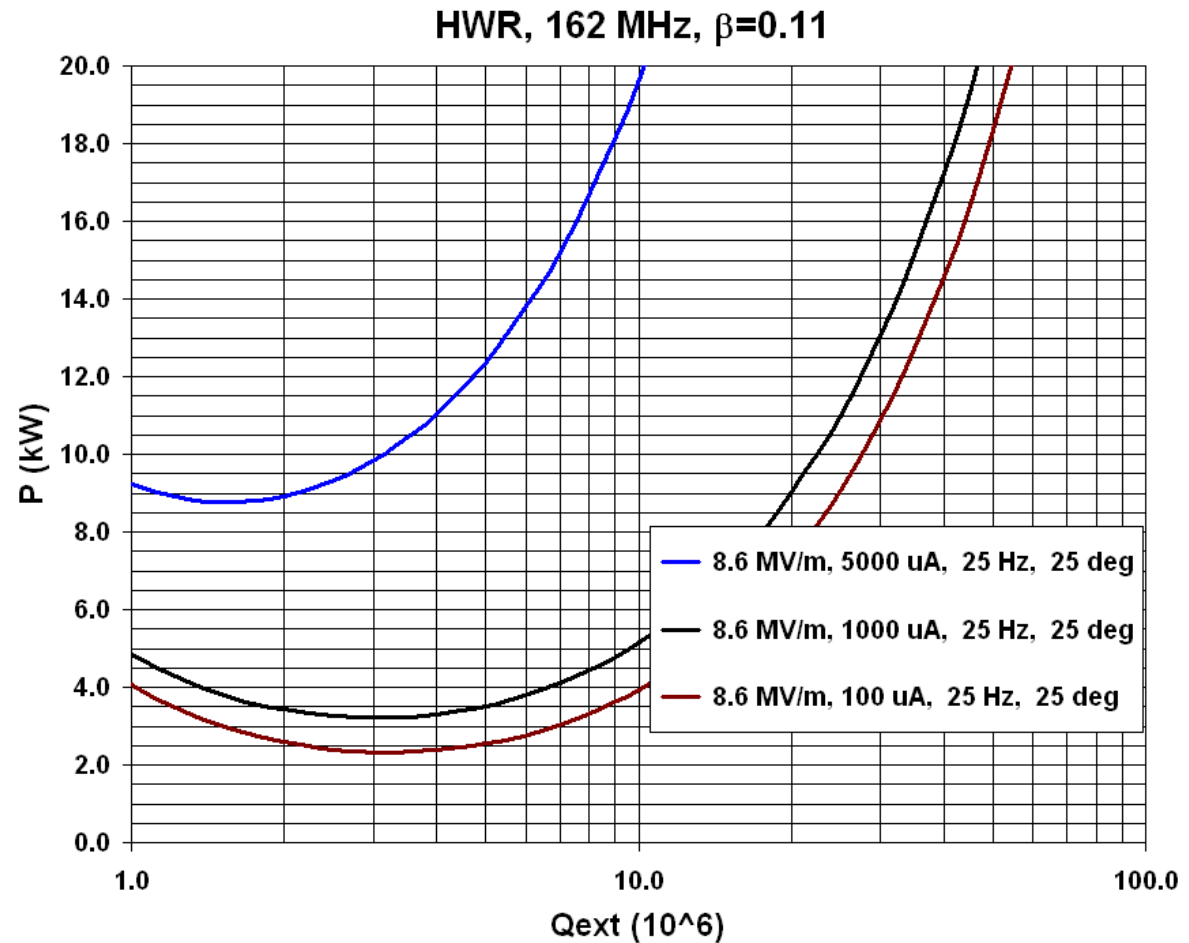
# Power Coupler for $\beta=0.11$ , 162.5 MHz SC Half-wave Cavity for PXIE

Half section through cavity and coupler, with the beam axis perpendicular to the page: The clean portion of the coupler mounts to a 'standard' 50 mm diameter coupling port oriented at 90° to the beam axis.



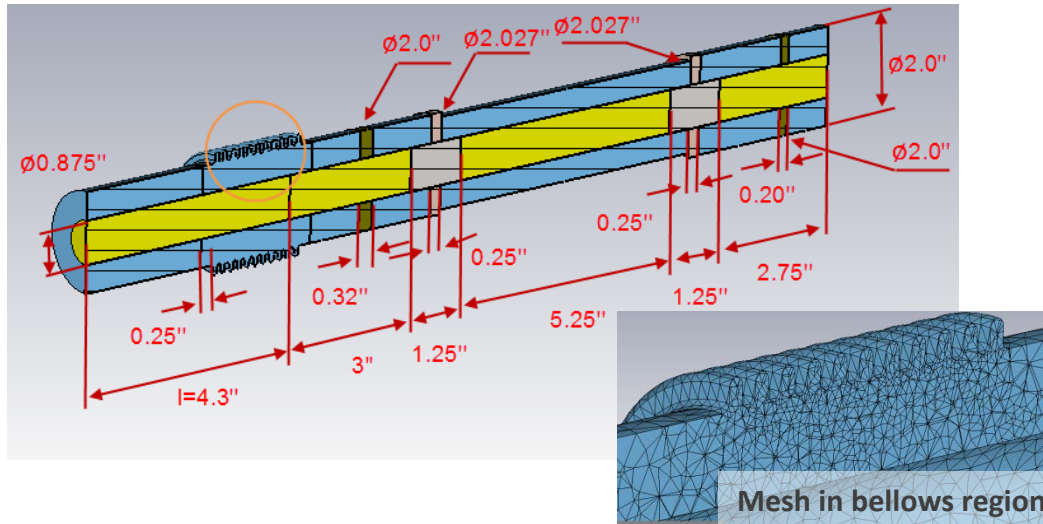
# PXIE Coupler RF power requirements

- PXIE operations at 1 mA beam current require 3 kW forward power, mostly for rf phase control
- The option to operate at higher beam currents (5 mA) without the need for a new coupler is desirable

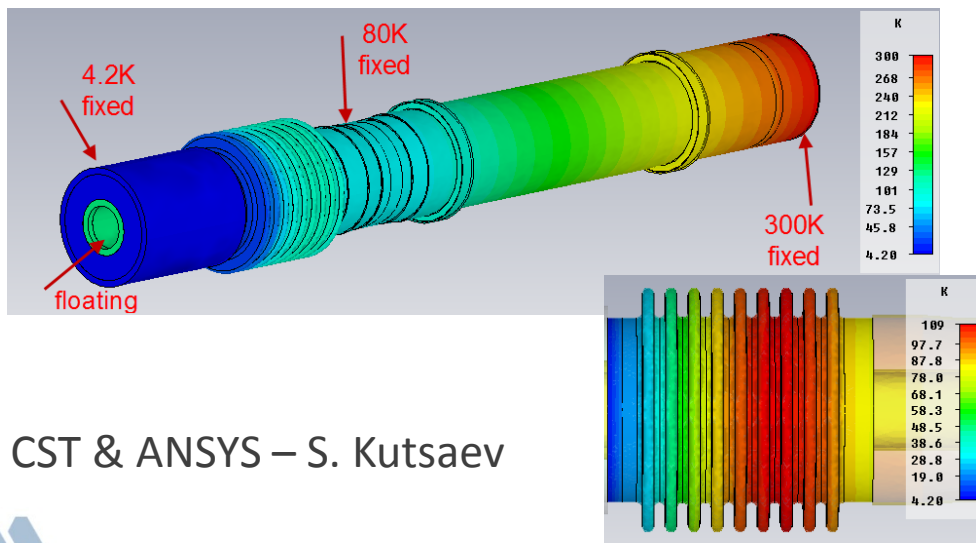


# Initial RF Simulations

CST STUDIO 2011 simulations using realistic materials and temperature dependent electrical and thermal conductivities



**RF & Mechanical Models:** Scaled up dimensions from the ATLAS coupler to a 50 mm outer conductor, matching the full inside diameter of standard ANL cavity coupling port. The bellows was shortened because ability to critically couple was not considered important.



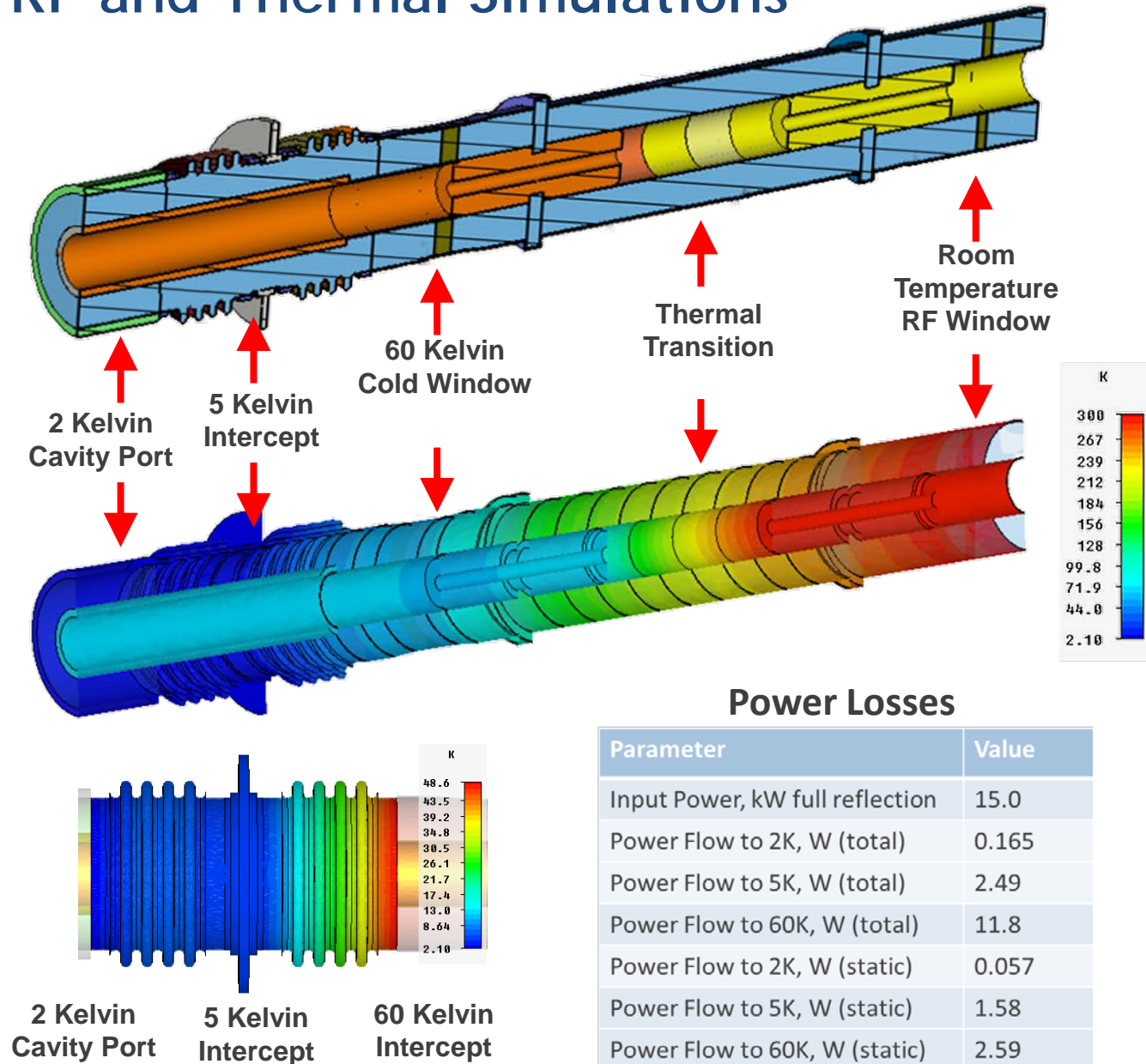
With 15 kW forward power, using frequency domain solver with tetrahedral mesh:

Some heating, approximately 30 K, predicted in the bellows

CST & ANSYS – S. Kutsaev

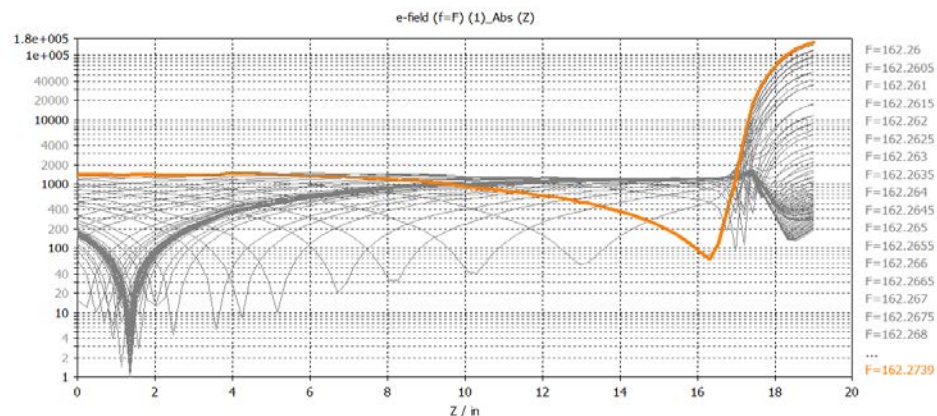
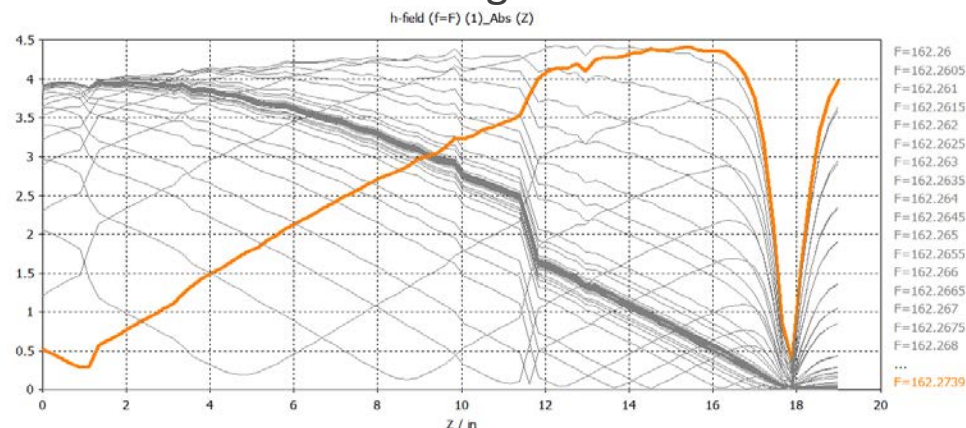
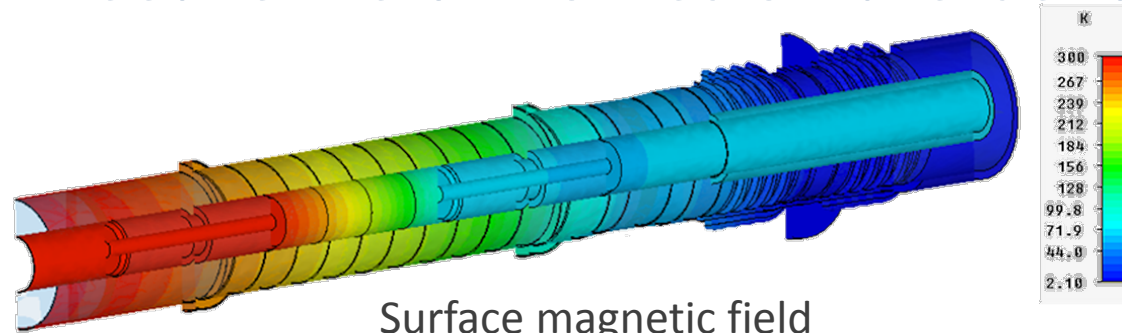
# Final Coupler RF and Thermal Simulations

- Simulation for 15 kW forward power in fully matched condition
- No 'hot spot' along bellows, *i.e.*, temperature changes monotonically from 2 K to 60 K
- Total (static + dynamic) power into 2 K is only  $\frac{1}{4}$  Watt





# Magnetic and Electric Field Profiles on the Central Conductor



- On resonance (orange curves) the magnetic field rises to a maximum toward the cavity port; electric field minimum
- Off resonance the peak fields can be anywhere along the coupler
- The peak electric field on the coupler tip is one order lower than the peak field on the cavity (fields here are normalized to 0.5 W forward power)

# Heat Transfer Through Ceramic Window

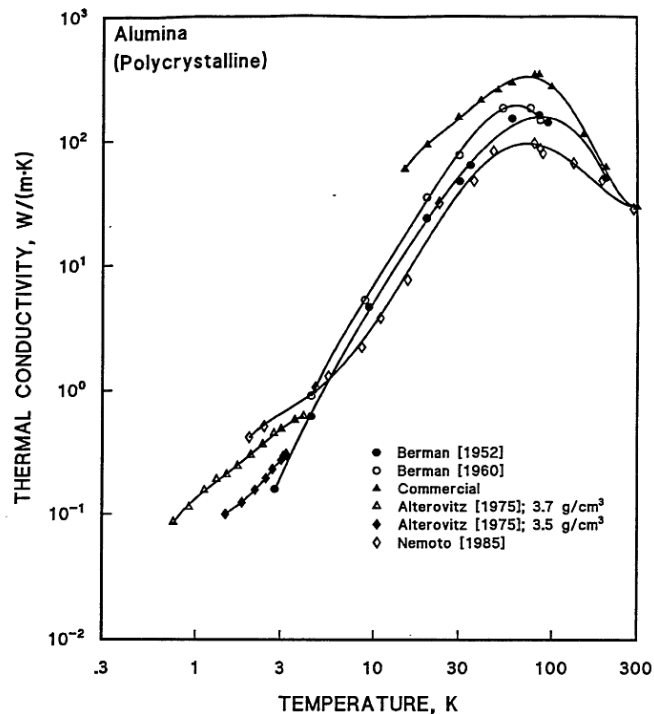
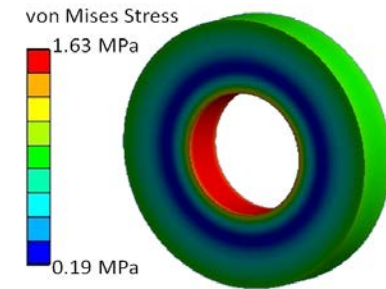
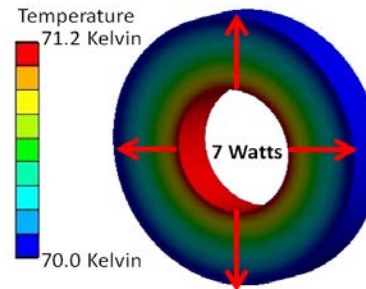


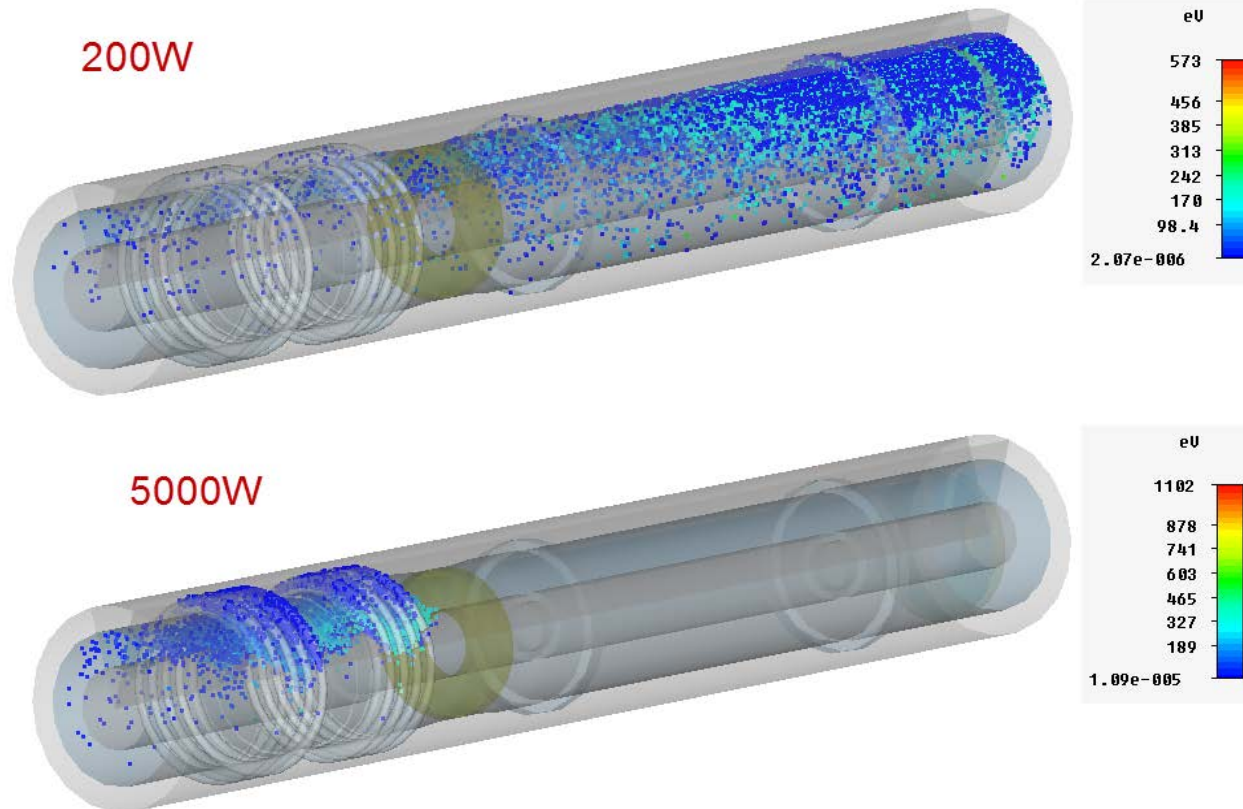
Figure 2.4.2. Thermal conductivity of polycrystalline  $\text{Al}_2\text{O}_3$  vs. temperature. Data from Berman [1952], Berman et al. [1960], Alterovitz et al. [1975], Nemoto et al. [1985], and Touloukian et al. [1970; citations therein].



Warm and cold windows are fabricated from the 97.6% WESGO Al 300 alumina. ANSYS model simulations indicate that stresses are about 100 times lower than the values (120-220 MPa) where cyclic fatigue loading has been shown to be important. However, cycling directly into  $\text{LN}_2$  could produce stresses this high.

# Multipacting Simulations in CST Particle Studio

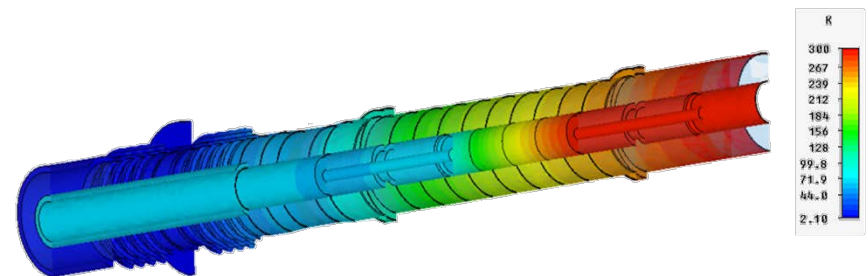
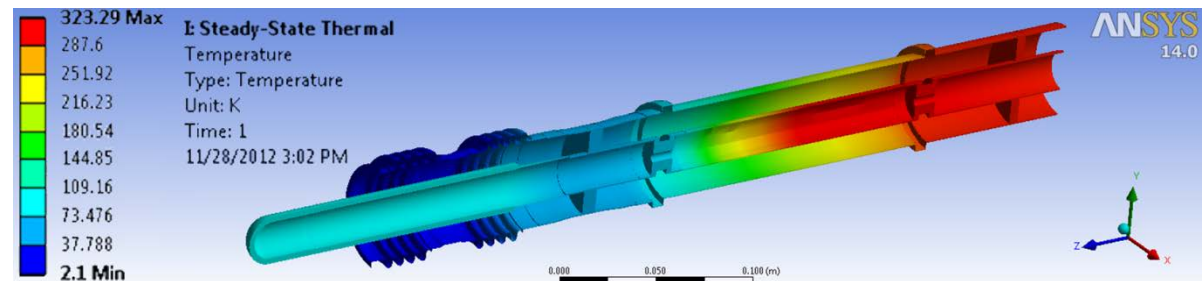
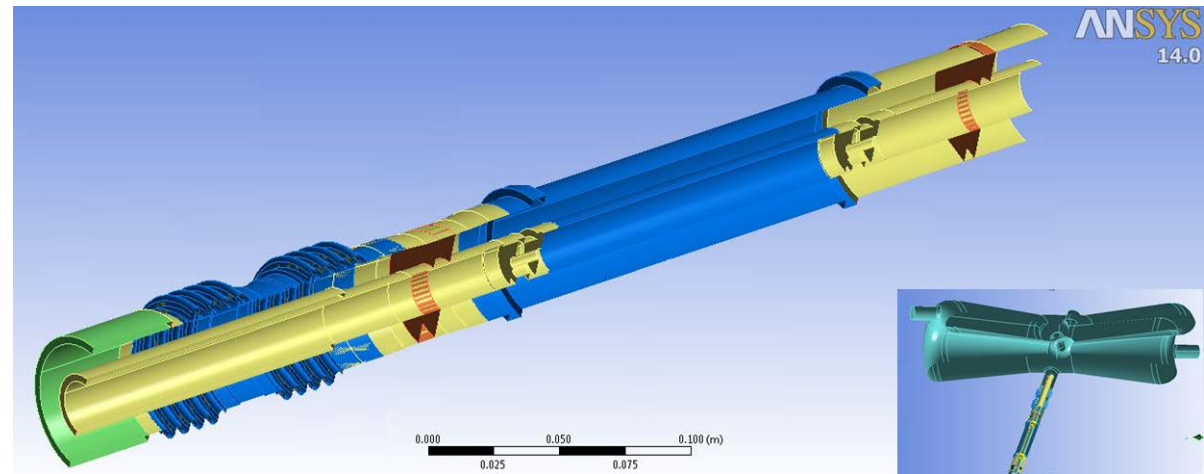
- At this frequency resonant particle growth predicted to begin at power levels of 50 W, reaches maximum at 500 W and disappears at 2.5 W
- Simulations show resonance condition can be interrupted by applying a bias voltage to the central conductor of 300 W



# Comparison of ANSYS and CST

## 15 kW Forward Power in Matched Condition

- CST MWS 11.0 required breaking the coupler into many pieces each with material properties at a given temperature
- ANSYS uses continuous electrical and thermal conductivities, heat capacities
- No real difference in RF losses or heating between the two simulations

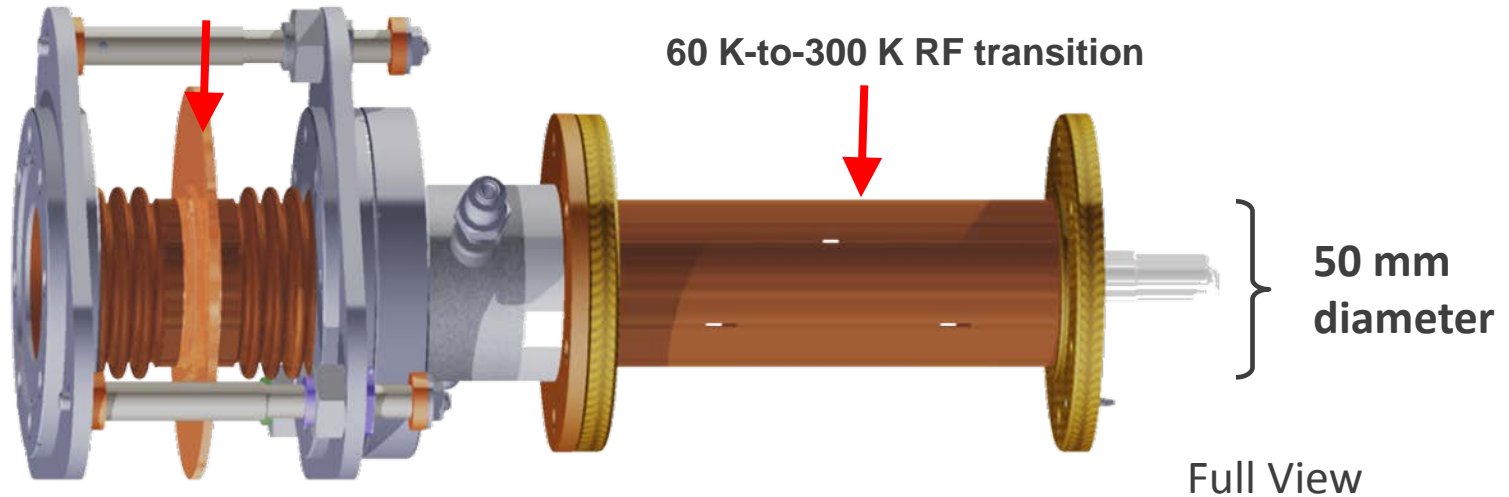




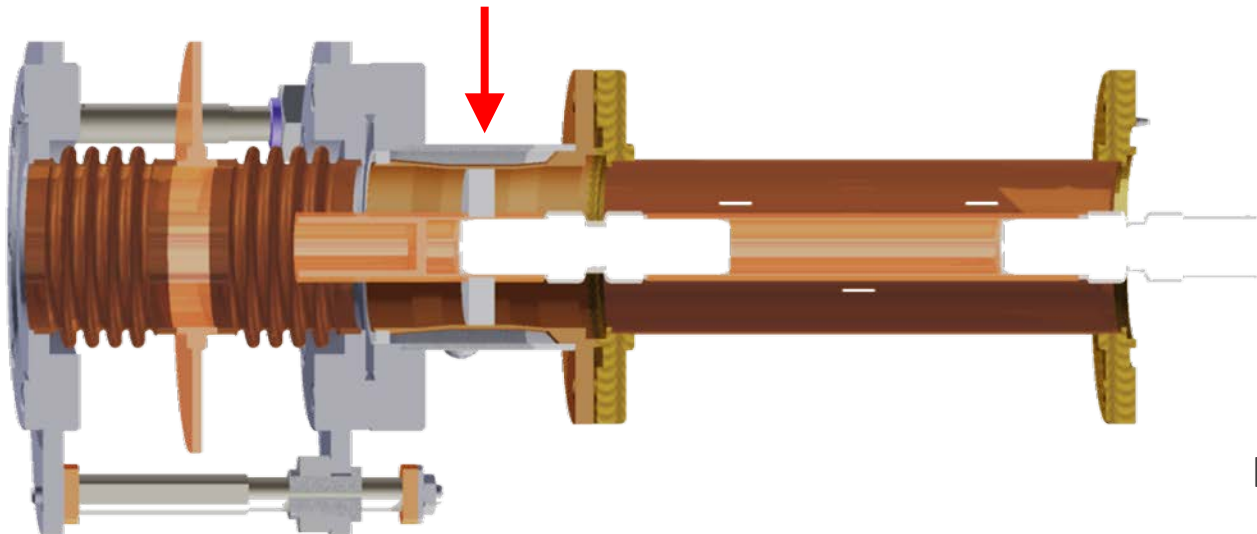
# PXIE Power Coupler Mechanical Model

2 K-to-60 K, variable bellows w/ 5 K intercept

60 K-to-300 K RF transition



60 K RF window



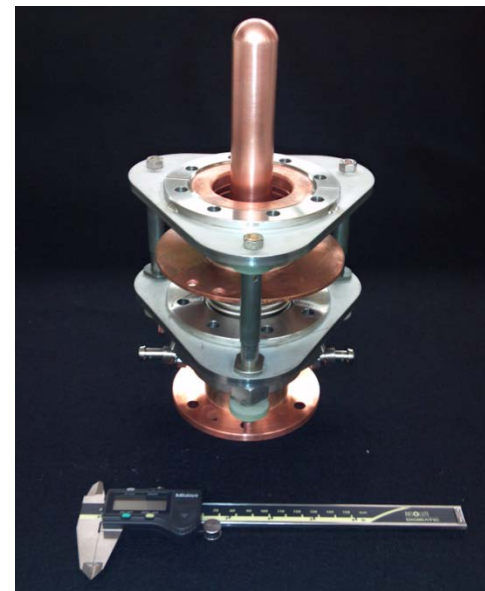


# Prototype Fabrication



- Pair of cold window braze assemblies fabricated by MPF Inc.
  - Capability to braze large ceramics (40-50 mm diameter) into copper developed together with ANL
  - MPF now a supplier to BNL and FRIB/MSU
- Pair of bellows assemblies built by ANL
  - 15-20  $\mu\text{m}$  Cu plating at Saporito; techniques for this developed by ANL personnel and transferred to FRIB

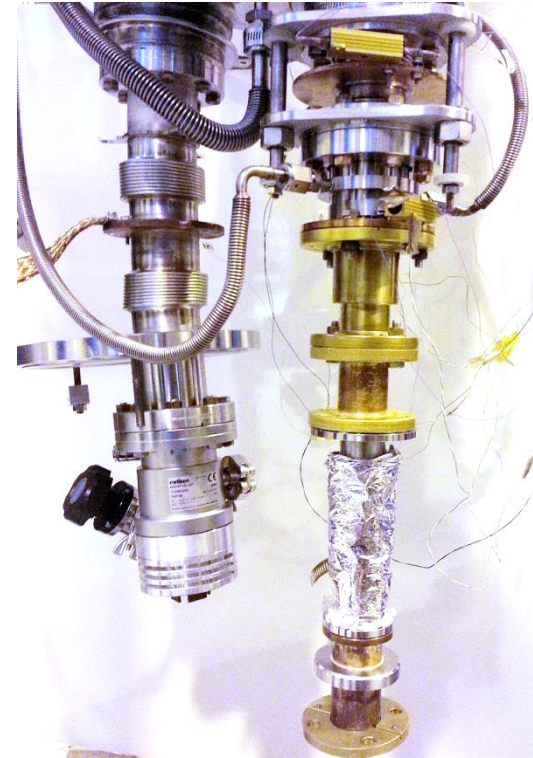
Cold window, bellows and antenna



# Initial RF Test of PXIE Cold Window and Bellows

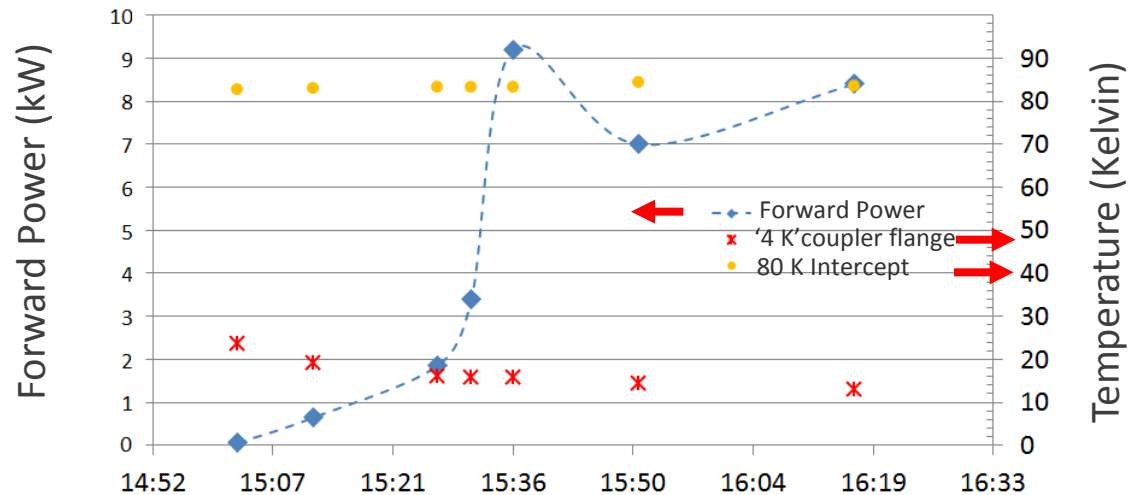
Initial cold testing with 72 MHz QWR at 4 K (off resonance)

- ‘10 kW’ 162.5 MHz RF supply
- Through a 75 kW circulator
- 4 K cavity/coupler flange fitted with Si diode thermometers and a 0-50 Watt heater
- Bellows intercept ‘floating’ thermally; fitted with Si diodes and a heater
- Cold window cooled with 30 SCFH flowing LN<sub>2</sub> and fitted with Si diodes and a heater
- Thermal transition fitted with a Si diode
- Cavity and insulating vacuum pressure measured

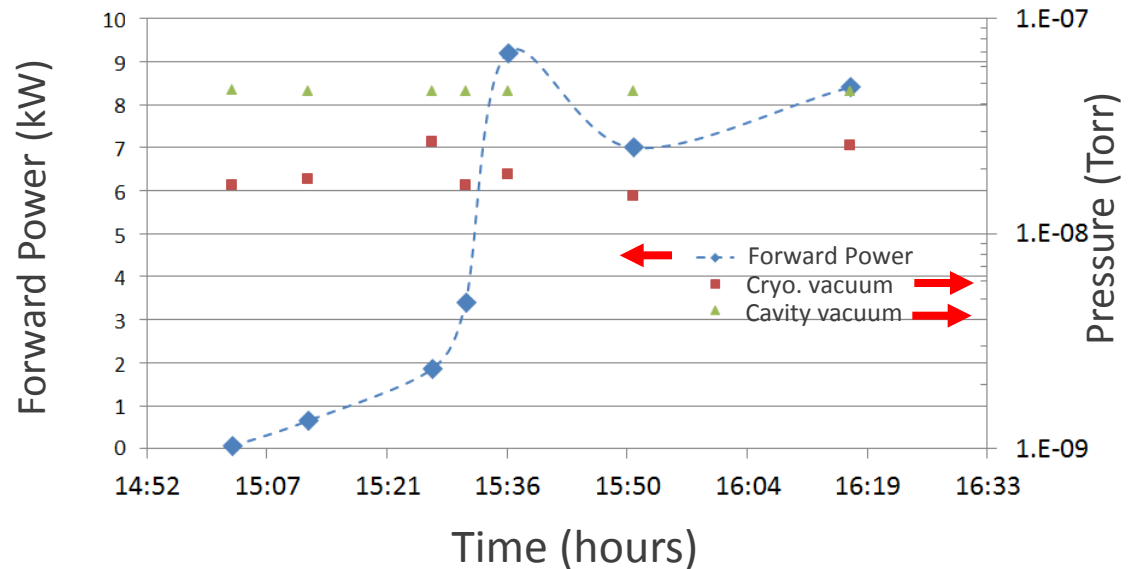


# Thermometry and Vacuum Pressure During Short Test up to 9 kW Forward Power

Top panel – cavity flange still cooling from initial cool down, 80 K intercept shows no measureable heating

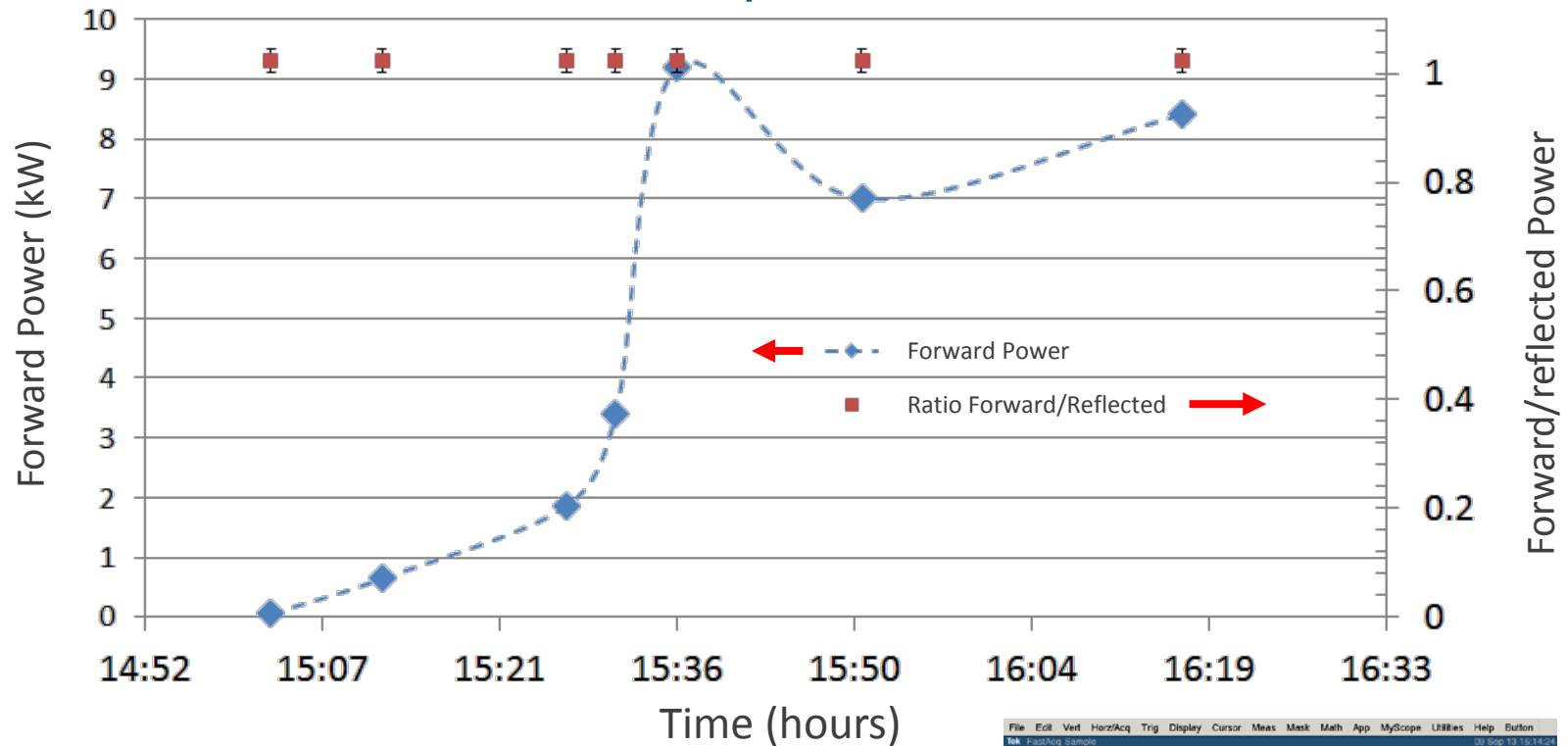


Bottom panel - No evidence of conditioning or multipacting from cavity or cryomodule vacuum gauges

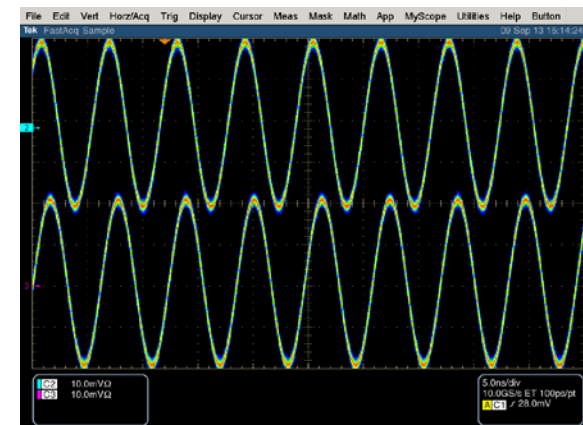


# Forward and Reflected Power in Coupler Drive Line

## Measured from Dual-directional Coupler Just After Circulator Out (Port 2)



Right panel – Forward and reflected power just after the circulator output measured continuously on digital scope; ***other than for a few seconds during power ramp, no power absorbed in the cavity coupler downstream of directional coupler***



- **Coupler has no major flaws; multipacting is not a severe problem**
- **First tests provide high confidence that the coupler will provide several kW RF power to HWR with little problem**
- **Need more testing to establish high confidence above ~5 kW, though first tests results at high power are fine**



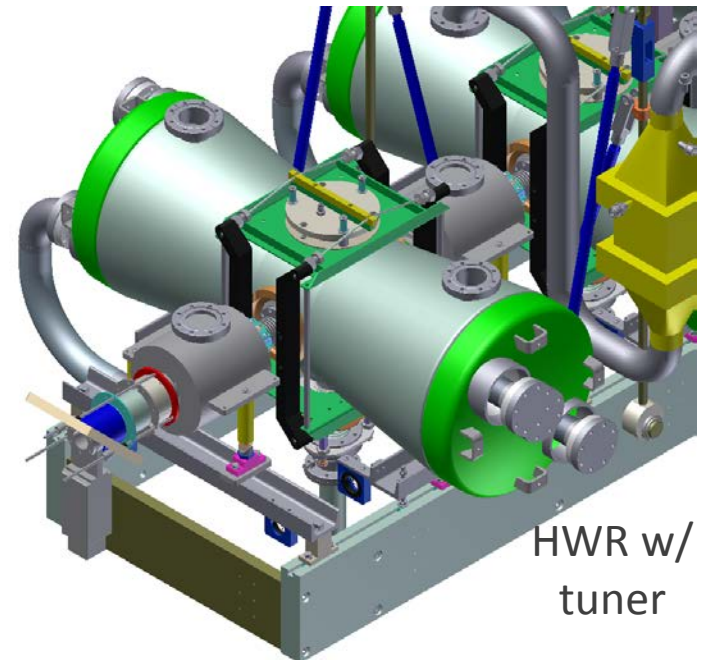


# PXIE HWR SLOW TUNER

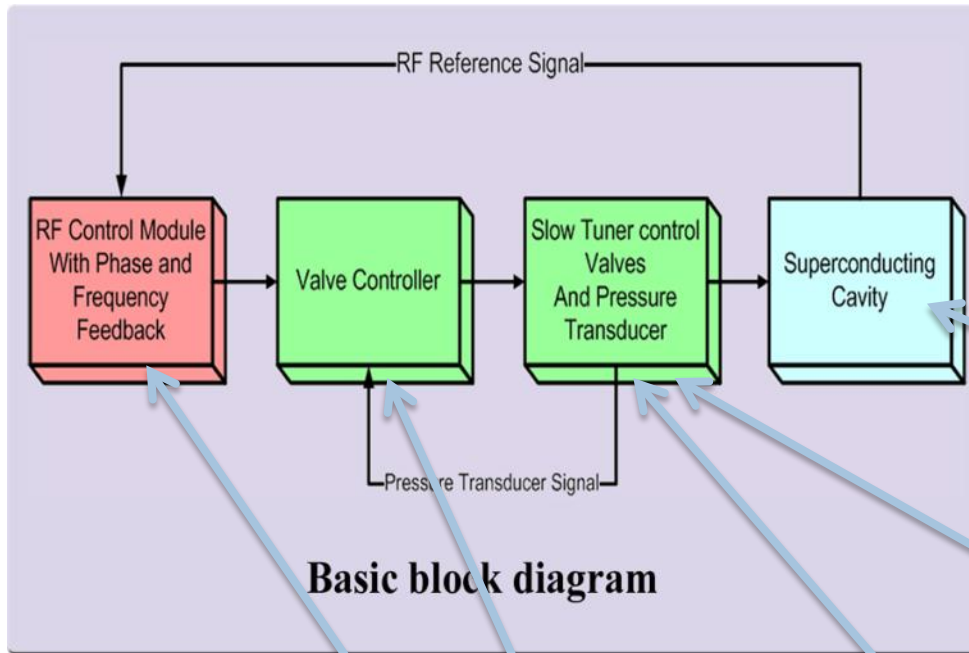


# ANL Pneumatic Slow Tuner

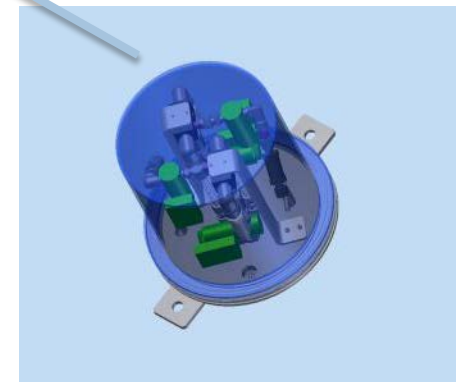
- No hysteresis
- No backlash
- No vibration; does not excite microphonics
- Operates in a continuous feedback mode
- Bellows is the only moving part
- Operates at 80 K <200 mW heat leak into 4.5K
- 109 MHz quarter wave cavity 32kHz tuning window 1000 kHz / sec slew rate
- Over  $5 \times 10^6$  integrated operating hours with only 77.82 hours of downtime (downtime records are from 1994 to 2011)



# Slow Tuner Block Diagram and Components



97 MHz cavity unit

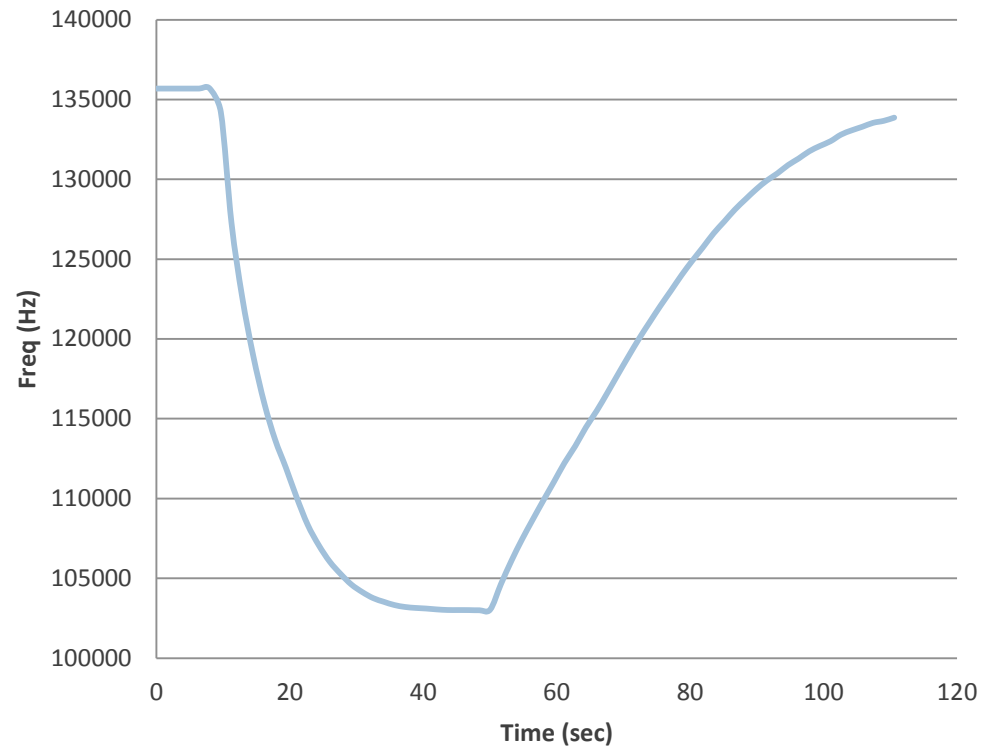


109 MHz cavity unit

# Example of the Tuning Range on a 109 MHz Cavity

Cavity #7 9/17/2009

- 30 kHz tuning range
- Approximately 1 kHz slew rate in the pressure state
- Approximately 700 Hz slew rate in the vacuum state



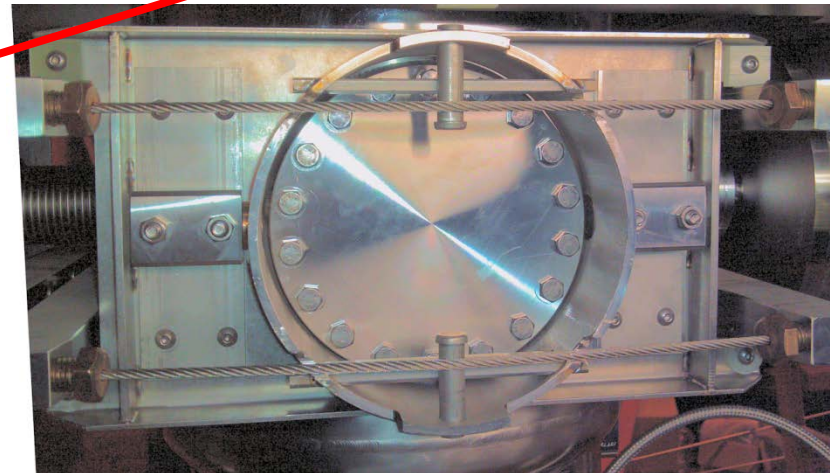
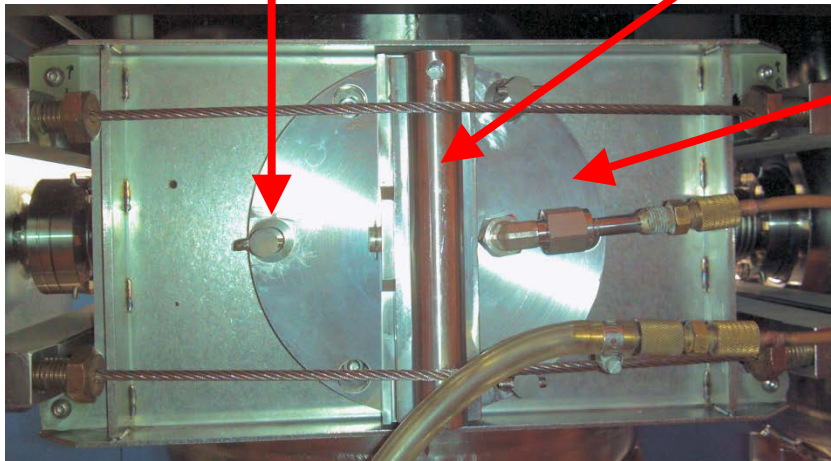
# PXIE Slow Tuner Will be Based on Recent Design for 72 MHz QWR

- Development was needed due to requirement for a large compressive force of 20 kN, in turn due to compliance with ASME pressure code
  - considerable increase in stiffness of the guide mechanism and low friction materials
  - note, only 10 kN tuning force needed for PXIE HWR
- Operation from 17-80 PSIA for 20 kHz tuner range for  $f_0=72.75$  MHz
- ***We need a full test on a HWR before going to production***

Guide post & bushing  
(Dichronited stainless and  
brass)

'Rocker arm' to equalize  
rope tension

½" thick stainless plate to  
resist deformation





# SC Solenoid

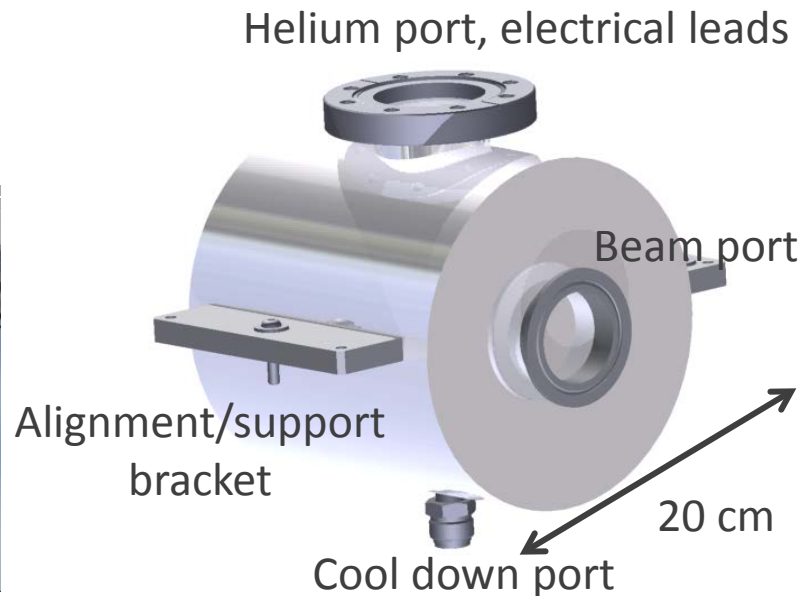
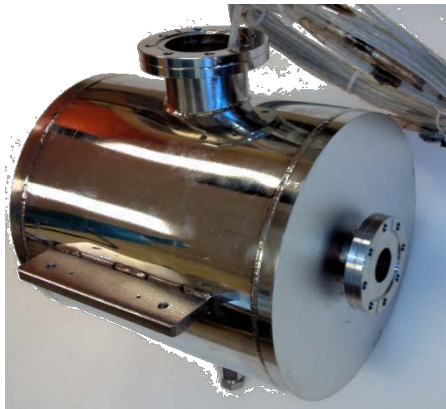


# Proposed Magnet Exceeds PXIE Needs:

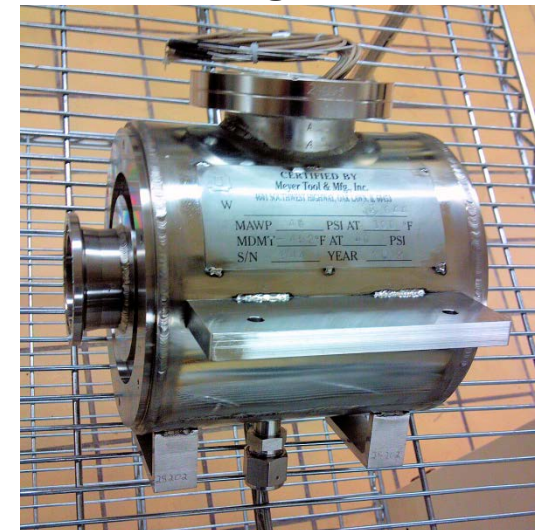
## 6 Tesla, 35 mm bore, 0.75 T-m SC solenoid

Wire:	NbTi
Operating temperature:	1.8-4.6 K
Magnetic field integral:	$\int B_z dz = 0.75 \text{ T-m}$
Operating current:	82 amps
Inductance:	1 Henry
Shielding:	$B < 100 \text{ G}; z \geq 15 \text{ cm}$
Steering coils:	0.2 T, 30 T-mm
Bore diameter:	35 mm

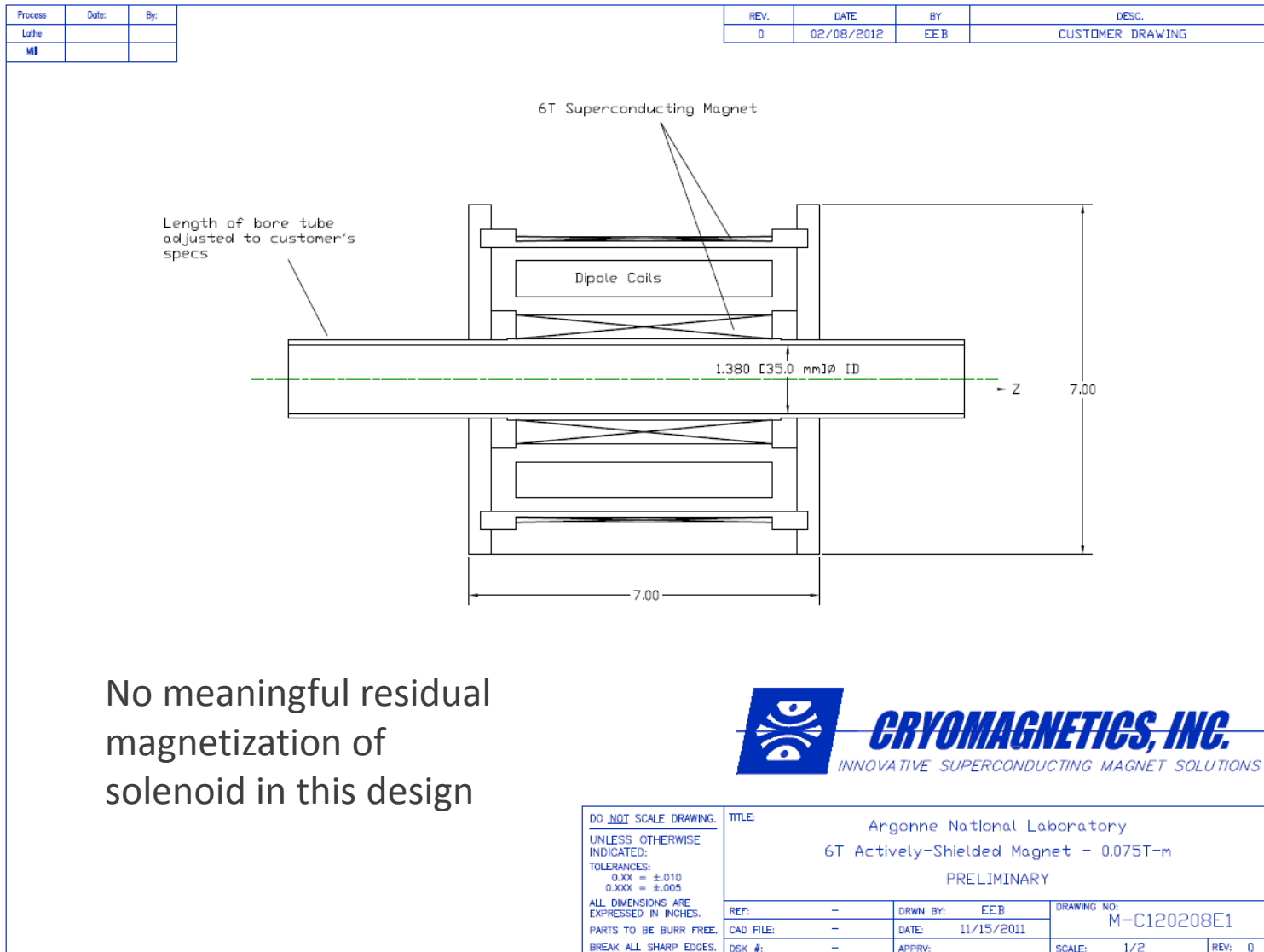
ATLAS Intensity  
Upgrade Magnet



PXIE Prototype  
Magnet



# Cryomagnetics 0.75 T-m SC solenoid



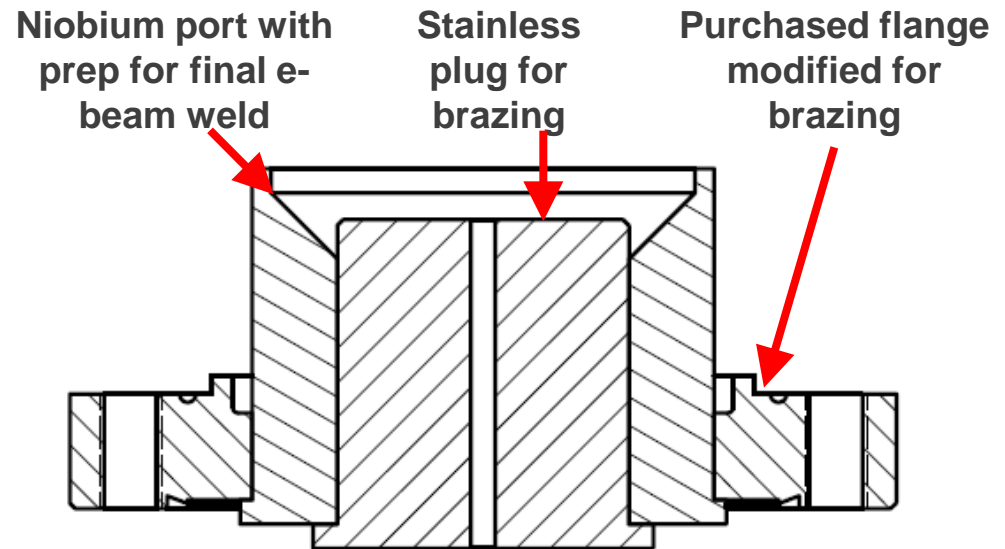
# ‘Value Engineering’ for PXIE



# Coupling Ports (5 per cavity @ 50 mm ID) To Be Fabricated from Pre-machined Flanges



Left panel – A precisely machined thick-wall niobium tube is brazed into a stainless ‘donut’ and then finish machined into a CF flange



Right panel – A purchased CF flange is modified (by any ‘non-high tech’ machine shop) and brazed into an almost finished niobium port; a prototype has been brazed, thermal cycled, leak checked and pull tested