Argonne NATIONAL LABORATORY

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HWR Cryomodule Development

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U.S. DEPARTMENT OF ENERGY

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  - Alignment system
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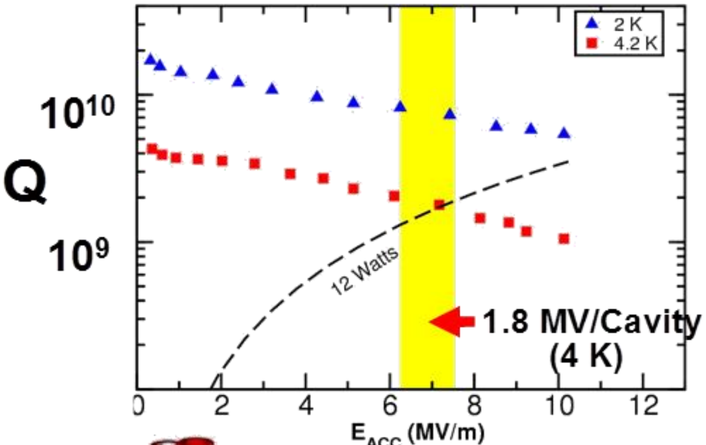
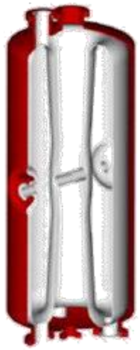
Half Wave β_{OPT}=0.11 Resonators for PXIE

- Only one cryomodule of 162.5 MHz HWRs is required for acceleration from 2.1 MeV to 10 MeV
- Total available accelerating voltage in the HWR CM is 1.7 MV×8=13.6 MV
  - First 2-3 accelerating periods - just 1 MV
  - Significant margin in available voltage
- Can be realized in a reasonable length of the cryomodule below 6 meters
  - Comparable with the ATLAS cryomodules built at ANL Physics Division

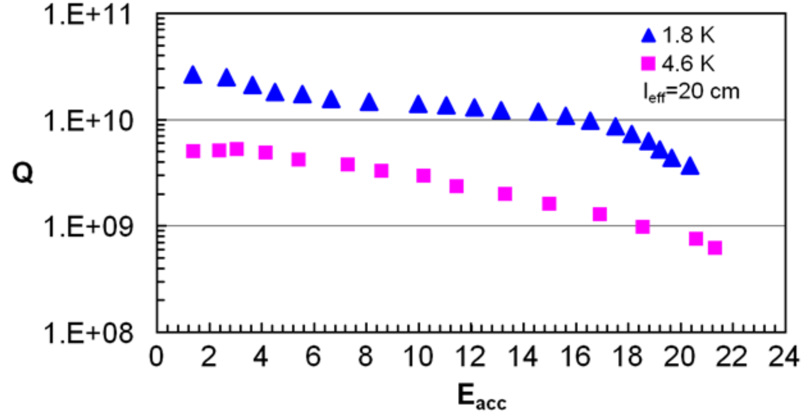
Recent ANL Experience with QWRs and HWR

- 170 MHz HWR (beta=0.26) was built and tested in 2004
- The first conical QWR was designed, built and tested in 2011 with phenomenal results





β=0.25 HWR, f_0=172.5 MHz

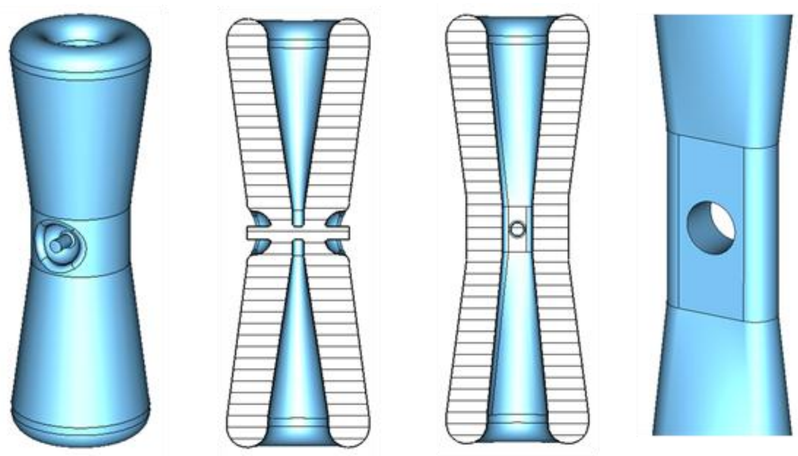


- 72 MHz QWR
- EP after all mechanical work complete
- 4.4 MV voltage
- Very low surface resistance 1- 3 nΩ

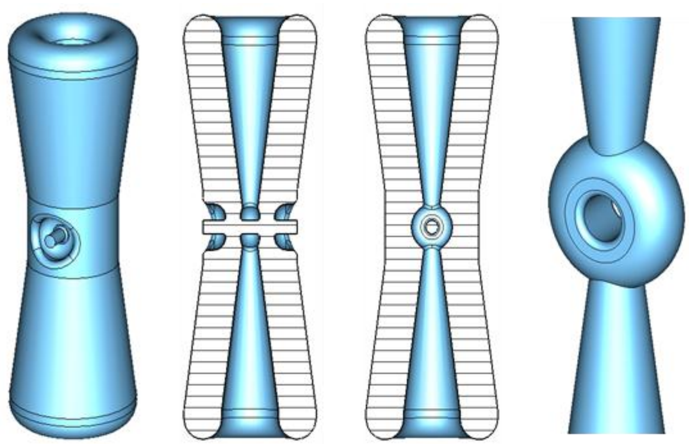
Cavity Design Concepts

- Design and technology have been significantly improved since 170 HWR was built in 2003-2004
  - Highly optimized EM design, reduced B_{PEAK} and E_{PEAK}
  - Conical inner and outer conductors to substantially reduce B_{PEAK}
- Two major geometries were investigated: "racetrack" and "donut"
  - Racetrack: quadrupole component of the E-field is minimized by elliptical aperture
  - Donut: quadrupole component of the E-field is minimized by donut shape

Racetrack

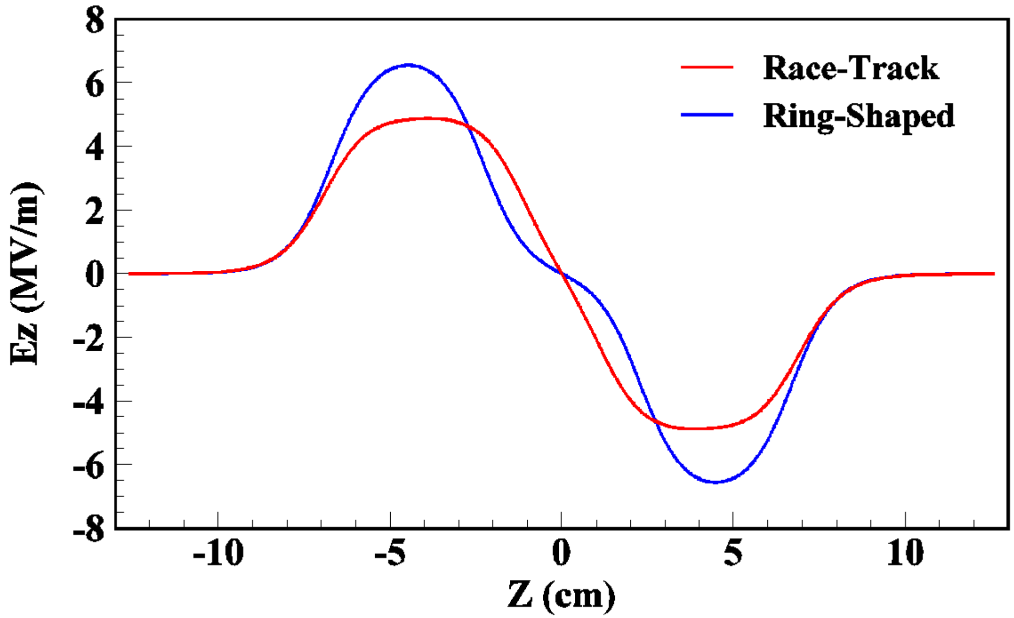


Donut



Cavity Shunt Impedance and Quality of Electric Field

- Race-track: requires elliptical aperture to correct quadrupole component of the electric field, low shunt impedance, Rsh/Q=195 Ω
- Donut (or ring-shaped): round aperture is fine, much lower residual quadrupole field, appreciably higher shunt impedance Rsh/Q=262 Ω

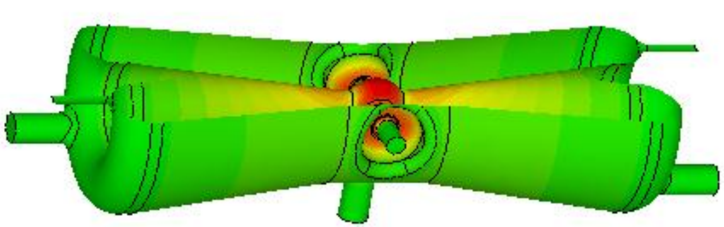


EM Optimization

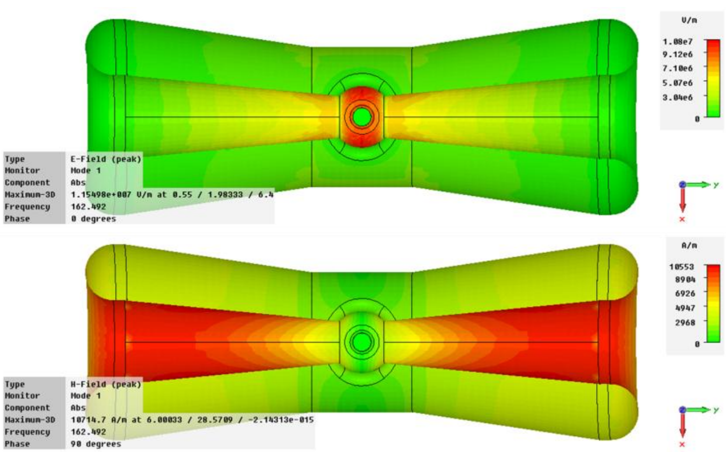
- Excellent EM properties. Recommended design voltage is 1.7 MV which corresponds to E_{PEAK} = 38 MV/m and B_{PEAK} =44 mT
- Quadrupole component of the electric field is negligible with donut shape

Freq MHz	β_{OPT}	L_{EFF} (cm)	E_{PEAK}/E_{PEAK}	B_{PEAK}/E_{PEAK} mT/[MV/m]	R/Q Ω	G Ω
162.5	0.112	20.7	4.6	5.4	262	48

With ports

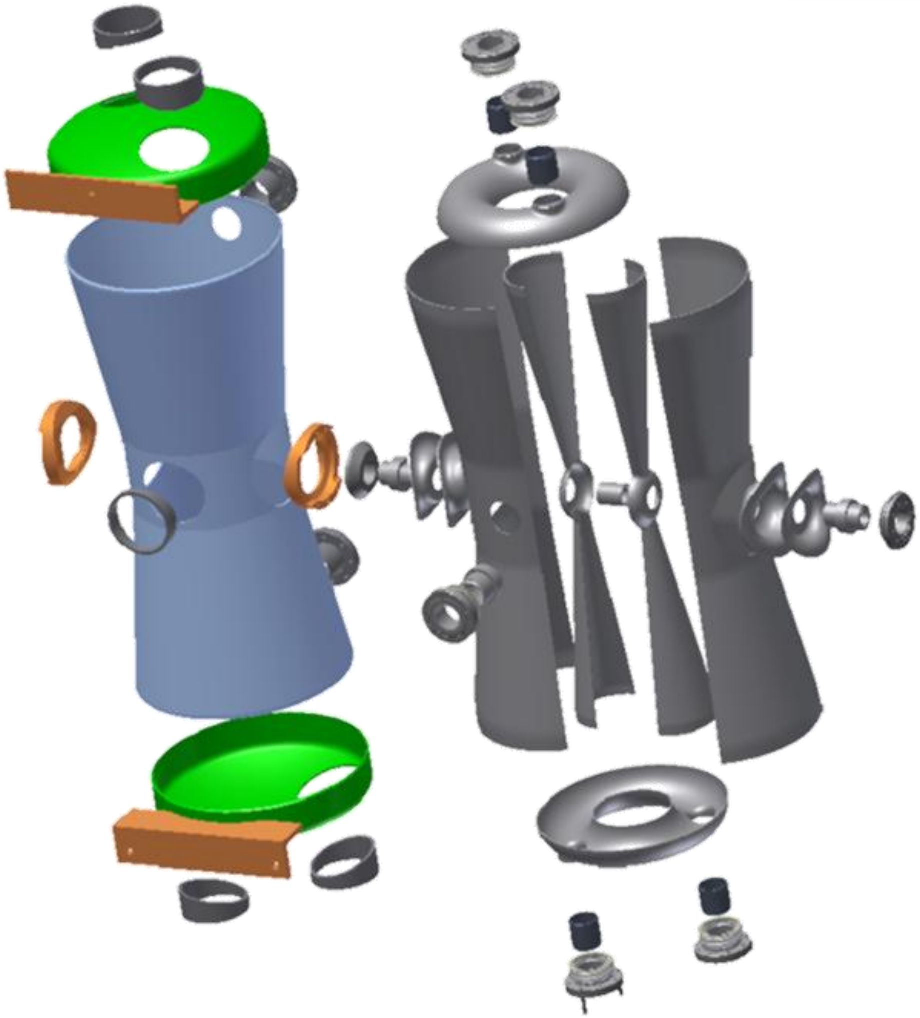


No ports



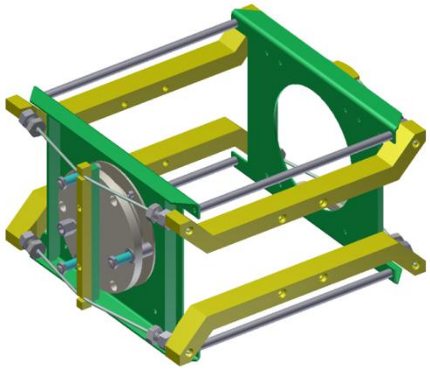
Mechanical Design

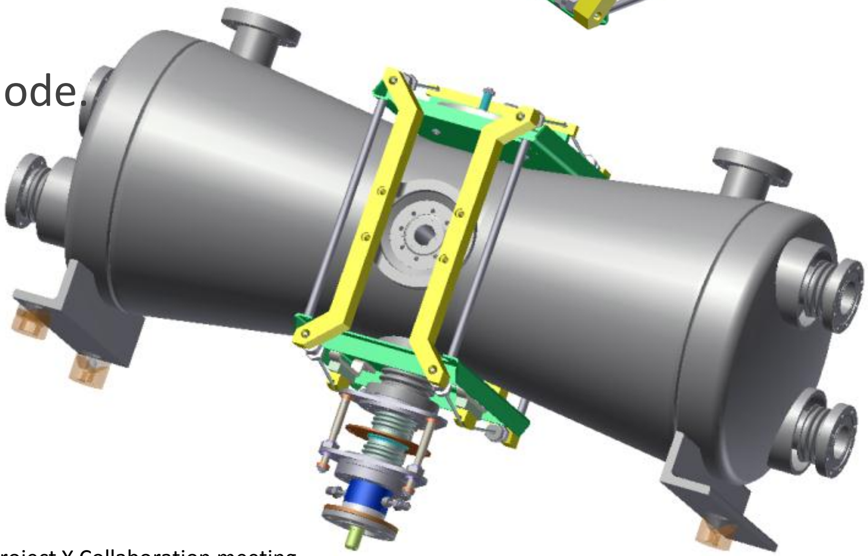
- Based on ANL-developed technologies
  - Die forming of Nb sheets
  - Wire EDM
  - EBW
  - Nb-SS transitions brazed through copper
  - SS He vessel



Resonator and Sub-Systems

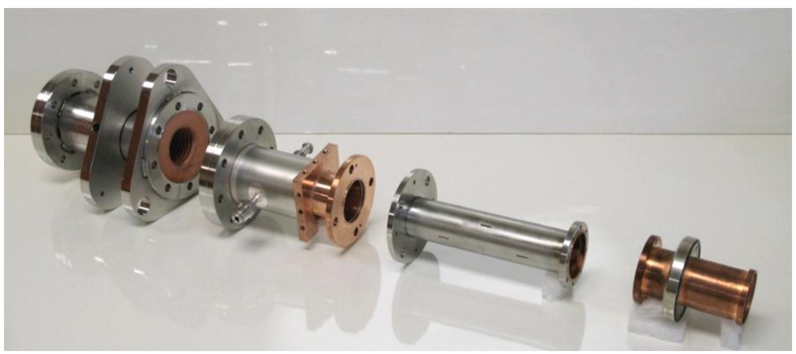
- Four 2-inch diameter ports for EP, 2 ports will be used for pumping and pick-up loops, one 2-inch port is for the high power coupler
  - Blending radius on toroid-port joints is 0.5” – significant development by AES to minimize B_{PEAK}
- 10-kW RF coupler, fast tuner is not required
  - 4-kW RF power will provide ~20σ at 1 mA (σ is the rms frequency noise)
- Pneumatic slow tuner
  - No hysteresis, backlash and vibration
  - Operates in a continuous feedback mode.
  - Bellows is the only moving part.
  - Large tuning range
  - Very reliable in operation at ATLAS (more than 25 years)

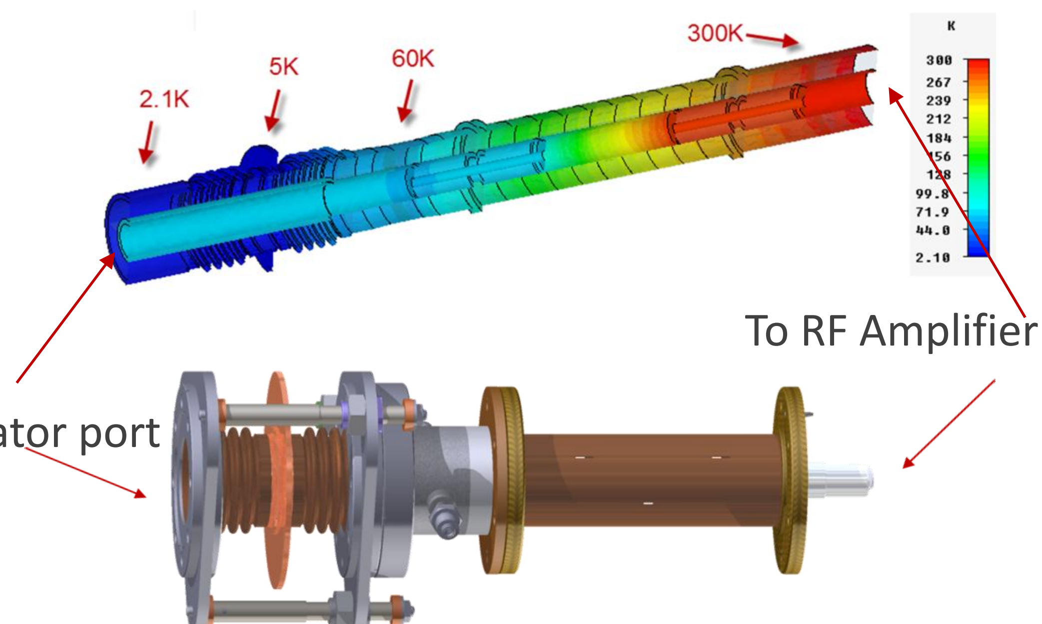




10-kW Adjustable Coupler

- Based on successful development of 4-kW input coupler (1-5/8” coax) for 72 MHz cavities
- Increased diameter of the outer conductor, 2”
- 1” stroke, 70K cooled alumina window, 4.6K intercept, heat load is minimized
- The protoype coupler is being fabricated

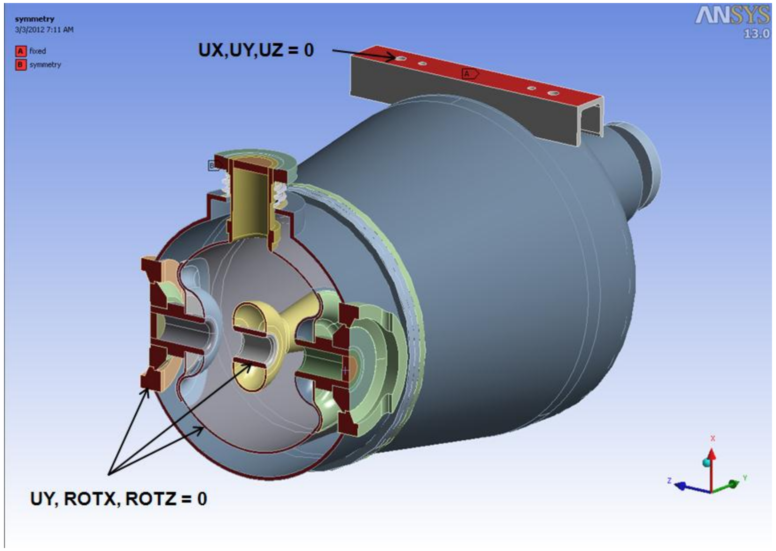


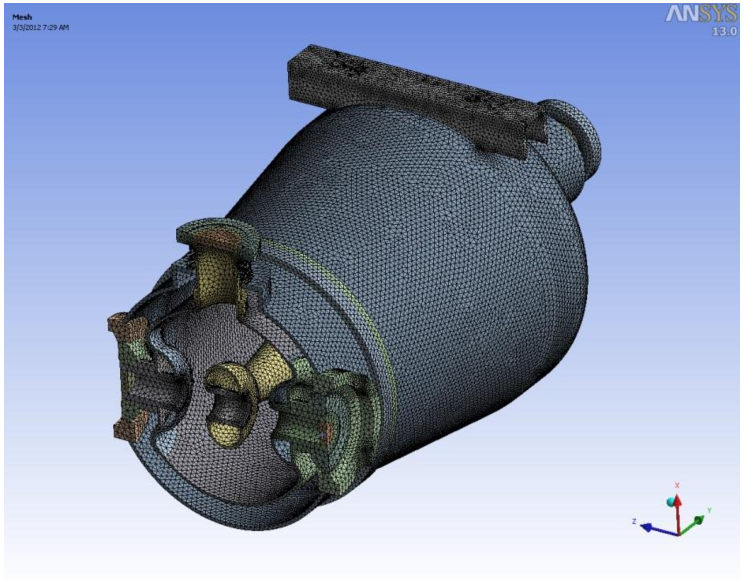


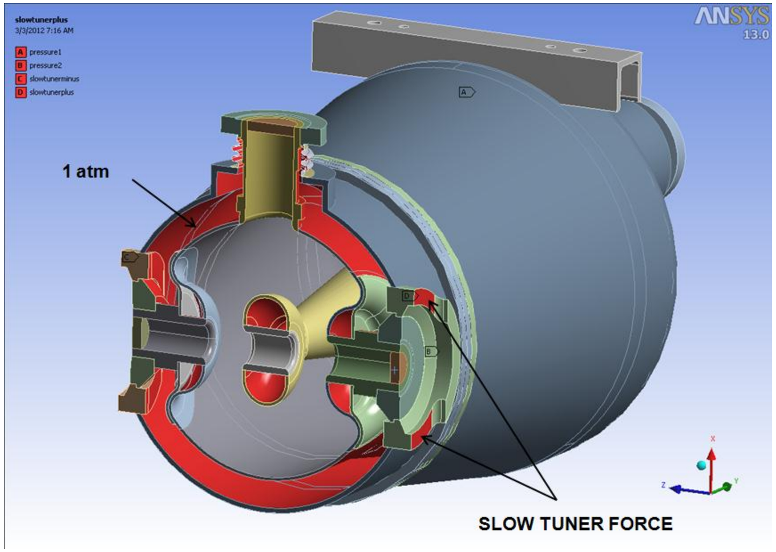
Engineering Analysis

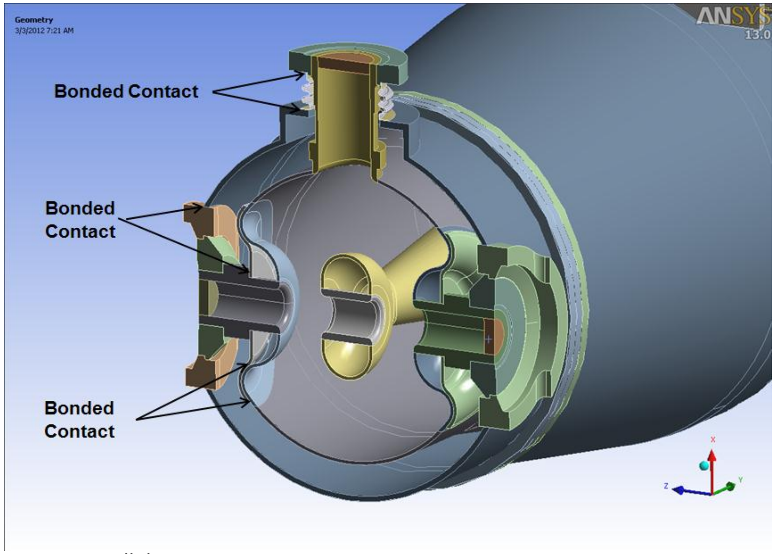
- 3D engineering model of the jacketed cavity
  - Nb thickness = 1/8”
  - S.S. Jacket Thickness = 3/16”, 1/8” is being analyzed
- Main goals of the analysis
  - Satisfy the design requirements set by ASME pressure vessel code
  - Satisfy ANL and FNAL pressure vessel safety requirements
  - Satisfy Functional Requirements Specifications to the HWRs developed by FNAL & ANL
  - Minimize df/dP
  - Optimize slow tuner

Boundary Conditions



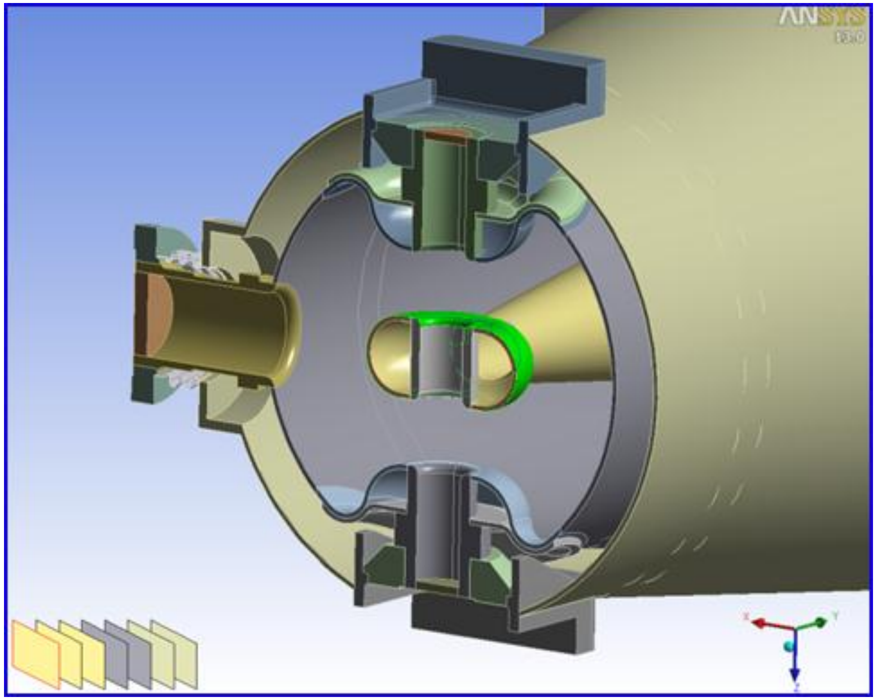


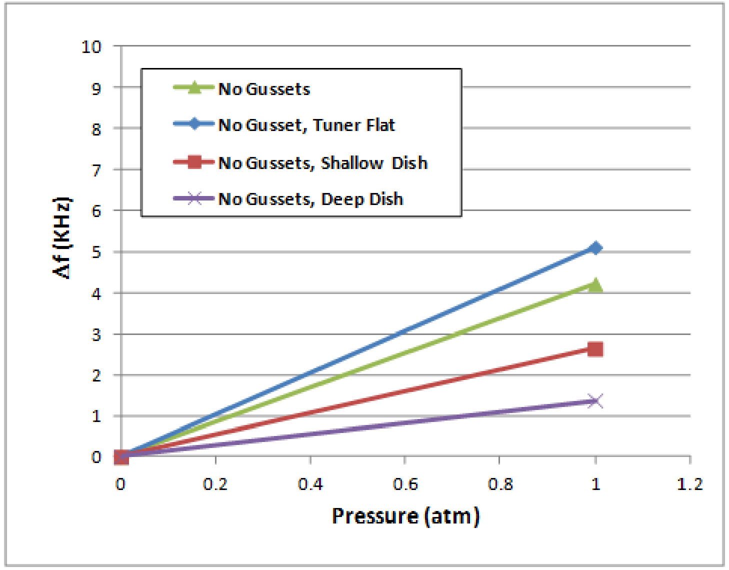


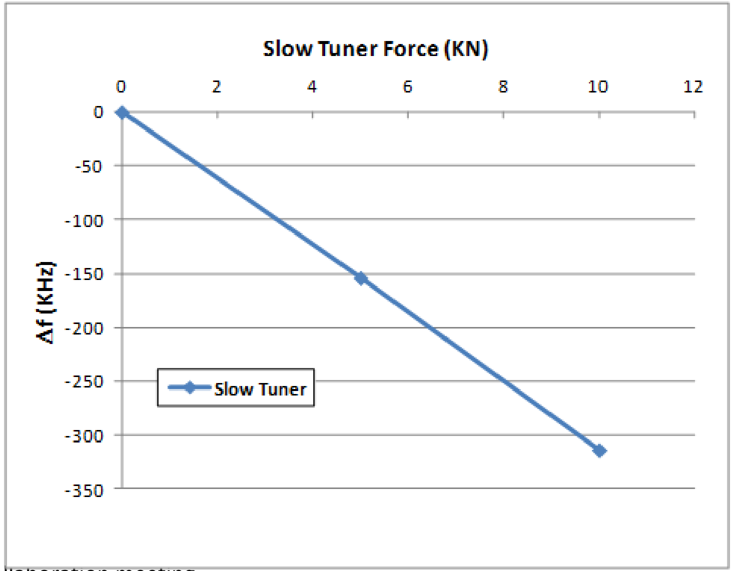


df/dP and Slow Tuner Studies

- Rectangular flanges for slow tuner
  - Gussets on toroid
  - “Flat” surface on the outer conductor
  - df/dP less than 4 kHz/atm for all cases
  - Slow tuner range is 300 kHz at 10 kN







Cryomodule Design Highlights

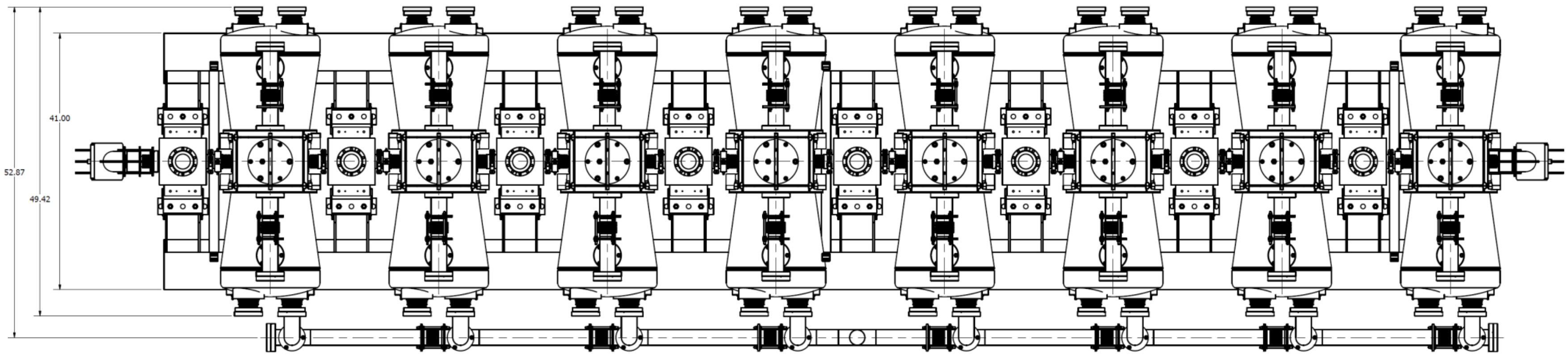
- In October 2011 we started with the cryomodule concept which included 9 cavities and 5 SC solenoids
- Beam physics and engineering integration have resulted in 8 cavities, 8 solenoids, 8 BPMs
- The first upstream element is a SC solenoid to mitigate vacuum transition from NC to SC linac
- 2K operation
- Relatively short cryomodule, 5.9 m
- Compact lattice: short focusing periods permit high accelerating voltages
- Compact SC solenoid
  - no-iron, return coils to reduce stray fields
  - H- and V-steering correctors
- Improved alignment techniques
- BPMs attached to each SC solenoid
- Incorporate JT valve and heat exchanger into the cryomodule

PXIE HWR Cryomodule

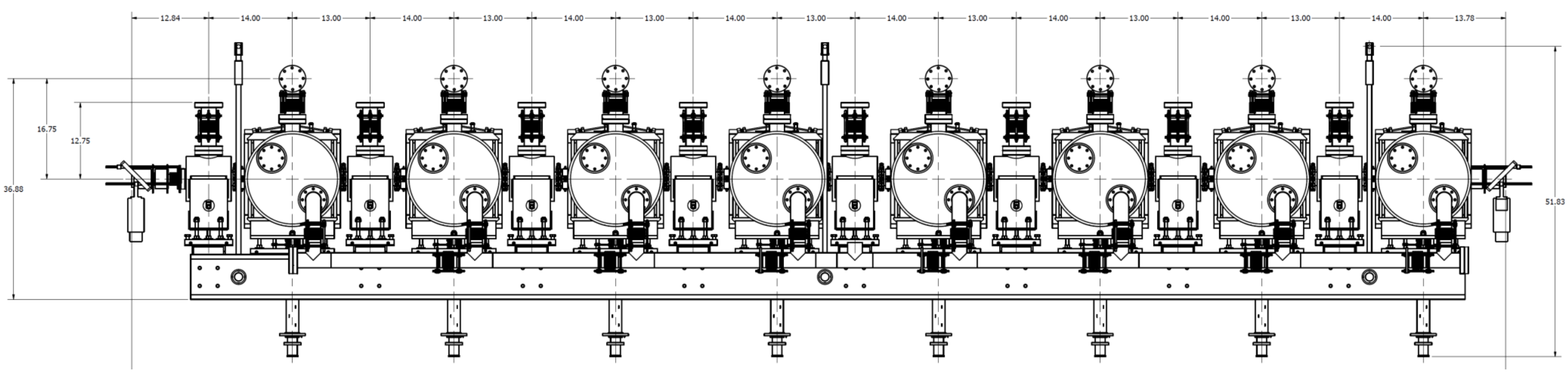
- Cryomodules vacuum/pressure design based upon ANL's experience and best practices to comply with FNAL ESH.
- The cryomodule design is being developed to comply with the FRS interface requirements:
  - Helium Supply/Return Bayonets
  - Cryogenic Valve Control Connections
  - Pumping and Pressure Relief Connections
  - Cryomodule Positioning and Alignment Supports
  - Low-Particulate Gate Valve Beam Tube Connections
  - RF Input Coupler Cables
  - Instrumentation
  - Solenoid/Corrector Magnet Feedthroughs
  - Alignment Fiducials
- The cryomodule will include all requested instrumentation: BPMs, Cavity Field Probes, Temperature Sensors, Helium Level, Heaters, Vacuum Sensors, Magnet Quench Protection, etc.

Cryomodule Layout

- 8 cavities, 8 SC solenoids and 8 BPMs
- The first upstream element is a SC solenoid to mitigate vacuum transition
- Top view



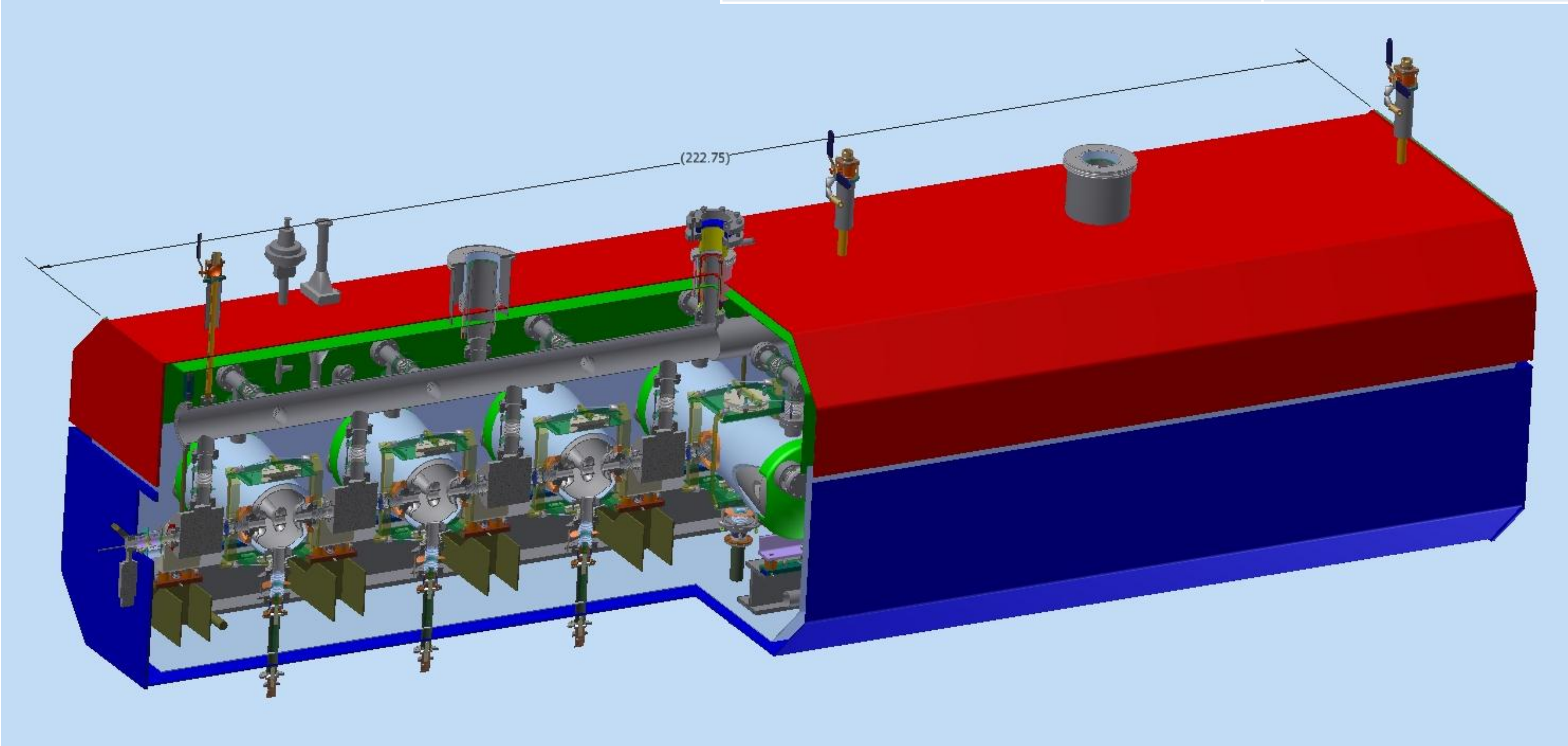
- Side view



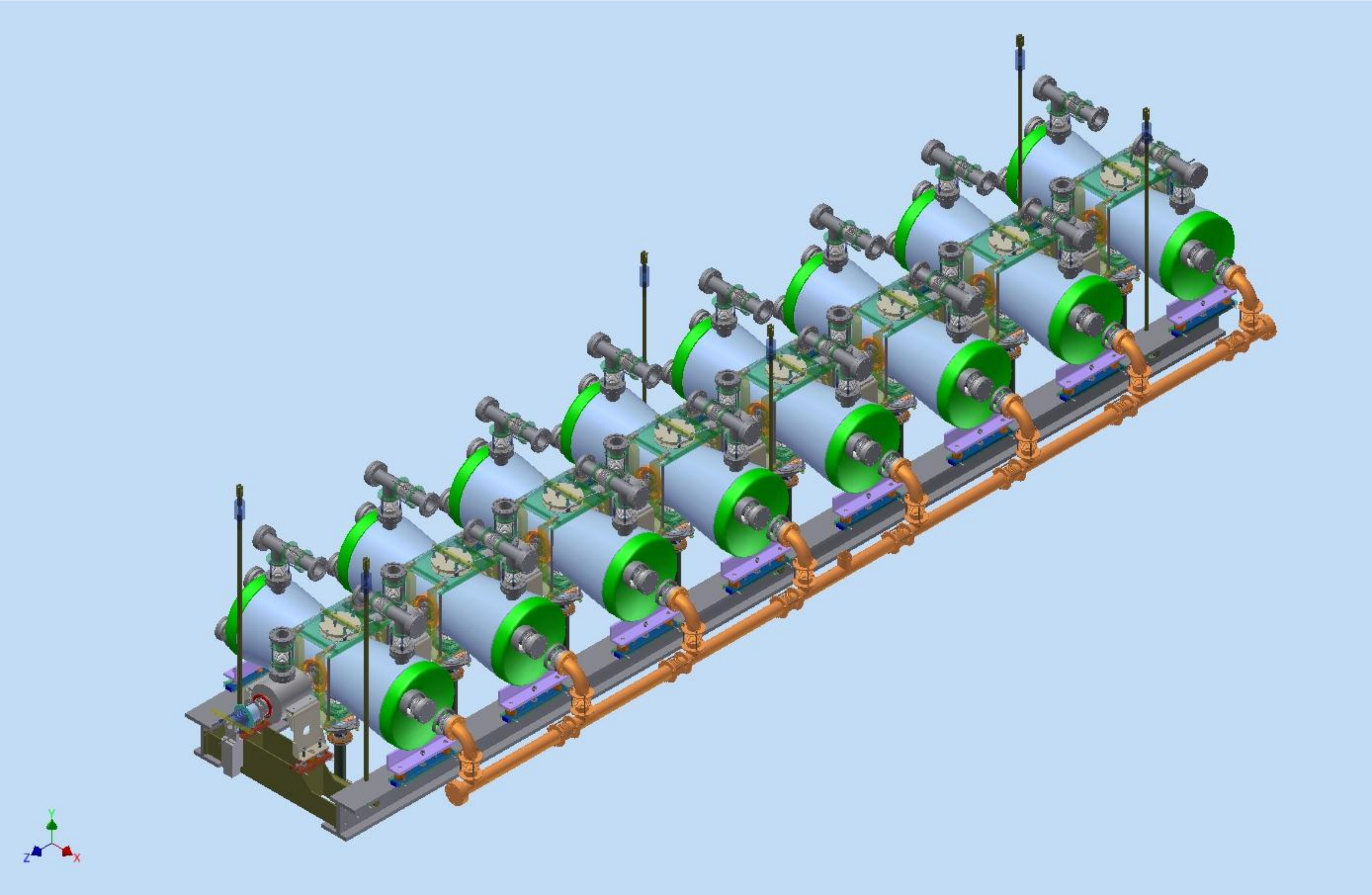
Cryomodule Overall Dimensions

- Remaining detailed design work
  - He distribution system
  - Vacuum vessel with thermal and magnetic shielding

Parameter	Dimension
Cryomodule Width (m)	1.6 m
Cryomodule Height (m)	1.8 m
Cryomodule Length (m)	5.9 m



Clean Room Assembly: Cavity Solenoid String

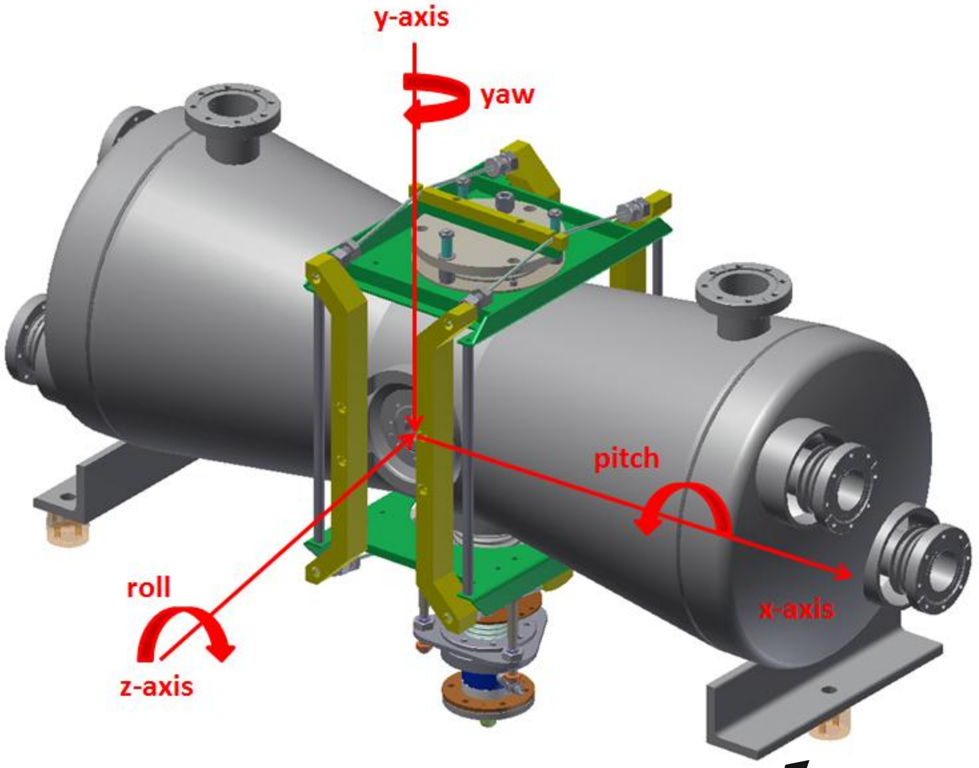


Beam-Line Alignment Tolerances

Dimension	Energy Upgrade	Intensity Upgrade	PXIE HWR
x (mm)	±0.25	±0.25	±0.25
y (mm)	±0.25	±0.25	±0.25
z (mm)	±1	±1	±0.50
Pitch	$\pm 0.1^0$	$\pm 0.1^0$	$\pm 0.06^0$
Yaw	$\pm 0.1^0$	$\pm 0.1^0$	$\pm 0.06^0$
Roll	$\pm 0.5^0$	$\pm 0.1^0$	$\pm 0.06^0$

Results of Measurements with Beam

Alignment Coordinate System

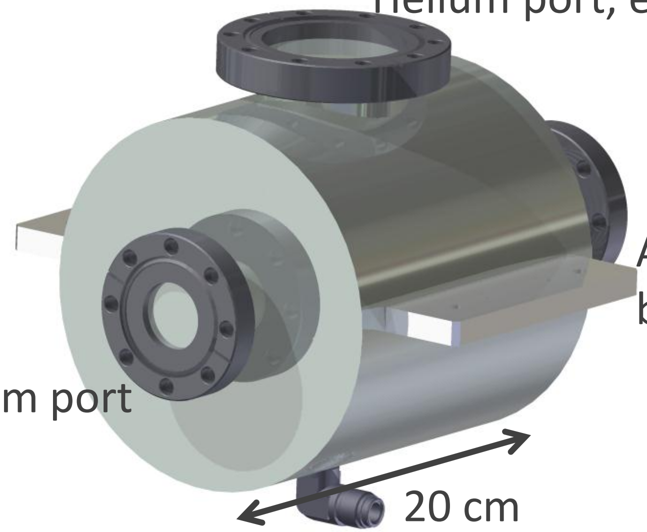


Alignment Puck (QNT 3)

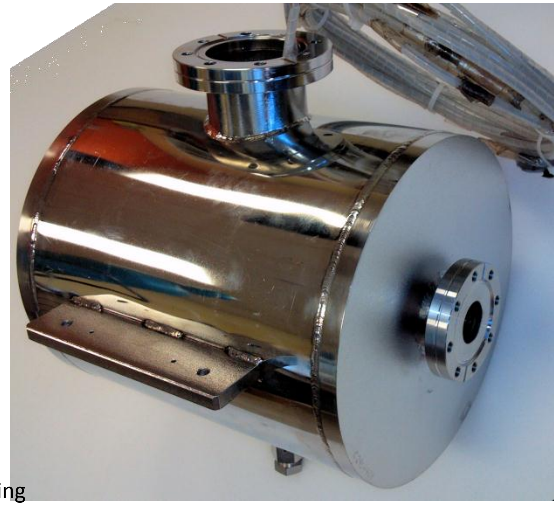
Alignment Hardware Examples

Proposed Magnet Exceeds PXIE Needs: 6 Tesla, 35 mm bore, 0.75 T-m SC solenoid

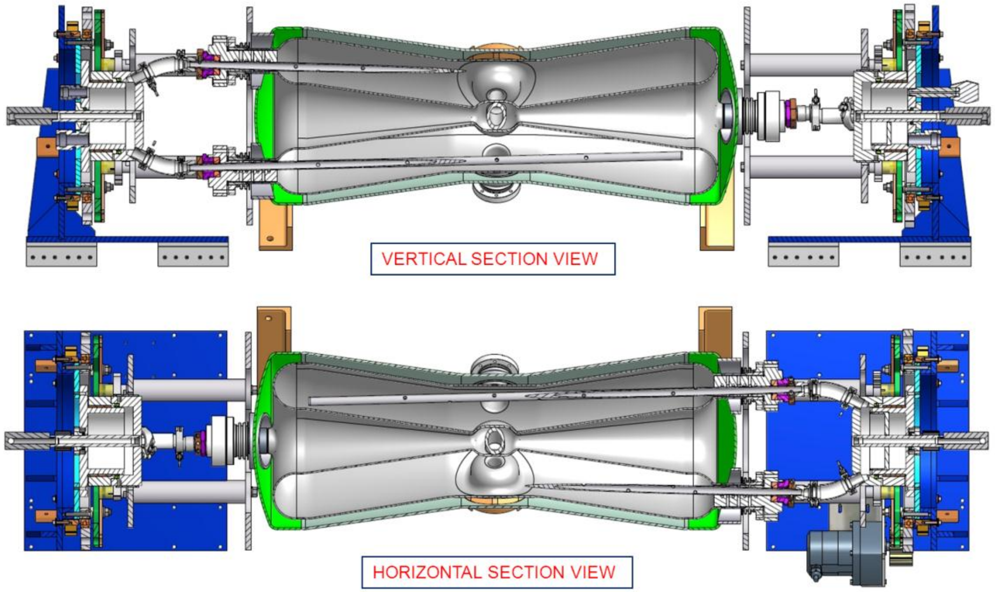
Wire:	NbTi
Operating temperature:	1.8-4.6 K
Magnetic field integral:	$\int Bz\,dz$ = 0.75 T-m
Operating current:	~79 amps
Inductance:	1.1 Henries
Shielding:	B<100G: z >= 15cm
Steering coils:	0.2 T, 30 T-mm
Bore diameter:	35 mm



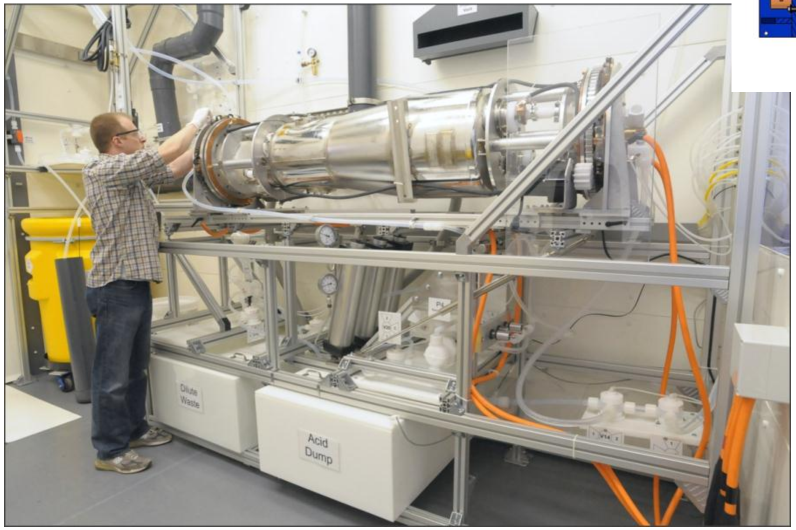
ATLAS Intensity Upgrade Magnet



Electropolishing after all Mechanical Work is Complete



72 MHz QWR

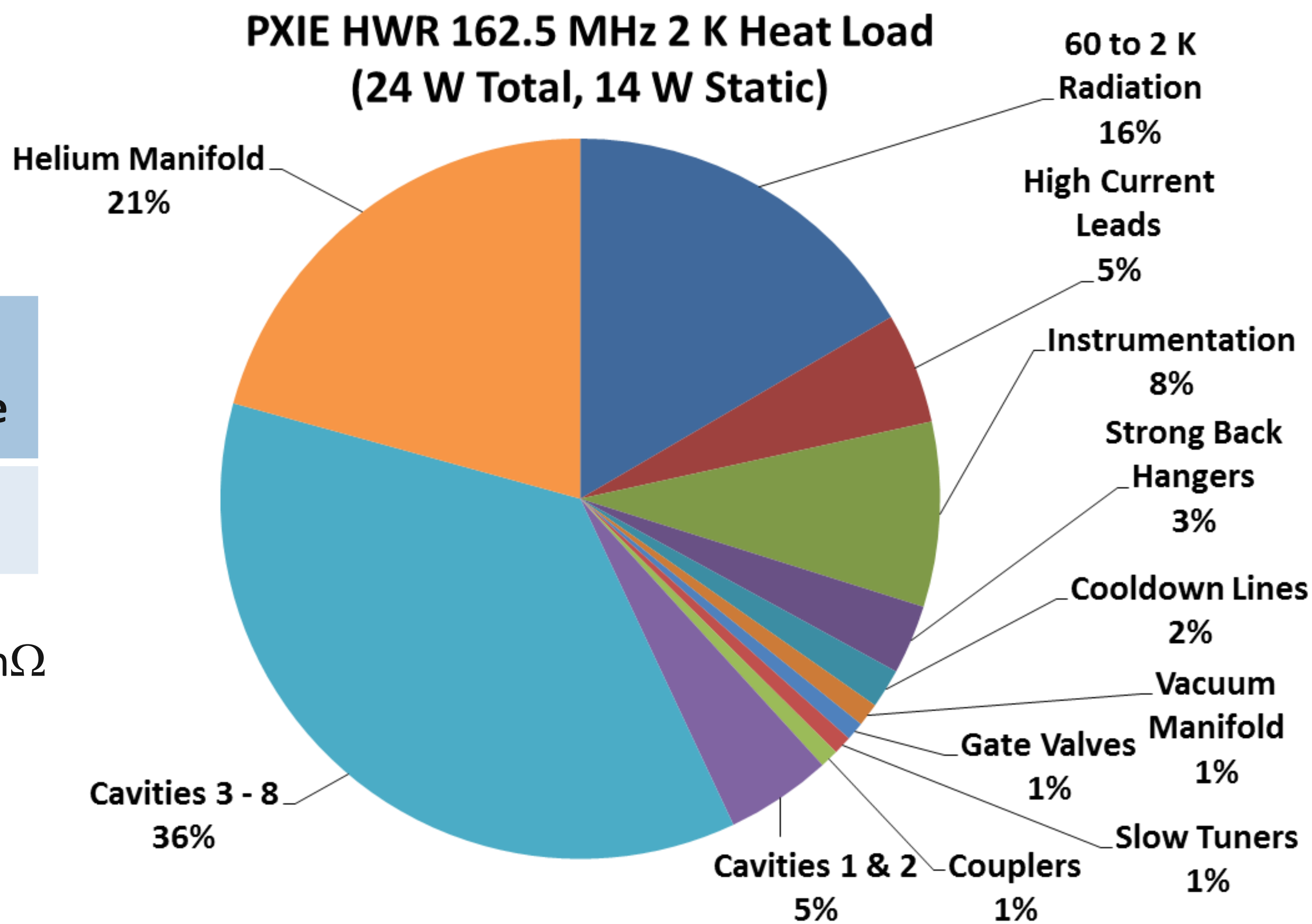


162.5 MHz HWR

Cryomodule Heat Load Estimates I: 2 K

BCS Resistance	Residual Resistance
0.2 nΩ	6 nΩ

2 K Load = 30 W if 10 nΩ



Design and Development Status

- **Project started 6 month ago**
- Cavity EM design and optimization is complete
- Engineering analysis of the cavity and LHe vessel is nearly complete
  - Detailed documentation is being prepared for the ANL/FNAL pressure vessel safety Committee
- Contract with AES for the dies and Nb parts for the prototype HWR is in place
- Bids for niobium purchase were received. Contract will be awarded in 2-3 weeks
- Prototype 10-kW RF coupler is being fabricated
- Prototype SC solenoid is being purchased
- New EBW technique of crossing weld beads has been tested
- Cryomodule
  - Detailed drawings have been developed for cold mass
  - Heat exchanger and J-T valve are being incorporated into the common vessel
  - Final design of the vacuum vessel is being developed