Argonne NATIONAL LABORATORY

HWR Cryomodule

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Physics Division

March 6, 2012

U.S. DEPARTMENT OF ENERGY

Content

- Review of the HWR Cryomodule design, March 5, 2012
- Project motivation
- Functional specifications of the HWR cryomodule
- Cryomodule design features
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- Design of sub-systems
  - SC solenoid
  - BPM
  - RF-coupler
  - Slow tuner
- Management
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- Summary

Review of the

"Design and Fabrication of a 162.5 MHz HWR cryomodule for Project X"

March 5, 2012

Physics Division, Argonne National Laboratory

ANL Guest House, Conference Room A

Monday, March 5

8:30	Executive Session	
9:00	Overview of the Project (Technology, Management, ES&H)	P.N. Ostroumov
9:40	Cryomodule Production Quality Assurance	J. Morgan
10:00	***Coffee Break***	
10:15	Electromagnetic Design of the HWR	B. Mustapha
10:35	Mechanical Design and Engineering Analysis of the HWR	Z. Conway
11:05	HWR Parting and Fabrication Plan	M. Kelly
11:25	Electromagnetic Design of High-Power Coupler	S. Kutsaev
11:45	***Lunch - Executive Session***	
12:45	Tour: ATLAS and SRF Facility in bldg. 208	
13:30	Cavity String Assembly, Solenoid and Coupler for PXIE 162.5 MHz HWR Cryomodule	M. Kelly
14:00	Electropolishing Plan	S. Gerbick
14:20	PXIE HWR Cryomodule Preliminary Design	Z. Conway
14:50	Summary	P.N. Ostroumov
15:00	***Coffee Break***	
15:15	Executive Session	
17:00	Closeout	

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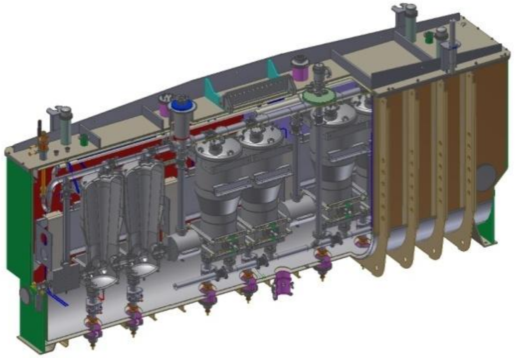
Committee: J. Kerby (chair), R.P. Stanek, A.L. Klebaner, C.M. Ginsburg, V.A. Lebedev, H. Padamsee (Cornell), R. Laxdal (TRIUMF)

Project Motivation

- Acceleration of H^- beam from 2.1 MeV to 10 MeV in CW regime
- Difficulty: transition from very low accelerating gradients in RFQ to much higher gradients in the SC section – not efficient use of SC structure
- Total accelerating voltage 1.7 MV×8=13.6 MV
  - First 2-3 accelerating periods - just 1 MV
- Replaces 3 cryomodules of 325 MHz spoke cavities from the original design of Project X (beginning of 2011)
  - More naturally fits to 162.5 MHz RFQ
- Significantly reduces the cost of the front end (PXIE) as compared with the 325 MHz system
- Favorable beam dynamics: higher accelerating gradients, less defocusing, linear motion in longitudinal phase space
- Can be realized in reasonable length of the cryomodule below 6 meters
  - Comparable with ATLAS cryomodules

Basis for HWR Cryomodule Development

Parameter	ATLAS AEU Cryomodule	ARRA Cryomodule
Frequency, MHz	109	72.75
β_{OPT}	0.15	0.077
Voltage per cavity/total, MV	2.1/14.5	2.5/17.5
Length, m	4.5	5.2



PXIE HWR Cryomodule Design Features

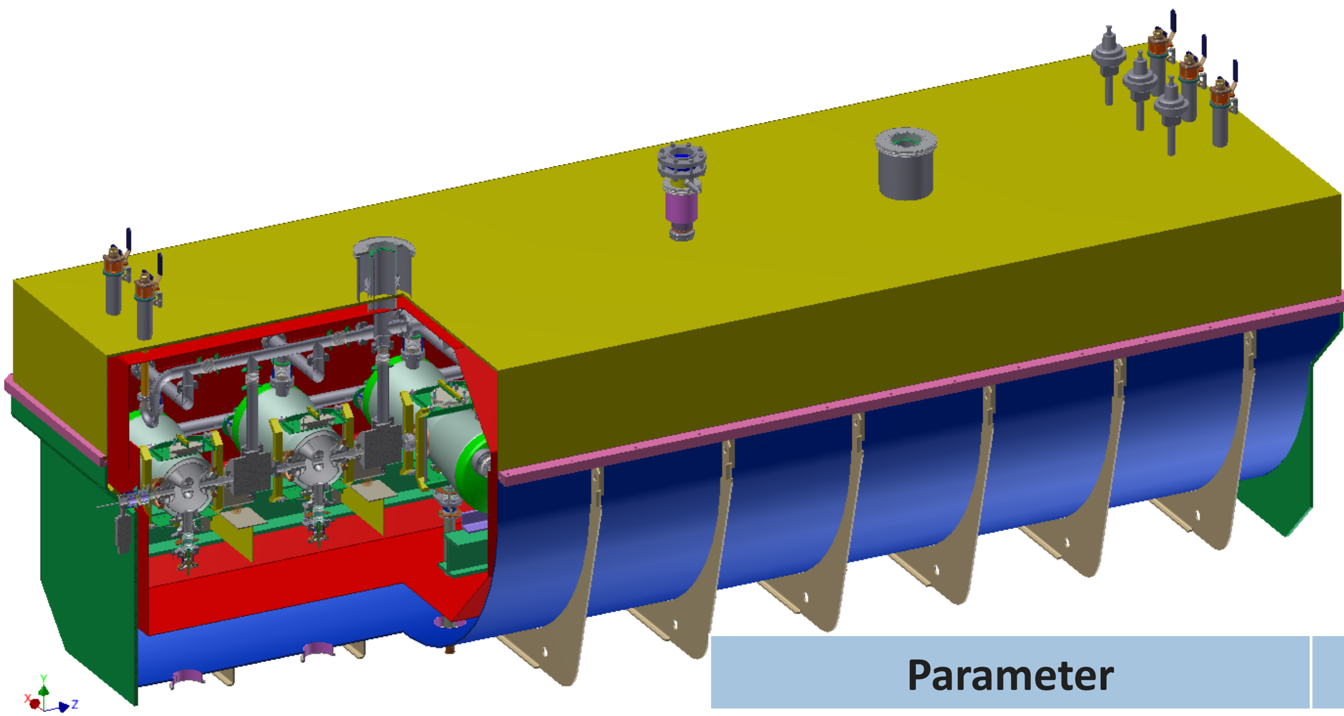
- In October 2011 we started with the cryomodule concept which included 9 cavities and 5 SC solenoids
- Beam physics studies resulted in 8 cavities, 8 solenoids, 8 BPMs
- The first upstream element is a SC solenoid to mitigate vacuum transition from NC to SC linac
- 2K operation
- Relatively short cryomodule, 5.9 m
  - Reduction of the length by ~10" is being pursued
- Compact lattice: short focusing periods to be able to apply 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 Interfaces

- 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.

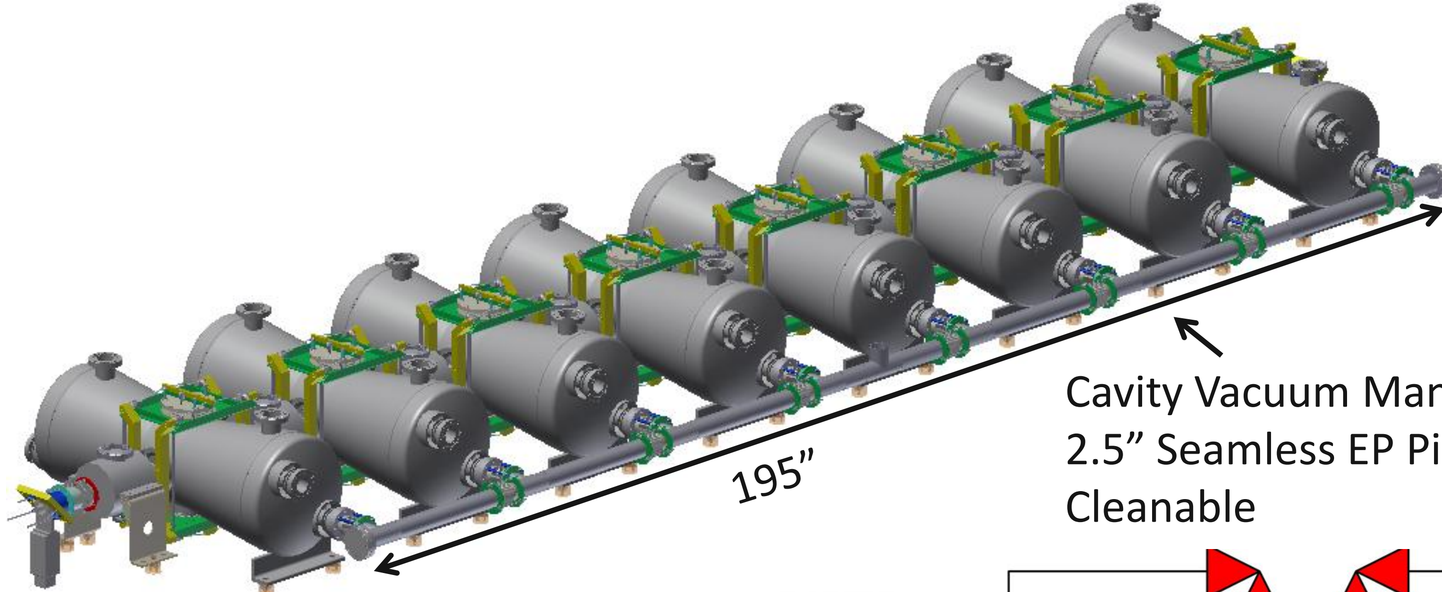
Preliminary Cryomodule Design

- Cryomodule design is still being developed
- Cavity, RF coupler, slow tuner design complete

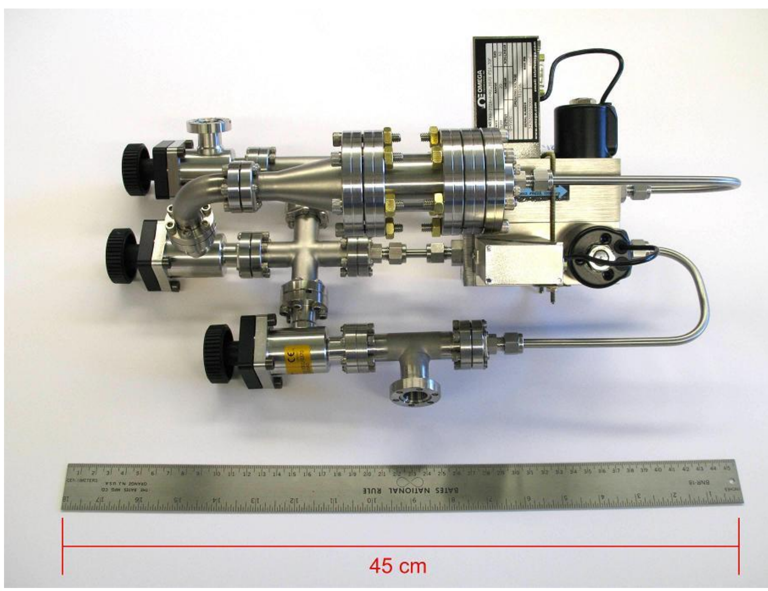


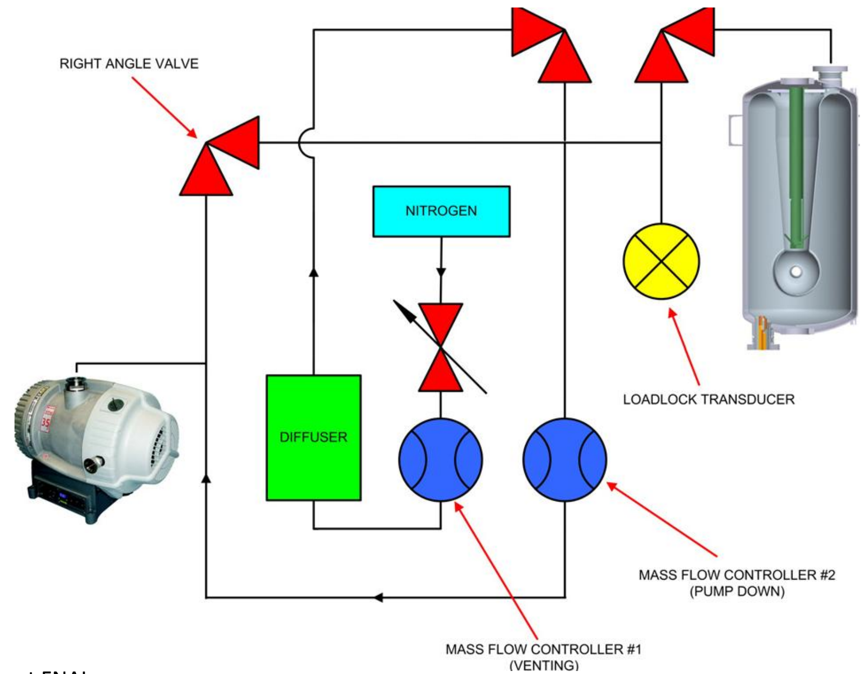
Parameter	Dimension
Cryomodule Width (m)	1.8(2) m
Cryomodule Height (m)	2.0(2) m
Cryomodule Length (m)	5.9(2) m

Low-Particulate Vacuum and Up to Air Systems



Cavity Vacuum Manifold
2.5” Seamless EP Pipe
Cleanable





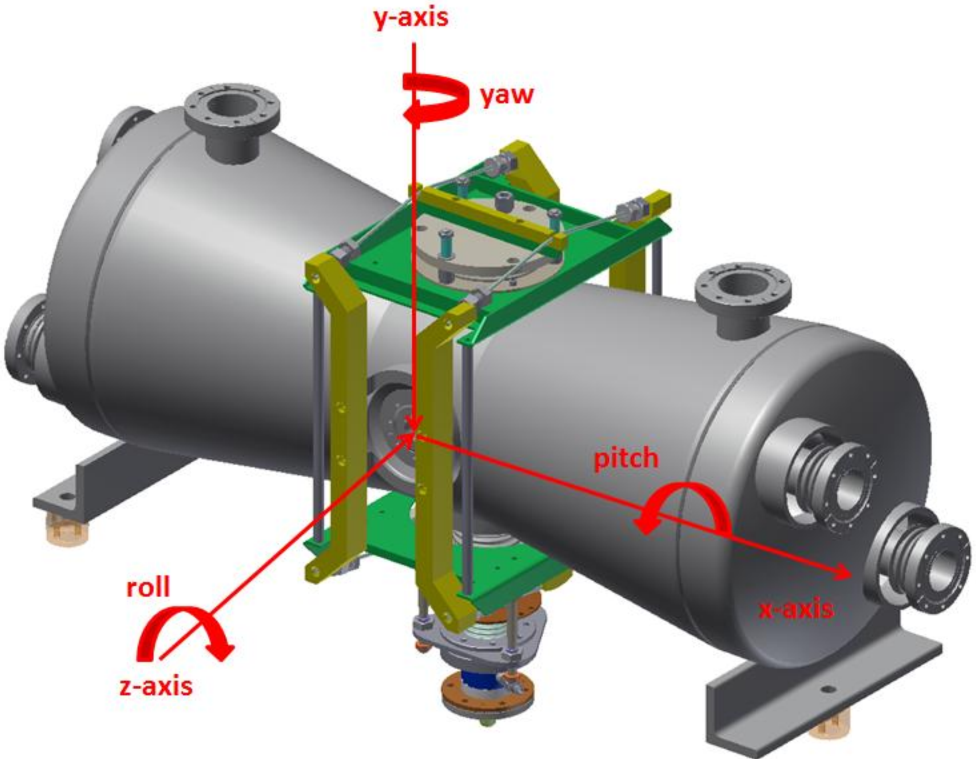
Gerbick et al, SRF 2009

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	$\pm 0.15^0$	$\pm 0.1^0$	$\pm 0.06^0$
Yaw	$\pm 0.15^0$	$\pm 0.1^0$	$\pm 0.06^0$
Roll	$\pm 0.5^0$	$\pm 0.5^0$	$\pm 0.5^0$

Results of Measurements with Beam

Alignment Coordinate System

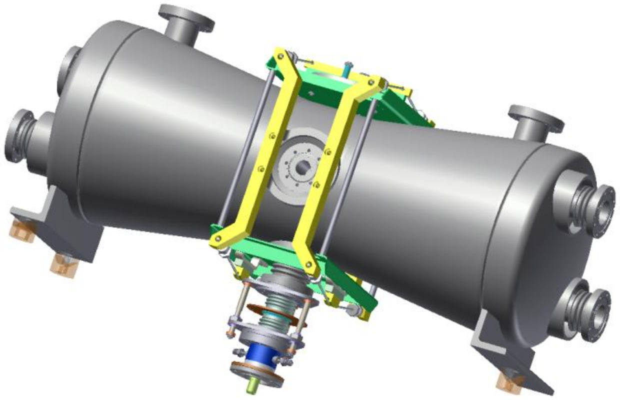


Alignment Puck (QNT 3)

Alignment Hardware Examples

Resonator Design Features

- Highly optimized
  - Low B_{PEAK} due to double conical shape of the CC and OC
  - Increased shunt impedance
  - “Donut” shape of the CC drift tube to eliminate quadrupole component of the accelerating field
- 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 joins is 0.5” – significant development by AES to minimize B_{PEAK}
- Pneumatic slow tuners
- 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)

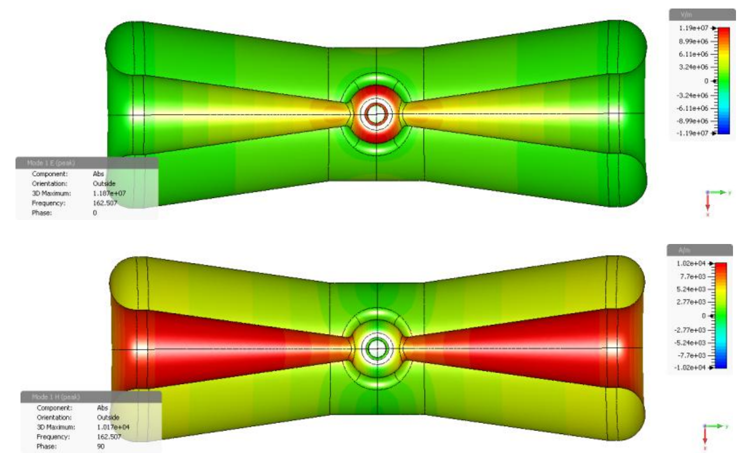


EM optimization

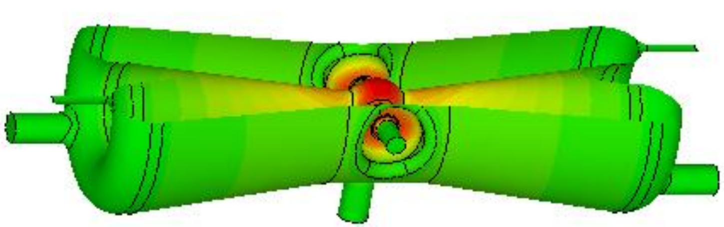
- Excellent EM properties. Recommended design voltage is 1.7 MV which corresponds to E_{PEAK} = 38 MV/m and B_{PEAK} =44 mT

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	5.0	271	48

No ports

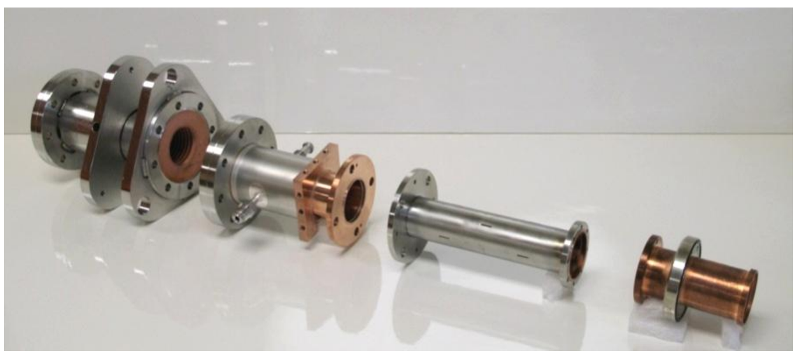


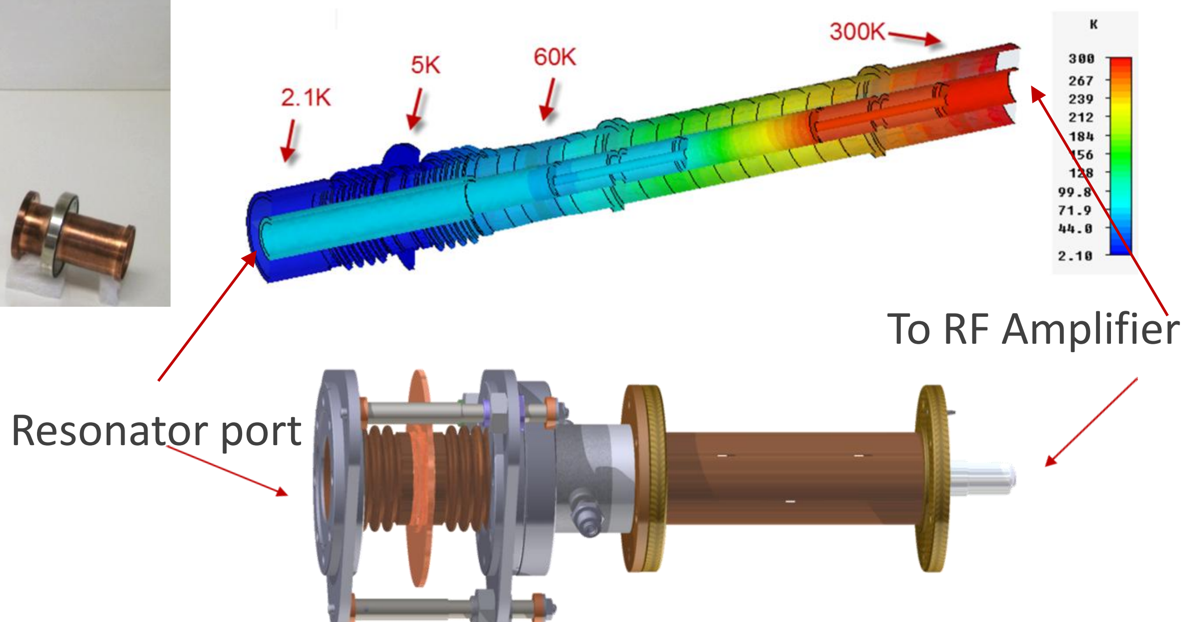
With ports



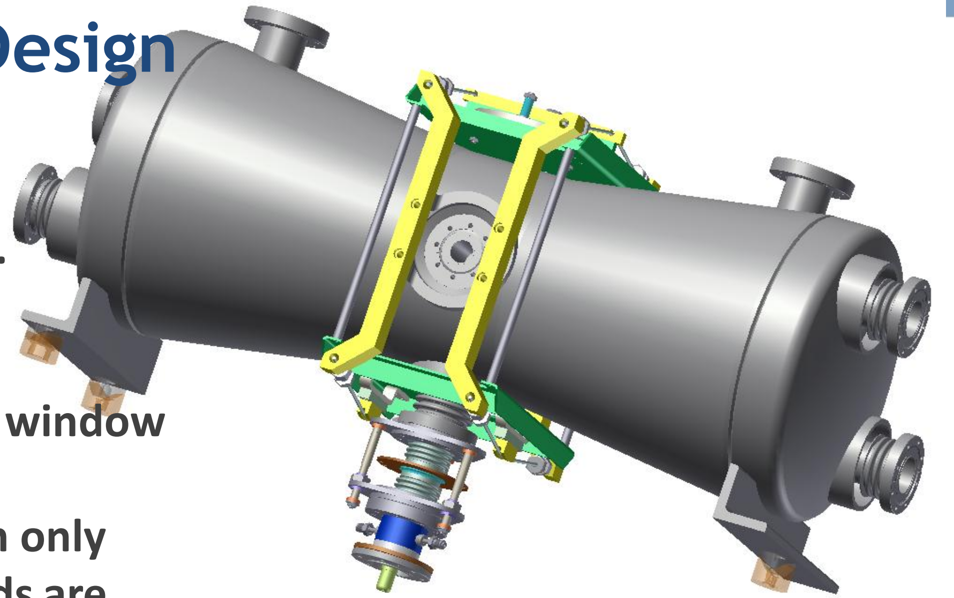
10-kW Adjustable Coupler

- 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
- The coupler is being fabricated

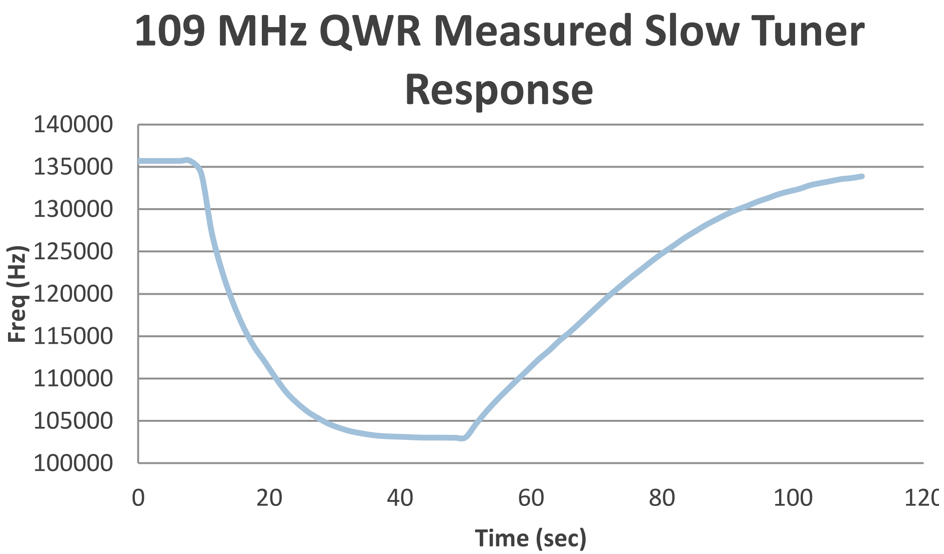


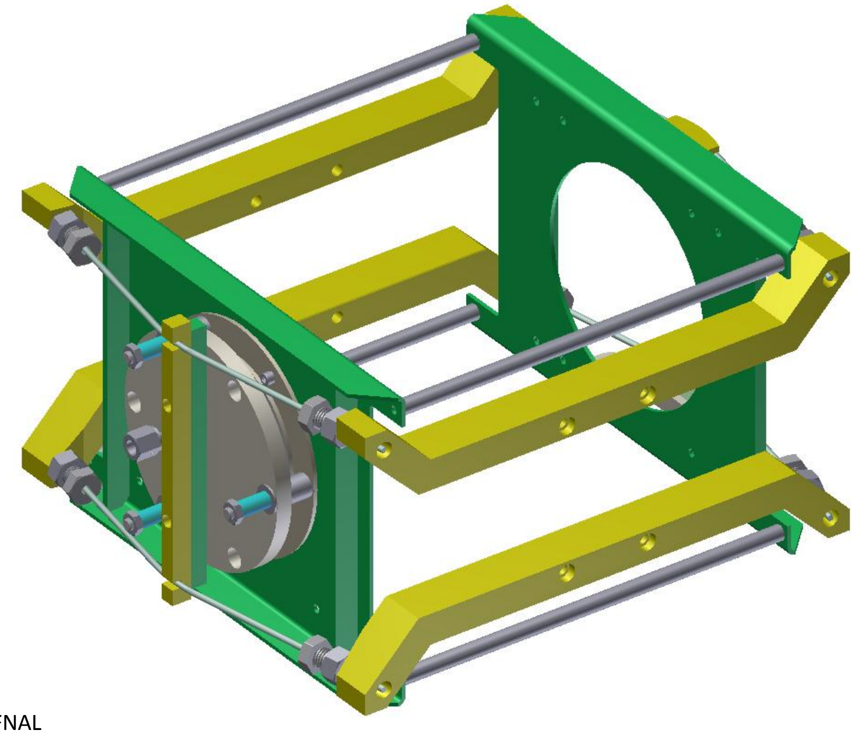


ANL Pneumatic Slow Tuner Design



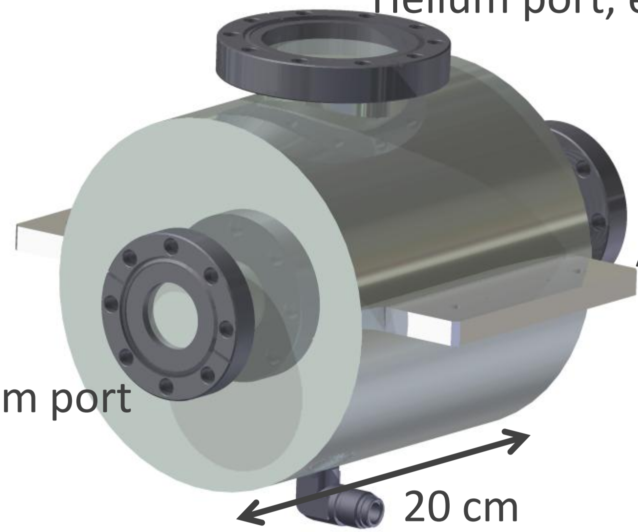
- No hysteresis.
- No backlash.
- No vibration; does not excite microphonics.
- Operates in a continuous feedback mode.
- Bellows is the only *moving part.*
- 109 MHz quarter wave cavity 32kHz tuning window ~1kHz / sec slew rate.
- Over $5X10^6$ integrated operating hours with only 77.82 hours of downtime (downtime records are from 1994 to 2011).
- Can be easily applied for HWRs.



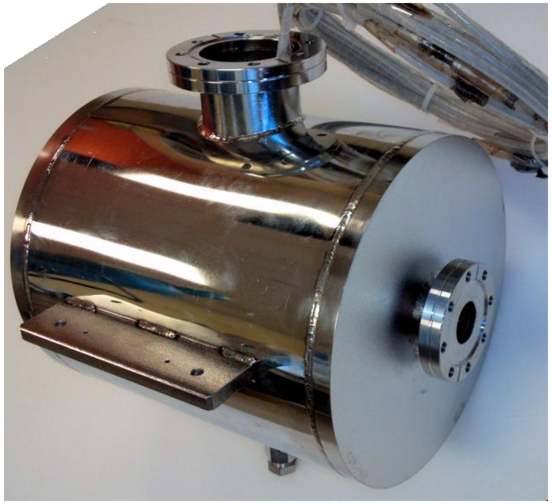


Proposed Magnet Exceeds PXIE Needs: 6 Tesla, 35 mm bore, 0.75 T-m SC solenoid

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

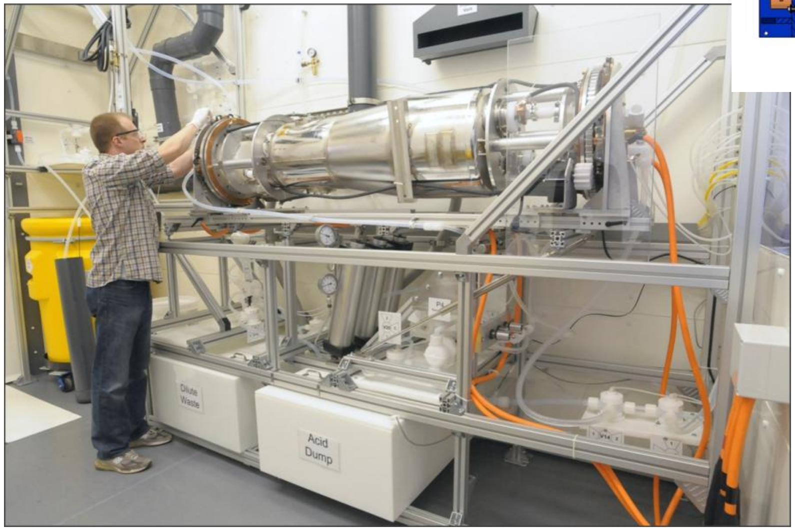


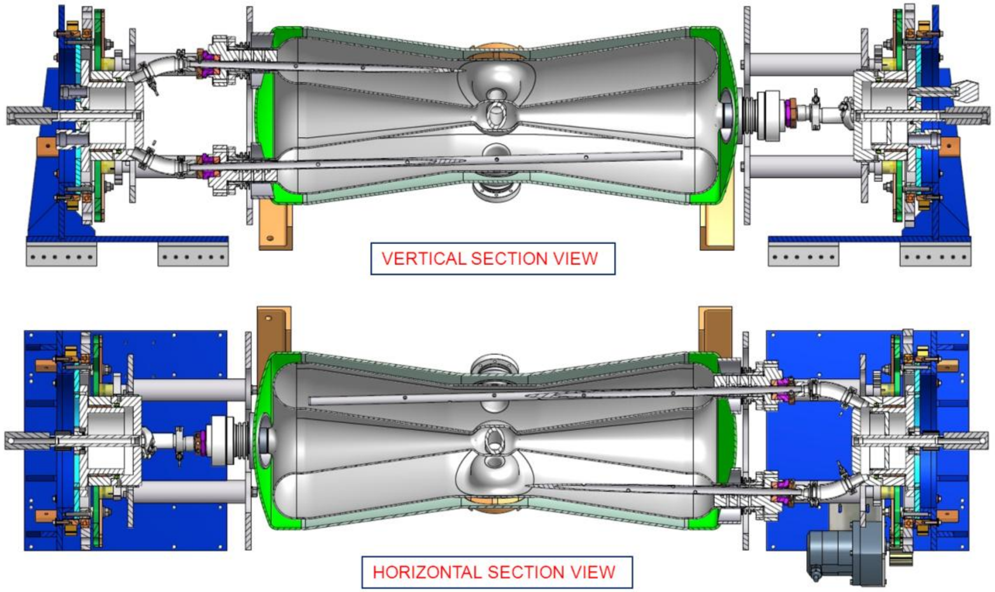
ATLAS Intensity Upgrade Magnet



Electropolishing after all Mechanical Work is Complete

72 MHz QWR

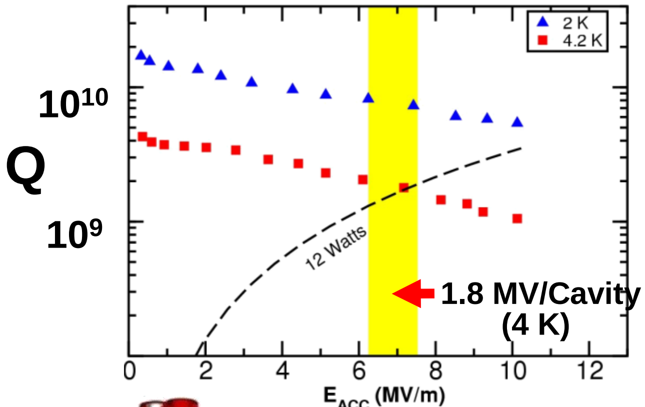




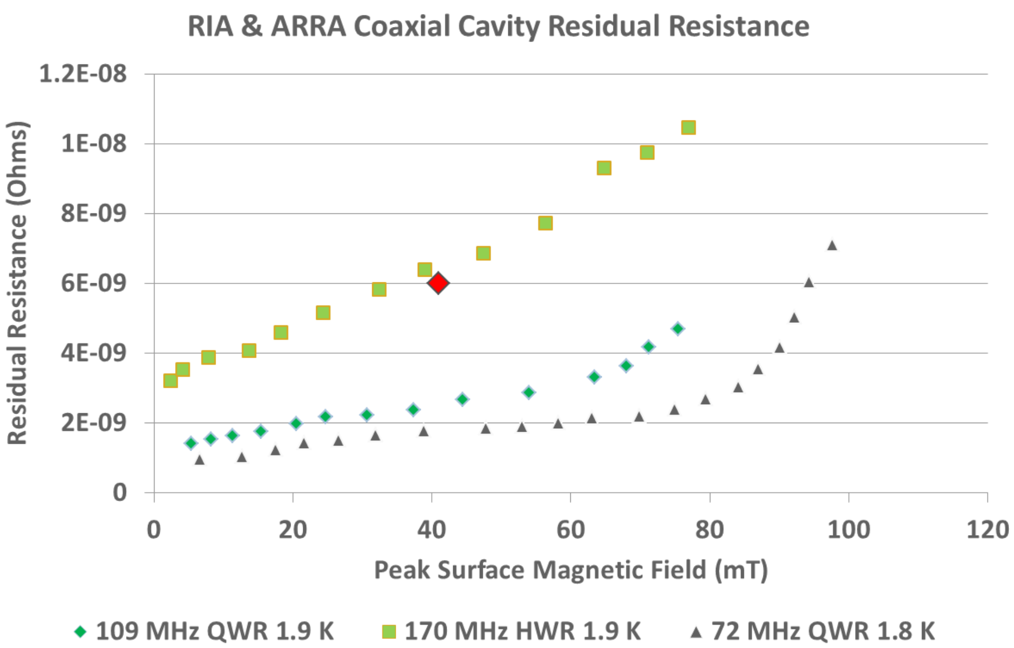
162.5 MHz HWR

Performance of 170 MHz HWR (2004), 109 MHz QWR (2004) and 72 MHz QWR (2011)

- Technology has been improved since 170 HWR was built in 2003-2004
  - Highly optimized EM design, reduced B_{PEAK} and E_{PEAK}
  - Extensive wire EDM of all parts prior to EBW
  - EP after all mechanical work is complete (+600C baking)



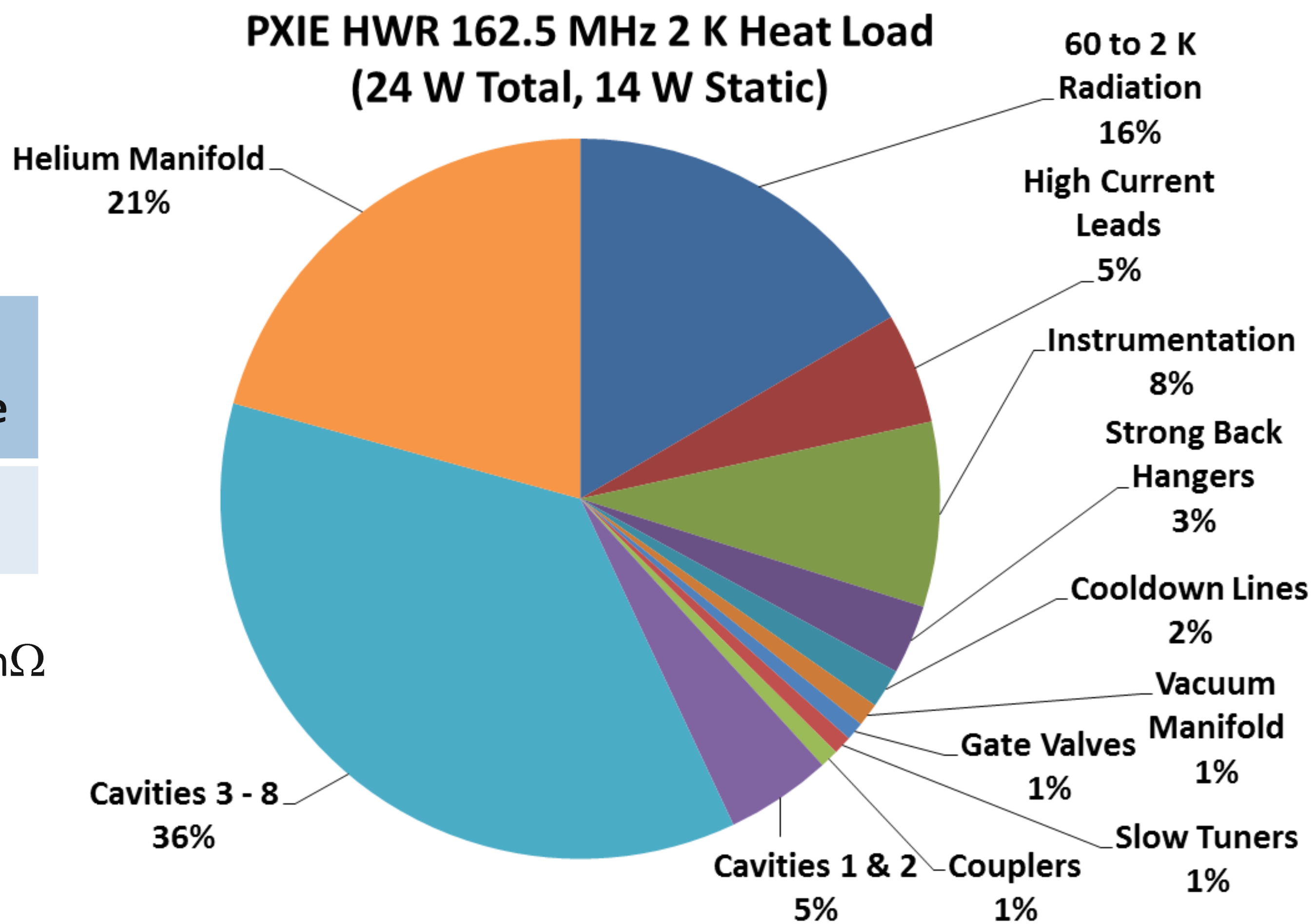
β=0.25 HWR, f_0=172.5 MHz



Cryomodule Heat Load Estimates I: 2 K

BCS Resistance	Residual Resistance
0.2 nΩ	6 nΩ

2 K Load = 30 W if 10 nΩ



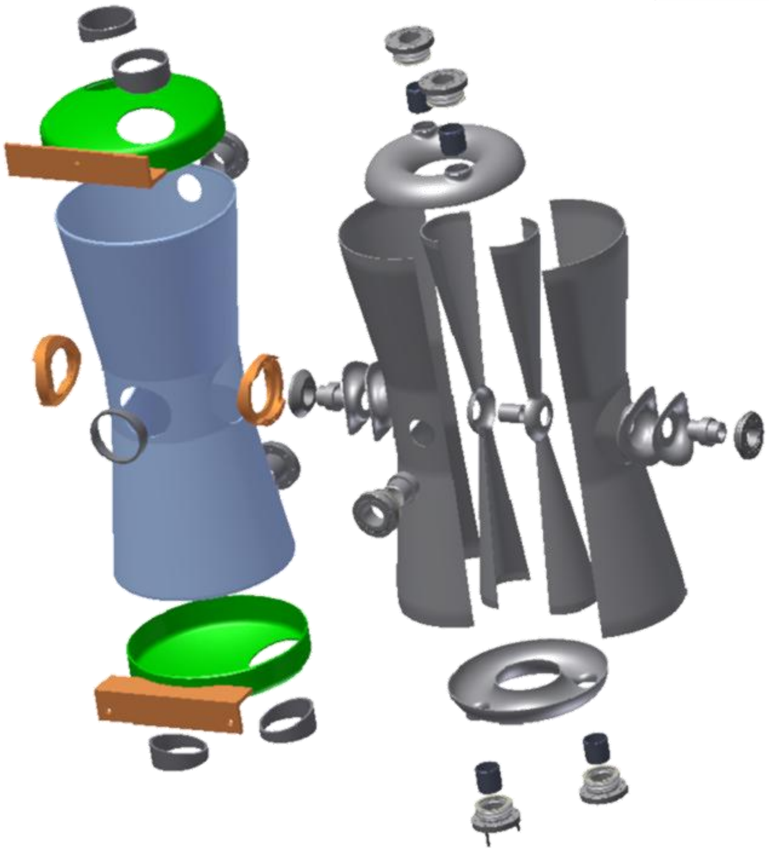
Project Management, ES&H and QA

- We have created detailed budget and schedule for development, construction and commissioning of the HWR cryomodule
- ES&H and QA are well understood and followed procedures and policies of FNAL and ANL
- All these issues were discussed in detail on yesterday's Review

#	Milestone	Date
1	Place contract for niobium dies and forming of the prototype cavity	Q2FY12
2	Conceptual and Preliminary Design complete Niobium for production cavities is delivered and inspected	Q4FY12
3	Complete fabrication drawings and start procurement of the cryostat vessel including thermal and magnetic shields. Fabrication of the prototype cavity including SS vessel	Q2FY13
4	Prototype cavity tested	Q4FY13
5	Fabrication of the cryostat vessel complete	Q2FY14
8	Fabrication of production cavities complete	Q4FY14
7	Mock-up cavity string assembly	Q2FY15
8	Cryomodule off-line testing complete	Q4FY15
9	Cryomodule installed on PXIE beamline	Q2FY16

Cavity Design Status

- Multi-physics and engineering design of the niobium cavity is complete
- Nb and SS vessel stresses are within specs
- df/dp is +4.3 kHz/atm and can be nulled with further optimization of the SS vessel
- Comfortable range of slow tuner – 85 kHz at 6000# of applied force
- ProE model is created per AES request
- Specifications for Nb purchase are out for bid

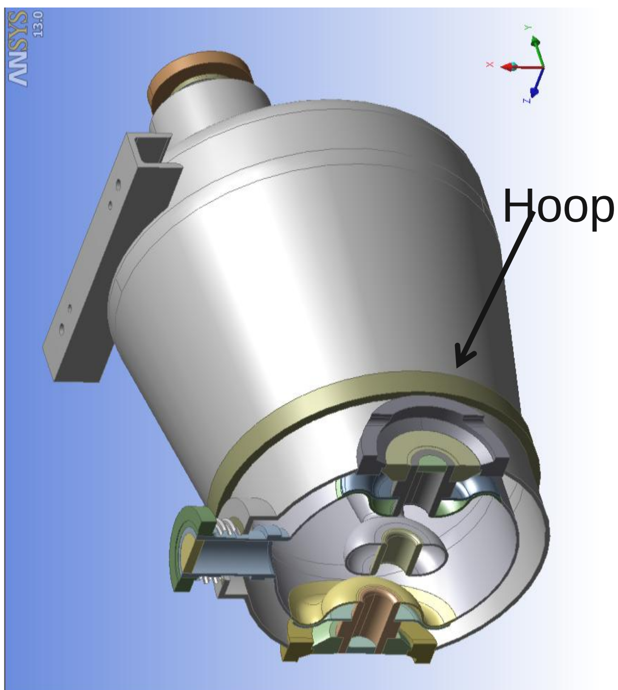


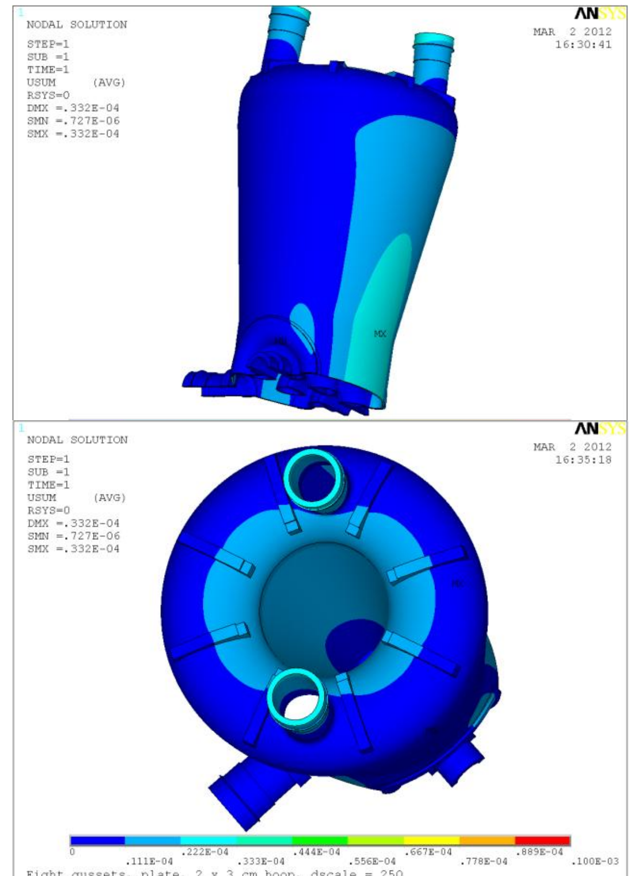
df/dP: Toroid Gussets and Hoop

	No Hoop	1 cm x 3 cm Hoop	2 cm x 3 cm Hoop
df/dP (Hz/mbar)	5.8	5.5	4.3

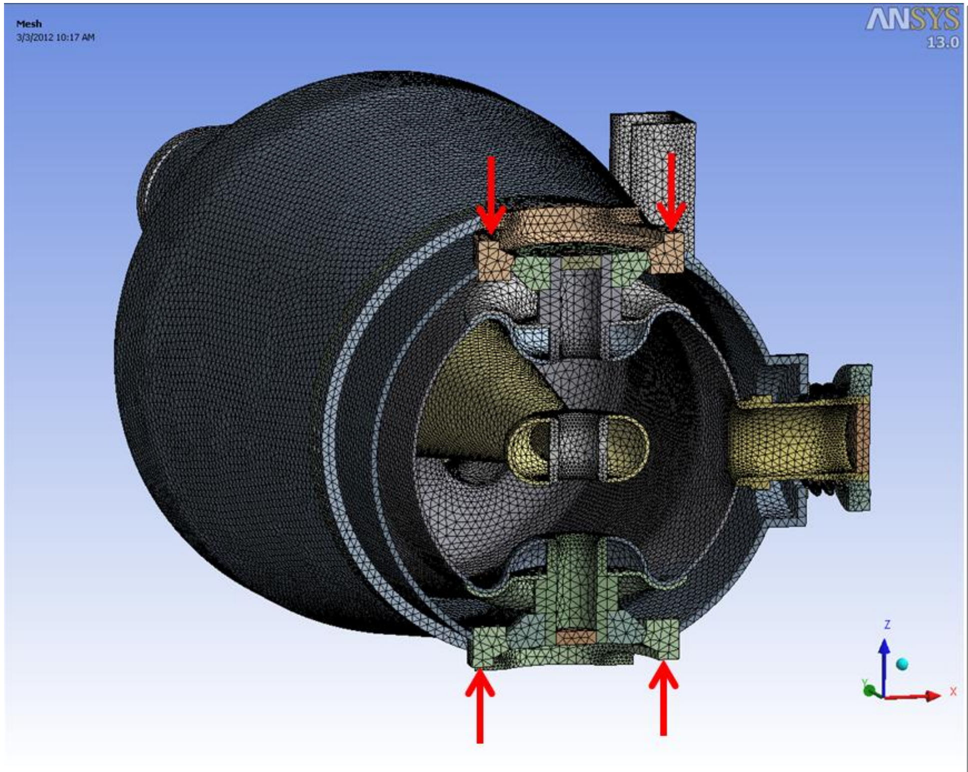
Geometry has 8 Gussets on Toroids and Ti Plate.

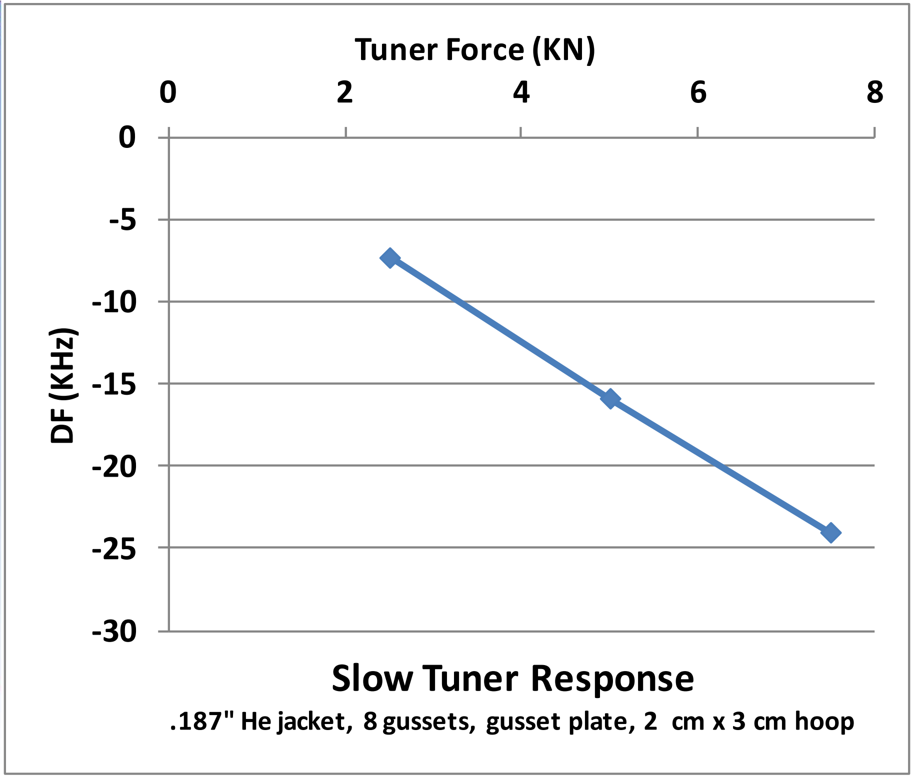
With both gussets and hoops df/dP = + 4.3 Hz/mbar





Slow Tuner Simulation





85 kHz Tuning Range with Stiffest Helium Jacket Geometry: 2 cm thick x 3 cm wide hoop
8 Gussets & Ti Plate
With 26.6 kN applied force (6,000 lbf)

Cavity Fabrication in US Industry

Nb parts forming

Center conductor

Toroid top side

Lower housing

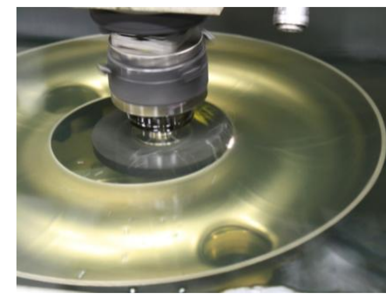
Cavity port braze assemblies

Bellows attached (welded) to cavity flange and also helium vessel

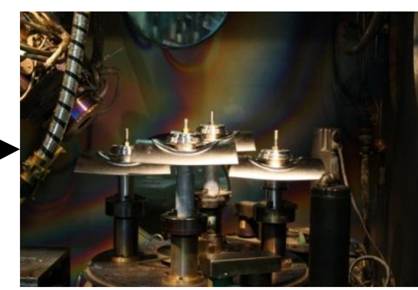
EBW ↔

Nb wire cutting

Wire EDM



Sinker EDM



Procurements in FY12

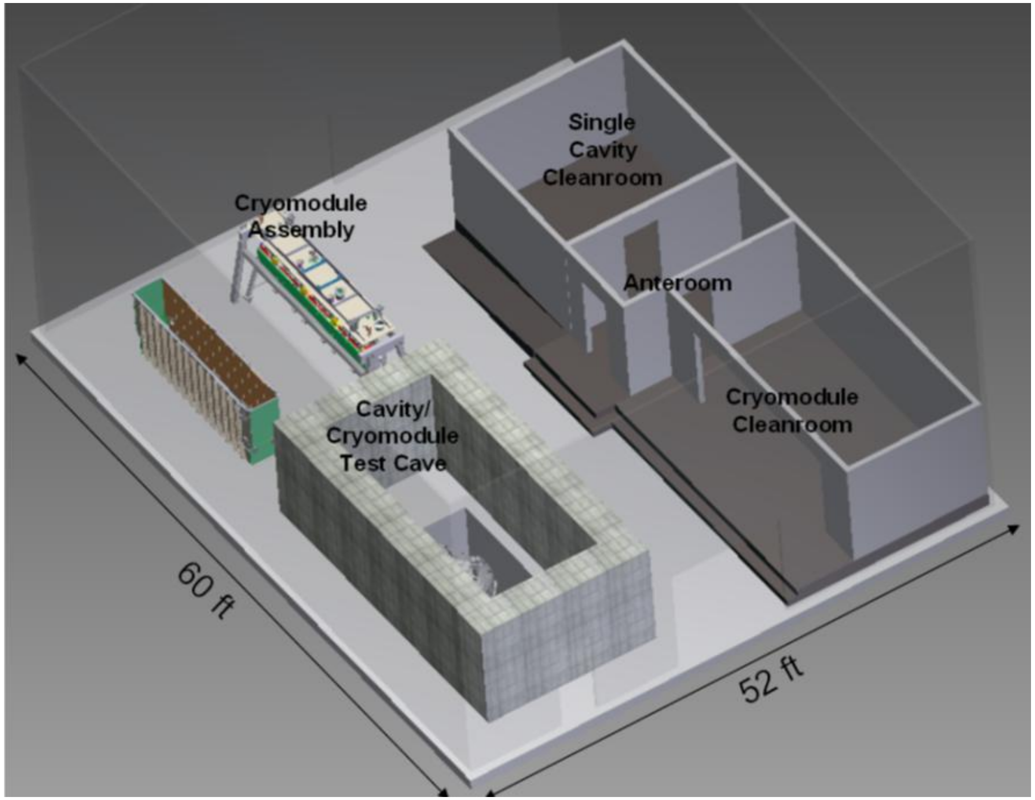
- Prototype cavity
  - Niobium procurement
  - Hydroforming dies and fabrication of cavity parts
  - Machining, brazing, wire EDM, includes fixturing for these operations
  - Stainless steel Helium vessel
- Niobium procurement for production cavities
- Procurements in early FY13
  - EBW of the prototype cavity
  - Fixturing for EP and HPR
  - Niobium forming for production cavities

Project Status

- HWR cryomodule project is well advanced
  - Management plan was created
  - Management of ES&H and QA are well understood
  - Schedule and budget were developed
  - Procurement plan exists and being implemented
- Next steps are:
  - Place contract with AES for Nb forming
  - Continue engineering analysis and optimization of the jacketed HWR
  - Start procurement of the prototype cavity parts (braze joints, bellows,..)
  - Call Safety Committee to finalize mechanical design and engineering analysis of the dressed cavity
  - Place contract to purchase Nb for production cavities
  - Fabricate and test 10-kW coupler
  - Complete Conceptual and Preliminary design of the cryomodule
  - Revise and update cost estimate per most recent FRS and current status of the design

Remaining Issues: Cryomodule Assembly and Testing Area

- Currently we do not have space for cryomodule assembly
- We propose to clean-up high-bay area in bldg. 208 (D-wing), next to the existing ANL-FNAL joint SRF facility
- Refrigerator exists
- Requires funding from several sources, projects
- Some funding will be available from PHY-AIP



Recommendations of the Review Committee

- The current schedule does not incorporate necessary technical reviews. These should be shown as tasks with milestones at completion. The schedule should be checked to assure that the time required to properly document engineering analysis and assumptions is included and that there is a process for peer review of these calculations.
- Nb should be ordered ASAP; other long lead items should be a priority of the design team; and commonalities with FNAL designs pursued where possible.
- There appears to be a gap between Fermilab and Argonne on the appropriate level of communication, oversight and review for the project.
- The cleanroom for assembly of the HWR is an open issue that needs to be resolved.
- Full document should be here

https://indico.fnal.gov/conferenceDisplay.py?confId=5307

Summary

- Preliminary design of the cryomodule is in advanced stage
- FNAL requirements are satisfied in design
- Multi-physics analysis of the cavity and SS vessel are complete
  - Prototype cavity is ready for fabrication
  - ProE model is created (for AES)
  - Additional optimization of the SS vessel is desirable
- 10-kW RF coupler is a moderate step up from the existing 4kW ATLAS coupler and is being fabricated
- Nearly all fabrication techniques are similar or identical for QWR's and HWR's and are well understood
- Primary infrastructure and techniques for cavity string assembly established
  - A suitable space (similar to the ATLAS clean room) will be required for string assembly