Development of Multi-spoke Superconducting Cavities and Cryostats for Nuclear Physics, Light Sources and Driven Systems Applications

A Collaboration between

Center for Accelerator Science
Old Dominion University
(Jean Delayen)

and

Thomas Jefferson National Accelerator Facility
(John Mammosser)

Introduction and Background

- For several decades, the Department of Energy (in particular NP and HEP) have supported the development of the superconducting rf technology.
- The results have been successfully applied to a number of NP and HEP (and BES) projects
- These results could also have relevance and be applied to a much wider range of accelerator applications (e.g. energy production, environment, and defense)
- The R&D activities have often taken place in direct support of projects with limited opportunities to explore and optimize new concepts

Project Goals

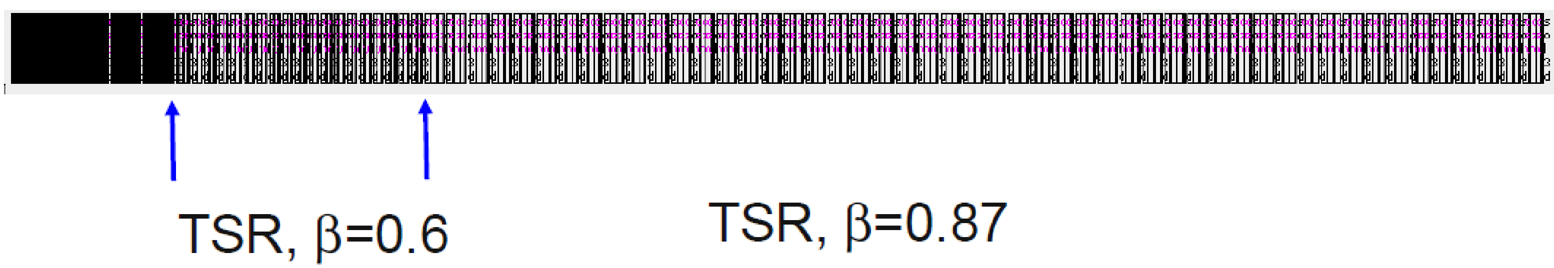
- Extend the applicability of DOE NP/HEP-supported SRF cavity developments to a wider range of applications
  - Light sources
  - Accelerator Driven Systems
  - …
- Explore new concepts in
  - Cavity designs
  - Cavity fabrication techniques
  - Cryomodule design
- Cost reduction and ease of manufacturing and maintenance
- Involve Physics and Engineering students in all activities

(GeV,10's mA)-class Proton Accelerator

2.5 GeV Superconducting Single-Frequency Linac, pulsed current is 100 mA, f=325 MHz

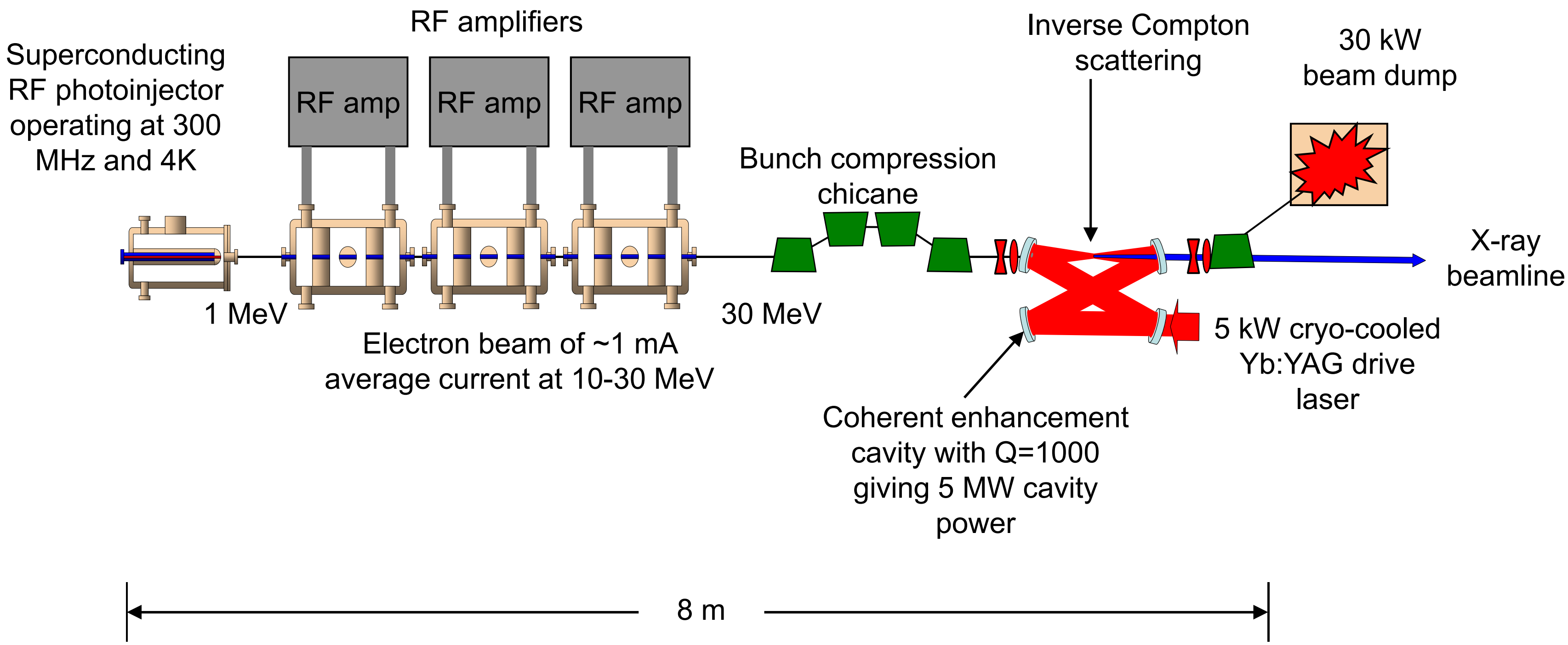
- Input energy – 7 MeV
- 2 types of spoke cavities, length =48 m, 135 MeV

- 2 types of spoke cavities + 2 types of 3-spoke cavities, total length =480 m, 2.3 GeV (total = 250 SC cavities)



- Focusing with SC solenoids, eff. length = 20 cm, B=from 4T to 10.4T

Compact Light Source



SRF Linac Parameters	
Energy gain [MeV]	25
RF frequency [MHz]	352
Average current [mA]	1
Operating temperature [K]	4.2
RF power [kW]	30

Student, Postdoc, and Faculty Involvement

- Subashini de Silva, Physics Graduate Student, ODU
- Christopher Hopper, Physics Graduate Student, ODU
- Rocio Olave, Physics Post Doctoral Fellow, ODU
- Milos Basovic, Engineering Graduate Student, ODU
- Mileta Tomovic, Professor and Chair Engineering Technology Department, ODU
- Jean Delayen, Professor of Physics and Director of the Center for Accelerator Science, ODU

ODU Milestones

Appendix A: Project Control Milestones
Old Dominion University
NP Multi-Spoke Superconducting Cavities

		Projected Completion Date	Actual Completion Date	Milestone Description	Critical Path	Issues
FY 2010	3Q	7 June	7 June	Assistance Agreement Signed - PI Notified 25 June		
	4Q	30 September	30 September	Cavity Parameters Specified		Lack of qualified design scientist. Post-doc position adverstised since August 2009. No suitable candidate found to-date. Work performed by graduate students
FY 2011	1Q			Complete Requirements Document		
	2Q			Complete Conceptual Design of Cavity		
	3Q			Complete Electromagnetic Design of Cavity		
	4Q			Complete Higher Order Modes Analysis		
FY2012	1Q			Complete Multipacting Analysis		
	2Q			Complete Cavity Engineering Design		
	3Q			Complete Couplers Concepts Evaluation		
	4Q			Complete Tuners Concepts Evaluation		
FY 2013	1Q			Complete Prototypes Fabrication	Y	
	2Q			Complete Prototypes Evaluation	Y	
	3Q			Complete Integrated Testing	Y	
	4Q					

ODU Project Schedule

Appendix B: Project Schedule
Old Dominion University
NP Multi-Spoke Superconducting Cavities

	FY10	**FY11**				**FY12**				**FY13**			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Electromagnetic Design of Cavity													
Higher Order Modes Analysis													
Multipacting Analysis													
Engineering Design (with JLab)													
Concepts for rf Couplers													
Concepts for Frequency Tuners													
Prototype Evaluation													
Integration and Testing (with JLab)													

ODU Control Milestones

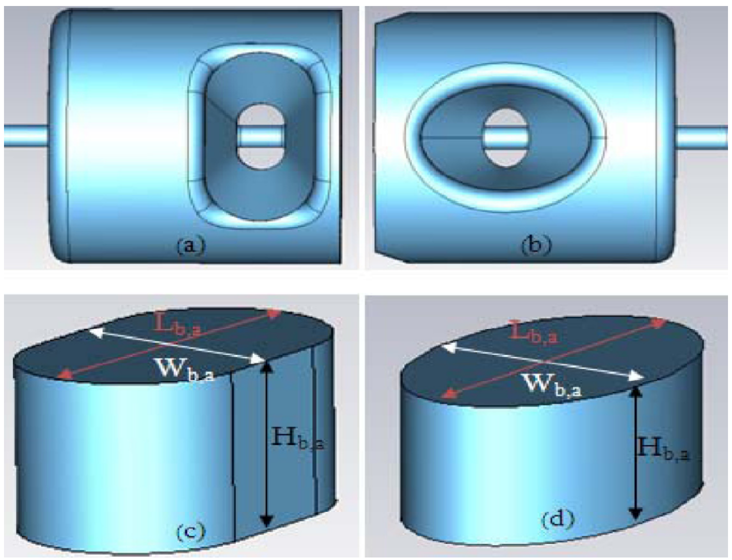
	Control Milestone Name	Baseline Date	Actual /Forecast Date
1	Cavity Parameters Specified	September 30, 2010	September 30, 2010
2	Complete Requirements Document	December 31, 2010	December 31, 2010
3	Complete Conceptual Design of Cavity	March 31, 2011	February 28, 2011
4	Complete Electromagnetic Design of Cavity	June 30, 2011	June 30, 2011
5	Complete Higher-order Mode Analysis	September 30, 2011	
6	Complete Multipacting Analysis	December 31, 2011	
7	Complete Cavity Engineering Design	March 31, 2012	
8	Complete Couplers Concepts Evaluation	June 30, 2012	
9	Complete Tuners Concepts Evaluation	September 30, 2012	
10	Complete Prototype Fabrication	December 31, 2012	
11	Complete Prototypes Evaluation	February 28, 2013	
12	Complete Integrated Testing	June 30, 2013	

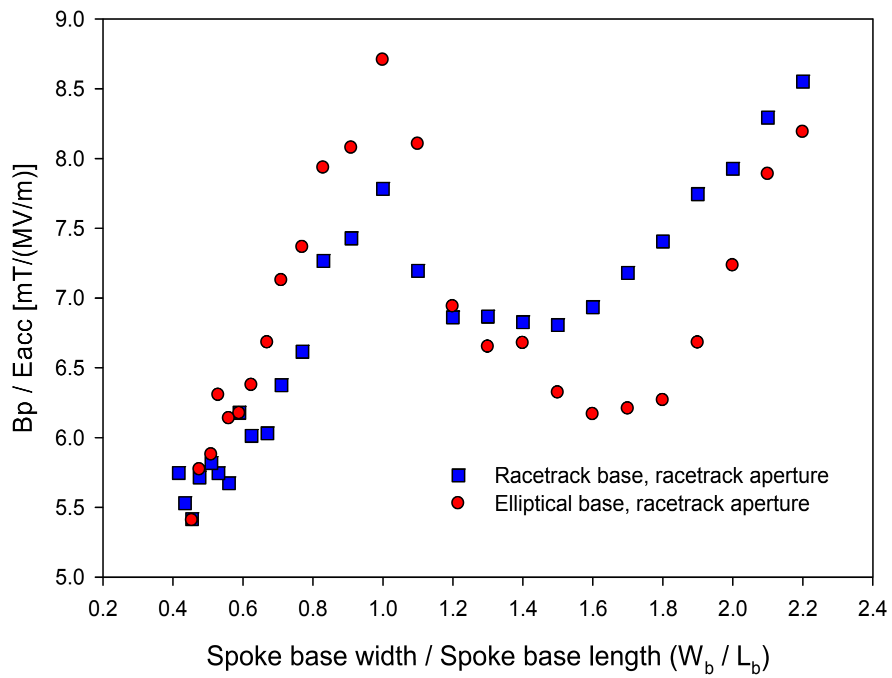
Electromagnetic Design of the Cavities

- We have designed 4 cavities
  - 325 and 352 MHz
  - Optimized for $\beta = v/c$ = 0.82 and 1

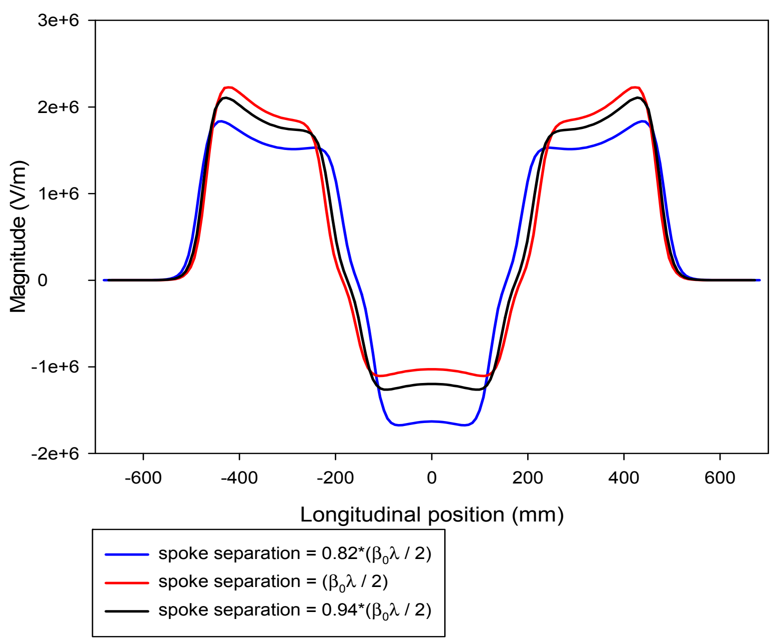
- We have systematically explored the parameter space (keeping frequency and β constant)

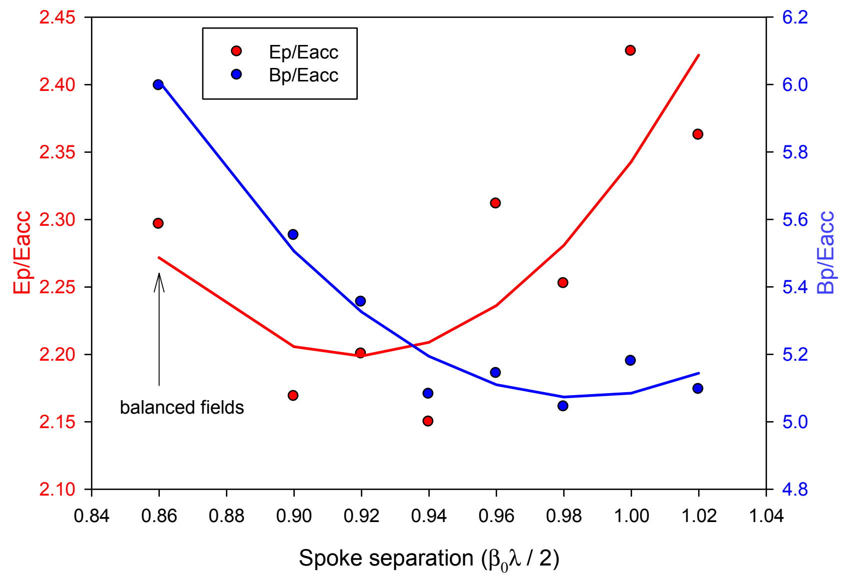
Optimizing Spoke Base Shape



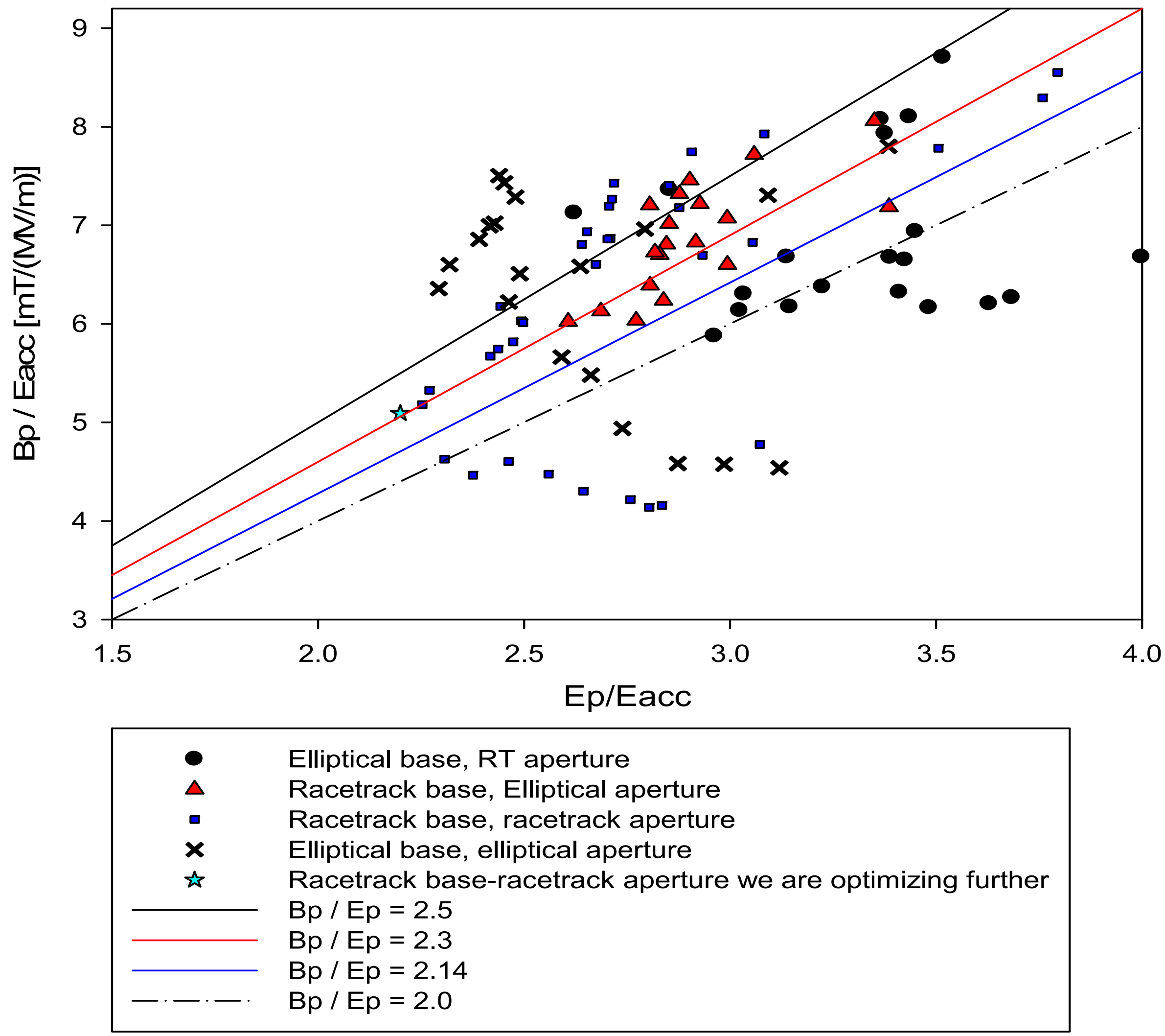


Optimizing Spoke Separation

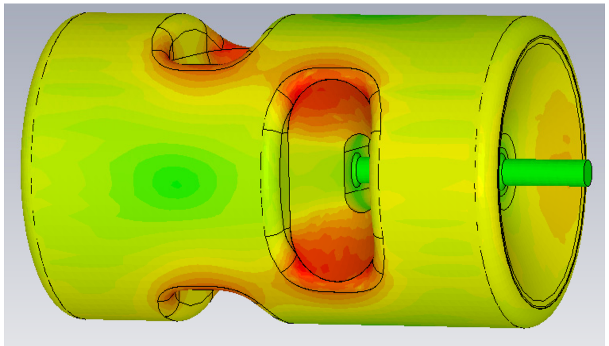


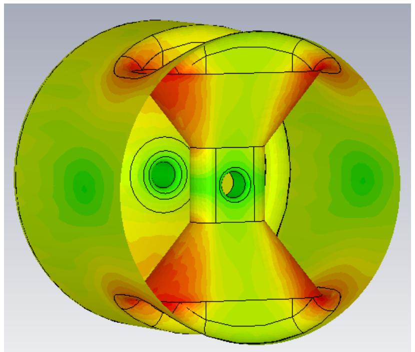


Optimizing B_{peak} and E_{peak} Balance

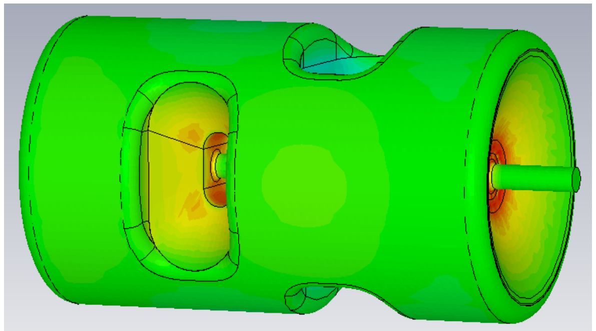


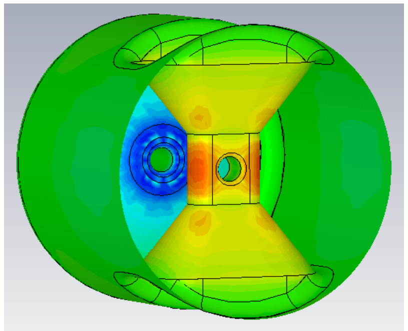
Surface Fields





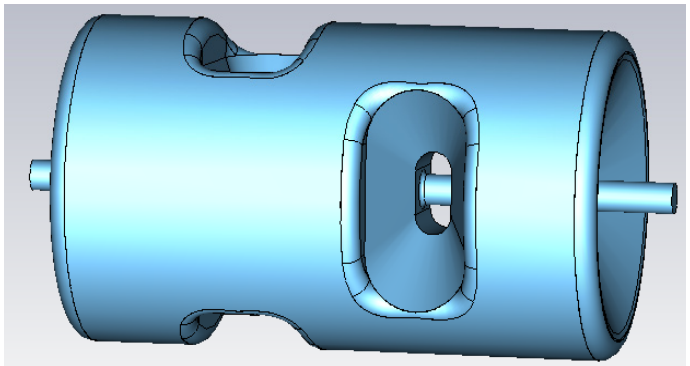
Peak surface magnetic field





Peak surface electric field

2-Spoke, 325 MHz



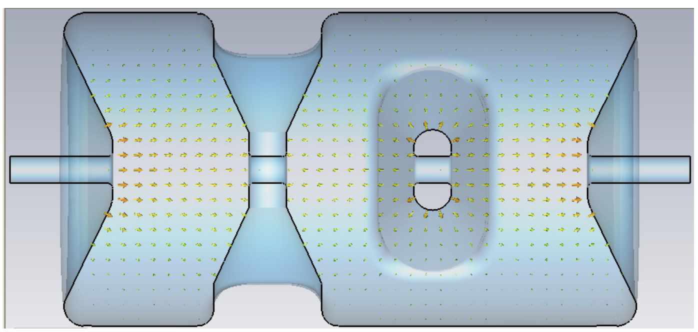


Table 2: Physical Dimensions

Parameter	$\beta_0 = 0.82$	$\beta_0 = 1.0$	**Units**
Cavity diameter	629	642	mm
Iris-to-iris length	956	1178	mm
Cavity length	1136	1370	mm
Aperture diameter	60	60	mm

Table 3: RF parameters

Parameter	$\beta_0 = 0.82$	$\beta_0 = 1.0$	**Units**
Frequency of 0 mode	325	325	MHz
R/Q	543	670	Ω
Geometrical factor	167	184	Ω
E_p / E_{acc}	2.49	2.20	
B_p / E_{acc}	5.4	5.56	mT/(MV/m)
B_p / E_p	2.17	2.53	mT/(MV/m)

At E_{acc} = 1 MV/m and reference length = $\beta_0\lambda$

2-Spoke 352 MHz

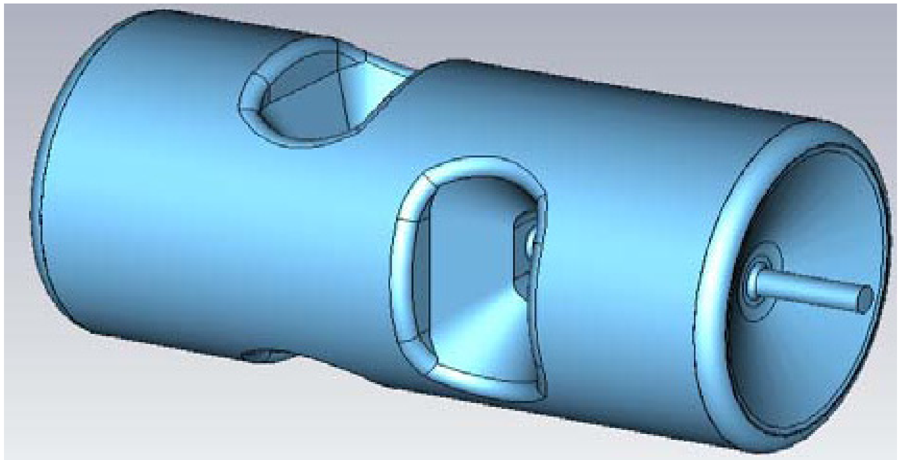


Table 2: Physical Dimensions

Parameter	β_0 = **0.82**	β_0 = **1.0**	**Units**
Cavity diameter	584.4	588	mm
Iris-to-iris length	877	1072	mm
Cavity length	1057	1252	mm
Aperture diameter	50	50	mm

Table 3: RF Parameters

Parameter	β_0 = **0.82**	β_0 = **1.0**	**Units**
Frequency of 0 mode	352	352	MHz
R/Q	545	670	Ω
Geometrical factor	172	184	Ω
E_p / E_{acc}	2.20	2.20	
B_p / E_{acc}	5.09	5.56	mT/(MV/m)
B_p / E_p	2.31	2.53	mT/(MV/m)

At E_{acc} = 1 MV/m and reference length = $\beta_0\lambda$

Higher-order Modes Study

We have identified and calculated the properties of all the HOM up to 3f

Table 2: Cavity modes up to $2f_0$ for $\beta_0 = 0.82$

Mode type	352 MHz Cavity Frequency (MHz)	325 MHz Cavity Frequency (MHz)
Accelerating	352.0, 358.9, 378.5, 501, 527, 663, 685.6, 713.8, 719, 775, 803, 819, 838, 866, 873	325, 329.5, 352.5, 465, 493, 613, 635, 682, 682, 756, 770, 796, 806, 823, 824, 836, 840
Deflecting	478*, 530*, 573*, 615*, 664, 673, 677*, 702, 709.*, 729*, 773*, 848*, 878*	443*, 498*, 534*, 567*, 639*, 648*, 672*, 706*, 773*, 786*, 805*, 813*, 841*
TE-Type	663, 672, 702, 735, 791, 820, 837, 850, 889, 931	628, 642,666, 689, 705, 739, 791, 815, 819, 860

*indicates degenerate modes

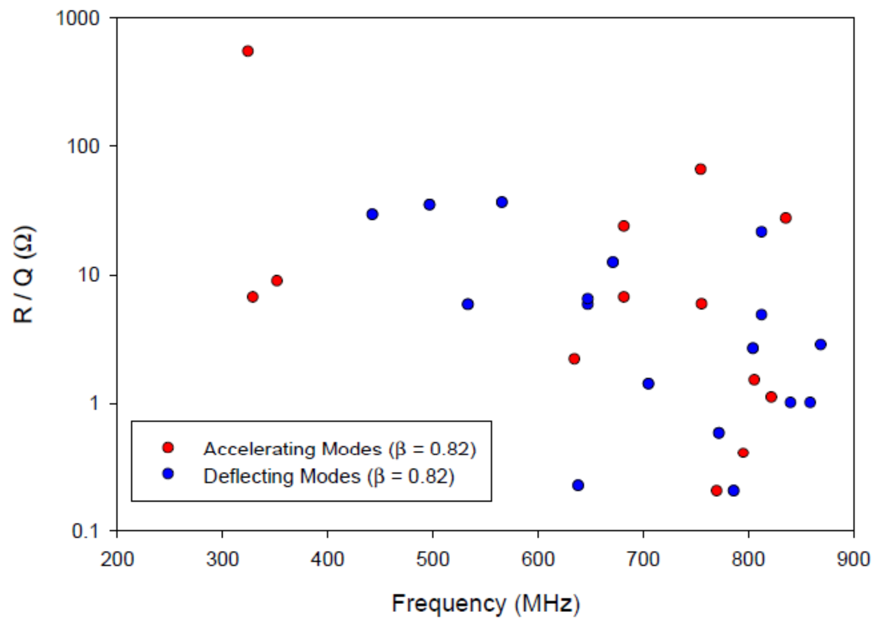


Figure 4: R/Q values for particles at the design velocity, $\beta_0 = 0.82$.

Higher-order Modes Study

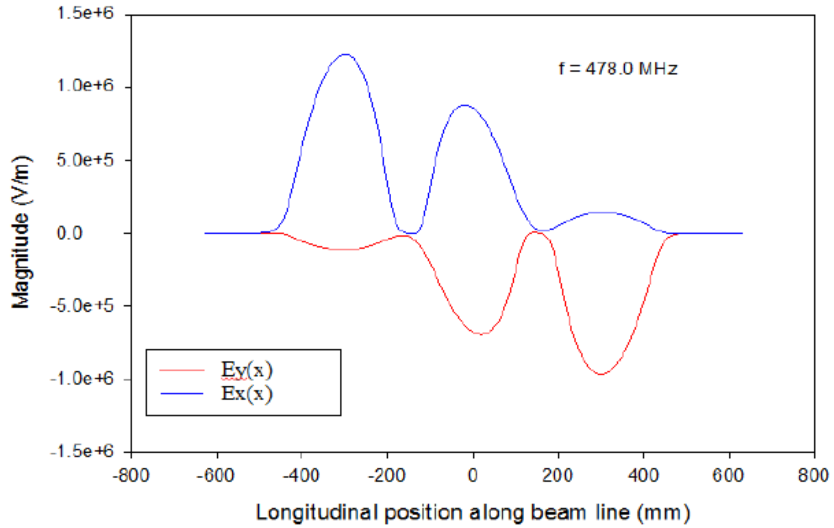


Figure 2: Transverse electric field components along the longitudinal direction for mode 4 (M4) of the 352 MHz, $\beta_0 = 0.82$ cavity.

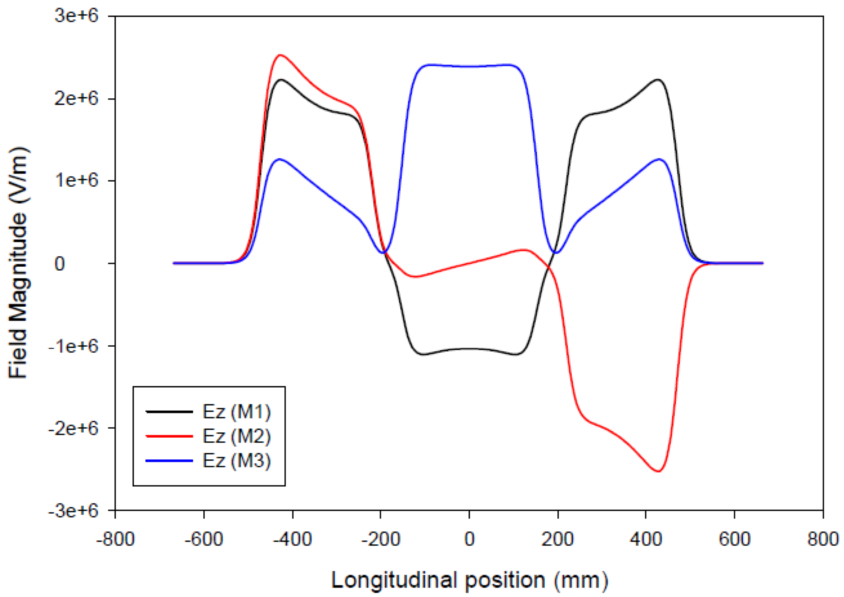


Figure 3: Longitudinal electric field components along the longitudinal direction for the first three accelerating modes of the 325 MHz, $\beta_0 = 0.82$ cavity.

Velocity-dependence of HOM Properties

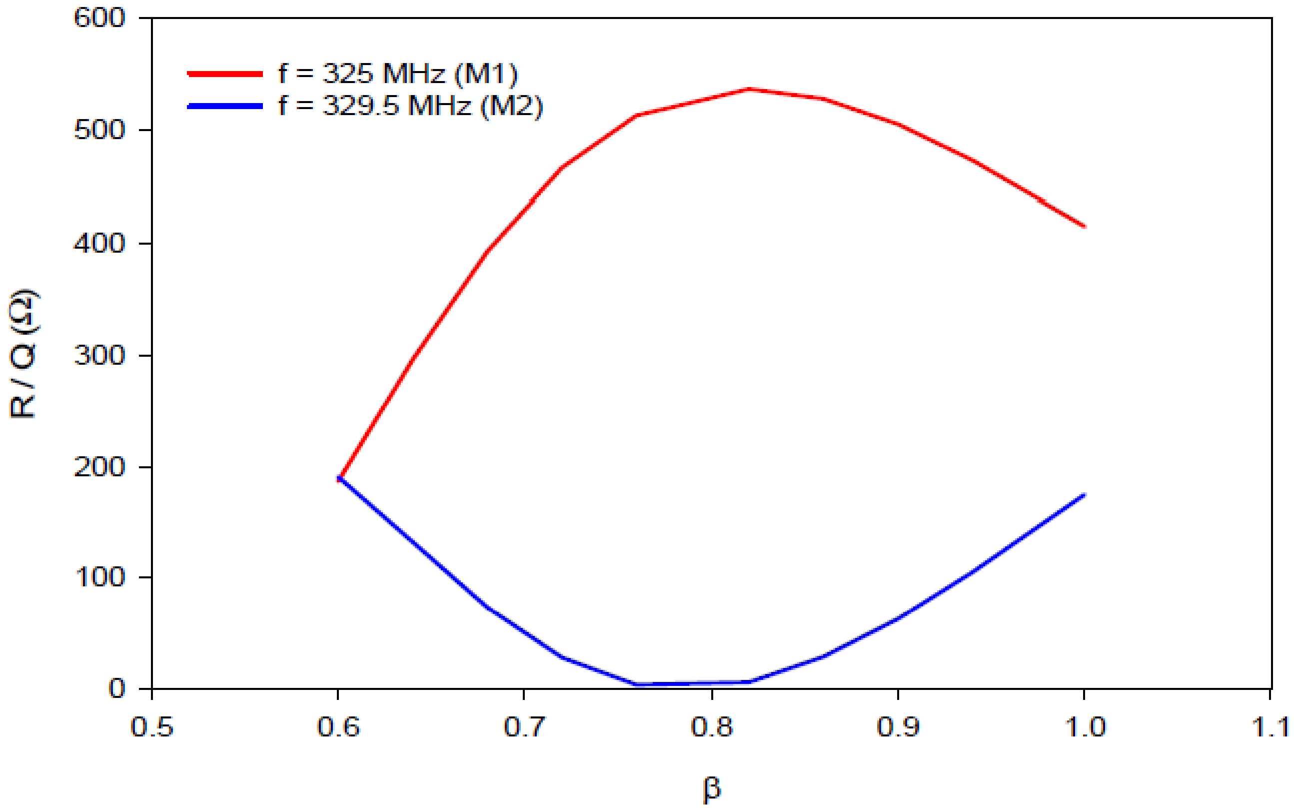


Figure 4: R/Q values for the fundamental mode and the next highest accelerating mode as a function of β.

Velocity-dependence of HOM Properties

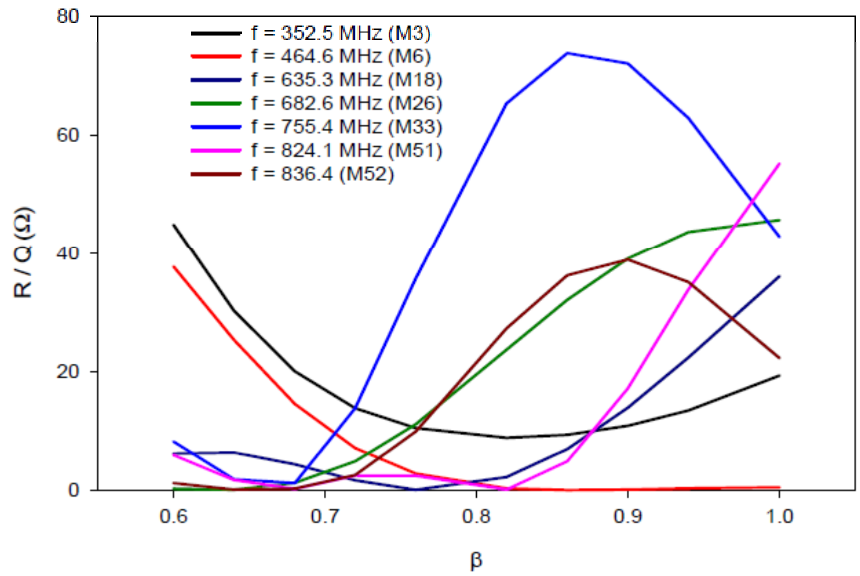


Figure 5: Highest R/Q values for the accelerating modes up to 900 MHz as a function of particle velocity.

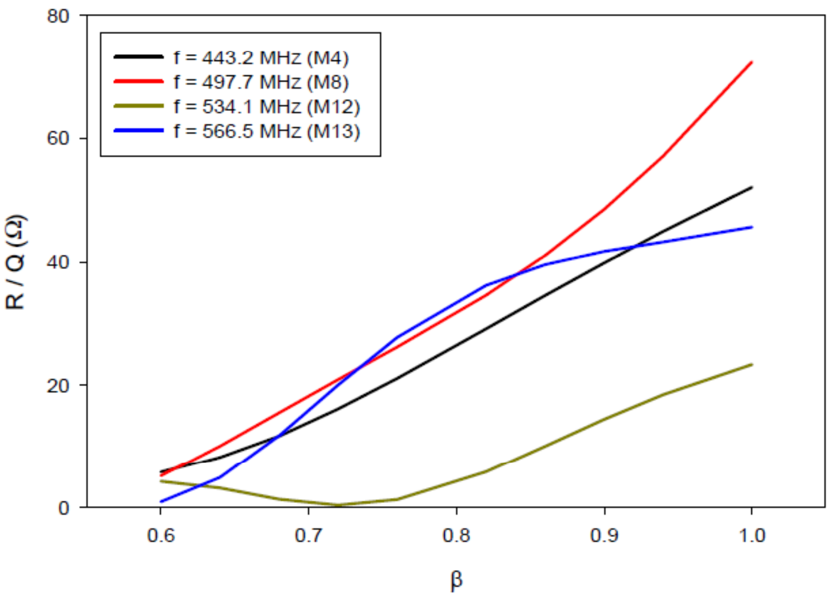


Figure 6: Highest R/Q values for the deflecting modes up to 900 MHz as a function of particle velocity.

Multipacting Analysis

- Will be performed using Omega3P suite of codes developed at SLAC
  - We are already using it for the development of deflecting/crabbing cavities
- 1 student participated in the SLAC workshop last October
- 2 more students and 1 post doc will participate in the workshop next October

Publications

Design of Superconducting Spoke Cavities for High-velocity Applications
J. R. Delayen, S. U. De Silva, C. S. Hopper
2011 Particle Accelerator Conference, New York, NY, 28 March-1 April 2011

Higher-order Mode Properties of Superconducting Two-spoke Cavities
C. S. Hopper, J. R. Delayen, R. G. Olave
2011 International SRF Conference, Chicago, IL, 25-29 July 2011

Design of Superconducting Multi-spoke Cavities for High-velocity Applications
C. S. Hopper, J. R. Delayen
2011 International SRF Conference, Chicago, IL, 25-29 July 2011

Design of Low-frequency Superconducting Spoke Cavities for High Velocity Applications
J. R. Delayen, S. U. de Silva, C. S. Hopper, R. G. Olave
2011 International Particle Accelerator Conference, San Sebastian, Spain, 5-9 September 2011

JLab Control Milestones

Appendix A: Project Control Milestones
Thomas Jefferson National Accelerator Facility
NP Low-Cost Cryostat Project

		Projected Completion Date	Actual Completion Date	Milestone Description	Critical Path	Issues
FY 2010	4Q	September 30	September 30	Cryostat Parameters Specified		
FY 2011	1Q	December 31		Complete Requirements Document		
	2Q	March 31		Complete Evaluation End-loaded Cryostat Concepts		
	3Q	June 30		Complete Evaluation Top-loaded Cryostat Concepts		
	4Q	September 30		Complete Evaluation Existing Cryostat Concepts		
FY2012	1Q	December 31		Preliminary Design of Low-cost Cryostat Concept		
	2Q	January 31		Complete Development Low-cost Cryostat Concept		
	3Q	June 30		Complete Design Cavity Test Bed		
	4Q	September 30		Specify Cavity Test Bed Components		
FY 2013	1Q	December 31		Procure Cavity Test Bed Instrumentation	Y	
	2Q	March 31		Complete Assembly Cavity Test Bed	Y	
	3Q	June 30		Complete Integrated Testing	Y	
	4Q	September 30				

JLab Project Schedule

Appendix B: Project Schedule
Thomas Jefferson National Accelerator Facility
NP Low-Cost Cryostat Project

	FY10	FY11				FY12				FY13			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Design													
Procurement													
Fabrication													
Testing													

JLab Control Milestones

	Control Milestone Name	Baseline Date	Actual /Forecast Date
1	Cryostat Parameters Specified	September 30, 2010	September 30, 2010
2	Complete Requirements Document	December 31, 2010	December 31, 2010
3	Complete Evaluation End-loaded Cryostat Concepts	March 31, 2011	March 31, 2011
4	Complete Evaluation Top-loaded Cryostat Concepts	June 30, 2011	June 30, 2011
5	Complete Evaluation Existing Cryostat Concepts	September 30, 2011	
6	Preliminary Design of Low-cost Cryostat Concept	December 31, 2011	
7	Complete Development Low-cost Cryostat Concept	March 31, 2012	
8	Complete Design Cavity Test Bed	June 30, 2012	
9	Specify Cavity Test Bed Components	September 30, 2012	
10	Procure Cavity Test Bed Instrumentation	December 31, 2012	
11	Complete Assembly Cavity Test Bed	March 31, 2013	
12	Complete Integrated Testing	June 30, 2013	

What are Cryostats?

- Cryostats are the hardware that surrounds the accelerating cavity structures that provide for:
  - Alignment of the beam apertures
  - Thermal isolation of cryogenic components to minimize operating costs
  - Support and alignment for required operational hardware (RF tuners, Instrumentation)
  - Cryogenic piping and controls

Cryostat Engineering?

- Cryostat Engineering Consists of:
  - Mechanical, vibrational and thermal analysis of cryostat components and systems
  - Mechanical CAD models and Design Drawings (packaging)

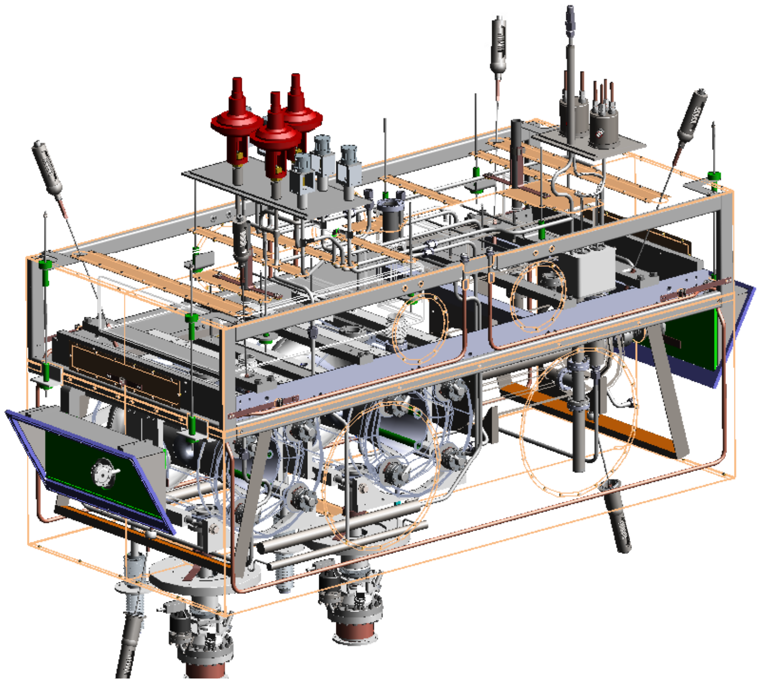
Typically:
- 500-800 Engineering Drawings
- 5-10 Fte's for 1 year
- 500 -600 Components Designed and Packaged

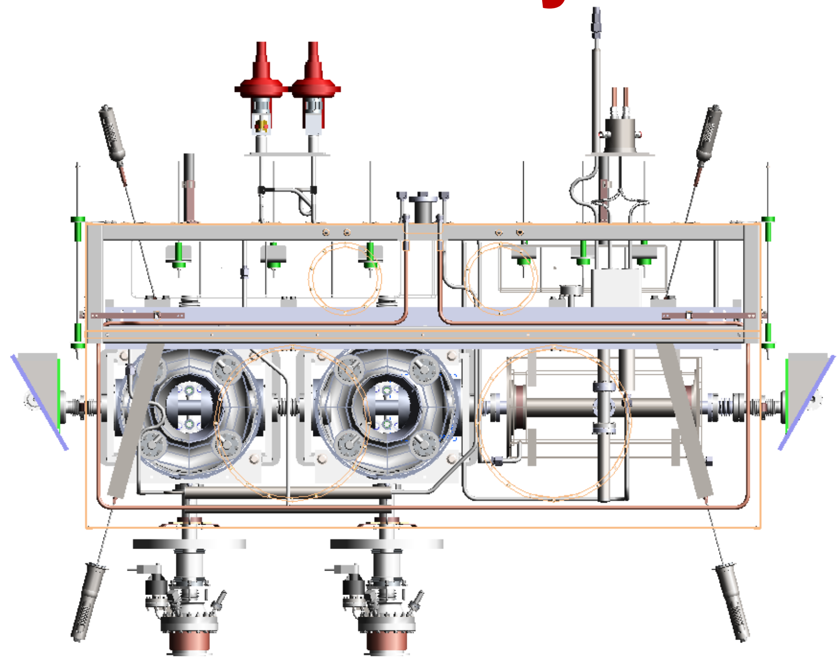
Analysis of Cryostat Designs

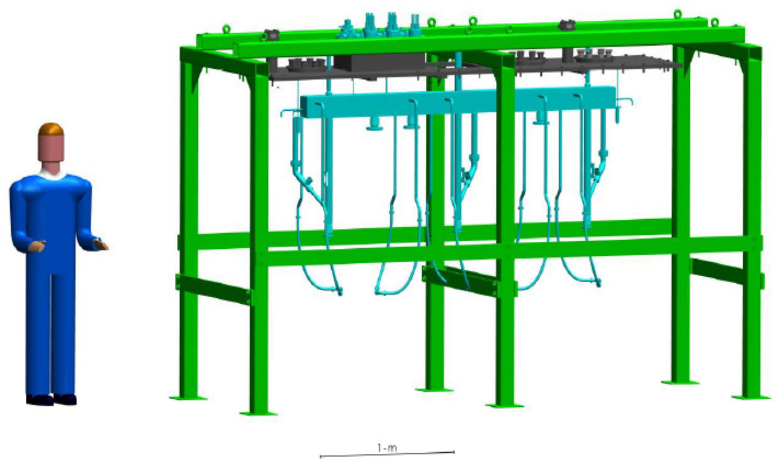
- There are two basic cryostat designs for superconducting accelerator structures (cavities):
  - Top Loaded, **box style** (FRIB, ANL/Atlas, TRIUMF)
  - End Loaded, **cylindrical tube style** (CEBAF, X-FEL, Project-X, ILC)

- In general designs have been chosen to best fit a number of design parameters:
  - **Accelerating cavity shape**, Tunnel dimensions, **Cryogenic system design/interface**, Mounting/alignment of cavities, Cryostat pressure vessel requirements, **Existing SRF tooling and facilities**, String assembly requirements.

FRIB Top Loaded: Assembly







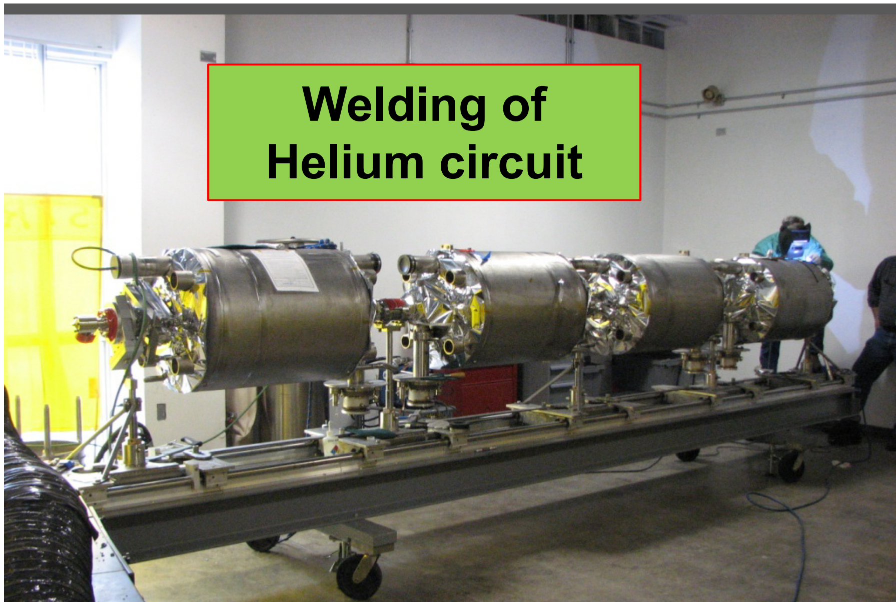
Cryostats are very complicated structures where the design requirements are of the collective system not individual components

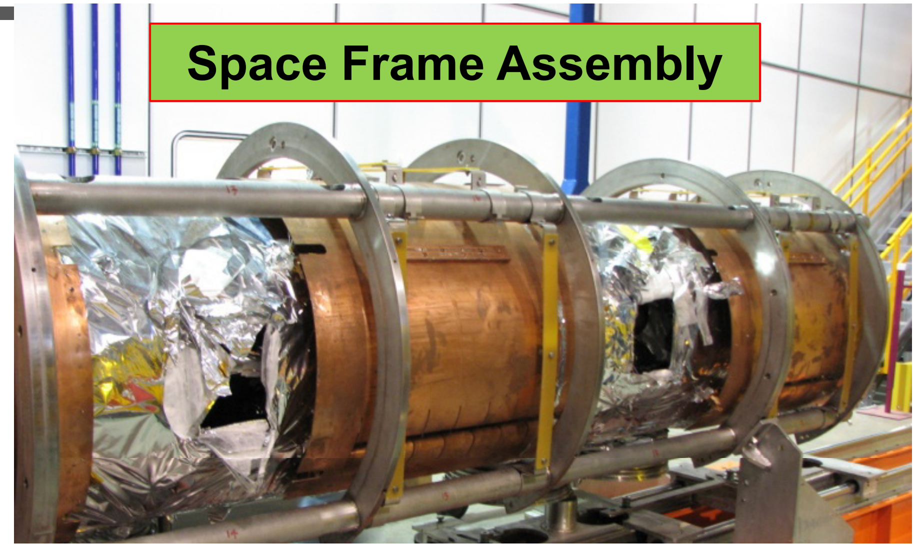
FRIB Top Loaded: Servicing Ports

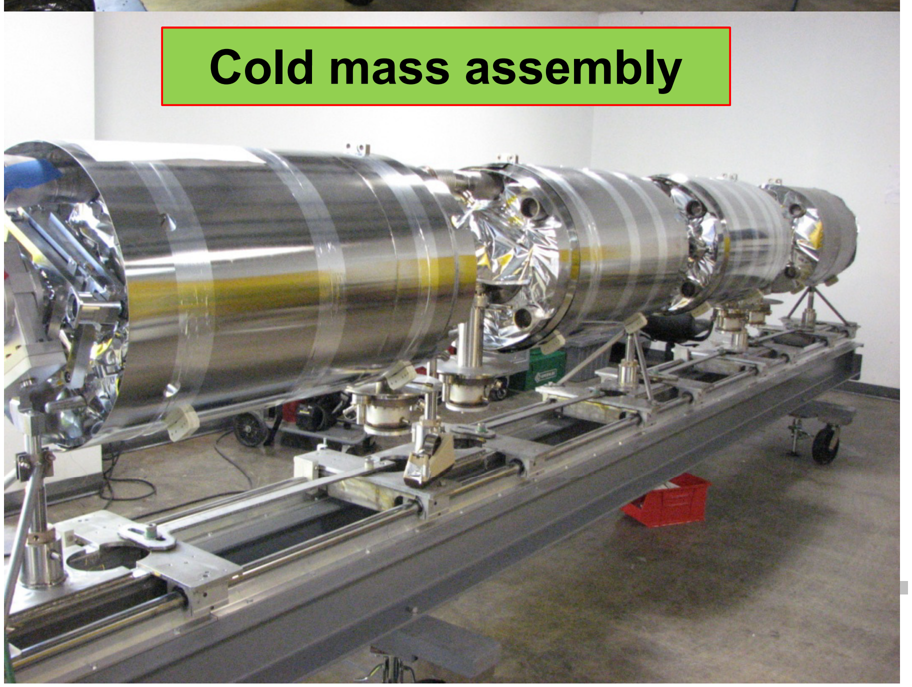
Thermal Shield with service ports

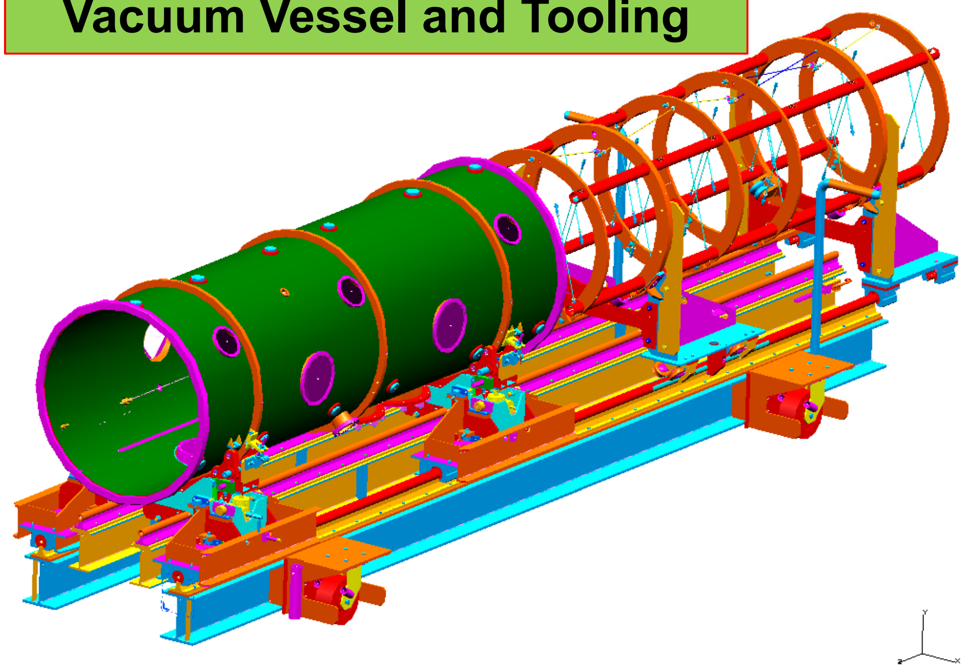
Vacuum Vessel with service ports

Jlab End Loaded Cryostat:


Welding of Helium circuit


Space Frame Assembly

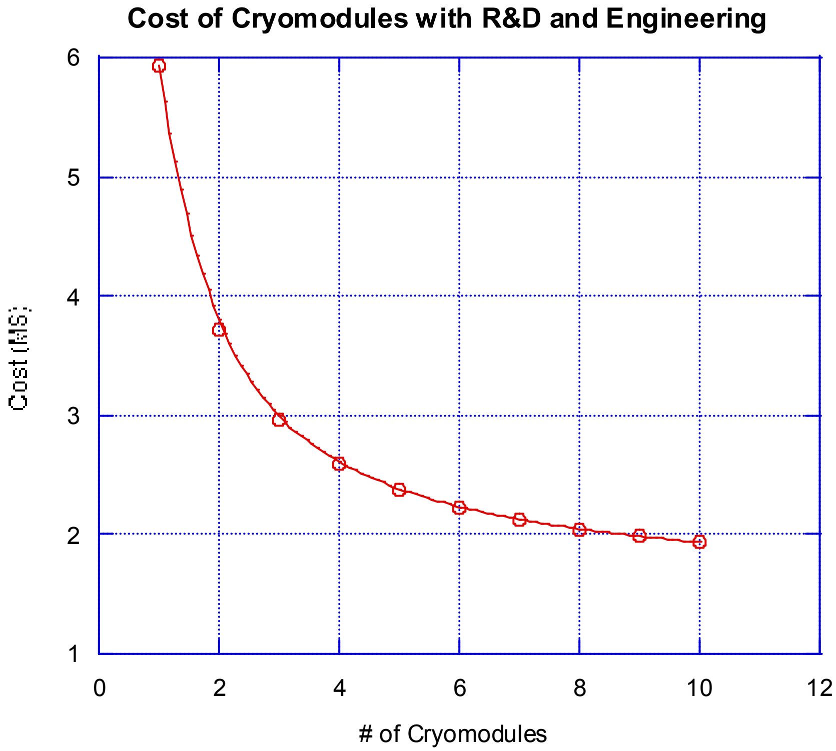

Cold mass assembly

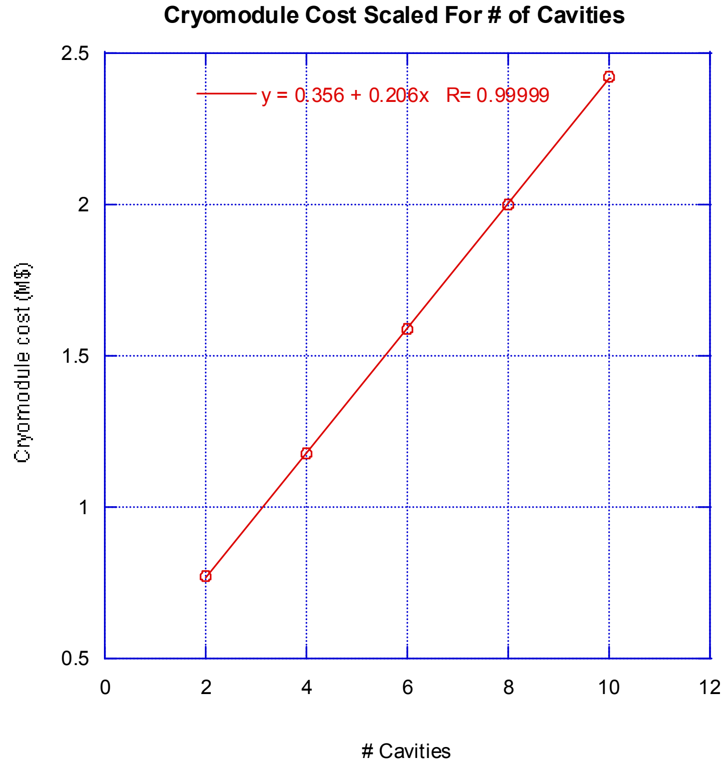

Vacuum Vessel and Tooling

SNS R&D & Engineering Cost

Cryostat R&D and Engineering Amortized Over Number of Cryomodules FY2004 $
Not Included : Project Management, Supplier Management, Installation and Commissioning

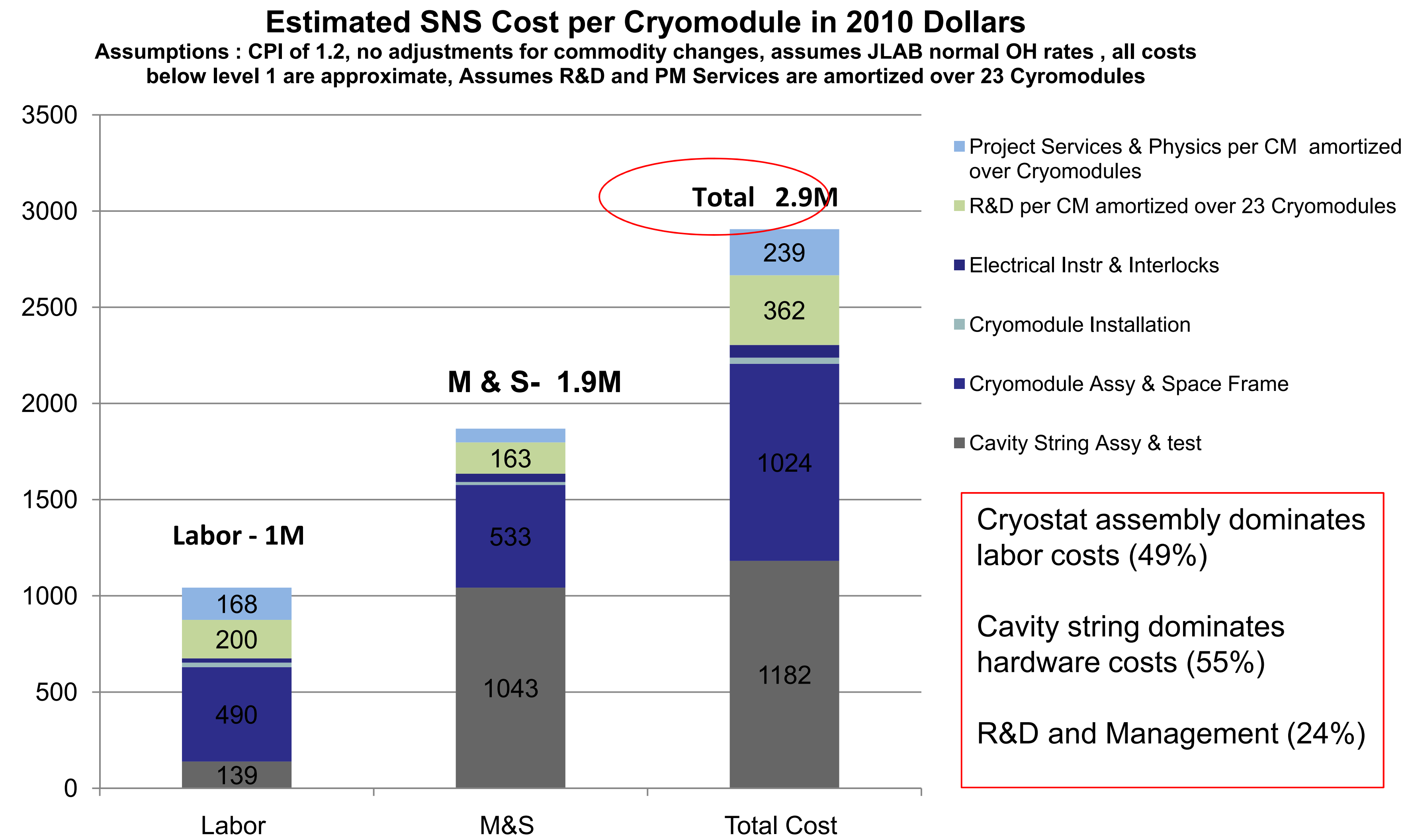
Cryomodule cost roughly driven by cavity string active length or number of cavities





Estimated Cost breakdown per Cryomodule

2010 Dollars, estimating correction for SNS OH rate



Cryostat assembly dominates labor costs (49%)

Cavity string dominates hardware costs (55%)

R&D and Management (24%)

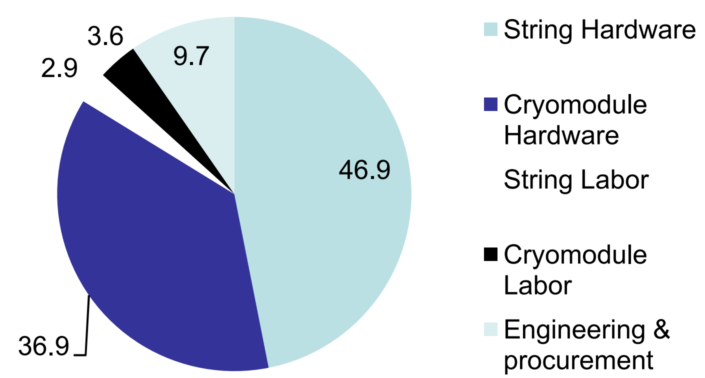
Comparison of SNS cost breakdown to C100 project:

SNS Project (4 -805MHz cavities)		Cost (%)	Cost ($)
String Hardware		40.6	$904,000.00
Cryomodule Hardware		31.1	$692,000.00
String Labor		6.2	$139,000.00
Cryomodule Labor		22.0	$490,000.00
		100.0	$2,225,000.00

Engineering Labor Included

Additional services not added, no R&D

C100 Project (8 1.5GHz cavities)		Cost %
String Hardware		46.9
Cryomodule Hardware		36.9
String Labor		2.9
Cryomodule Labor		3.6
Engineering & procurement		9.7
		100.0



Project not complete and may change over time

Cost Estimate Comparison of End Loaded C100 and Atlas Top Loaded:

	Atlas - Box 2006	2010	Jlab end loaded 2010	
Cryomodule Cost Estimate	Hardware + Labor		Hardware	Labor
Cavity String	(K$)	(K$)	(K$)	(K$)
Cavity Fabrication	946.8	1046.4	664.0	83.5
Helium vessel hardware	91.3	100.9	67.1	24.1
Beamline valves/bellows	20.6	22.8	27.8	0.5
String Assembly			92.6	55.3
RF feedthroughs			86.2	44.3
HOM Dampers	7	7.7		
Helium header			32.0	4.2
Tuner	56.6	62.6	91.0	16.6
Alignment			69.4	17.4
Hardware			9.2	6.9
Labor	**125**	**138.2**		
Sub total	**1247.3**	**1378.5**	**1139.3**	**252.9**
Cryomodule Hardware				
Vacuum vessel	124	137.0	71.3	8.6
Cryogenic controls/valves	15	16.6		
Cryogenic piping	11.3	12.5		
Endcans			126.7	6.6
Thermal shield	35.0	38.6	44.7	6.2
Alignment frame /hardware	63.0	69.6	69.4	17.4
Magnetic shielding	7.1	7.9	24.3	5.9
Instrumentation (thermal diodes, heaters)			115.9	68.0
Thermal Strapping			95.8	26.9
Fast tuner	8	8.8		
MLI			3.2	3.9
RF Coupler /waveguide/ window	75.6	83.6	125.2	25.6
Module stands	6.6	7.3	16.6	0.3
Cryogenic U-tubes	10	11.1		
Misc			10.8	5.5
Labor	**125**	**138.2**		
Sub total	**480.6**	**531.2**	**703.9**	**175.1**
Total Cost	**1727.9**	**1909.7**	**1843.2**	**428.0**

Each estimate for eight cavities:

Summary	Total	Labor	Material
Jlab End Loaded	**2271.1**	**428.0**	**1843.2**
ANL Top Loaded	**1909.7**	**250.0**	**1659.7**
Diff	**361.4**	**178.0**	**183.5**

Results: Top Loaded cryostat is less expensive equally both in Labor and Material by 16%

Data from Atlas cryostat provided by M. Kelly and J. Fuerst

Comments On The Cost of Cryostats:

1. Its hard to compare cryostats costs, some of the costs are hidden (engineering, procurement, management)

2. Typically cryostat designs are not optimized for cost but for functionality, serviceability and optimized packaging

3. Top loaded cryostats have clear advantages over end loaded mainly in servicing, ease of assembly, required space and cost

4. Each type cryostat requires the same functionality and therefore the same type hardware. Cost difference is in the packaging or shape, number of penetrations and packing factor:

Cost Driver for Each Type Cryostat:

Top Loaded		Bottom Loaded		End Loaded	
Material	**Labor**	**Material**	**Labor**	**Material**	**Labor**
String Cavities	Qualifying cavities	String Cavities	Qualifying cavities	String Cavities	Cold mass assembly
Vacuum vessel	Cold mass assembly	NA	Cold mass assembly	End-cans	Qualifying cavities
Couplers/windows	String assembly	NA	String assembly	Couplers/windows	String assembly

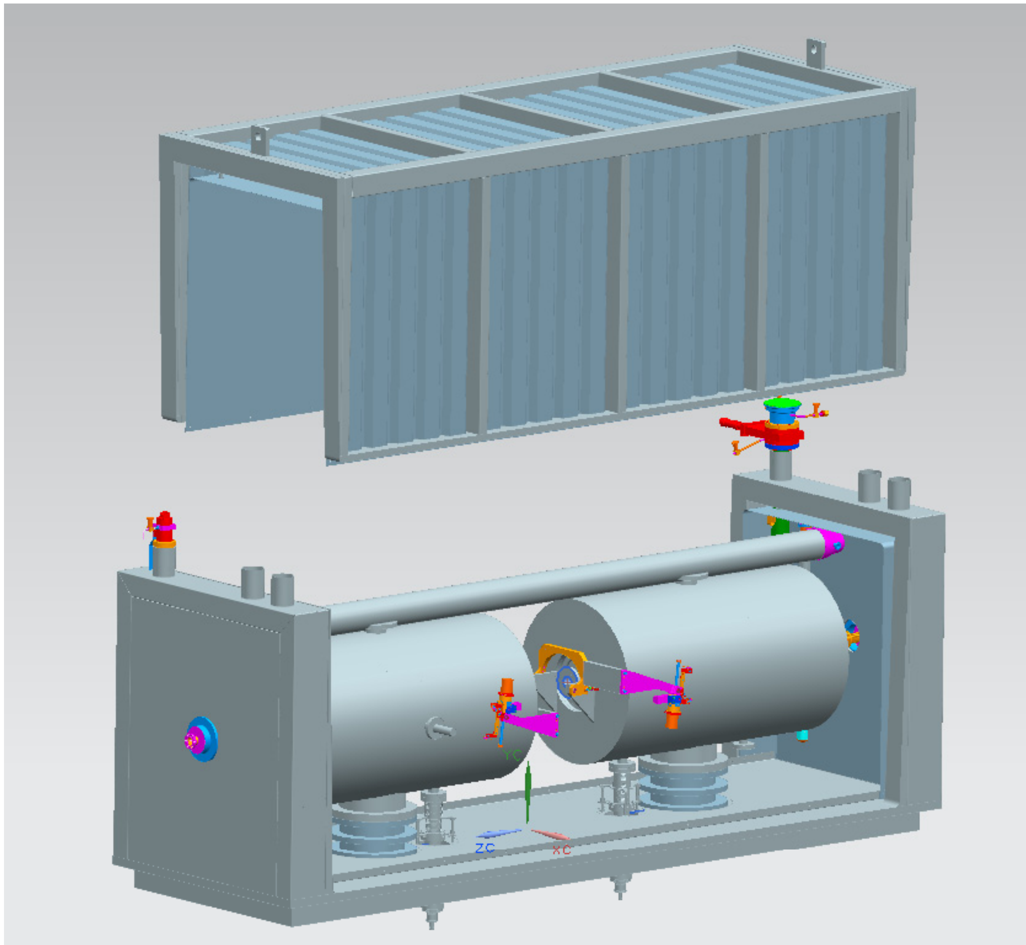
End Loaded cryostat requires more labor at the final stages of assembly and has the additional complication of separate cryogenic end cans

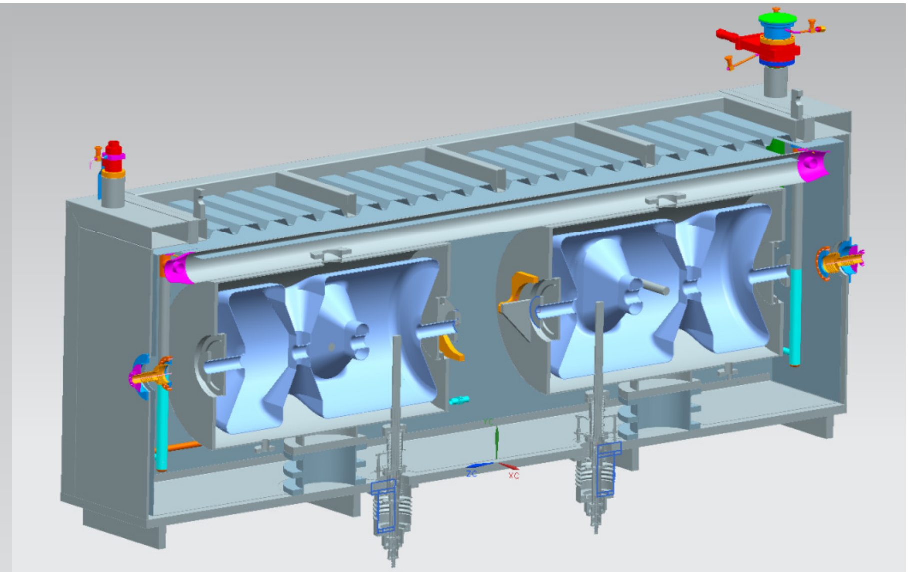
Reducing Cryostat Costs Beyond Top Loaded:

- To reduce costs further then the top loaded design one must look at reducing further assembly and hardware fabrication labor, evaluate alternative materials, reduce tooling costs and assembly facility costs.
  - Assembly labor can be easily reduced by providing better access to all components
  - Hardware fabrication labor can be reduced some by better designs
  - Tooling costs can be reduced by eliminating the need for specialized tooling
  - If the cryostat design is simplified by the above improvements then it can be easily manufactured in small industry

- After evaluating costs and there drivers we ended up with inverting the Top Loaded cryostat now called "Bottom Loaded"

Jlab Bottom Loaded Cryostat Design





Basic concept: Simple box style cryostat using commercial construction materials !!

Bottom Loaded Cryostat:

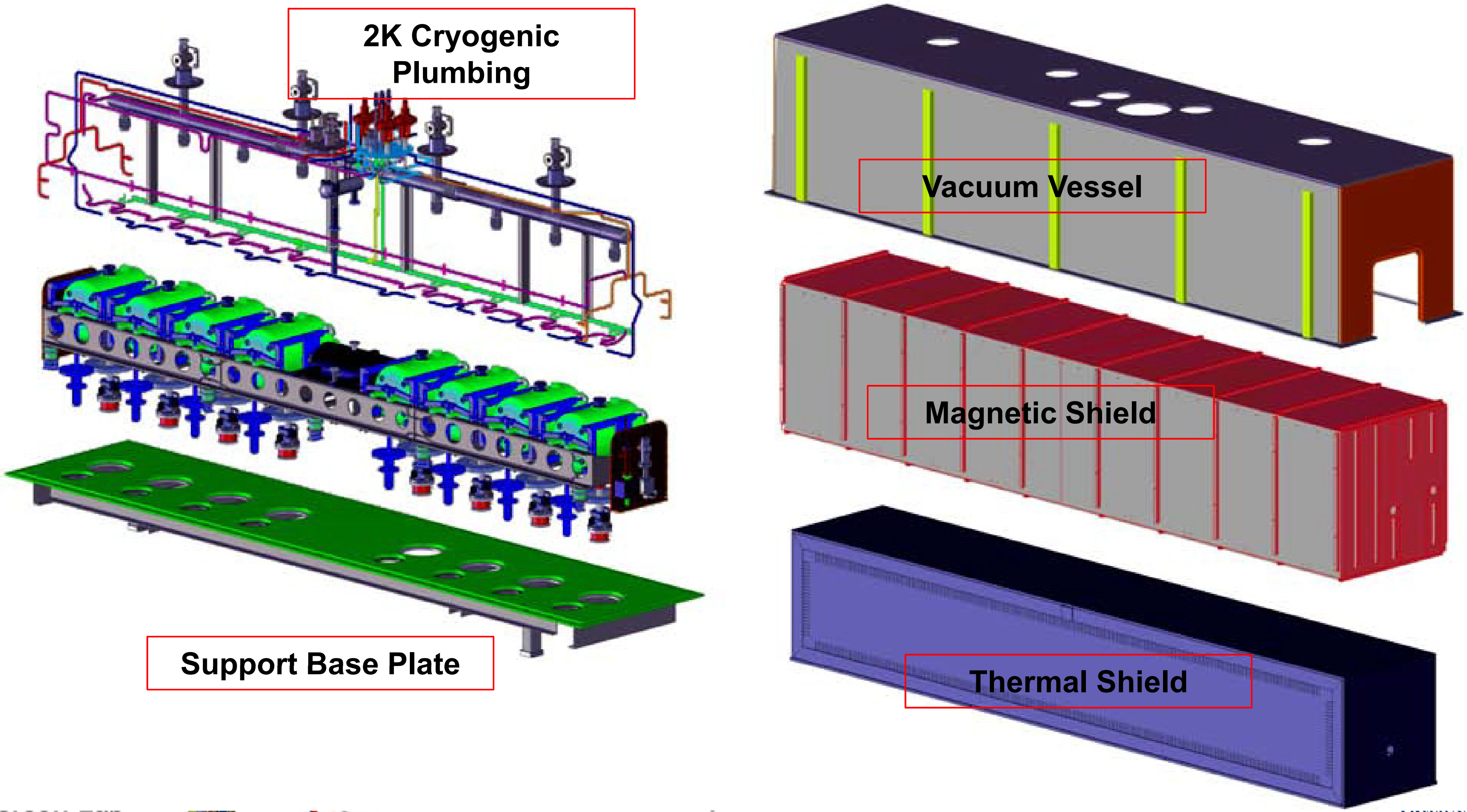
- A bottom loaded cryostat consists of:

  - A base plate or strong back that provides for:
    - The mounting and alignment of the cavity string (it eliminates the string and cryostat tooling)
    - This base plate incorporates most of the penetrations through the vacuum shell (reducing the complexity of the overall design)
    - Cryogenics plumbing and reliefs

  - Box Top that provides for:
    - Vacuum Shell Hermetically sealing the string (reduced penetrations simplifies cost and allows for standard construction materials)
    - Service access (greater access is possible as well as major repair service options)
    - Mounting of a simplified thermal shield and magnetic shielding (reducing costs of the major components)

FRIB's Bottom Loaded Cryostat Design:

Campaign Area 2: Final FRIB Cryomodule Design Is Developed In FY 2011/2012 [1]



Budgets as of 30 June

ODU

WBS or ID #	Item/Activity	Baseline Total Cost (AY$)	Costed & Committed (AY$)	Estimate To Complete (AY$)	Estimated Total Cost (AY$)
MSPD	Design	$250k	$106.9k	$143.1k	$250k
MSPP	Prototyping	$400k	0	$400k	$400k
MSPF	Fabrication	$598k	0	$598k	$598k
MSPT	Testing	$200k	0	$200k	$200k
Totals:		$1448k	$106.9k	$1341.1k	$1448k

JLab Cryostat

WBS or ID #	Item/Activity	Baseline Total Cost (AY$)	Costed & Committed (AY$)	Estimate To Complete (AY$)	Estimated Total Cost (AY$)
MSSCCT	Engineering Design for Cryostat	$440.0	$110.7	$329.3	$440.0
MSSCCT	Assemble and Test Cryostat, Cavity, Tuner & Coupler	$125.0	0	$125.0	$125.0
Totals:		$565.0	$110.7	$454.3	$565.0

JLab Cavity

WBS or ID #	Item/Activity	Baseline Total Cost (AY$)	Costed & Committed (AY$)	Estimate To Complete (AY$)	Estimated Total Cost (AY$)
MSSCCA	Complete Engineering Design for Cavity, Coupler & Tuner	$137.0	16.8	120.2	$137.0
MSSCCA	Fabricate & Test Cavity, Coupler & Tuner	$448.0	0	448.0	$448.0
Totals:		$585.0	16.8	568.2	$585.0

Deliverables for this Project

- One high-velocity, low-frequency, 2-spoke cavity
  - tested at cryogenic temperature (2 to 4K)
- Evaluation and prototyping of new concepts for cryomodule designs
  - Low cost
  - Ease of assembly
  - Operation at 2 – 4.2K
- Evaluation and prototyping of new concepts for
  - Couplers
  - Tuners
- Engineering drawings and cost estimates

Follow-on Work

- Develop, fabricate, and test a fully engineered cryomodule based on the concepts developed in the present work
  - At least 2 cavities
  - Fully instrumented
  - Suitable for installation and operation in a beamline