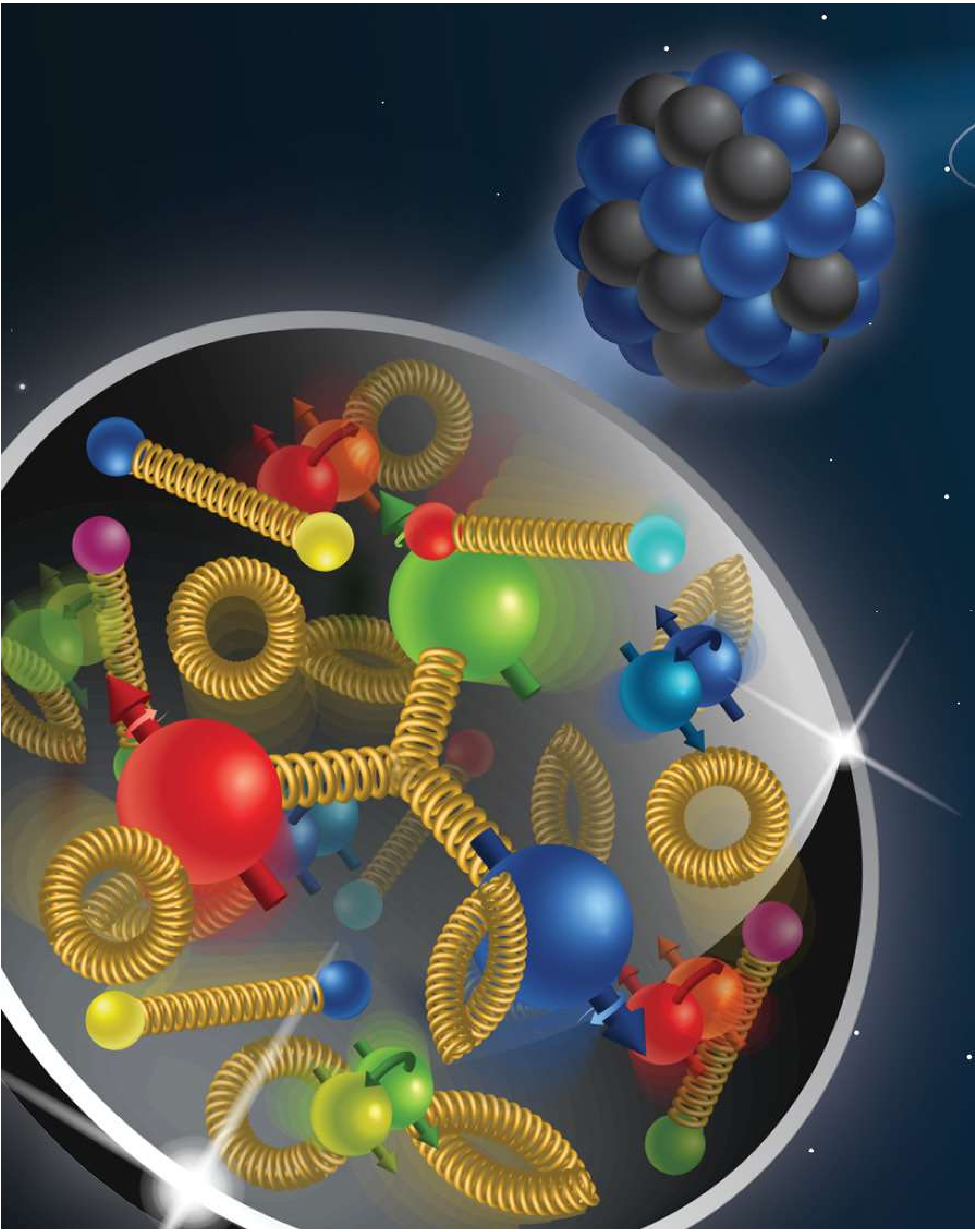


EIC
Spin Rotator Solenoids
FY’20 Task Force Results

October 2021

Tim Michalski

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY Office of Science

Presentation Overview

- Overview of Requirements
- Coil Electromagnetic Design
- Conductor / Coil Analyses
- Mechanical Design
- Coil Assembly Structural Analysis
- Considerations for the Detailed Design
- Summary

Overview of Requirements

Overview of Requirements

Description		Requirement		Comments
Parameter	**Unit**	**Short Solenoid**	**Long Solenoid**	
Integrated Field	T-m	18.33	57.6	
Magnet Length	m	2.7	9	See note 2
Solenoid Central Field max (B0)	T	6.79	6.4	See note 2
Operating Temperature	K	4.5	4.5	
Good Field Radius	mm	20	20	
Conductor	-	NbTi	NbTi	
Cooling method		Recondensing Cryostat	Recondensing Cryostat	Connected to IR6 cryogenic plant
Current operating margin from load line	%	>20	>20	
Required field quality (homogeneity within good field radius)	%	0.1	0.1	
Fringe Field at 0.5m from beam center	mT	50	50	Design Assumption – requirement still pending
IMPLEMENTATION DETAILS				
Physical Length	m	3.00	9.05	See note 1
Magnetic Length (as implemented)	m	2.7	8.1	See note 2
Solenoid Central Field	T	6.79	7.11	See note 2

Notes:

1. The pCDR describes a baseline design requirement of using the same, cryostated coil design for both the long and short SRS
2. This drives a single 2.7m coil design (2.7m magnetic length for the short SRS and 8.1m magnetic length for the long SRS) with a mechanical length of ~3m
3. The total number of magnets is 16

Overview of Requirements

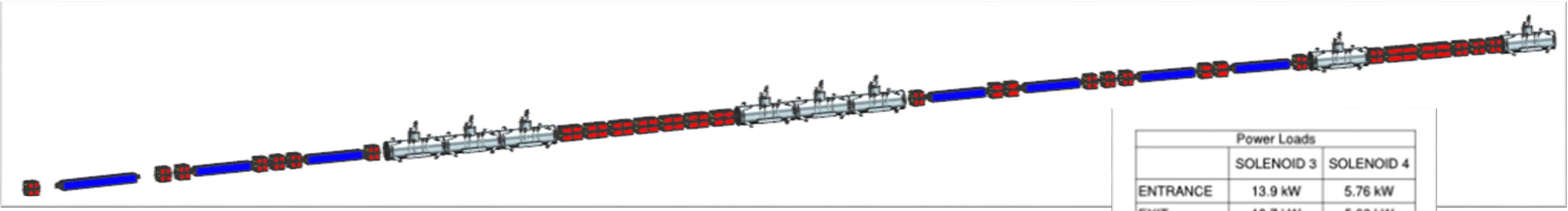
Description		Requirement		
Parameter	**Unit**	**Short Solenoid**	**Long Solenoid**	
Integrated Field	T-m	18.33	57.6	
Magnet Length	m	2.7	9	See note 2
Solenoid Central Field max (B0)	T	6.79	6.4	See note 2
Operating Tem				
Good Field Rad				
Conductor				
Cooling metho				
Current operat				
Required field good field radiu				
Fringe Field at				requirement still pending
IMPLEMENTATION DETAILS				
Physical Length	m	3.00	9.05	See note 1
Magnetic Length (as implemented)	m	2.7	8.1	See note 2
Solenoid Central Field	T	6.79	7.11	See note 2

- *A baseline design requirement – use the same, cryostated coil design for both the long and short SRS*
- *This drives a single 2.7m coil design – slight increase in peak field for the Long Solenoid version (6.4T→7.11T)*
- *The total number of magnets is 16 – all the same*

Notes:

1. The pCDR describes a baseline design requirement of using the same, cryostated coil design for both the long and short SRS
2. This drives a single 2.7m coil design (2.7m magnetic length for the short SRS and 8.1m magnetic length for the long SRS) with a mechanical length of ~3m
3. The total number of magnets is 16

Spin Rotator Solenoid Synchrotron Radiation Assessment

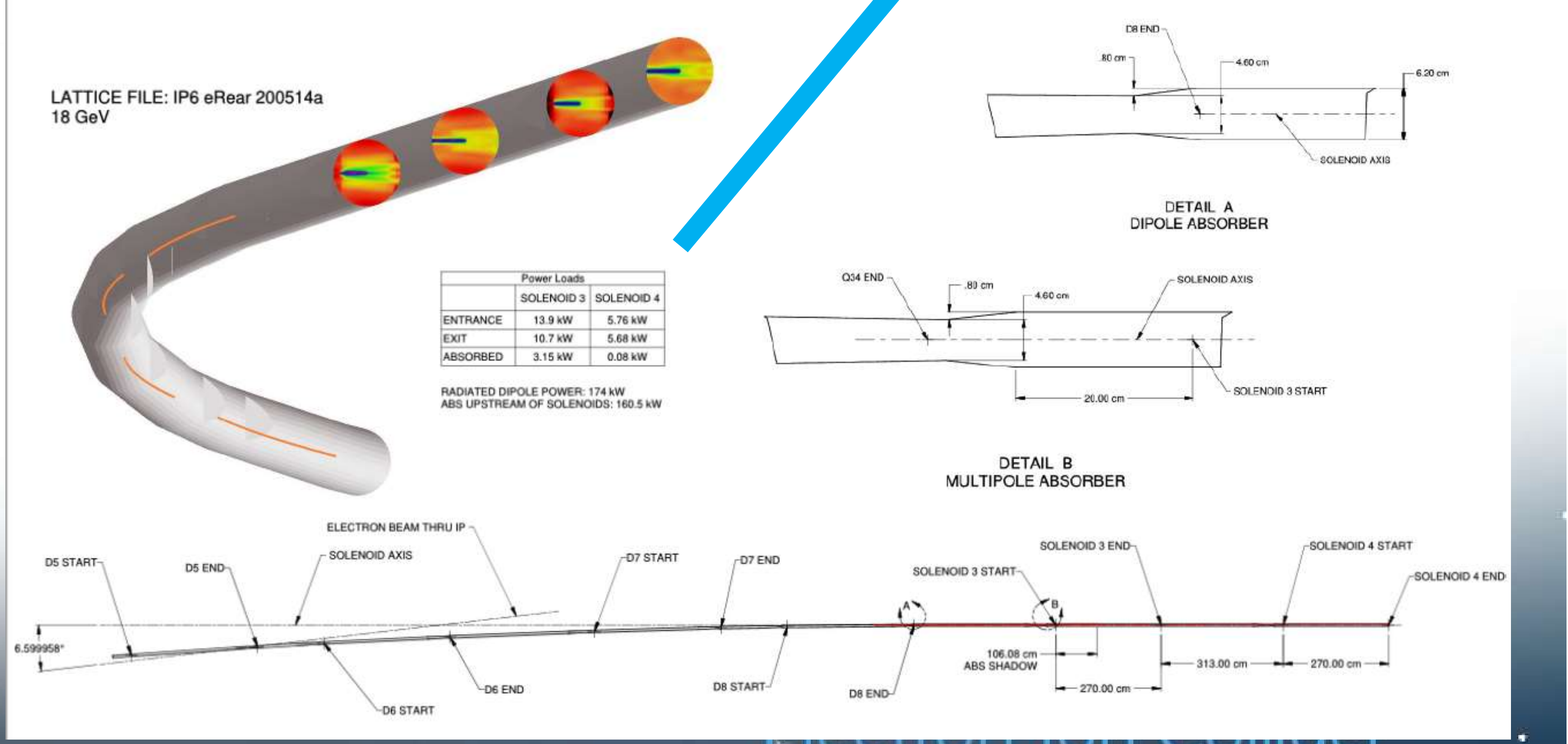


Power Loads		
	SOLENOID 3	SOLENOID 4
ENTRANCE	13.9 kW	5.76 kW
EXIT	10.7 kW	5.68 kW
ABSORBED	3.15 kW	0.08 kW

RADIATED DIPOLE POWER: 174 kW
ABS UPSTREAM OF SOLENOIDS: 160.5 kW

- Early assessment of the Spin Rotator Solenoids (SRS) within the ESR lattice showed strong dipoles next to the solenoids
- Assessment of the resulting synchrotron radiation dictates using an inserted vacuum beam pipe with adequate cooling and distributed vacuum pumping

Spin Rotator 3 and 4 (2.7m long) Downstream of Detector

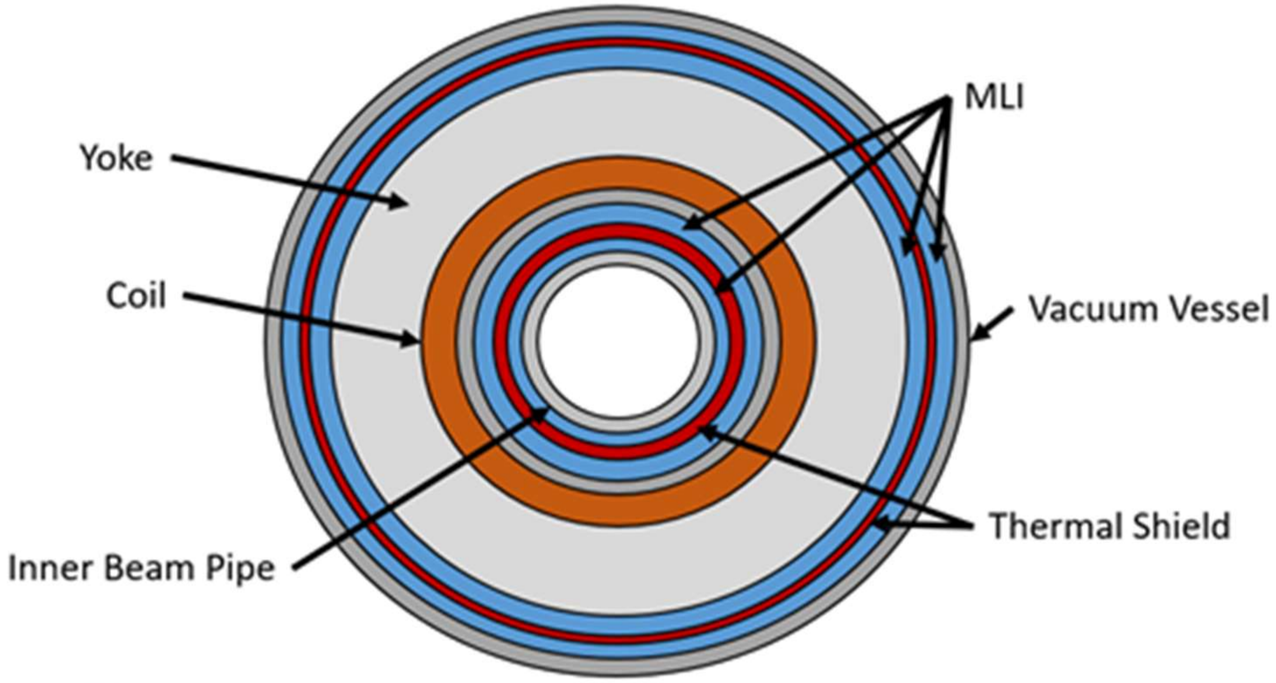


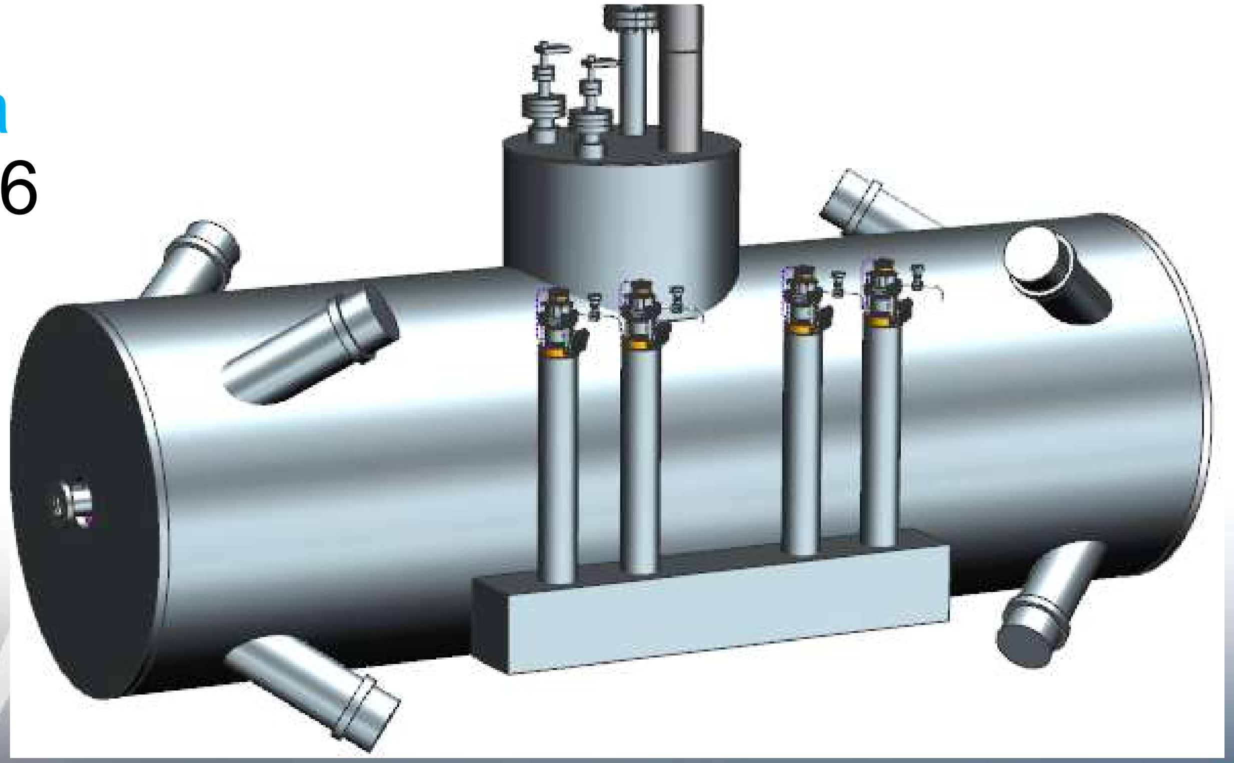
Power Loads		
	SOLENOID 3	SOLENOID 4
ENTRANCE	13.9 kW	5.76 kW
EXIT	10.7 kW	5.68 kW
ABSORBED	3.15 kW	0.08 kW

RADIATED DIPOLE POWER: 174 kW
ABS UPSTREAM OF SOLENOIDS: 160.5 kW

Overview of Requirements and Design Decisions

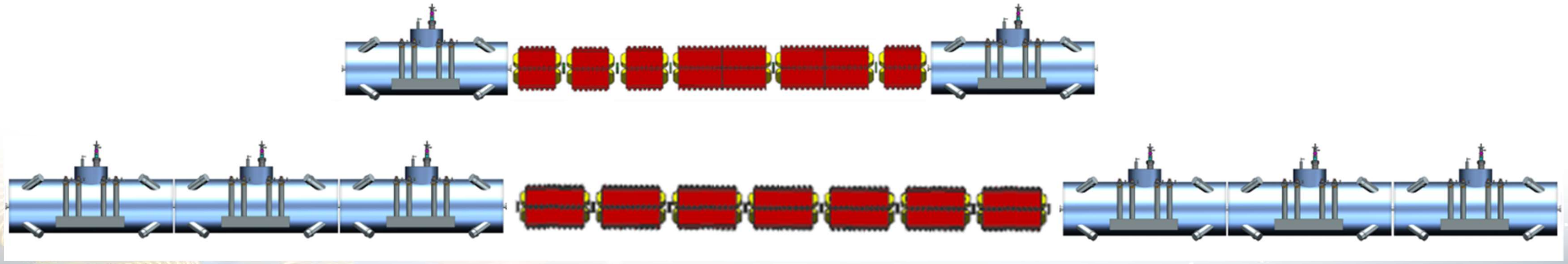
- The result of the synchrotron radiation assessment was a decision to use a warm bore magnet design with an aperture large enough to fit a vacuum flange
- The initial decision was to contain all magnet elements within the cryostat (yoke and shielding)
- LHe cooling will be provided via bayonets, to connect to the IR06 cryogenic distribution system





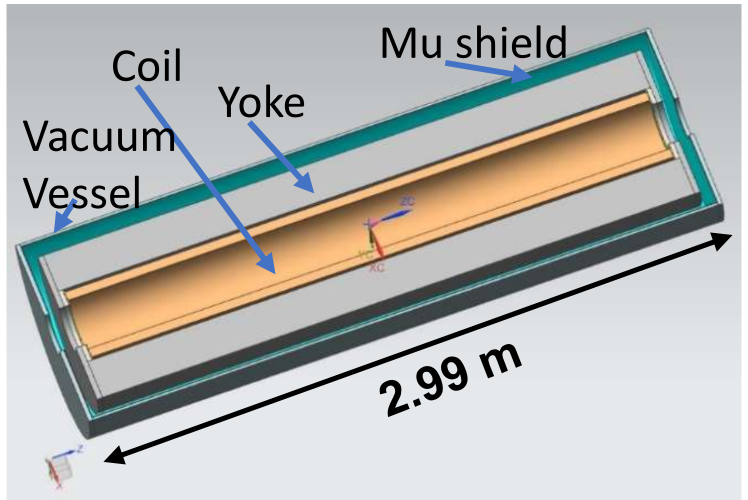
Short and Long Spin Rotator Solenoid Conceptual Design Implementations

- Concept layouts based on April 28, 2020 snapshot of the ESR lattice file.
- Warm magnets are based on magnetic length plus ends.
- Consideration will be required for vacuum chambers.
- Vacuum chambers through SRS magnets will probably require distributed pumping ports and LCW cooling connections outside of the SRS magnets.

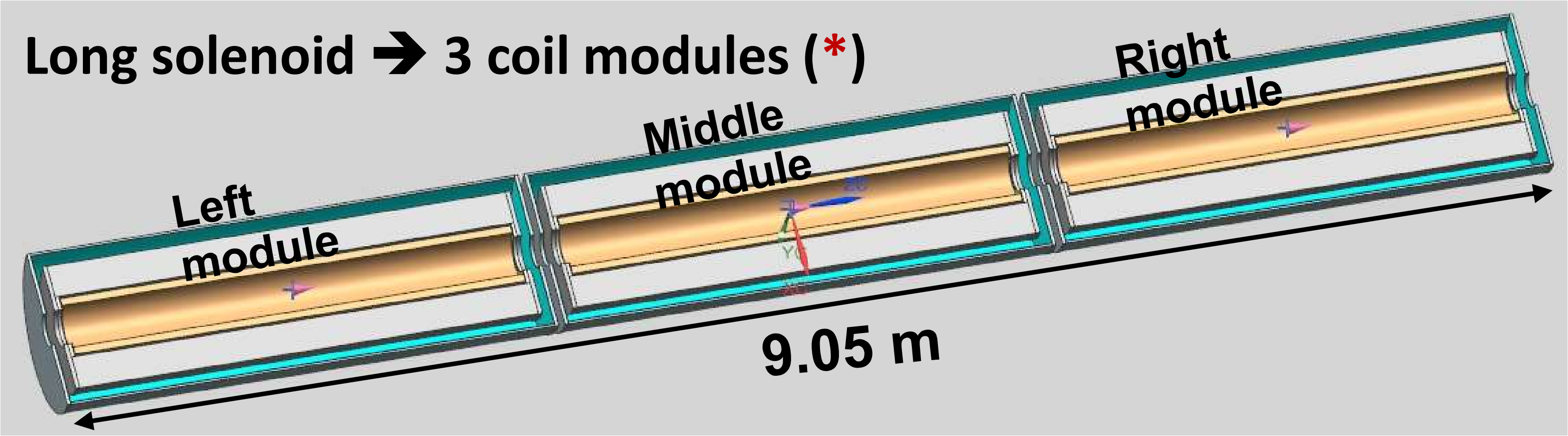


Coil Electromagnetic Design

Assumptions for the Modular Coil Design



Short solenoid ➔1 coil module (*)



Longitudinal cross section

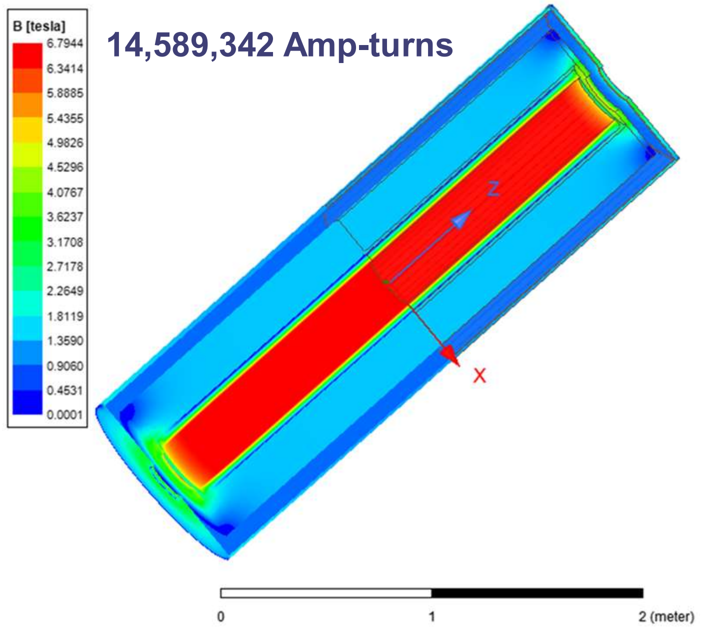
1. One coil design to suit both short and long spin rotator applications.
2. Each coil is individually cryostated.
3. The inner radius of the coil = 135 mm (determined by warm bore radius of 68 mm in consideration of the potential synchrotron radiation loads + space allocation for the magnet system components).
4. Integrated field is the main requirement, no requirement for field straightness.
5. Corrector coils (to tune the solenoid field straightness) are not needed (design decision at the time).
6. Magnetic shielding elements can be included to accomplish the fringe field requirements at 0.5 m radially away from the longitudinal axis of the magnet.
7. The parameters under consideration for magnet operational safety are (a) Operating current margin : 20% (requirement), (b) Hot spot temperature : < 150 K

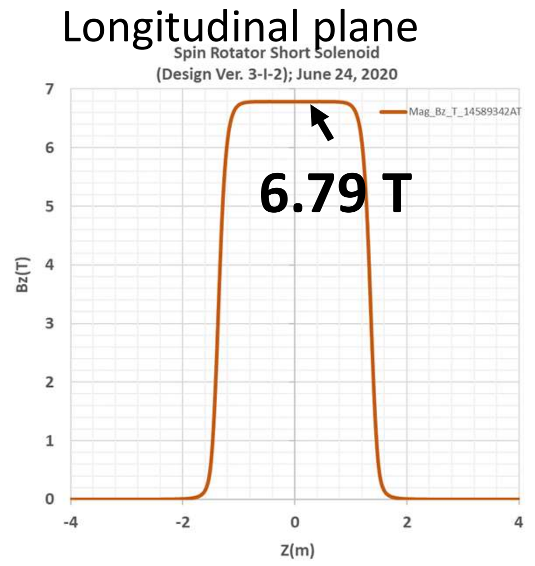
EM Performance of the Spin Rotator Short Solenoid (Magnetic Length- 2.7 m)

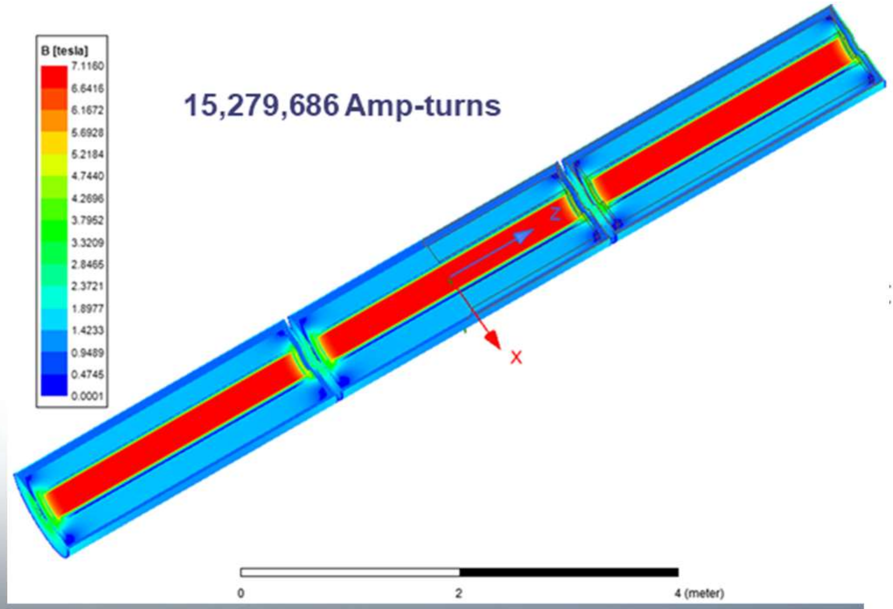
- The EM design analysis results are compared with the magnetic performance requirements from BNL.
  - —Fulfills the requirements (☑)

Spin Rotator Short Solenoid performance parameters

Parameter	**Unit**	**Value**	
		Short	Long
Operating current	Amp-turns	14,589,342	15,279,686
Central field	T	6.79	7.11
Integrated field strength along longitudinal (Z) axis	T-m	18.33	57.6
Magnetic length	m	2.7	8.1
Peak field in the coil winding	T	6.794	7.12
Magnetic Stored Energy	MJ	3.37	11.1

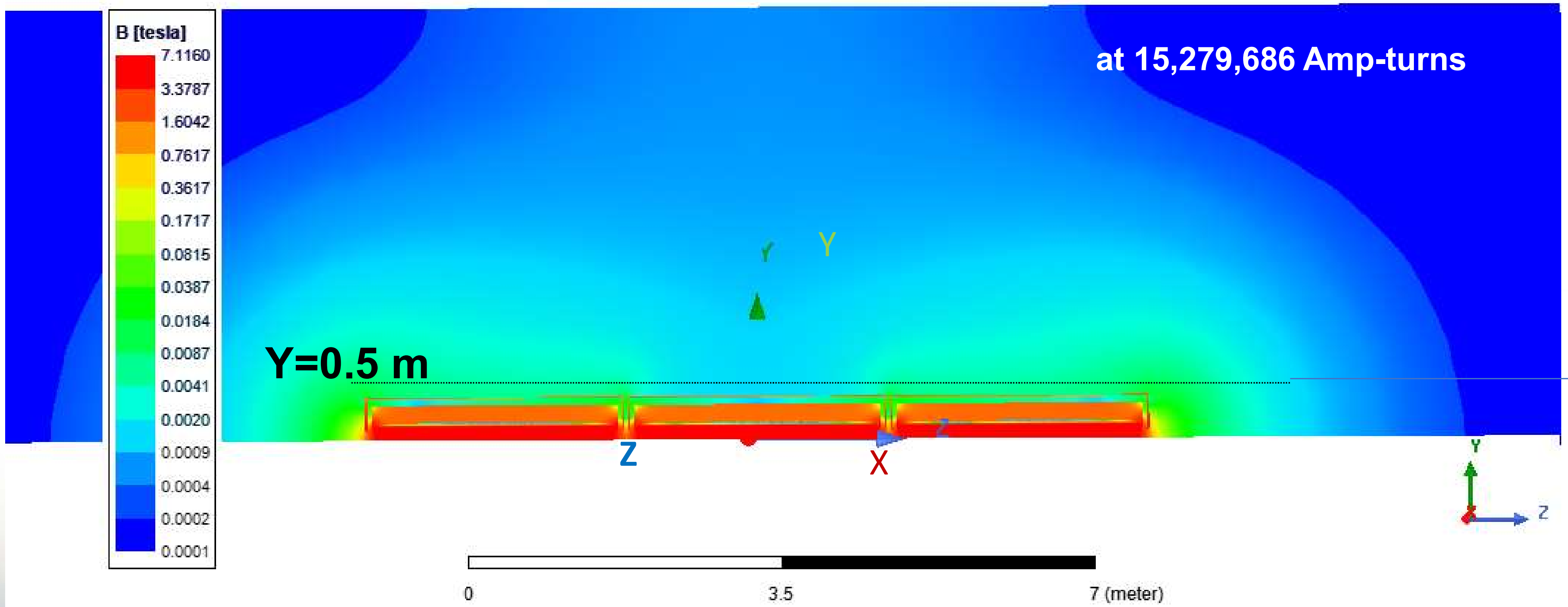






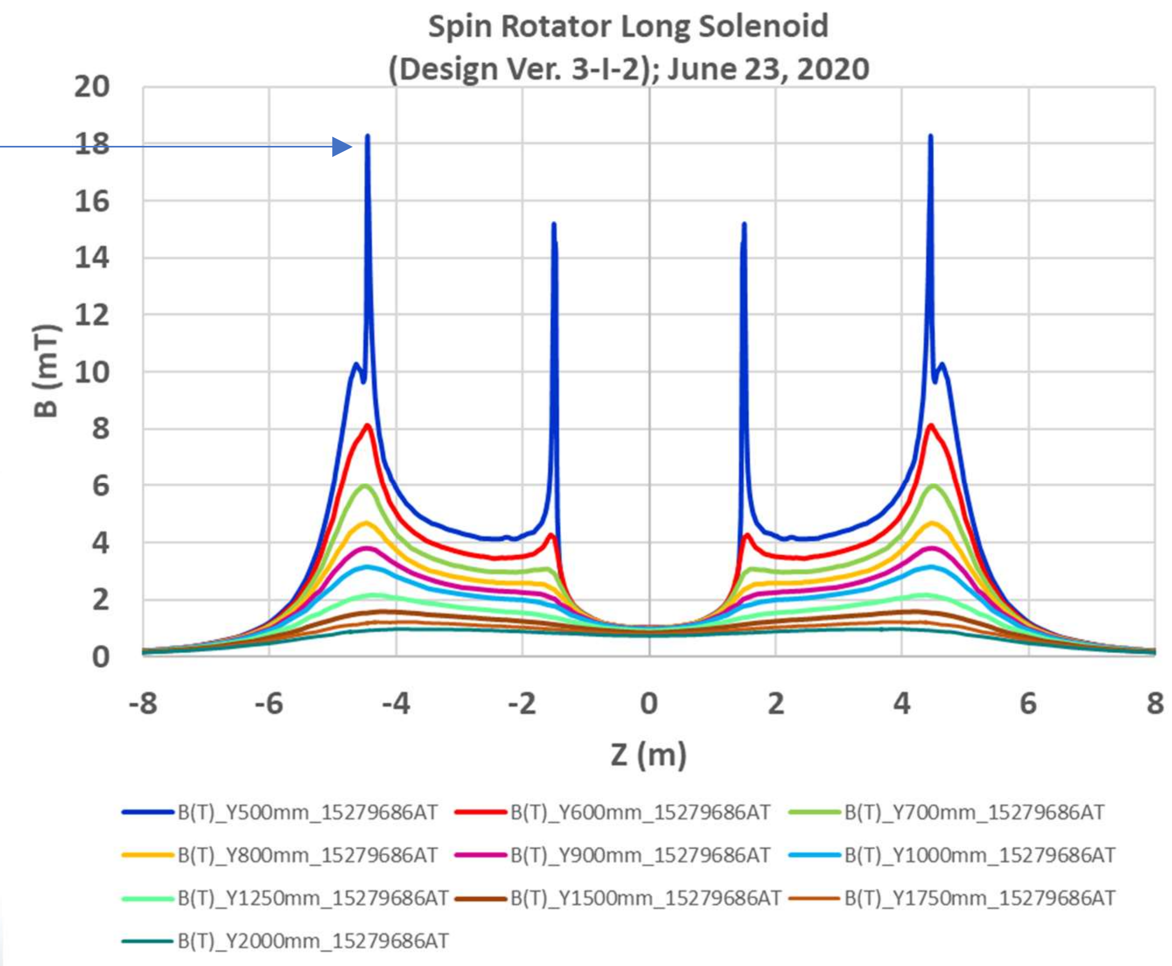
Fringe Field Distribution in the Spin Rotator Long Solenoid (Magnetic Length- 8.1 m)

- Fringe field distribution at 0.5m-2 m away radially (along Y axis) from the longitudinal axis (Z-axis) of the magnet.
  - maximum of 18.1 mT @ y=0.5 m (< 50 mT, Fulfills the requirements ☑)



at 15,279,686 Amp-turns

Design Ver: 3.I-2 (June 23, 2020)



Conductor / Coil Analyses

Conductor and Coil Analyses

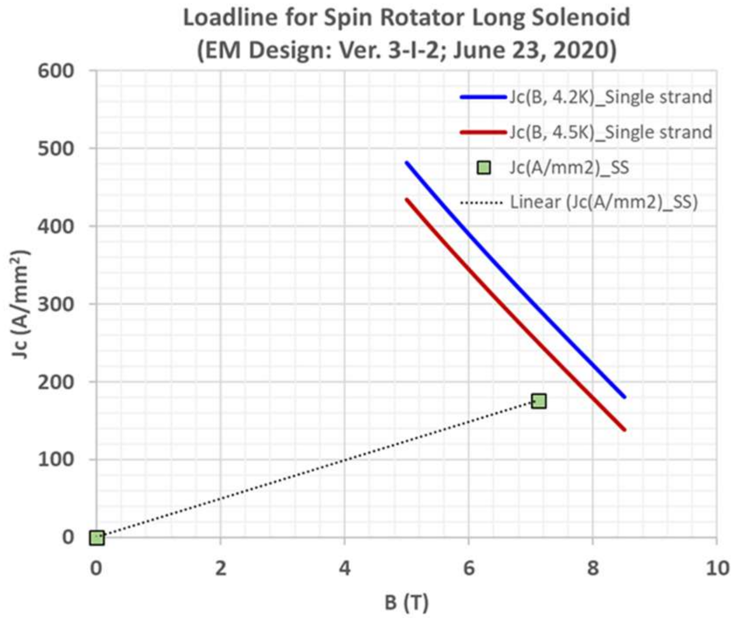
Choice of commercial superconductor for the Spin Rotator Solenoid

Parameter	Unit	Value
Conductor material/ shape		Cu stabilized NbTi; Rectangular; multi-filament strand
Bare strand dimensions	mm	1.175 × 2.41
Cu:SC ratio		4.75
I_c (5 T, 4.2 K) / I_c (7 T, 4.2 K)	A	1363 / > 860
RRR		100
Twist pitch length	mm	50
Coil operating current at 4.5 K (I_{op})	A	498.34
Coil operating current density at 4.5 K	A/mm^2	175.82
Operating current margin at 4.5 K, 7.12 T (I_{op}/ I_{SC})	%	**29.7** (> 20)
Current sharing temperature (T_{cs})	K	5
Temperature margin	K	**0.5**

Quench Analysis Results at the Maximum Operating Conditions of the Spin Rotator Long Solenoid

Parameter	Unit	Value
Inductance of each modular unit	H	29.8
Longitudinal quench velocity	m/s	24.5
Hot spot temperature	K	82.3
Maximum quench voltage in the coil	V	914
Maximum voltage across the dump resistor	V	500

- Conductor evaluation is based on the peak field in the coil winding at the max. operating conditions of the long solenoid (57.6 T-m)

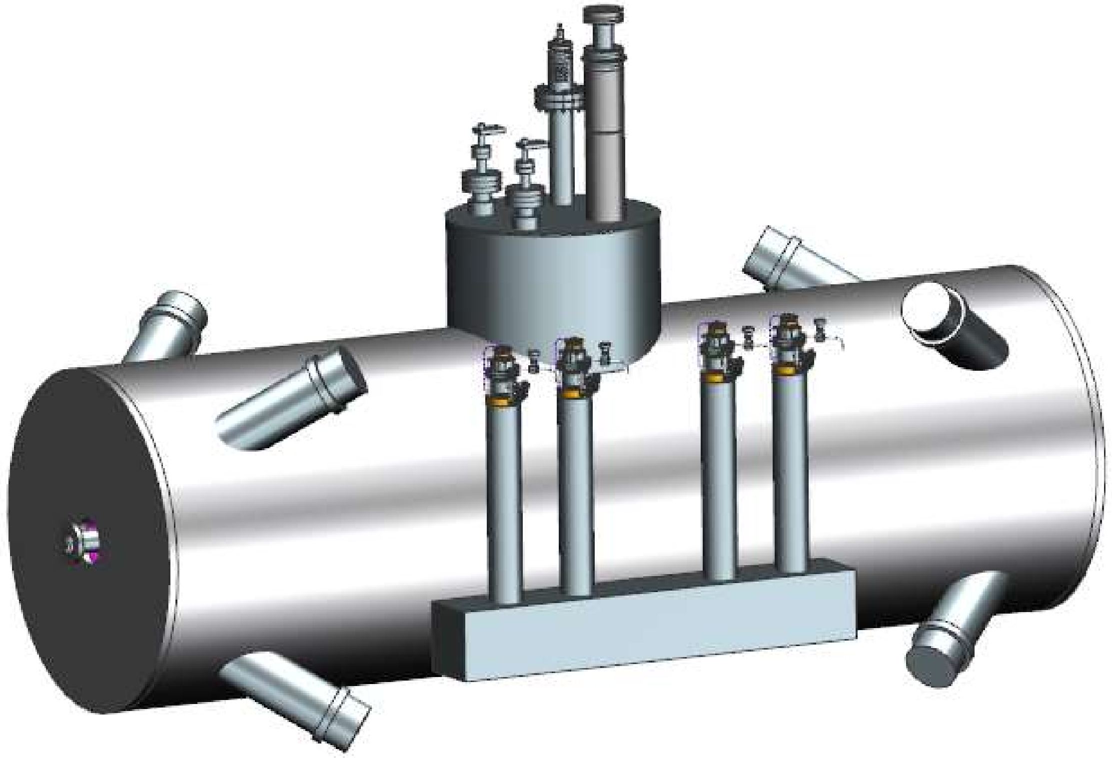

Loadline for Spin Rotator Long Solenoid
(EM Design: Ver. 3-I-2; June 23, 2020)

Fulfills the requirements (☑)

- Magnet quench analysis:
  - Each coil module contains 12 segments and a quench protection system with 1 ohm, 500 V dump resistor across each segment.
  - The magnet can be protected during a quench.

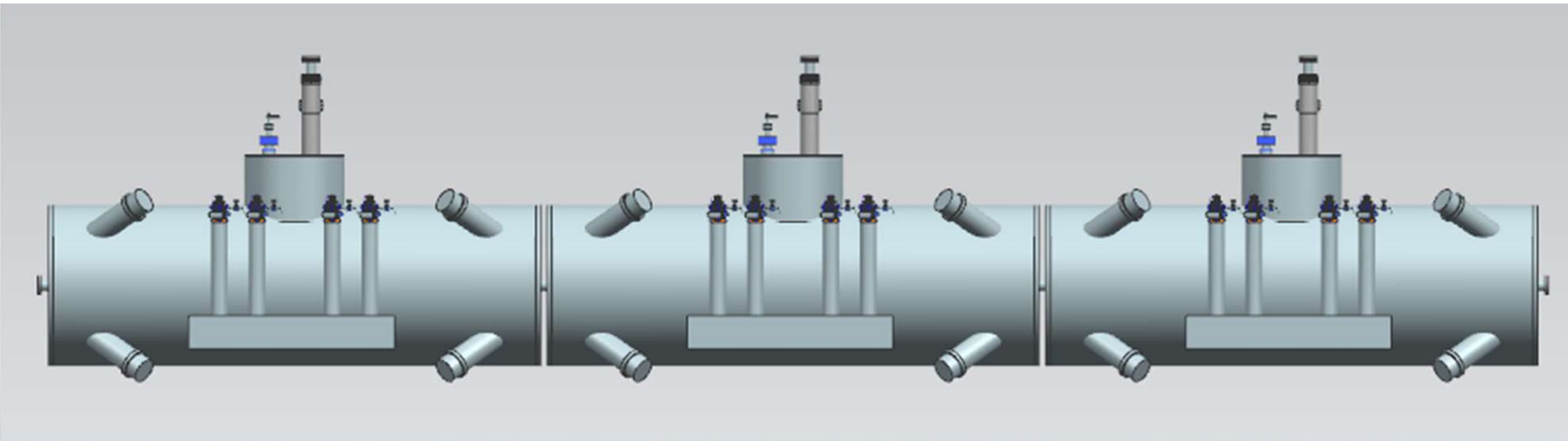
Mechanical Design

Design Overview – cryostat and interface features



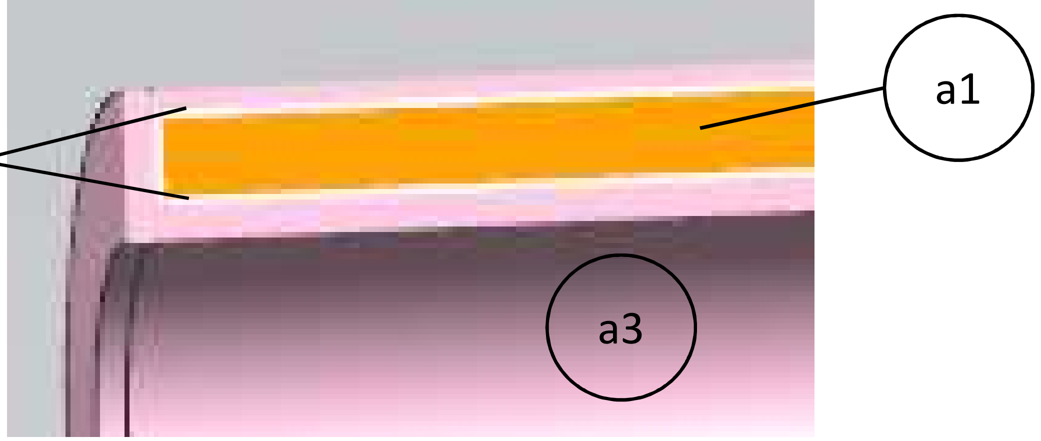
- 136 mm ID warm bore
- Eight tension supports
- Four JLab style 1.5” bayonets
- Central tower
  - Two commercial vapor cooled leads
  - Control valve
  - 2” NPS sch10 relief pipe

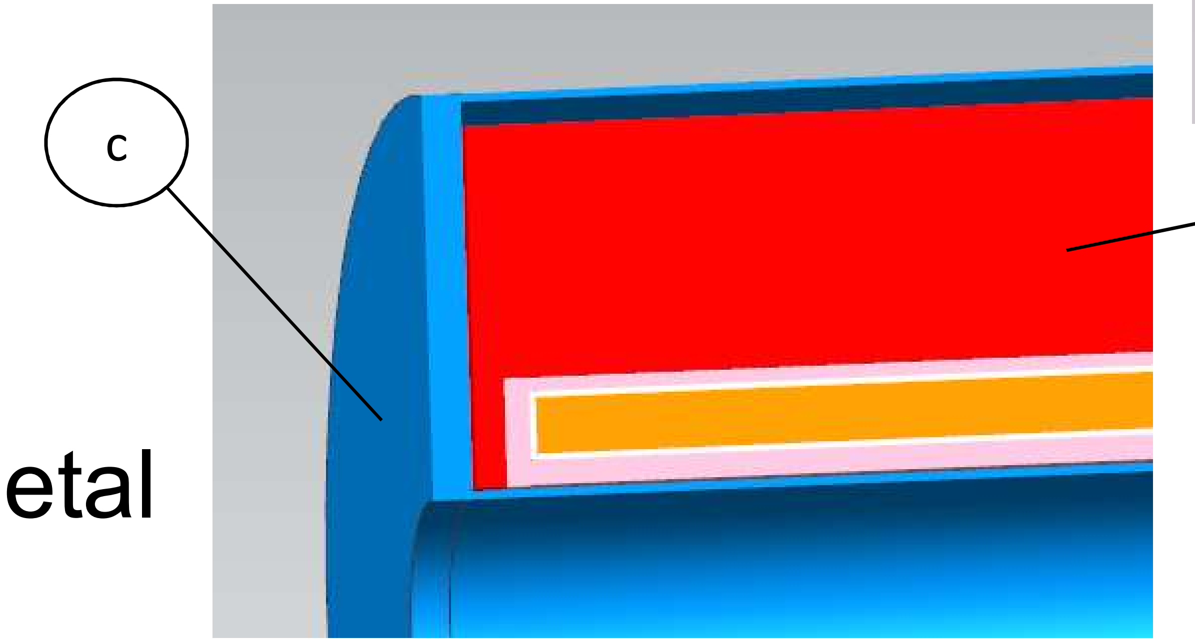
- Long Spin Rotator Solenoid
  - Total physical length at 9.05 m
  - 4 cm between magnet solenoids
  - Single beam vacuum chamber through all three magnets

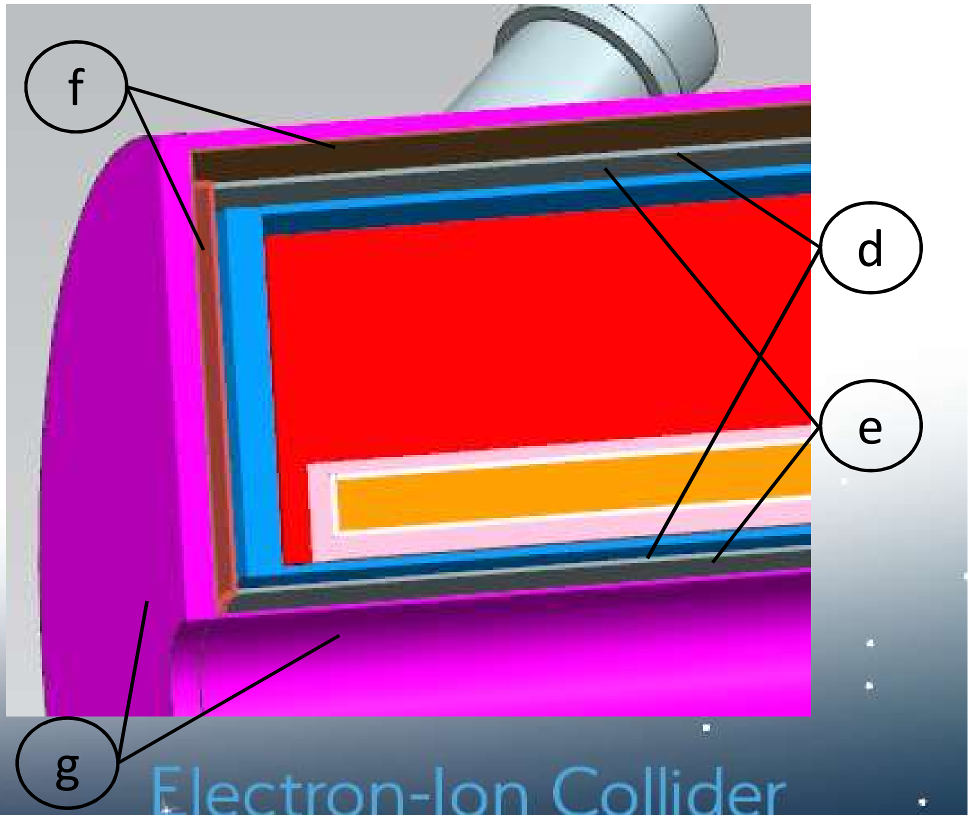


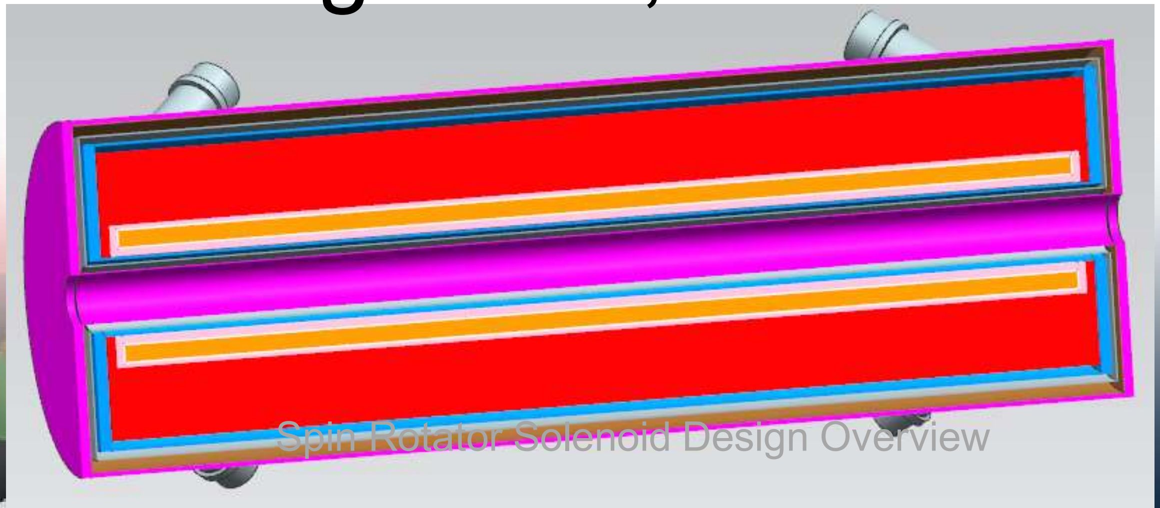
Design Overview – cryostat and interface features

a) Coil Assembly – coil, insulation, mandrel
b) Cold Yoke
c) Helium Vessel
d) Thermal shield
e) Insulating space
f) 3 mm warm mu-metal
g) Vacuum Vessel
h) Cold mass estimated weight ~26,000 lbs









Preliminary Heat Loads (per magnet)

- Heat load through MLI
  - 0.2 watt/m^2 for 4 K
  - 4.6 watt/m^2 for 50 K
  - Includes radiation, conduction, and gas load contributions
  - Not all geometry modeled yet so includes an extra area added as margin
- Suspension system is an estimate for now
  - Working on a better number based on the cold mass weight estimate and initial magnetic forces
  - Current estimate = twice ICH magnet values[1]
- Lead flow based on a commercial 1000 amp vapor cooled design and 120% of design current
- Bayonets based on JLab 1.5" design
- Control Valve based on commercial valve
- Relief stack 2" NPS sch10 pipe (length TBD)
- Instrumentation and other sources are estimated

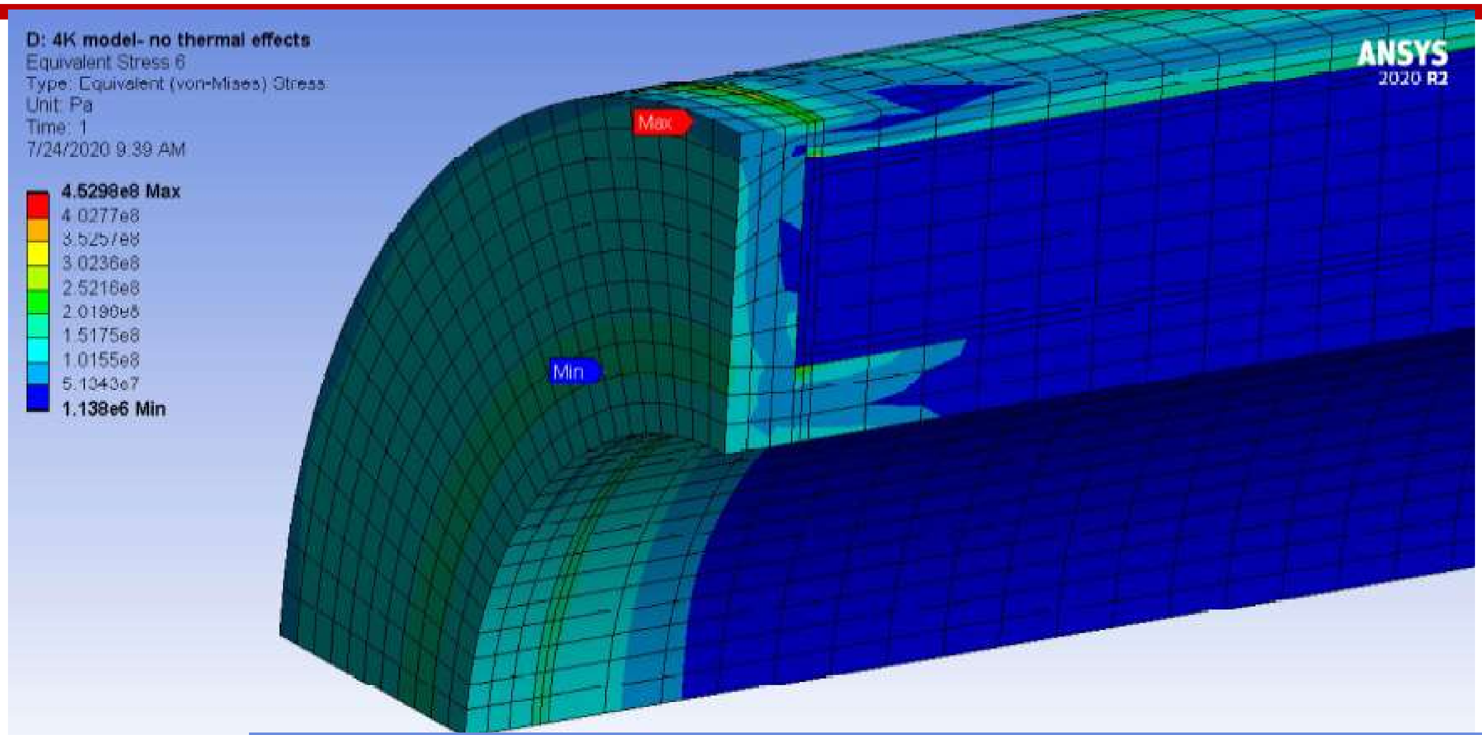
HEAT SOURCE	50 K HEAT LOAD (W)	4K HEAT LOAD (W)	Lead Flow (gr/s)
Thermal radiation through MLI, all heatshield surfaces	66	2.6	
Suspension system intercepts, all eight	25	2.6	
Lead liquifaction load (120% current rating)			1.9
4K Bayonets (2)	1.6	0.12	
50K Bayonets (2)	0.8		
Control Valve	0.3	0.1	
Relief Stack	3.9	0.3	
Instrumentation(estimated)		0.2	
All other sources combined (estimated)	2.0	0.2	
TOTAL	**99.6**	**6.1**	**1.9**

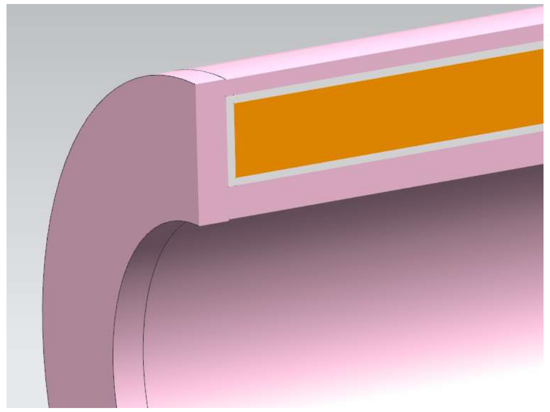
[1] ICH magnet from M. Anerella et. al., "MPEX Conceptual Design Report "

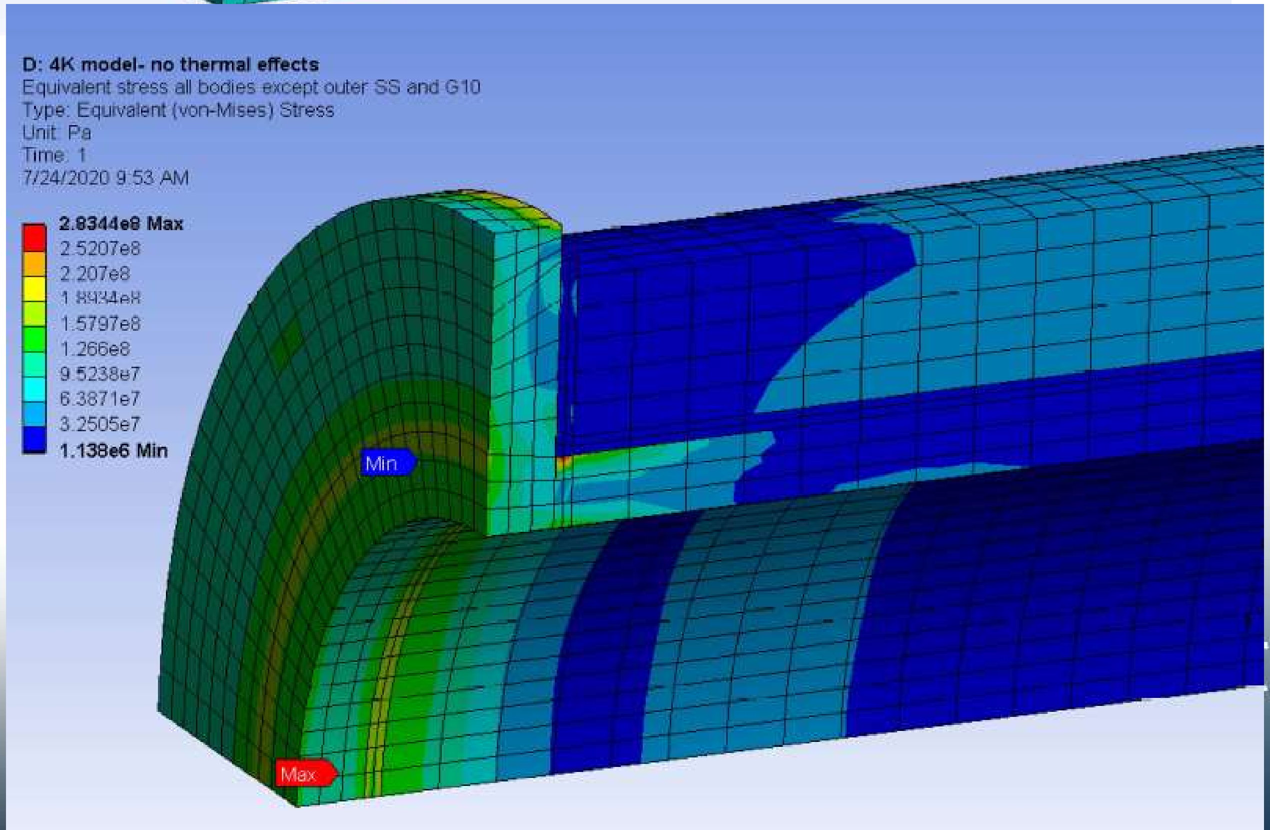
Coil Assembly Structural Analysis

Coil Assembly Structural Analysis

- A preliminary stress analysis has been completed on the coil pack assembly
  - No thermal effects
  - Coil properties from;
    - I. Dixon, R. Walsh, W. Markiewicz, and C. Swenson, “Mechanical properties of epoxy impregnated superconducting solenoids”
  - Highest stresses in the outer magnets of the three magnet string
- Stress in the coil and inner mandrel show no issues







Analysis by
B. Crahen
and E. Sun

Considerations for the Detailed Design

Considerations for the Preliminary and Detailed Design

- System optimization with magnet and vacuum chamber – goal to reduce the warm bore diameter and coil ID → reduce stored energy and amount of conductor
- Synchrotron radiation is impactful on leading end solenoids – evaluate different versions of solenoids for leading and trailing solenoids
- Warm yoke and external shielding elements
  - No issue with coil design or field in good field radius
  - Reduces weight of cold mass – quicker cool down, reduced load on supports
  - Potential reduction in overall size of solenoid
- Assessed Rutherford cable as an option to eliminate segmenting coil for quench protection – need to assess magnet/power supply as a system
- Preloading coil radially and axially will better control stresses and displacements in the coil structure as it goes through cool down and powering.
- If needed, can put 3 coil assemblies in a single cryostat for 9 m SRS
- Cryogenic interface can be hard piped rather than bayonets

Summary

- The Spin Rotator Solenoid conceptual design meets all current requirements.
- The design is feasible using strand conductor.

- Requirements are being updated as the ESR lattice matures. Tradeoffs of space vs SRS field strength are being evaluated.
- Further optimization will be required on coil and shielding design.
- Cost should be taken into account during the detailed design phase.

- **JLab Team:**
  - Bill Crahen, Chase Dubbe, Ruben Fair, Probir Ghoshal, Chuck Hutton, Lakshmi Lalitha, Tim Michalski, Renuka Rajput-Ghoshal, Eric Sun, Mark Wiseman
- **BNL Team:**
  - Holger Witte, Vadim Ptitsyn, Steven Tepikian, Mike Anerella, Charles Hetzel, Brett Parker