Brookhaven National Laboratory | Jefferson Lab | U.S. DEPARTMENT of ENERGY | Office of Science

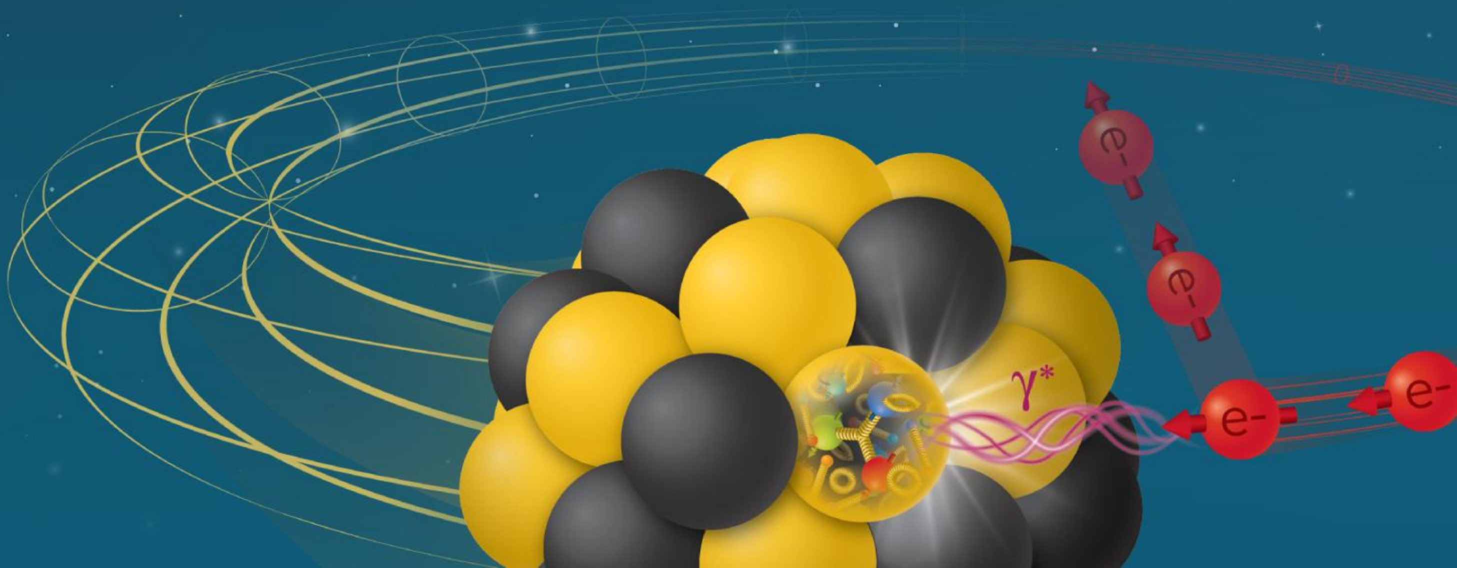
Detector Solenoid Magnet

Renuka Rajput-Ghoshal

Magnet Engineer / L3 CAM

10th EIC DAC Review

June 11th – 13th, 2025



Electron-Ion Collider

Outline

- Charge Questions
- Detector Solenoid- Scope and Overview
- Detector Solenoid Status
- Detector Solenoid Magnet Specifications
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- Magnet Power Supply
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- Magnet Installation and Mapping
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- Summary

Charge Questions

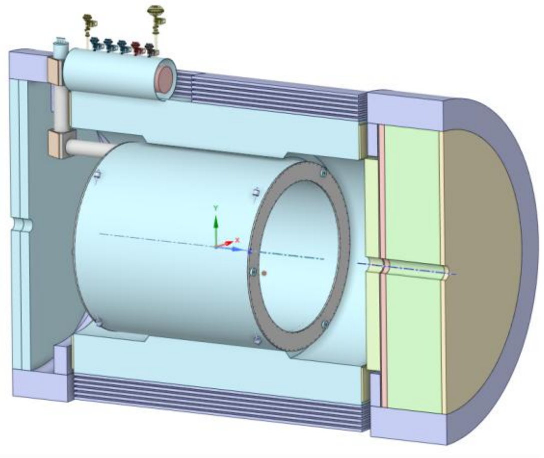
1. Is the design of the ePIC detector and its sub-systems appropriate and progressing well?
2. Are the remaining work and technical, cost and schedule risks adequately understood? Are there opportunities?
3. Will the detector be technically ready for baselining by late 2025?
4. Are the detector integration and planning for installation and maintenance progressing well? Are there areas where further ideas should be pursued?
5. Will the detector be ready for start of construction by late 2026?

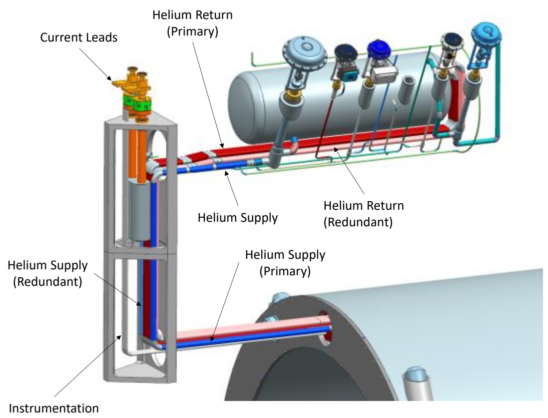
Detector Solenoid- Scope and Overview

WBS	WBS Name	WBS Manager	WBS Description
6.03.06	Detector Magnets	R. Rajput-Ghoshal	**Scope Definition:** -Procure and fabricate the central Detector superconducting solenoid Magnet. This will also include the magnet cold test, magnetic field mapping, installation & commissioning of the magnet system. The magnet system includes superconducting coils, support structure, cryostat, control & instrumentation for the magnet, quench protection, magnet power supply, and current leads. This will also include all the vendor visits related to superconducting magnet and associated various sub-systems. **Deliverables:** -A superconducting magnet system with a 1.7 T central field and 2 T stretch goal, and the subsystems to control and operate it.

Superconducting Detector Solenoid

- 3.5 m long coil, 2.84 m room temperature bore diameter
- 2 T on-axis field
- Operating Temperature 4.5 K
- Conductor: Copper Cladded, Rutherford Cable made with NbTi superconducting strands





CD-3A Scope	Conductor, Magnet Construction, vendor and technical oversight
CD-3B Scope	Magnet power Supply
CD2 and beyond scope	Water cooled leads, Cryocan and Cryoflex line, Magnet cold test, Magnet commissioning, Magnet Installation, and Magnet field mapping

Detector Solenoid Magnet-Status

- Magnet will be “In-Kind Contribution” from INFN.
  - Magnet Design report and other relevant documents were prepared by JLab and shared with CEA and INFN.
  - INFN technical team, in collaboration with JLab and CEA, is working on the procurement package.
  - The procurement package is expected to be completed in June 2025
  - Waiting for the iCRADA documents to get approved from DOE.
- Conductor will be procured by JLab and supplied to the magnet vendor as “Government Furnished Material”.
  - The expected award date for the conductor is June 30, 2025.
- Magnet power supply will be procured by JLab and shipped directly from the power supply vendor to BNL.
  - Power supply FDR was done in May 2024.
  - The procurement package is ready for approval.
  - This can be awarded after the CD-3B ESSAB Approval.

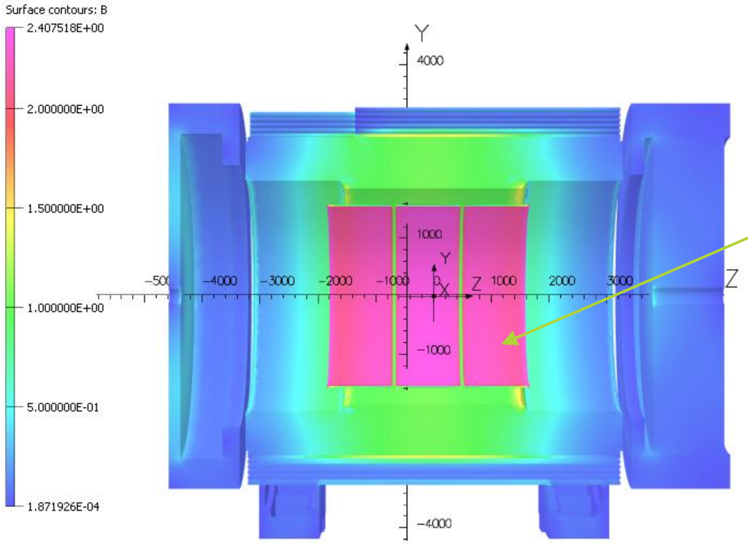
Detector Solenoid Magnet Specifications

Parameter	Detector 1-Solenoid	Comments
Nominal Central Field at IP (T)	2	Safe Operation
Operating Field Range (T)	0.5-2.0	
Magnetic Field Polarity	Bipolar	
Coil length (mm)	3492	To keep the same envelope as the existing BaBAR magnet
Warm bore diameter (m)	2.84	
Cryostat length (m)	<3.85	
Cryostat outer diameter (m)	<3.54	
Flat Field area	± 100 cm around center 80 cm radius	1. Magnetic field properties 2. Stray field requirement is based on IR magnet location
Field uniformity in Flat field Area (%)	12.5	
RICH area	From z=+180 cm to 280 cm	
Projectivity in RICH Area (mrad@30GeV/c) Projectivity in RICH Area (T/Amm^2)	0.1 10	
Stray field requirement	<10 G @ z=-5.3 m, @z=+7.4 m, ~~and @R=3.4 m~~	
Charging voltage (V)	10	
Fast discharge voltage maximum (V)	500	
Quench hot spot temperature (K)	<150	
Temperature margin (K)	>1.5	
Current margin (%)	<30	
Charging time (hr)	2-3	
Cooldown time (weeks)	3-4	
Cooling scheme	Thermosiphon	
Conductor	Cu Stabilized NbTi Rutherford cable	
Operating Temperature	4.5	

- The stray field on the IR magnet was assumed to be <10G. This number will be updated in consultation with IR Magnet Designers.
- The stray field requirement does not affect the coil design, it mainly depends on the steel around the magnet.

Magnetic Design

Parameter	V7.6.2.2.10 3D	Units
Current	**3924**	**A**
# turns	1668	
B_0	**2.000**	**T**
Homogeneity	**12.7**	**%**
Projectivity	**3.28**	**Tmm²/A**
Bpeak (MOD 3)	2.671	T
Energy	**45.010**	**MJ**
Inductance	5.846	H
Fz MOD 1	11.88	MN
Fz MOD 2	57.5	kN
Fz MOD 3	-11.97	MN
Fz tot	**-32.4**	**kN**
Fr Tot	**112**	**N**
B5300	**15.3**	G
B7200	**10.9**	G
B3400	**2.4**	G



Coil is divided in 3 module
Each module has 6 layers

3 modules are chosen, mainly
- Feasible single length conductor manufacture
- Ease of coil manufacturing
- Magnet quench protection

Magnet is 10 cm off center

Note: Mitigation of higher stray field on lepton was done using extra steel around the magnet, latest model B5300 <10G

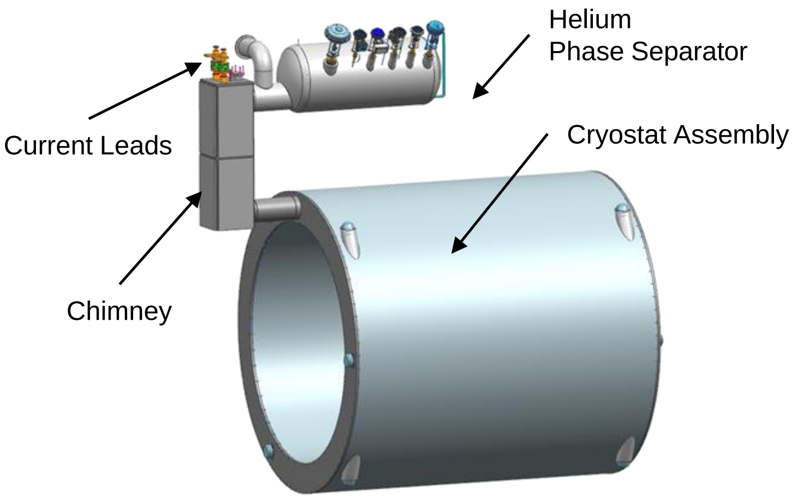
B_0	2.0 T	Units
Current	3924	A
T_{op}	4.7	K
B_{peak}	**2.67**	T
Temp. margin	**2.45**	K
Load line margin	**46.1**	%
I / Ic(T,B_{peak})	**29.3**	%

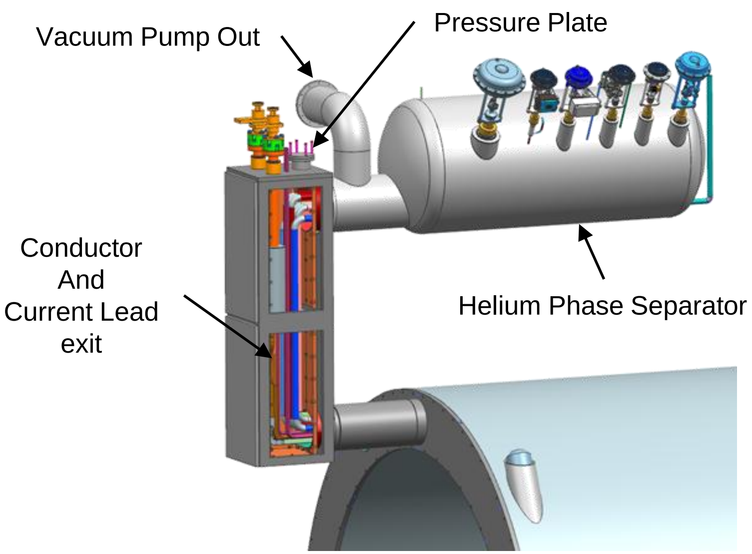
Robust and safe operating parameters

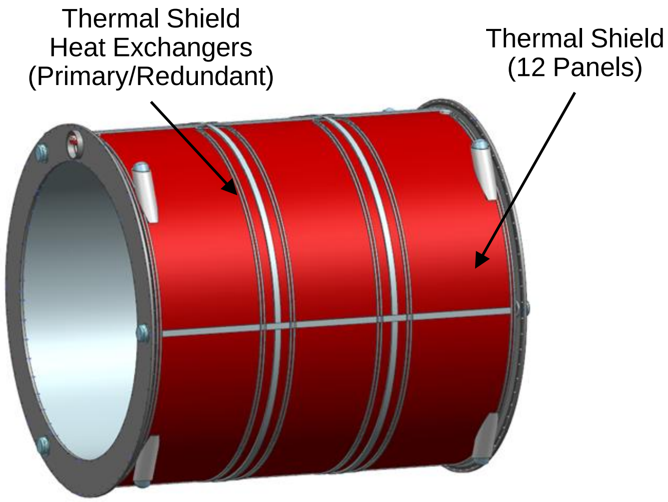
> 1.5 K

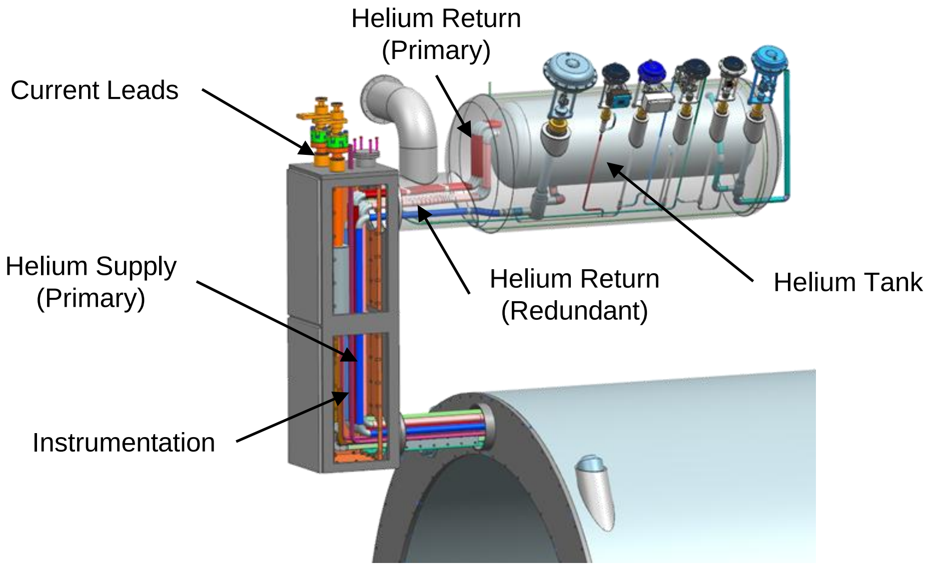
<30 %

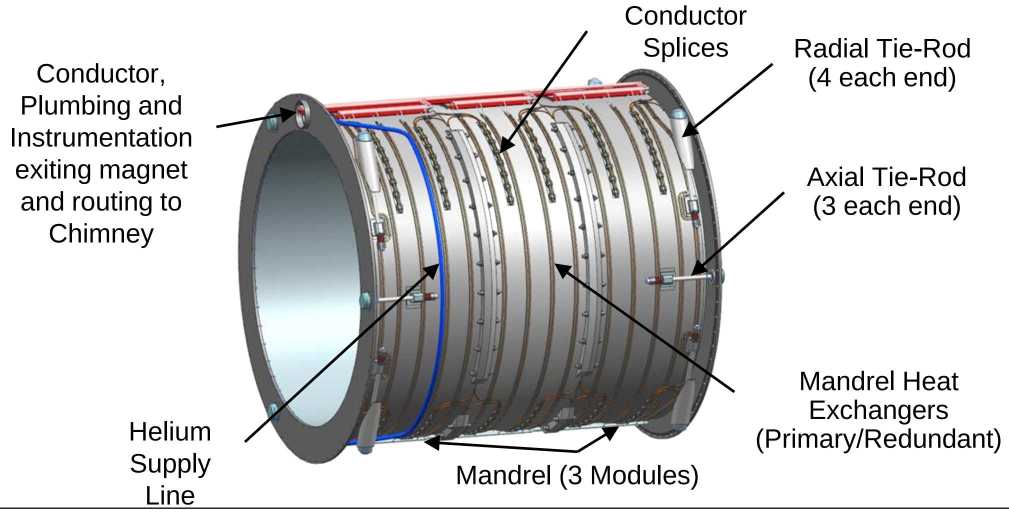
Magnet Assembly











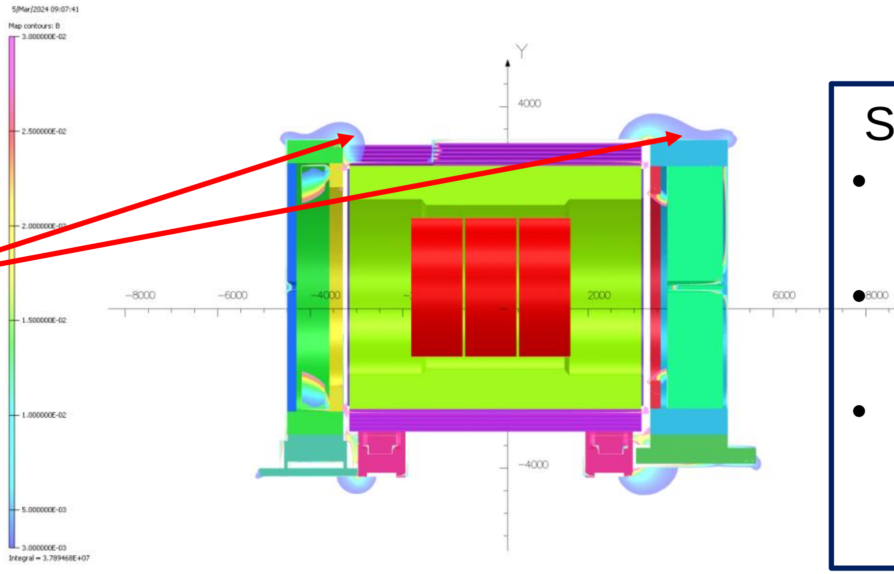
Magnetic Design- Stray Field Reduction

Parameter	ePIC Requirement	Design Value at magnet FDR
Nominal Central Field at IP (T)	2	2
Stray field requirement at IR Magnets	<10 G @ z=-5.3 m, @z=+7.4 m	15.3 G at z=-5.3 m 10.9 G at z=7.4 m
Stray field requirement at RCS Beam line ∫B.dl (T-m)	<0.007	0.029
Stray field requirement at RCS Beam line ∫B.dl updated in February 2024 (T-m)	0.0293 Tm longitudinal 0.024 Tm transverse	

These values were higher than the requirements!
We found a local solution independent of magnet design.

Now the RCS is not in the tunnel, therefore, no requirement of stray field on RCS

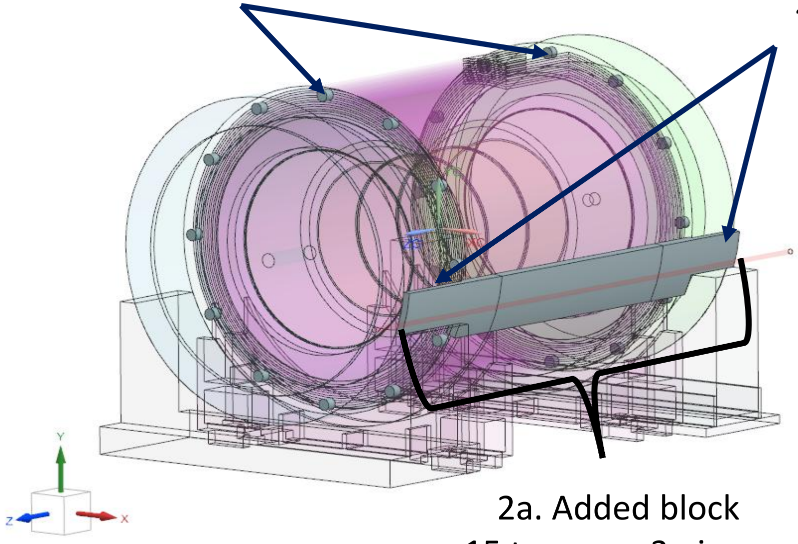
- Field leakage is primarily near the openings between the barrel and the endcap HCal.



Since RCS has moved out now:

- There is no requirement of lower stray field in the radial direction
- The extra steel around the HCal barrel is not required any more
- The need of extra steel on the lepton side end cap and hadron side end cap is being evaluated

Magnetic Design- Stray Field Reduction



Stray Field Reduction Studies:

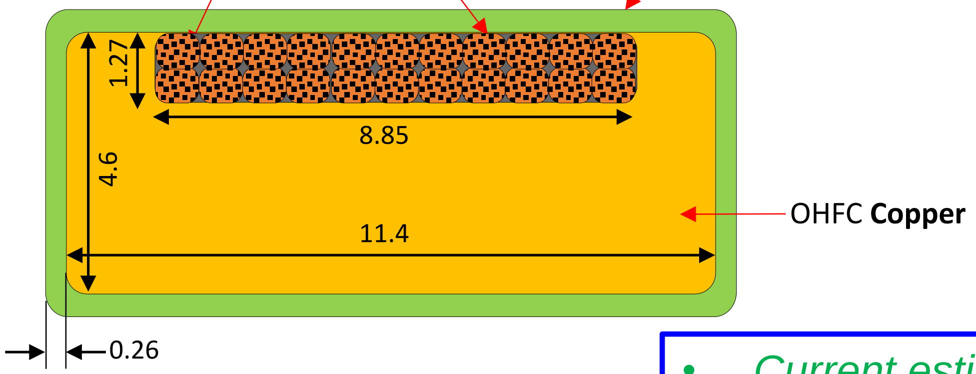
- Various solutions were tried to minimize the stray field at the IR magnet and on RCS line
- The best solution is using small links bridging the service gaps and a block closer to RCS

	Case	B (0,0,-5.3 m) (G)	B(0,0,7.4 m) (G)	$\int$Bx.dl (T-m)	$\int$By.dl (T-m)	$\int$Bz.dl (T-m)
1	Baseline	8.83	7.05	-0.0012	-0.0014	0.0091
2	Baseline+links+Block	1.84	0.94	-0.0003	0.0000	0.0013
3	Baseline+link+end blocks	2.69	1.65	-0.0006	0.0001	0.0022
4	Baseline+ links	8.22	3.53	0.0029	-0.0031	0.0051
5	Baseline+block	4.29	3.17	-0.0004	-0.0003	0.0041
6	Baseline+end blocks	5.30	3.94	-0.0013	0.0001	0.0052

- Since RCS has moved out of the tunnel, stray field need to be minimized only at the IR magnet.
- The use of small links bridging the service gaps meets the stray field specification at IR magnets.

Detector Solenoid Conductor

	Parameter	Value	Unit
Strand	Strand diameter	0.847	mm
	Cu/NbTi	1.31	
	I_c @ 3T & 4.7K	> 735	A
	Filament diameter	< 30	µm
	Filament twist pitch	30	mm
Cable	NbTi strands	22	
	Transposition pitch	50	mm
	Width	8.85	mm
	Thickness	1.49	mm
Conductor	Copper channel section	43.7	mm^2
	Nominal current @2 T	3924	A
	RRR conductor	>= 80	
	Yield strength $\sigma_{0.2\%}$ @ 293 K	>= 165	MPa
	Unit length	1.05	km
	Total length	18.9	km



Dimensions in mm

Total 18 lengths of 1.05 km are required for the magnet.
We have added 2 lengths to account for production yield.

- *Current estimated award date for the production conductor is 06/30/2025*

- *Order of conductor samples put in place based on these specifications !*
- *Sample conductor strand tested and shows very good quality strands.*
- *Waiting for cabled and soldered samples.*

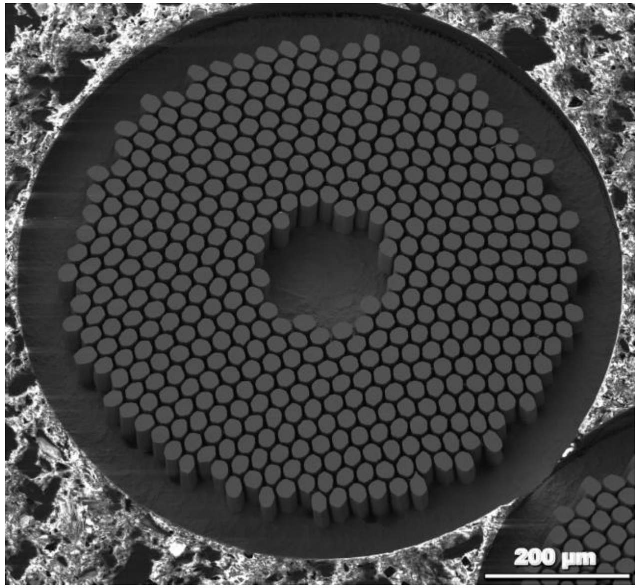
- *Production conductor proposal came much higher than expected and higher than P6.*
- *We looked at the alternate plans for the conductor procurement. The alternate plan is more risky and almost same cost as the updated quote from the vendor,*

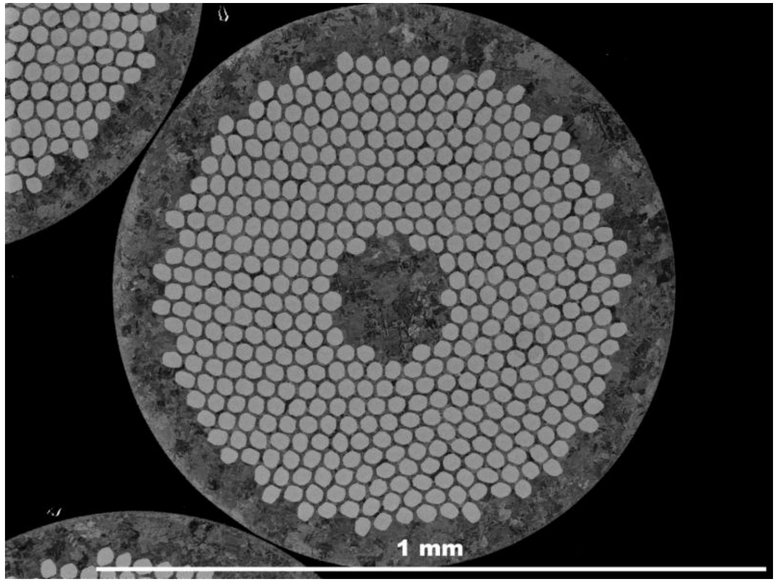
CD3A Status- Sample Conductor

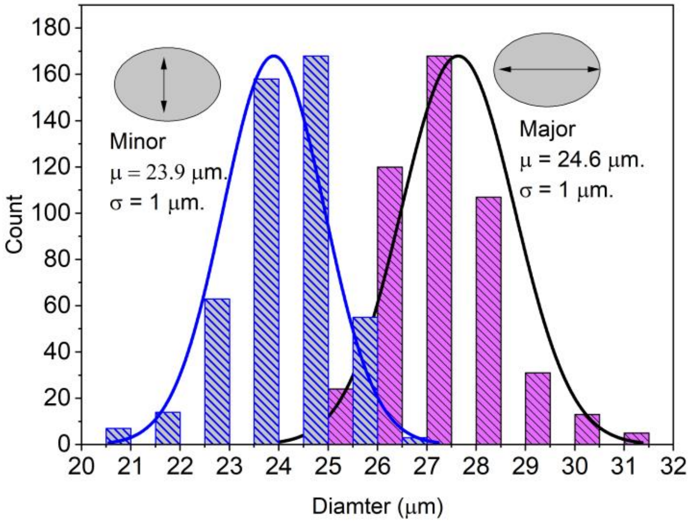
- Sample Conductor Status
  - Strand received from the vendor,
  - Vendor submitted the test results
  - Sample strand was sent to University of Twente for further test
  - Delay from the vendor for making cable and copper channel,

Strand Sample meets the Specifications

The filaments in the strand are well organized, the distribution of filament size is very uniform







Acknowledgement for SEM:
Shreyas Balachandran, SRF S&T, JLab

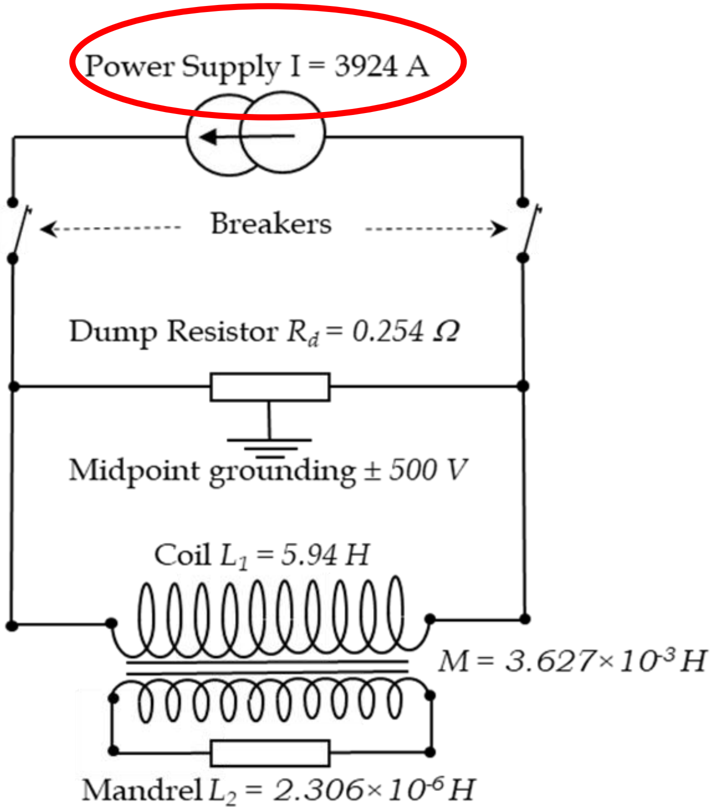
Production Conductor- QA/QC

1. Production units to adhere to same requirements as the sample conductor.
   - Critical current:
   - Cabling Ic degradation < 5%
   - Soldering Ic degradation < 5%
   - 0.2% Yield strength > 165 MPa
   - RRR conductor > 100
2. External Conductor Tests
   - Will be based on strand utilization and test cost per sample
   - 8-10 billets needed for 21 Unit lengths
   - Possibly 10 Sample test, Conductor only

Layer	Mid-radius (mm)	Unit length 3 modules (m)
L1	1512.1	908.09
L2	1517.4	908.1
L3	1522.7	908.11
L4	1528.0	908.12
L5	1533.3	908.13
L6	1538.7	908.14
Unit length no margins		910
Unit length with margins		1042

Total 18 lengths are required for the magnet
We plan to add 2 lengths to account for production yield

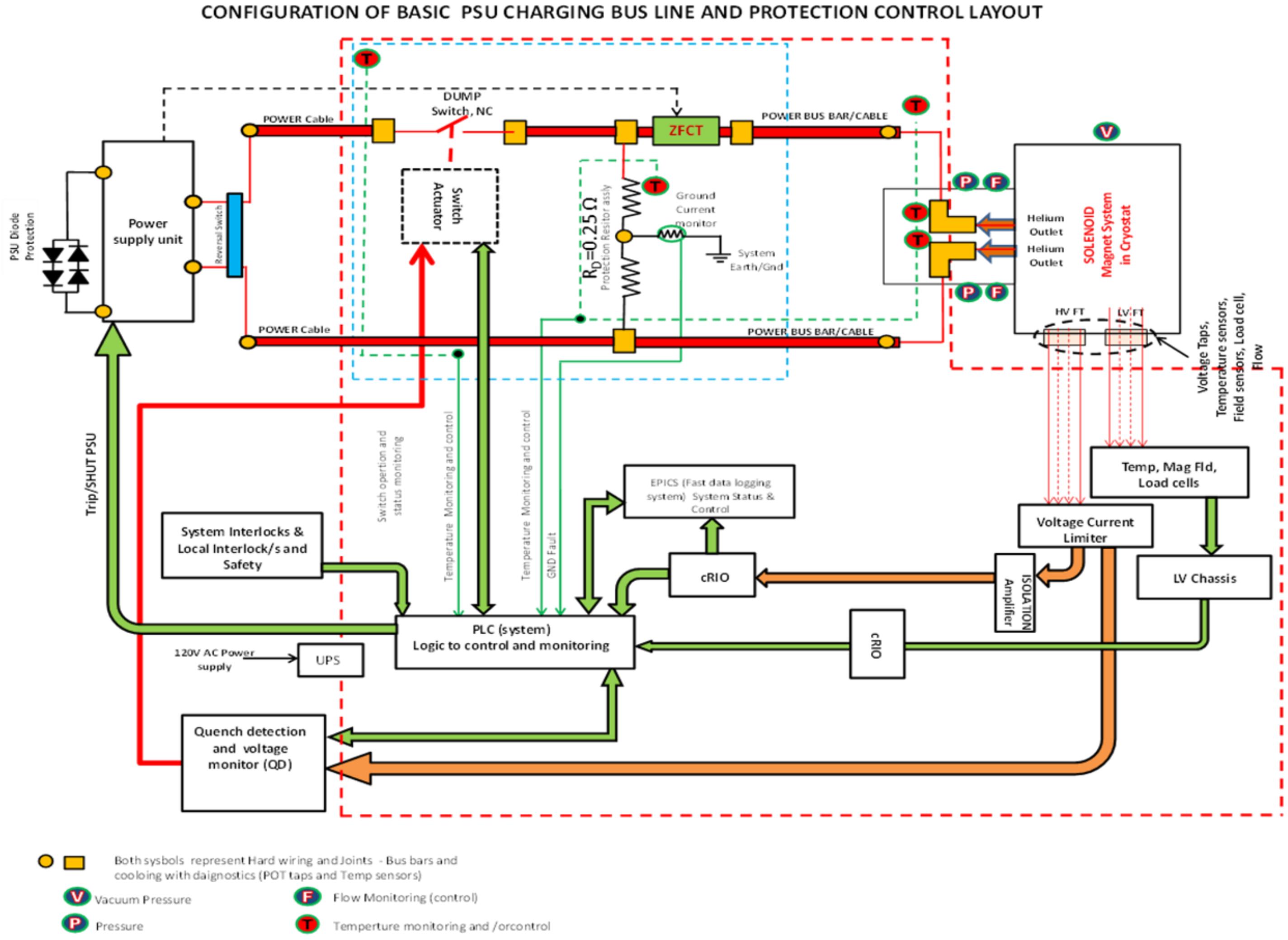
Magnet Power Supply



The solenoid power supply is a standard superconducting magnet power supply. The power supply will be located about 300 feet far from the magnet.

- The power supply is a 5000A, ±20V power supply.
- A polarity reversal switch is also included in the power supply. Is part of power supply procurement.
- The MPS will be built to BNL/JLAB standard.
- An integral tunable magnet quench detection will also be part of the power supply procurement.
- test

Protection System Layout



- ❑ Dump resistor – Center tap
- ❑ Hard wired QD
- ❑ Software QD (PLC)
- ❑ Interlocks
- ❑ Monitoring- Temp, Load cells, Mag field, Voltages

Primary security level

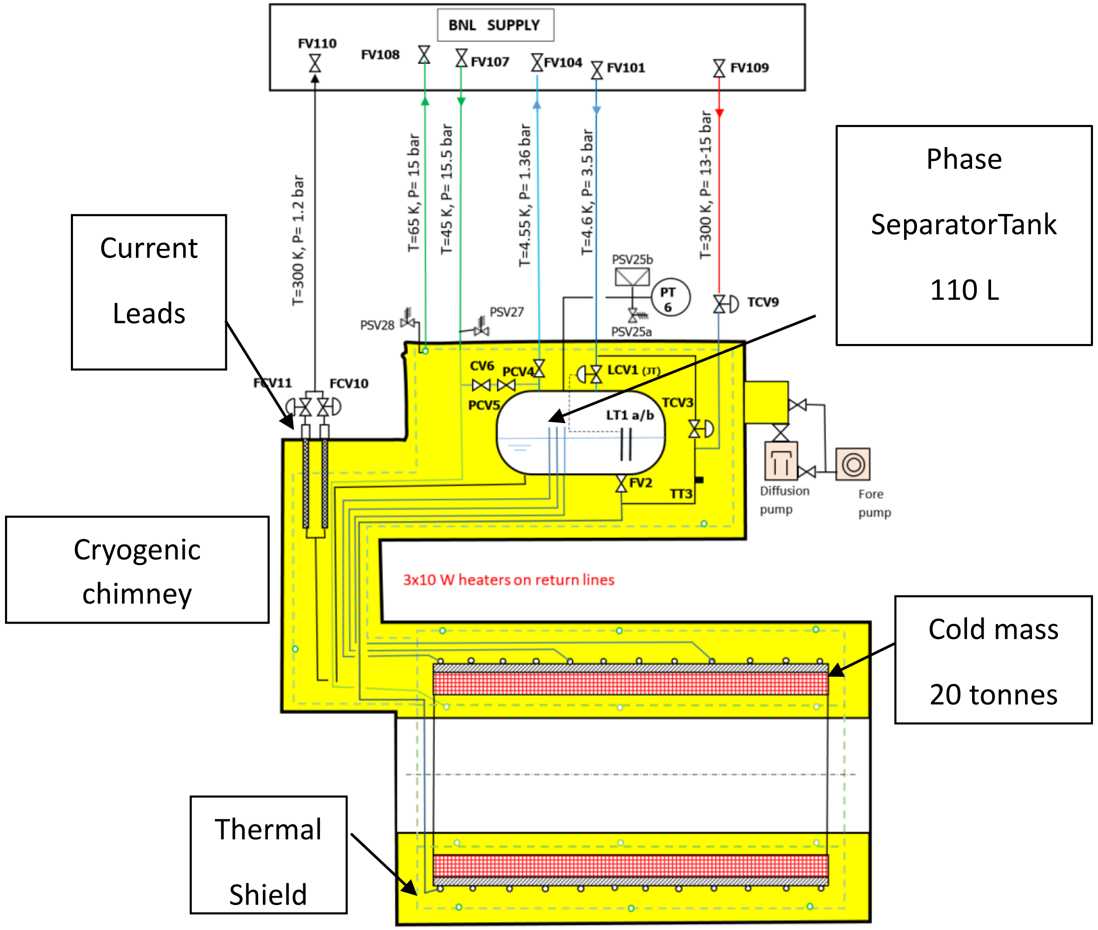
Secondary security level

Outlook to CD2 and Beyond

CD-3A Scope	Conductor, Magnet Construction, vendor and technical oversight
CD-3B Scope	Magnet power Supply
CD2 and beyond scope	Water cooled leads, Cryocan and Cryoflex line, Magnet cold test, Magnet commissioning, Magnet Installation, and Magnet field mapping

- Water cooled leads:
  - There are existing leads in the experimental Hall, we need to qualify these for use in this magnet, if not, this will be open procurement after CD3 and the design is based on similar leads bought for 12GeV magnets.
- Magnet Cryogenics
  - The scope and design of this will be done in consultation with BNL cryogenic group.
  - Preliminary design review will be in September/October 2025
- Magnet Cold Test
  - Magnet will be cold tested after installing the HCal end caps
- Magnet Field Mapping
  - Magnet Field mapping will be done after installing the Barrel HCal, HCal end caps and extra steel required for minimizing the stray field,
  - Field mapping will be done by JLab, CEA engineers and techs from BNL

Magnet Cryogenics



- The MARCO magnet is a conduction-cooled magnet.
- The internal cryogenic system involves a cold mass, thermosiphon system, a phase separator, and one cryogenic chimney.
- The MARCO magnet is cooled using cold and warm helium during operation.

Magnet Cryogenics-Contd.

Magnet Thermal Parameters

1. The magnet cooldown time is approximately **7 days**
2. The maximum temperature of the magnet during long term shut-down is **100 K**
3. During transfer of magnet between halls, the coil temperature drifts from 4.5 K to **80 K** in approximately 1.5-2 days.

Magnet transfer during Halls

The different scenarios in which the magnet will be moved :

1. From assembly hall to experimental hall (during installation)
2. From experimental hall to assembly hall -during shut down or maintenance
3. From assembly hall to experimental hall -after shutdown or maintenance

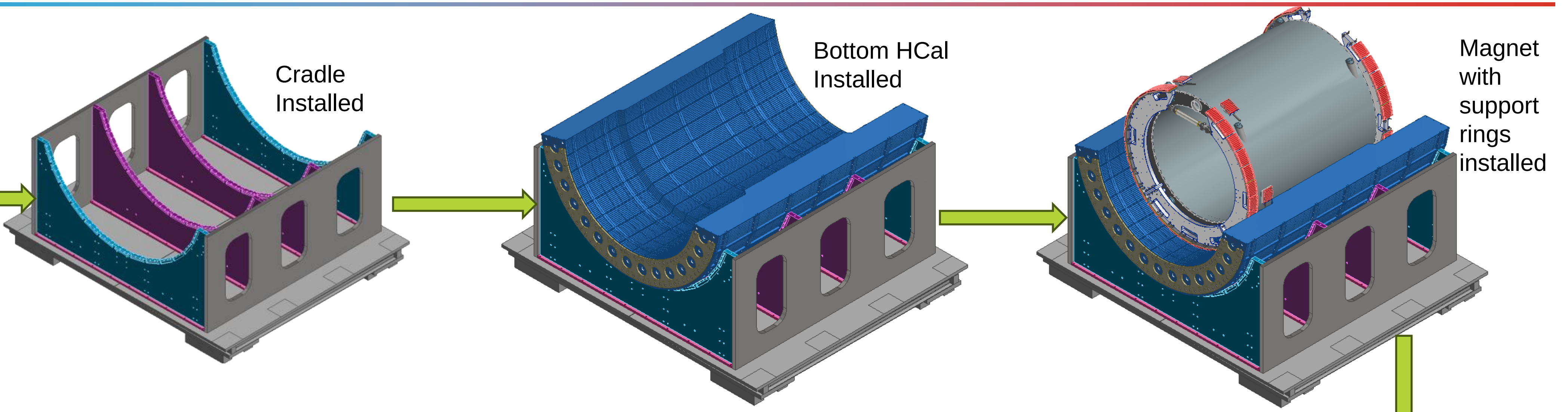
Helium Requirement during Magnet transfer

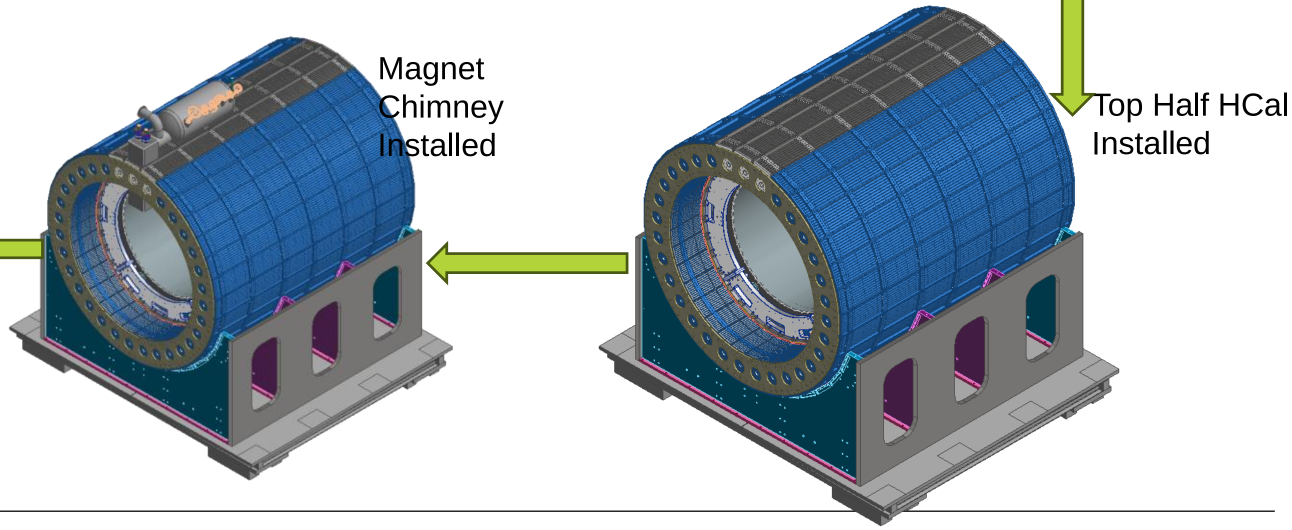
- There is no active cryogenic cooling during transfers.
- During magnet transfer the temperature of the magnet to increases to ~80 K.
- On the completion of the transfer, the cryogenic connections are to be made to limit the temperature of the magnet to 100 K

Either Two distribution boxes or one distribution box with a penetration through the wall is required to meet the cryogenic requirements of the magnet.

Magnet Installation

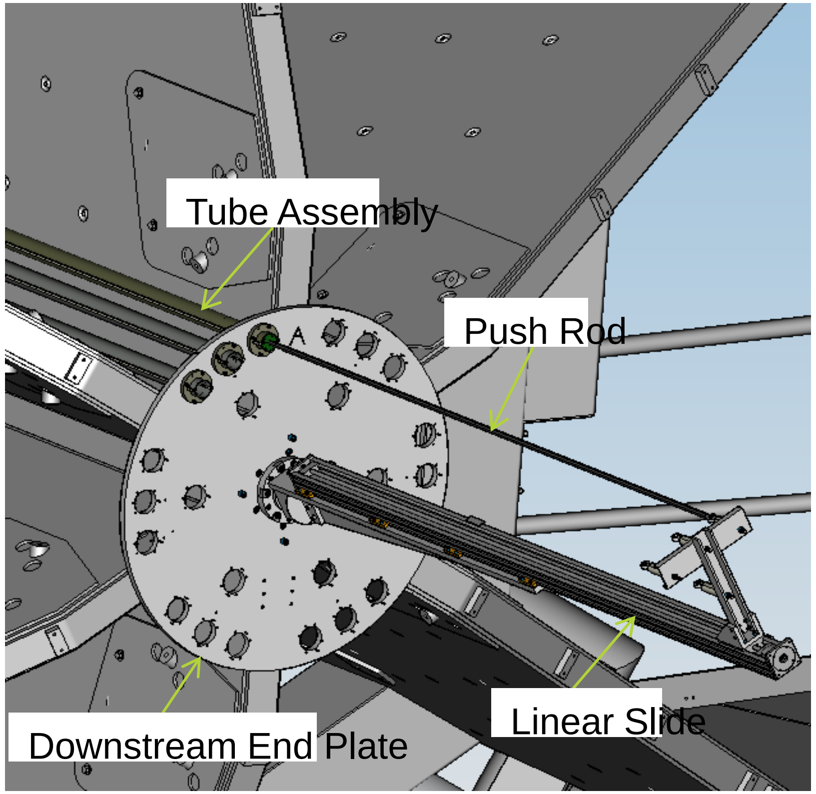
Magnet Arrival Checks





- Instrumentation cables and cryo connections
- Vacuum check
- Low current Test
- Move the magnet to the Hall
- Cool Down magnet
- Install the end-caps
- Energize to the full current
- Map the magnet

Magnet Mapping



- Three transverse Hall probes positioned in the probe holder to measure Bx, By, and Bz
- Holder made from Delrin

- Precisely machined upstream and downstream plates
- The plates will be surveyed prior to install to know hole locations
- Precise pins locate and orient the carbon fiber tubes
- Pins assure locating/repeatability of carbon fiber tubes to 0.05mm [0.002”]
- Carbon fiber tubes will be moved from one sector to another
- Linear slide/motor/controller accurate to 0.010mm [0.0004”]

ESH&Q- Electrical & Pressure Vessel

1. Magnet Power supply, electrical and Instrumentation feedthroughs will comply as per 6210 Electrical Safety Manual
   I. NFPA 70E, 2015 - Standards for Electrical Safety in the Workplace
   II. National Electric Code (NEC) Handbook
   III. DOE–HDBK-1092, 2013 – Department of Energy Electrical Safety Handbook
   IV. ES&H Manual 6230 Electrical Safety Manual
   V. JLAB-6220 AC Electrical Equipment Safe Work Program
2. All the vessel are designed according to the requirements of ASME codes
3. Pressure piping is governed by ASMEB31.3
4. Reciprocal arrangements are in place between JLab and BNL
5. Experimental Hall will be updated for the required ODH.

Summary

- Magnet Design is complete and magnet procurement documents are being prepared with international collaborators.
- The expected award date for conductor is end of June 2025.
  - Sample conductor testing is going well, the strand received from the vendor is of very good quality and meets the specification.
- Magnet power supply procurement documents are ready for approval and the procurement will start after CD3-B ESAAB approval.
- Cryo review will be in September/October 2025.
- Magnet mapping is planned, and details will be worked out after CD2/3.

Back up

How We Work

1. Collaboration of Jefferson Lab, CEA Saclay and Brookhaven National Lab
    - All the design work is done as in-kind/contract with CEA Saclay augmented with Jefferson Lab work
2. CEA Saclay is involved in reviewing all the procurement documents and sample conductor testing.
3. Expectation is that vendor contract may follow similar pattern for vendor oversight.
4. Further discussions are ongoing on with INFN for in-kind contribution
5. Magnet team members:
    - JLab: Renuka Rajput-Ghoshal, Probir Ghoshal, Sandesh Gopinath, Eric Sun, and Dan Young
    - BNL: Rahul Sharma, Roland Wimmer and Roberto Than
    - CEA, Saclay: Valerio Calvelli, Christophe Berriaud, Jean-Pierre Lottin, Hugo Reymond, and Francesco Stacchi