# 1st International Workshop on a 2nd Detector for the EIC

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## Design considerations and constraints for the ePIC magnetic field

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Electron-Ion Collider

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

# Outline

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# Magnet from Various Perspectives

Magnet User/Physicist:

- Maximum field strength,
- Very high field homogeneity over a larger volume
- No-to-minimum space,
- fastest ramping, no quenching,
- Absolute transparent (least amount of material)
- No fringe/stray field
- reuse of existing old magnet
- …

Magnet Manufacturer/Industry:

- Maximum margin (low field),
- Low Homogeneity/ no stringent requirement
- No space Constraint
- Maximize probability of success on 1st ramp (90% of nominal is "Good Enough")
- Minimum cost to build with maximum profit
- No restriction on material usage
- Other nearby things like detectors are not so important

- Magnet Engineer-3rd perspective:
  - Somewhere between these 2 perspectives!
  - The most rational agent in the equation that can bring together both sides,
  - Come-up with a practical solution and reasonable agreement between the above 2 perspectives

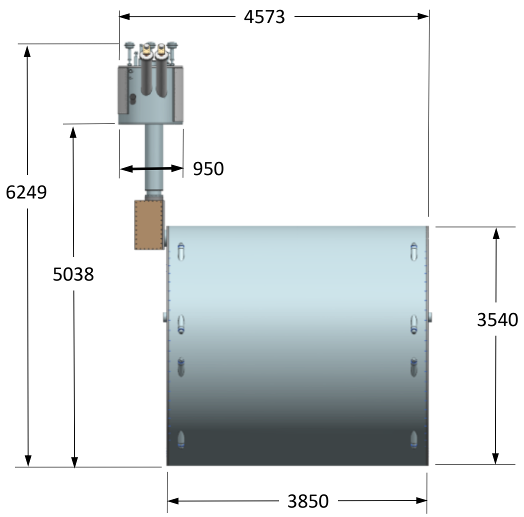
# Practical Problems with Larger Magnets

- Stored Energy
  - Larger the volume, higher the stored energy
  - Higher the field, higher the stored energy
  - ePIC magnet stored energy is approximately 50 MJ ➡ A Honda Pilot Car going on 480 miles per hour speed!!
    - Energy management during a quench
- Material/ Conductor Availability
  - Conductor- largest market for conductor is MRI magnets
  - The big detector projects come around every 15-30 years around the world
  - All detector magnets have unique requirement and design aspects
- Manufacturability
  - One-off magnets, therefore, no prototyping
  - Limited vendor base
  - The big detector projects are not frequent, therefore, by the time next big project come there is no experienced people available
  - All this leads to longer design time and longer built time
- Testing
  - Testing can only be done at site
  - Longer installation time

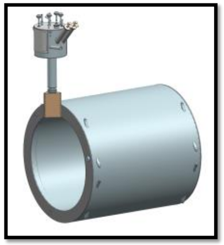
# ePIC Detector Solenoid (MARCO) Overview

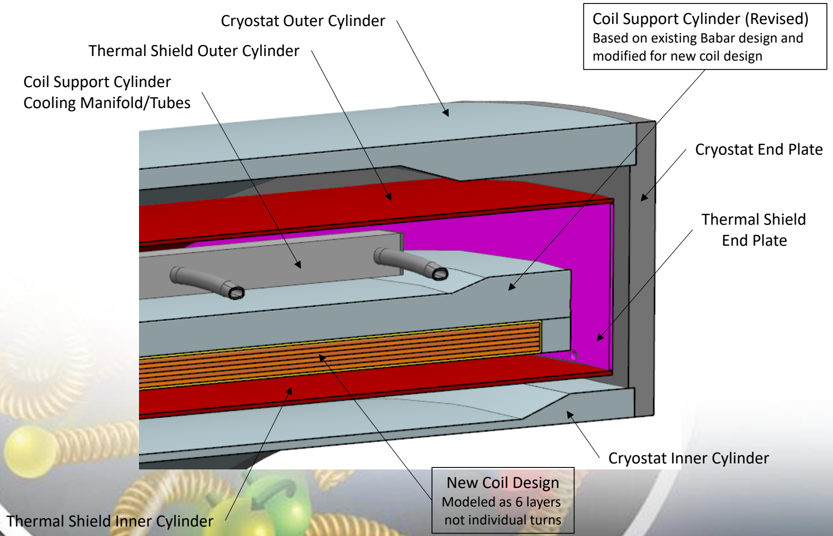
Superconducting Detector solenoid

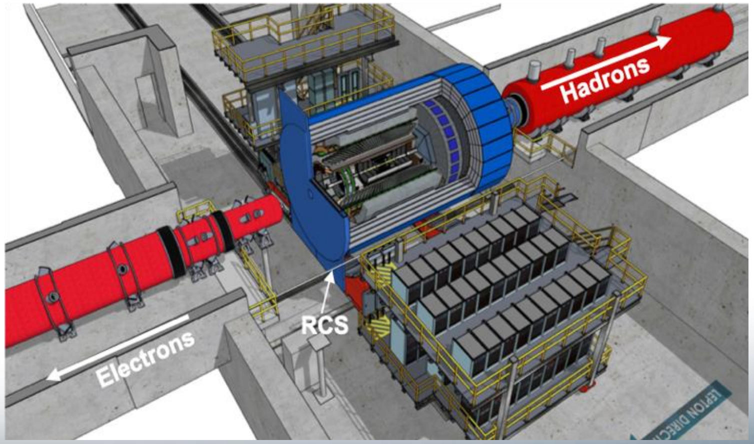
- 3.5 m long coil, 2.84 m room temperature bore diameter, 2 T on-axis field
- Operating Temperature 4.5 K
- Conductor: Copper Cladded, Rutherford Cable made with NbTi superconducting strands




**EIC Magnet Assembly Envelope**
Based on existing BABAR design and drawings





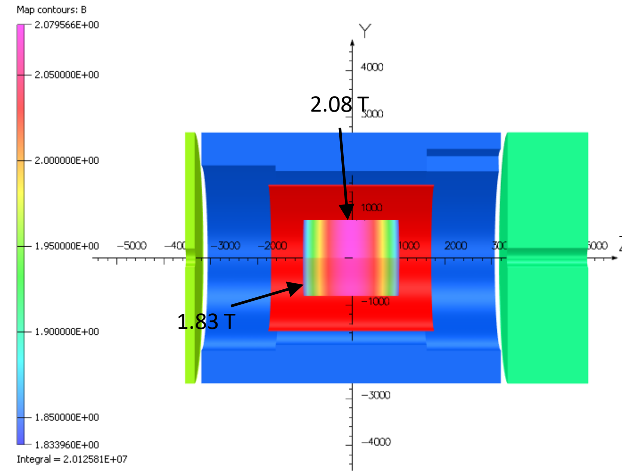
# ePIC Detector Solenoid Magnet Specifications

| 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<br>80 cm radius | 1. Magnetic field properties<br>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)<br>Projectivity in RICH Area (T/Amm$^2$) | 0.1<br>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 | |

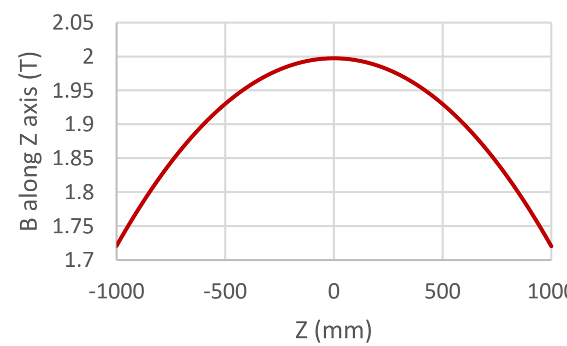
# 3D Magnetic Design Results with Single Long Coil

| Parameter | Parameter Value | Units | Validation |
|---|---|---|---|
| Coil $R_{in}$ | 1509.5 | mm | OK |
| Coil $R_{out}$ | 1543.1 | mm | OK |
| Coil Length | 3492.0 | mm | OK |
| **3D RESULTS** | | | |
| B @ (0,0,0) | 2.000 | T | OK |
| Bpeak+self field | 2.602 | T | |
| Stored Energy | 45.7 | MJ | |
| B @ (0,0,-5300) | ~13 | G | Tbd |
| B @ (0,0,7200) | <10 | G | OK |
| B @ (3400,0,0) | <10 | G | OK |
| Projectivity | 2.41 | T/Amm² | OK |
| Homogeneity | 12.3 | % | Validated by physics group |

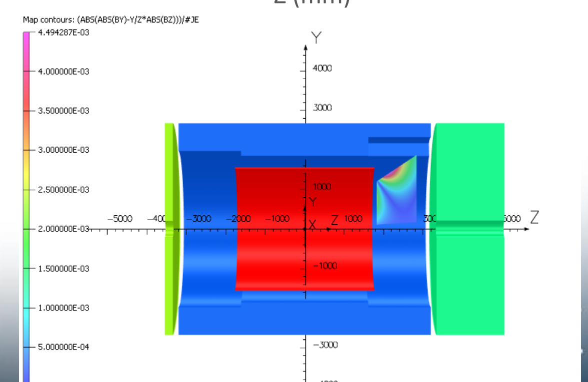
*Homogeneity region*




*B field along Z axis*

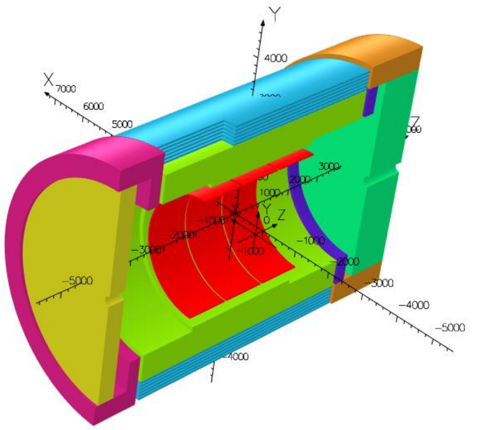



*RICH Projectivity*



# 3D Magnetic Design Results with 3- Module Coil

| Parameter | Specifications | Design parameters after 60% design |
|---|---|---|
| Nominal Central Field at IP (T) | 2 | 2.02 |
| Peak Field on the conductor (T) | | 2.6 |
| Stored Energy of the magnet (MJ) | | 45.73 |
| Inductance o the magnet (H) | | 5.94 |
| Coil length (mm) | 3492 | 3492 |
| Warm bore diameter (m) | 2.84 | 2.84 |
| Cryostat length (m) | ≤3.85 | 3.85 |
| Cryostat outer diameter (m) | ≤3.54 | 3.54 |
| Field uniformity in Flat field Area (%) | 12.5 | 12.3 |
| Projectivity in RICH Area ($A/Tmm^2$) | 10 | 2.41 |
| Stray field requirement | <10 G @ z=-5.3 m, @z=+7.4 m, and @R=3.4 m | 13.7 G @ z=-5.3 m, 8.8 G @z=+7.4 m, 1.5 G @R=3.4 m |
| Charging voltage (V) | 10 | 6 |
| Fast discharge voltage maximum (V) | 500 | 500 |
| Quench hot spot temperature (K) | <150 | 71.4 |
| Temperature margin (K) | >1.5 | 2.5 |
| Current margin (%) | <30 | 28.8 |
| Charging time (hr) | 2-3 | 3 |
| Cooldown time (weeks) | 3-4 | 3 |
| Operating Temperature | 4.5 | 4.7 |



# Al-cladded vs Cu-cladded conductor

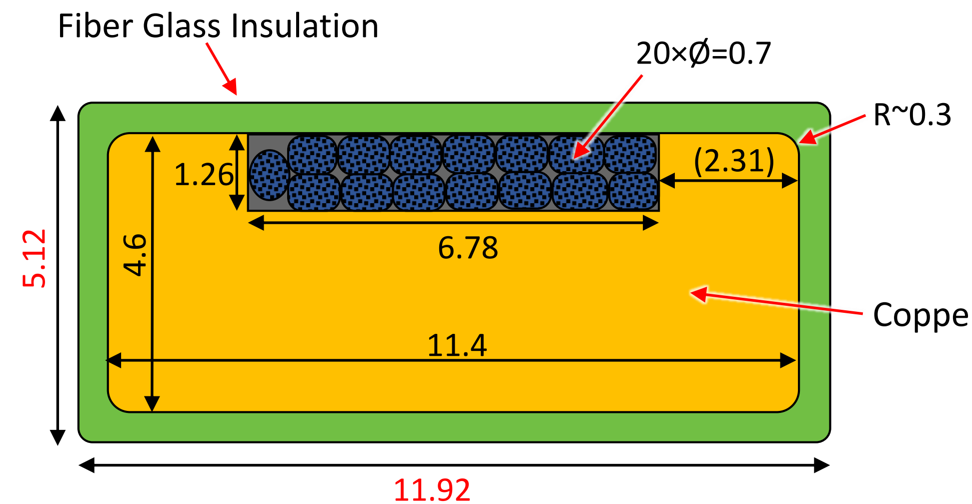
- The materials in the EIC detector, including those in the solenoid, need to be consistent with the overall material budget that allows detection of relevant particles for EIC science, with their specific energies.
- At the EIC, the barrel Hadron Calorimeter (bHCal) needs to act as tail catcher following the barrel Electromagnetic Calorimeter (bECal) that is ~ 1 $\lambda_I$ (nuclear interaction length). This implies that the solenoid material needs to be "light" (~1.3 $\lambda_I$) to contain 95 % of the hadrons with energy of science interest in EIC.
- This leads to the need for all the material thickness to be less than 1 interaction length (lower the better). The current material budget for Marco 2T design is well within this limit.

| Material | Thickness/Nuclear interaction length | | | |
|---|---|---|---|---|
| | BaBAR | ATHENA/SOCRATE | Marco 1.5 T | Marco 2T |
| Al | 0.382 | 0.650 | 0.113 | 0.113 |
| Cu | 0.011 | 0.170 | 0.114 | 0.166 |
| SS/Brass | 0.000 | 0.417 | 0.136 | 0.181 |
| NbTi | 0.007 | 0.020 | 0.003 | 0.008 |
| G10 | | | 0.023 | 0.028 |
| Total | 0.400 | 1.258 | 0.367 | 0.468 |

2T Marco is almost similarly transparent as BaBAR

# Conductor definition

| | Parameters | Values | Units |
|---|---|---|---|
| Strand | Strand diameter | 0.7 | mm |
| | Cu/NbTi | 1.3 | |
| | Ic @ 2.6T & 4.7K | > 680 | A |
| | Filament diameter | < 30 | µm |
| | RRR Cu | > 80 | |
| Cable | NbTi strands | 20 | |
| | Transposition pitch | 50 | mm |
| Channel | RRR Cu | > 100 | |
| | Copper section (Final) | 43.7 | mm² |
| Conductor | Nominal current | 3924 | A |
| | RRR conductor | > 100 | |
| | Temp. margin @ 2.6T & 4.7K | 2.5 | K |
| | Hot spot Temperature | 71.4 | K |
| | $\sigma_{0.2\%}$ @ 293K | > 165 | MPa |
| | Unit length (supposed) | 1.05 | km |
| | Total length (supposed) | 18.9 | km |




*Dimensions are in mm*

*Order of conductor samples put in place based on these specifications !*

# Margin @ 4.7 K

| $B_0$ | 1.5 T | 1.7 T | 2.0 T | Units | |
|---|---|---|---|---|---|
| Current | 2900 | 3296 | 3924 | A | |
| $B_{peak}$ | 1.925 | 2.187 | 2.602 | T | |
| Temp. margin | 3.1 | 2.9 | 2.5 | K | > 1.5 K |
| Load line margin | 60.6 | 55.3 | 46.8 | % | |
| $I / Ic(T_m, B_{peak})$ | 17.3 | 21.3 | 28.8 | % | <30 % |

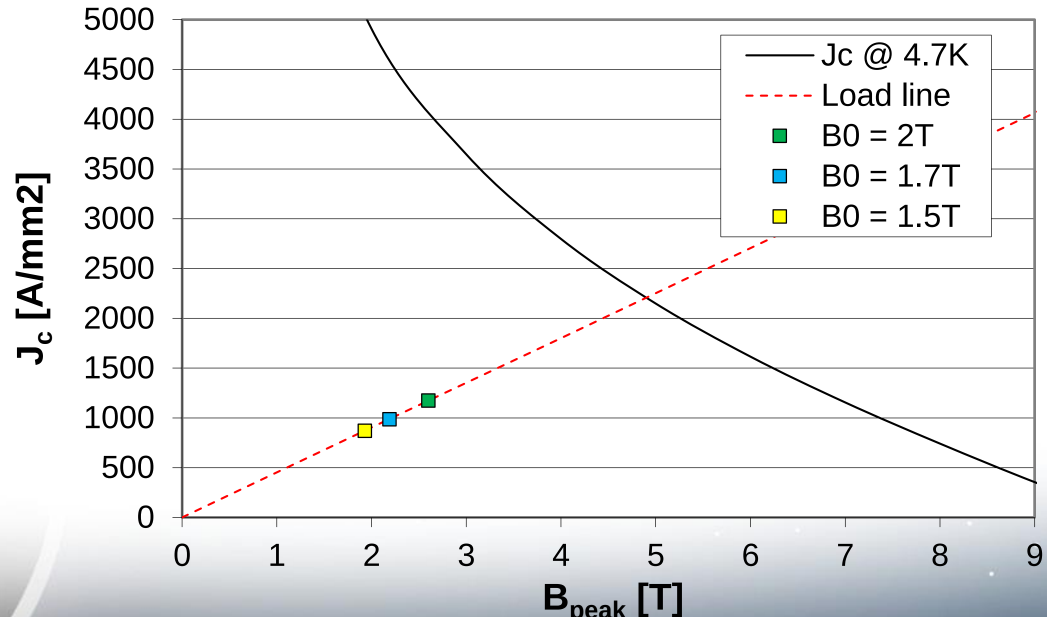
- Bottura scaling law [1]

Parameters for the fit (C.R. Spencer)

| | | | |
|---|---|---|---|
| Bc20 | 14.5 [T] | α | 0.57 |
| Tc0 | 9.2 [K] | β | 0.9 |
| n | 1.7 | γ | 1.9 |
| C0 | 73000 [TA/mm²] | | |

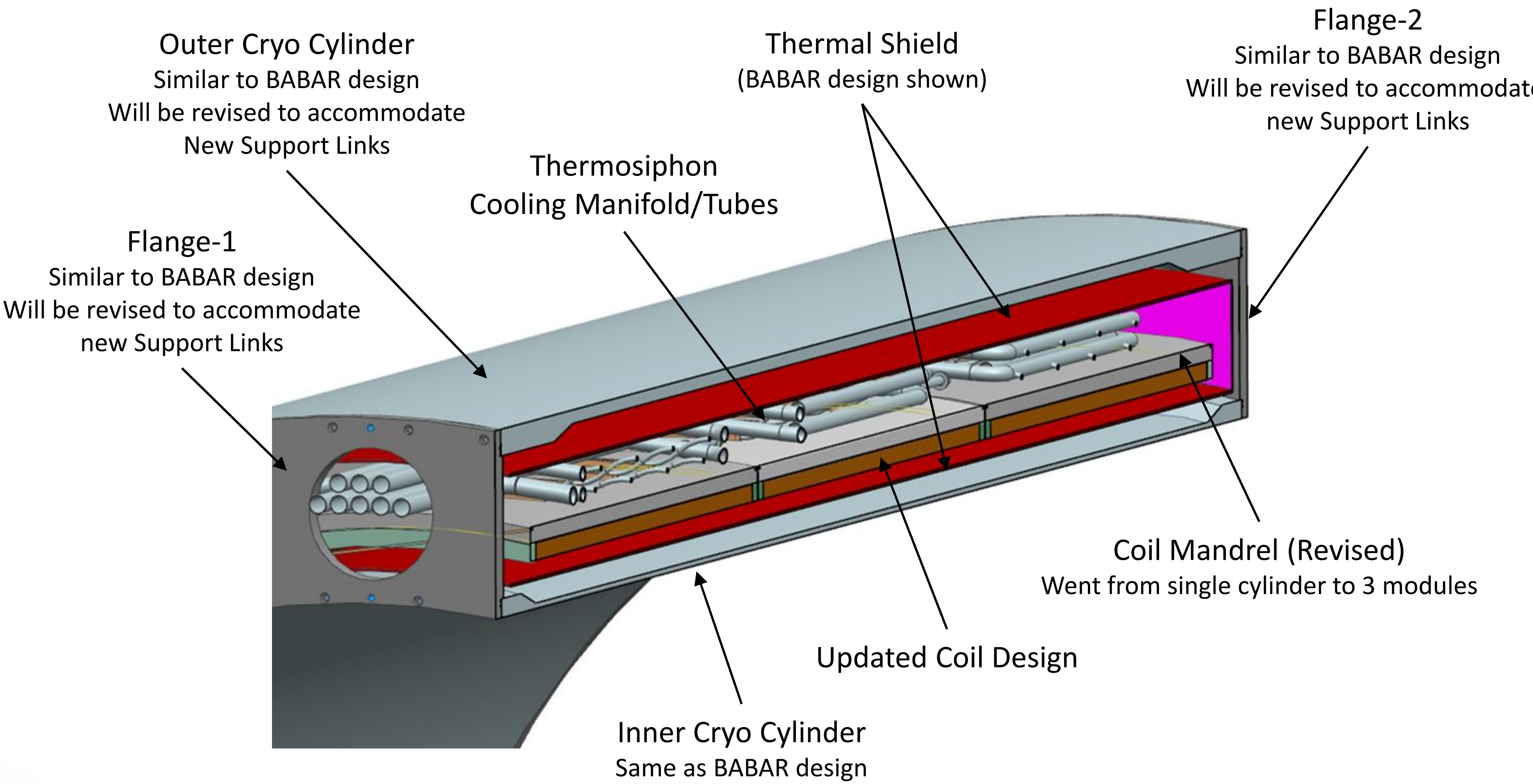
- $I_c$ degradation: 15%

| Iseult conductor | Ic degradation |
|---|---|
| Cabling process | <5% |
| Soldering process | <5% |




[1] Luca Bottura. A practical fit for the critical surface of NbTi. *IEEE transactions on applied superconductivity*, 10(1):1054–1057, 2000.

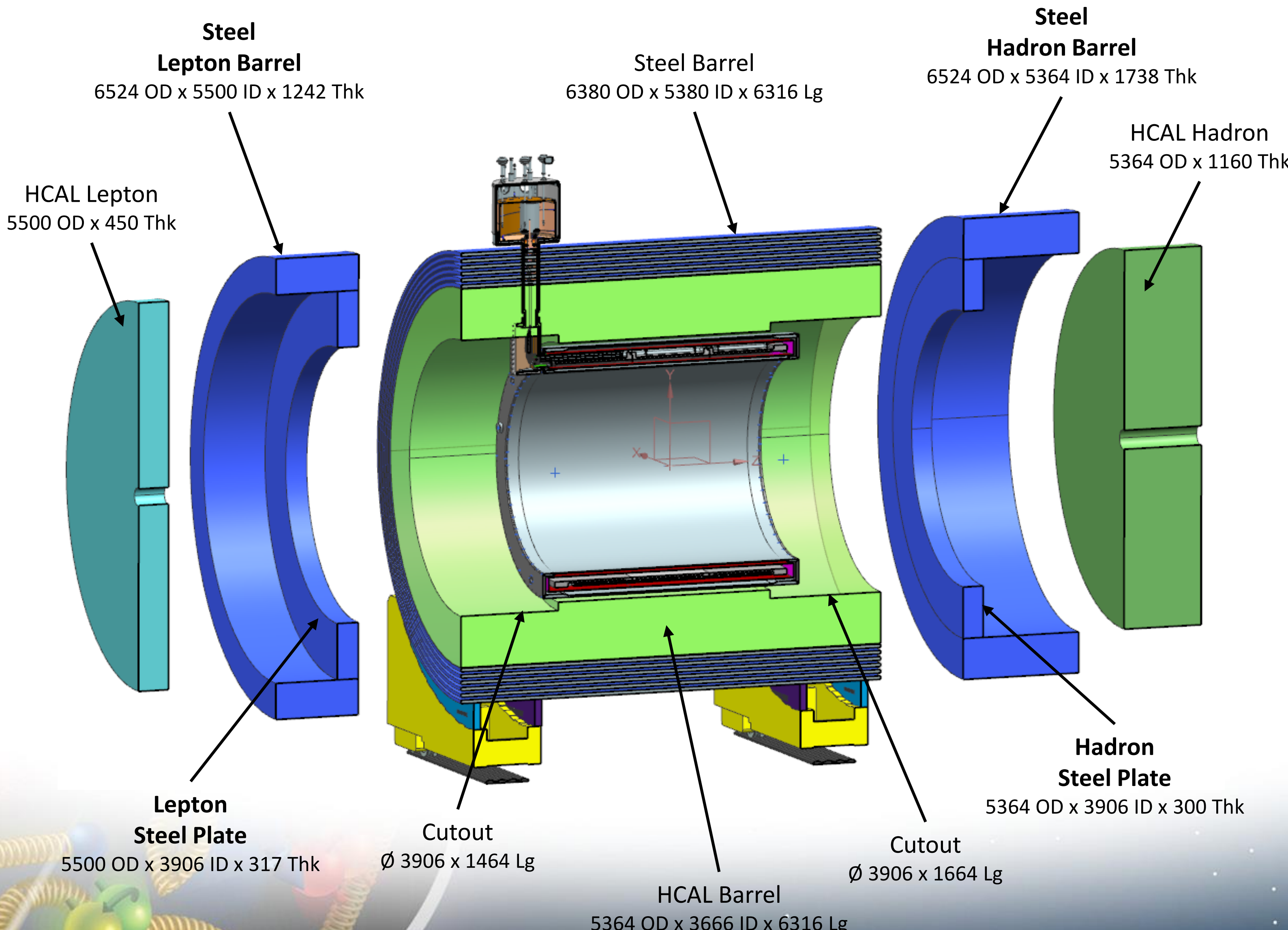
# Magnet Assembly




**Magnet Assembly**

Parametric models have been created based on existing BABAR design and drawings
Components will be revised upon completion of mechanical analysis

# Cross-sectional view-Exploded view



# How we work

- Collaboration of Jefferson Lab, CEA Saclay and Brookhaven National Lab
- 30% Design done as in-kind contribution by CEA Saclay in collaboration with Jefferson Lab Magnet Group
- BNL provides subject matter expert information on infrastructure and integration
- 60% design done as contract with CEA Saclay augmented with Jefferson Lab work and further in-kind contributions of CEA Saclay
- 90% design work is in progress in collaboration with CEA Saclay
- Expectation is that vendor contract may follow similar pattern for vendor oversight.
- Further discussions ongoing on international engagement on magnet construction phase.

# Summary

- Specifications
  - Should be clear and concise
  - Understand the implications of not meeting one or more specifications
  - Importance of various design parameters
  - Do not over constrain the magnet design
- Discussions with Magnet Engineers from the beginning of the project
- Discussions with Vendors at various stages of design (if possible)
- Design the magnet in collaborations with detectors design
- Detailed information about the environment that the magnet is required to operate in (Materials: support structure, equipment, target, etc.)
- Do not limit the magnet design by predetermining the type of conductor
- Magnet Design for ePIC detector magnet is very mature, 90% design review is scheduled for October.
- Sample conductor order placed.