Jefferson Lab
MAGNET GROUP

# EIC-Experimental Equipment

**(BABAR/sPHENIX JLab Engineering Risk Assessment)**

v2.00 - October 10th 2020 – updated risk tables

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# Outline of talk

- Background
  - Proposal for the use of this magnet
  - Magnet Construction
- Assessment Approach
  - SLAC Risk Analysis (2004, 2006)
  - BNL Low Current Test (2016)
  - BNL High Current Test (2018)
- JLab Risk Assessment (2020)
- JLab Recommendations

# Proposal to use the BABAR/sPHENIX solenoid as a detector solenoid for the EIC project

There is a proposal to re-use the existing 1.5 T BABAR magnet as a detector solenoid for the EIC project.

- The magnet for the BABAR experiment at PEP-II at SLAC, CA was manufactured by Ansaldo, Italy in 1997 and was commissioned in 1998
- It was then transferred to BNL, NY in 2015 for use in the sPHENIX experiment where it still resides today.
- Magnet History
    - November 1997- Factory Acceptance test at Ansaldo, Itlay
    - March 1998- Final Commissioning at SLAC
    - April 2008-BaBAR run ends
    - February 2015-Magnet arrived at BNL
    - March 2016- 100 A test
    - February 2018- tested to 4830 A
    - No further plans to energize the magnet till 2022 or 2023
- It should be noted that by the time the EIC project starts, this magnet will be more than 30 years old and will be required to perform for a further 20-25 years during the expected lifetime of the EIC project

# Assessment of magnet

The assessment of this magnet to determine its suitability as a detector magnet for the EIC project currently consists of two key activities:

1. Assessment of ability to satisfy physics requirements
   - *Status: Physics assessment is in progress – see Renuka Rajput Ghoshal's presentation for more details*
2. Engineering assessment to satisfy performance and reliability requirements
   - *Status: Preliminary engineering risk assessment complete and is presented here*

# Magnet Construction

- The conductor is composed of a NbTi superconducting 16-strand Rutherford type cable embedded in a pure aluminum matrix through a co-extrusion process.
- The double layer coil is internally wound on a 35 mm thick 5083 aluminum support mandrel.
- 11 parallel cooling pipes welded to the outside diameter of the support mandrel form part of the thermo-syphon system. The system has also been used in a forced flow mode supplied by a large helium dewar.
- The thermal shield is cooled by the return helium flow from the magnet.
- Electrical insulation consists of dry wrap fiberglass cloth and epoxy vacuum impregnation.
- In order to have a field homogeneity of +/- 3% in the large volume specified by the *B*a*B*ar experiment, the current density in the winding is graded: lower in the central region and higher at the ends.
    - The gradation is obtained by using conductor of two different thickness: 8.4 mm for the central region and 5 mm for the ends.
- The magnet is protected by a set of hardware and software interlocks that will either ramp the current in the magnet down or open a breaker which quickly discharges the current into an external dump resistor.
- There are 6 axial and 16 radial Inconel 718 tie rods supporting the cold mass.

# sPHENIX Superconducting Solenoid Magnet Design Specifications



The sPHENIX superconducting solenoid magnet was formerly the BABAR magnet. It has the following characteristics:

Field Parameters:

| | |
|---|---|
| Central Field | 1.5 T Max. |
| Stored Energy | 27 MJ |

Main Coil Parameters

| | |
|---|---|
| Mean Diameter of Current Sheet | 3060 mm |
| Current Sheet Length | 3513 mm |
| Number of layers | 2 |
| Operating Current | 4596 A |
| Conductor Current Density | 1.2 kA/ mm2 |
| Inductance | 2.57 H |

Cryostat Parameters

| | |
|---|---|
| Inner Diameter | 2840 mm |
| Radial Thickness | 350 mm |
| Total Length | 3850 mm |
| Total Material (Al) | ~ 126 mm |

Outer HCal Steel

| | |
|---|---|
| ID/OD | 1780/2595 mm |
| Length | 6010 mm |
| Weight | 320 plates @ 1.44 metric Tons ea = 461 metric tons |

Doors (each)

| | |
|---|---|
| ID/OD | 562/5190 mm |
| Thickness | 30 mm |
| Weight | 50 metric tons |

# Sizing Scale

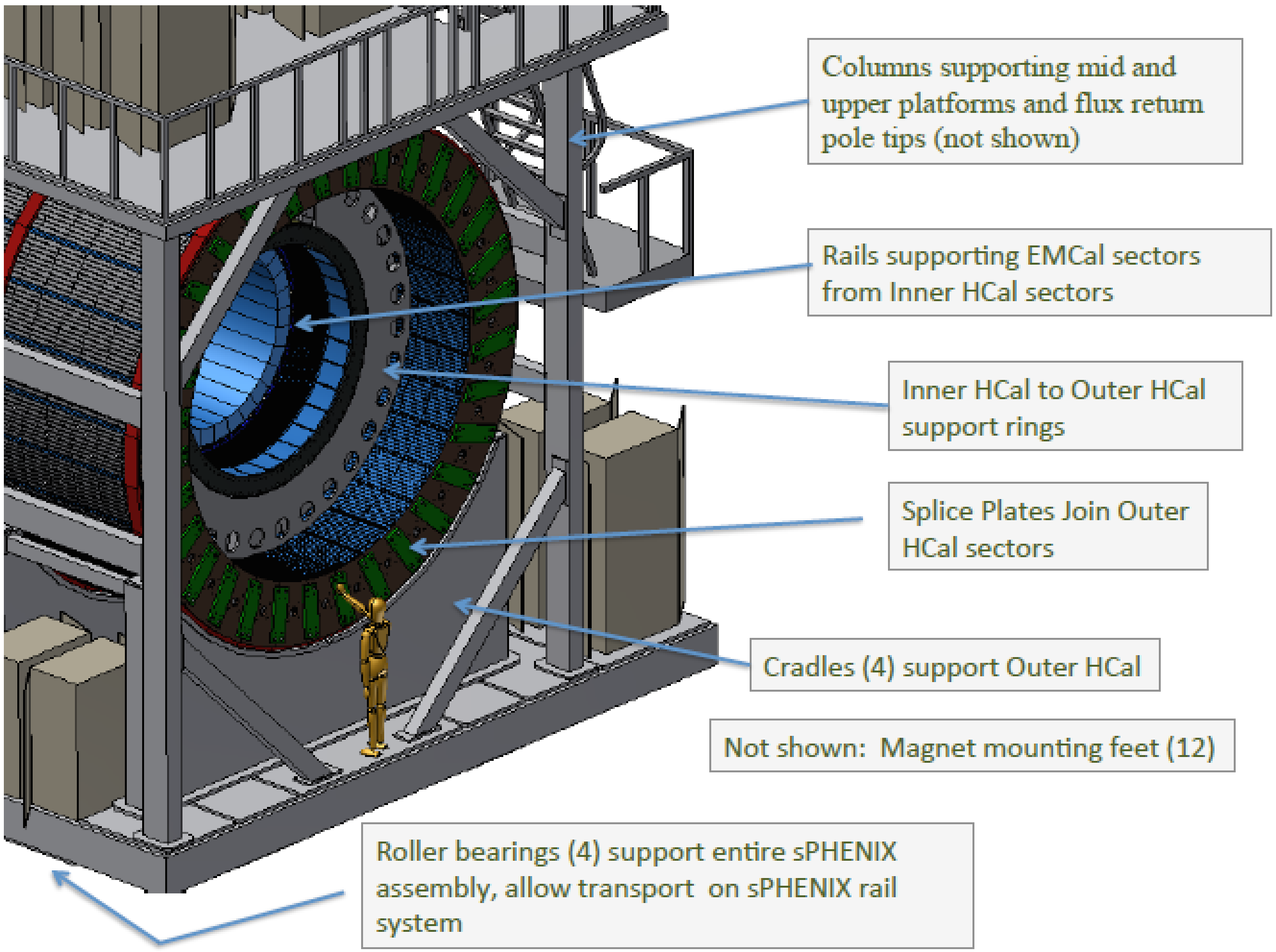



Figure C.7: sPHENIX Structural Support

# Sizing Scale

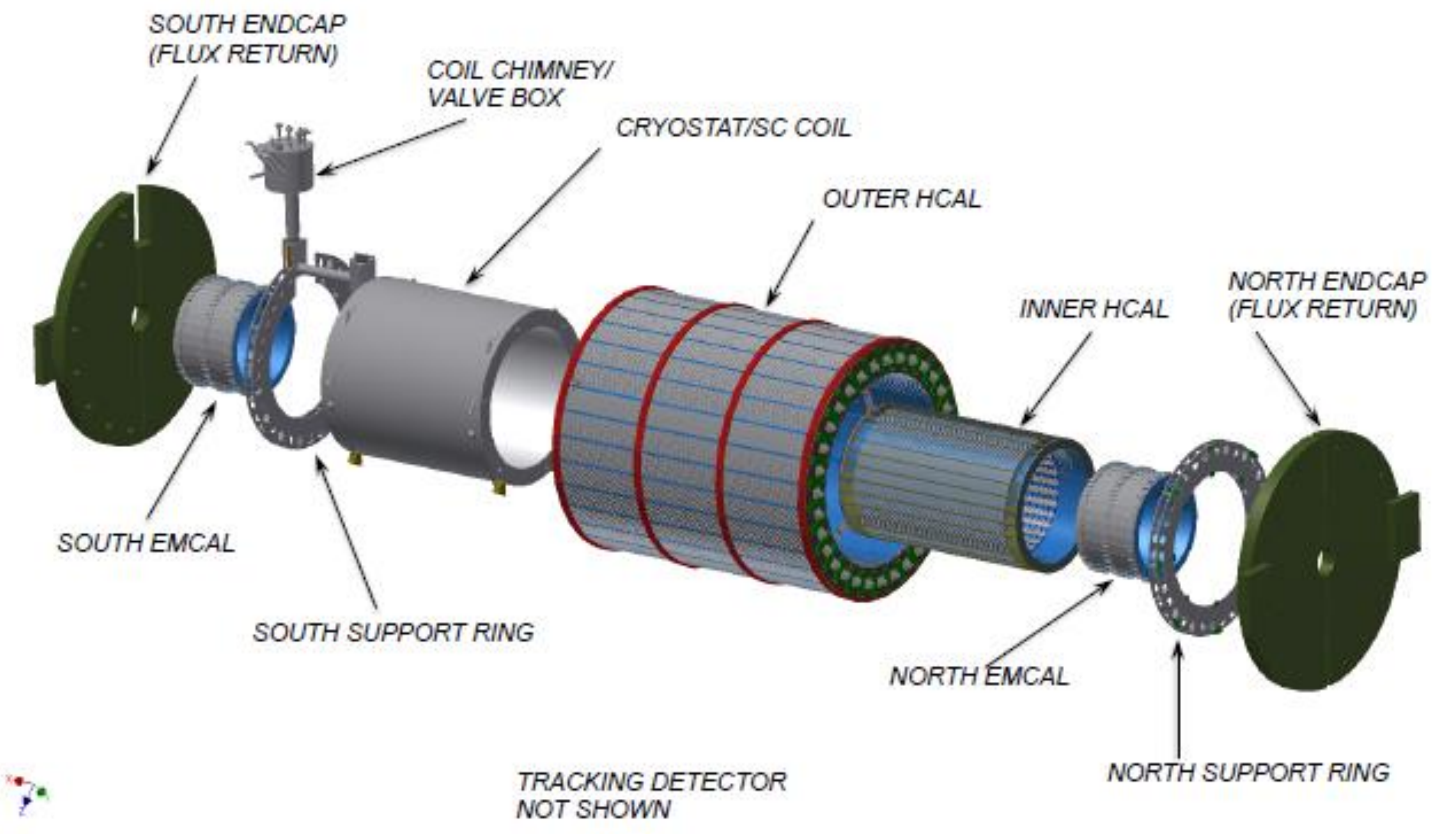
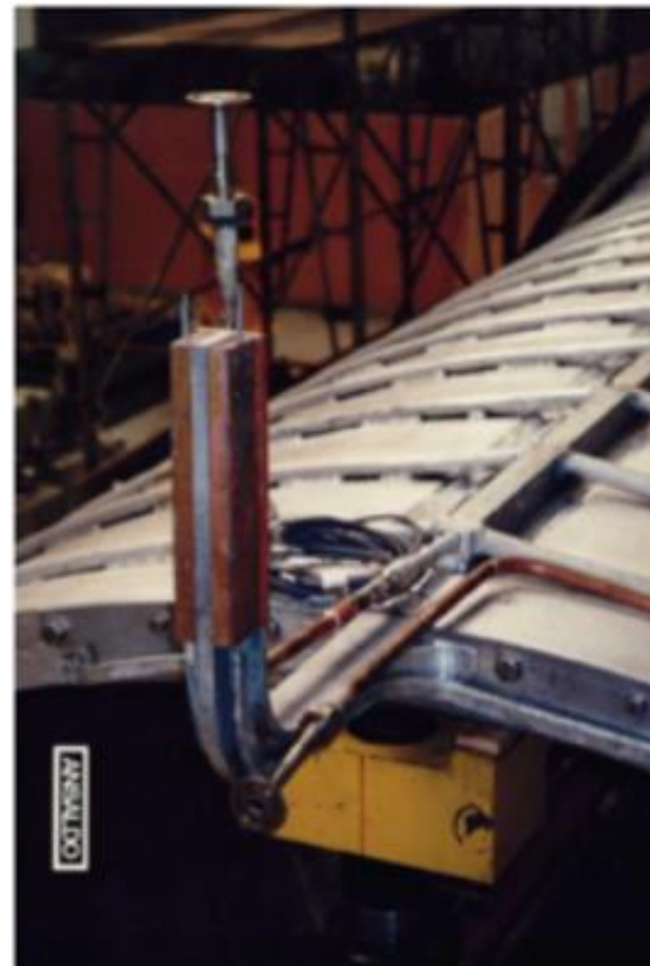



**Figure C.6:** sPHENIX exploded view

# Magnet Construction

Magnet in its cryostat (vacuum jacket)



Lead exit at end of coil

# Thermal shield

Inner thermal shield

Outer thermal shield

# Thermal Shield Assembly



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# Instrumentation wiring



# End view – internal support rods

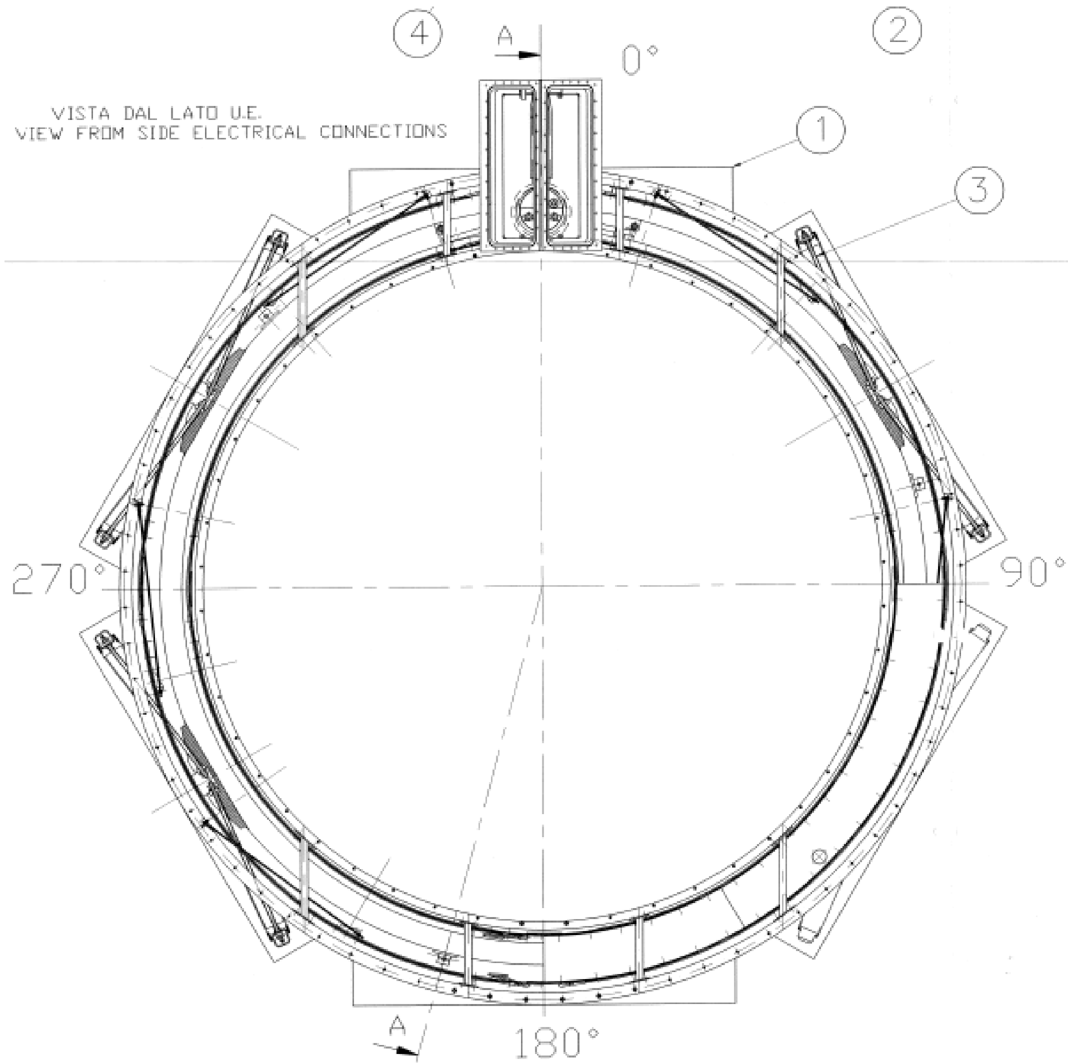


**Figure A.4:** Original Ansaldo drawing: Cryostat Assembly

# Valve Box

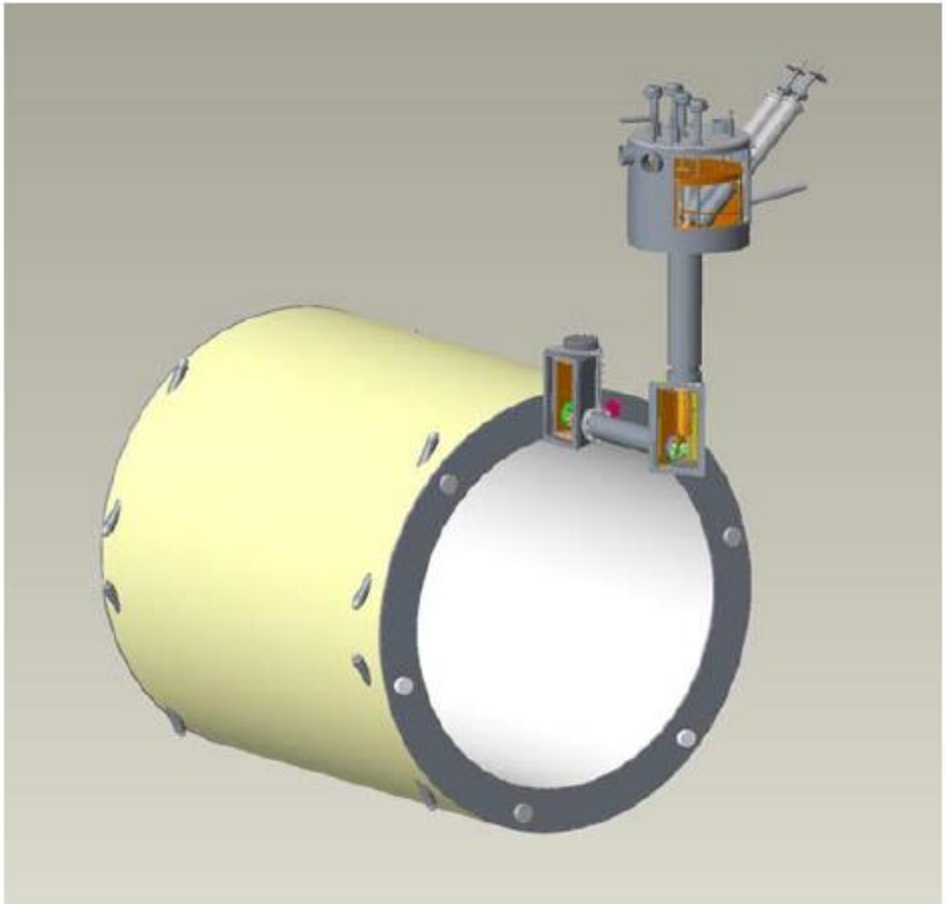

Figure A.7: The cryostat, the extension and the valve box.

# Approach used to conduct the engineering risk assessment

| Document Title | Existing BABAR (sPHENIX) Solenoid - JLab Engineering Risk Assessment |
|---|---|
| Project | EIC Experimental Equipment |
| Purpose of document | To collate information pertaining to the long term engineering robustness and suitability of using the existing BABAR (sPHENIX) solenoid as the EIC detector solenoid |
| Version No. | 3.00 |
| Date | **09.02.2020** |
| Engineer | R. Fair |
| Reviewed by | R. Rajput-Ghoshal |

| Version | Date | Who | Changes from previous version |
|---|---|---|---|
| 1.00 | 08.28.20 | R. Fair | Initial release |
| 2.00 | 09.01.20 | R. Fair | Updated after review by R. Rajput-Gho |
| 3.00 | 09.01.20 | R. Fair | Updated after initial review by R. Ent, recommendations |
| | | | |

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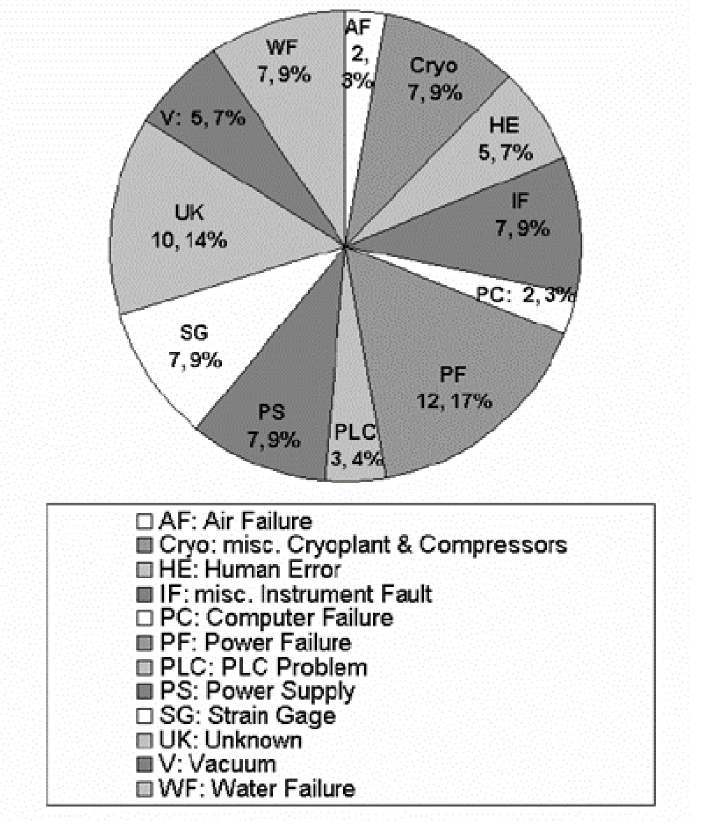
# sPHENIX Magnet-SLAC Risk Analysis (2004, 2006)

- The magnet started operation in May 1999. Two formal risk assessments were carried out at SLAC in 2004 and 2006 following 5 to 7 years of operation.
- From May 1999 – 2004, there have been 63 unplanned interruptions to magnet operations. None of these can be shown to be the result of a spontaneous quench in the coil. In nearly all cases, the interruptions can be traced to failures in utilities or supporting systems or to human error. Three notable categories-
  - Unknown: 10%
  - Miscellaneous instrument faults : 8%
  - Strain gauges: 8 %
- After mitigations were implemented – namely installing cooling and vacuum backup systems, changing the control programming and removing unneeded interlocks – the total number of interruptions after 2004 has been significantly reduced.
- Magnet availability between 2000 – 2004: approx. 98%



# sPHENIX Magnet- BNL Low Current Test (100 A)

The low field test of the sPHENIX Solenoid was completed successfully and accomplished the following important tasks and results.

1. The magnet was cooled down to 4.5 K and warmed back to room temperature without problems and the experience in the cool down and warmup will be useful for the future high field test cool down.

2. The magnet was shown to be electrically stable with no anomalies during ramping and shutdowns.

3. The energy extraction system switching process was verified.

4. The magnet maintained mechanical stability throughout cool down and warmup.

5. Important parameters for quench detection and operation were determined.

6. Magnetic field was verified up to the level of 100 A.

7. Strain gauges were read but more work needs to be done to understand the results before the high field test. *(Note: Five strain gauges were not working and one showed an unusually high reading was ignored).*

# sPHENIX Magnet- BNL High Current Test (4830 A)

The high field test was carried out after installation of a return flux steel box enclosing the superconducting magnet. The magnet achieved field – the following issues were noted:

- Several voltage taps (used for quench protection) failed before the test commenced
- New temperature sensors were fitted prior to the test but failed to read accurately
- Another voltage tap failed intermittently and caused a fast dump of the magnet
- The control system crashed causing a fast dump of the magnet
- Quench occurred at about 3000 A
- Quench occurred at about 4410 A (possibly due to the high ramp rate of 2.5 A/s)
- Achieved 4830 A after reducing ramp rates
- Magnet only stayed at full field for 36 minutes due to the lack of availability of Lhe
- Multiple hardware issues (mostly external to the magnet) were noted and will be addressed prior to the sPHENIX experimental runs.
- However, there were a few leaks, most of which were accessed and repaired. But there is still one small cold leak which is currently being managed by pumping
    - There is also evidence that both Ansaldo and SLAC had previous issues with leaks

# JLab Engineering Risk Assessment - 2020

## Executive Summary

Purely from an engineering perspective, if the changes (improvements) listed below are carried out in order to mitigate the identified risks, then this magnet should be suitable for prolonged use as part of the detector system for the EIC project. However, it should be borne in mind that several of the mitigation efforts described below involve the disassembly of the magnet and this therefore imposes a certain level of risk. Furthermore, if the physics studies currently underway, indicate that additional changes are required to the magnet, (for example the inclusion of trim coils and/or changes to the iron circuit); then the system as a whole, will have to be re-evaluated - to ensure that the magnet remains within the original design limits under both normal and abnormal operating conditions.

| Risk Rating | Before Risk Mitigation | After Risk Mitigation | Comments |
|---|---|---|---|
| HIGH | 1 | 0 | |
| MODERATE | 5 | 4 | Requires disassembly which can introduce additional risk |
| LOW | 2 | 4 | |
| **Total** | **8** | **8** | |

| Sub-System | Present Status | Failure Modes / Performance Limitations | Risk Rating Before Mitigation | Risk Mitigation | Risk Rating After Mitigation |
|---|---|---|---|---|---|
| **Coil Design** | Conservative electromagnetic design. | Micro-cracking of VPI resin is likely to have occurred after all these years of operation and thermal cycling, although this does not yet seem to have had a detrimental effect on the overall performance of the coil. | **LOW** | When magnet is not operating, keep coil at LN2 temperature.<br>Magnet has to be ramped to field no faster than 45 minutes to avoid eddy current heating and quenches – i.e. use 2.5 A/s or lower to 2000 A and then 1.5 A/s or lower to 4830 A. | **LOW** |
| **Coil Protection** | Standard design utilizing external dump resistor. VT11 open circuit, VT10 suspect – might affect quench detection and protection. Temperature sensors on splices reading high possibly due to poor mounting. | Additional critical voltage taps (for quench detection and protection) could be lost. Temperature sensors in key areas – coils, splices and current leads could either be lost or mis-read.<br>If the power supply, dump switch and dump resistor are original, they could fail. | **HIGH** | Purchase new magnet power supply, dump switch and dump resistor. BNL confirmed that they have refurbished the power supply (including the capacitors etc.) and the dump resistor (including the contactor and have added a snubber circuit) before the high-field test.<br><br>Add new redundant VTs and new temperature sensors or remount existing sensors – **requires disassembly of magnet.** | **MODERATE (risk could be incurred as soldering new VTs to magnet conductor can be troublesome and might cause damage to the conductor and insulation)** |

| Sub-System | Present Status | Failure Modes / Performance Limitations | Risk Rating Before Mitigation | Risk Mitigation | Risk Rating After Mitigation |
|---|---|---|---|---|---|
| **Internal Mechanical Support System** | Five strain gauges are not working and one shows unusually high readings and is ignored during tests. | If tie rods, disc springs have been overstressed, they could fail in the future although this is difficult to surmise as several gauges are not working and at least one is being ignored.<br>There could have been some overstressing of components during the transport from SLAC to BNL although there are no outward signs of this at present. | MODERATE | Fit new strain gauges – properly mounted and temperature compensated - **requires disassembly of magnet.** | MODERATE **(remains as moderate as the magnet requires disassembly which could lead to more rework)** |
| **Current Leads** | The leads seem to be functioning well and have had no issues associated with them. There are plans to improve (increase) the gas flow cooling by operating the Helium circuit at a higher pressure. | Operating the helium circuit at a higher pressure (1.45 bar) will cause the magnet to operate at a higher temperature (approx. 4.65 K which means an enthalpy decrease of only 2.5% which should be OK as confirmed by their technical committee magnet expert [10].<br>There could have been some overstressing of components (e.g. the current leads themselves or splice joints) during the transport from SLAC to BNL although there are no outward signs of this at present. | LOW | Relocate current lead heaters and control temperature sensor to improve ice-management control. Increase helium gas flow. | LOW |

| Sub-System | Present Status | Failure Modes / Performance Limitations | Risk Rating Before Mitigation | Risk Mitigation | Risk Rating After Mitigation |
|---|---|---|---|---|---|
| **Internal Cryogenic Cooling System** | Potential hard touch between inner thermal shield and helium vessel (temp sensor on shield reading 4.2 K). Internal leak when cold: $10^{-6}$ to $10^{-7}$ torr-liters/sec level – presently being managed by pumping | Additional thermal shorts occur increasing the heat load on the system. Existing leak gets worse or additional leaks open up. There is some indication that both Ansaldo and SLAC struggled with making certain joints leak tight. There could have been some overstressing of components (e.g. welds between cooling tubes and the coil support tube) during the transport from SLAC to BNL although there are no outward signs of this at present. | MODERATE | Fix leaks, survey all pipe work to ensure all joints are leak tight and no damage has been sustained by the years of operation and the transport from SLAC to BNL - **requires disassembly of magnet.** | MODERATE **(remains as moderate as the magnet requires disassembly which could lead to more rework and the leak may be difficult to locate)** |
| **Distribution Valve Box** | If the internal leak (noted earlier) is in the valve box, then this could be fixed. This leak has been confirmed by BNL to be within the valve box. | Leak could get worse or other leaks could open up. There could have been some overstressing of components during the transport from SLAC to BNL although there are no outward signs of this at present. | MODERATE | Fix leak – **requires disassembly of valve box which should be easier than disassembly of the magnet.** | LOW |
| **Instrumentation** | Strain gauges not working, temperature sensors on splices reading high, critical voltage taps lost or suspect. | Additional instrumentation could be lost or start mis-reading | MODERATE | Fix instrumentation - **requires disassembly of magnet.** | MODERATE **(remains as moderate as the magnet requires disassembly which could lead to more rework)** |
| **Control System** | One recorded failure while at high current, PXIe data acquisition system may not be adequate | Additional failures during operation | MODERATE | Replace complete system | LOW |

# sPHENIX Magnet- Summary

To provide a sufficiently high level of confidence in the reliability of this magnet (from an engineering point of view) and to meet the physics requirements:

1. The magnet should be refurbished to mitigate the risks identified.

2. If the valve box is to be re-used, it should also be disassembled to inspect cooling pipework and to repair any leaks. *(Note: the one small leak remaining has been established to be within the valve box and should therefore be accessible)*

3. The field will need to be shaped to achieve the required projectivity for RICH operation (see Renuka Rajput-Ghoshal's presentation)

# BACKUP

# sPHENIX Magnet- JLab Risk Analysis-Recommendations

To provide a sufficiently high level of confidence in the reliability of this magnet (from an engineering point of view), the magnet should be refurbished as suggested below.

1. The magnet should be disassembled sufficiently:
   - To allow the existing multi-layer insulation (MLI) to be removed and replaced with new MLI.
   - To allow inspection of the superconductor coil block – resin and insulation system.
   - To allow inspection and if necessary, repair of insulation and support of any internal bus bars.
   - To allow all cooling pipe work and welds to the coil support tube to be inspected and all leaks repaired.
   - To allow inspection of the thermal shield and cooling pipework ad welds.
   - To allow inspection of all vacuum seals and welds.
   - To allow inspection of all accessible conductor splices in particular the ones between the coil and the current leads.
   - To allow inspection and if necessary, replacement of insulating components – e.g. G10 collars, plates, etc.
   - To allow inspection and if necessary, replacement of the magnet current leads.
   - To allow broken voltage taps to be repaired and additional redundant taps installed.
   - To allow temperature sensors which are presently possibly malfunctioning to be either repaired or replaced.
   - To allow additional or redundant temperature sensors to be installed
   - To allow malfunctioning strain gauges to be either repaired or replaced.
   - To allow additional or redundant strain gauges to be installed.
   - To allow a full inspection and if necessary, replacement of the tie rods and disc springs for the internal mechanical support system.
2. If the valve box is to be re-used, it should also be disassembled to inspect cooling pipework and to repair any leaks. *(Note: the one small leak remaining has been established to be within the valve box and should therefore be accessible)*

# APPENDIX A: SOLENOID DATA

Table 1
Main characteristics of BaBar solenoid (as built)

| | |
|---|---|
| Central Induction | 1.5T |
| Conductor peak field | 2.3T |
| Winding structure | 2 layers graded current density |
| Uniformity in the tracking region | ± 3% |
| Winding axial length | 3512 mm *at R.T* |
| Winding mean radius | 1530 mm *at R.T.* |
| Operating current | 4596 A |
| Inductance | 2.57 H |
| Stored Energy | 27 MJ |
| Total turns | 1067 |
| Total length of conductor | 10 300 m |

Table 2
Summary of specification for strands, Rutherford and full conductor

| Component | Characteristic | Value |
|---|---|---|
| Strand | NbTi | Nb 46.5 +/- 1.5 wt % Ti |
| | Filament size | < 40 μm |
| | Cu/NbTi ratio | > 1.1 |
| | Wire diameter | 0.8 mm ± 0.005 |
| Rutherford | Transposition pitch | < 90 mm |
| | No. of strands | 16 |
| | Final size | 1.4 x 6.4 mm2 |
| Conductor | Al-RRR | >1000 |
| | Dim. (mm): | |
| | Thin conductor | (4.93 x 20)±0.02 |
| | Thick conductor | (8.49 x 20)±0.02 |
| | Rutherford-Al bonding | > 20 MPa |
| | Al/Cu/NbTi: | |
| | Thin conductor | 23.5:1.1:1 |
| | Thick conductor | 42.4:1.1:1 |
| | Edge curvature radius | > 0.2 mm |
| | Critical current @ T=4.2K B=2.5T | 12680 A |

# Cautions

- Magnet has a cold leak (nearly impossible to find (or therefore fix, so one simply hopes it doesn't worsen). From "BABAR Superconducting Solenoid Acceptance After Final Test at SLAC"

  "When cold it was observed that after closing the cryostat vacuum isolation valve the pressure increased from - 1.5 1 o-7 to 2 1 o-5 mbar in 18 h. This equates to a He leak of - 2 1 o-6 mbar 1 /s . This leak when cold is compatible with a 300 K leak of 1 10-8 mbar 1/s. Unfortunately, the leak requires that the cryostat be pumped constantly."

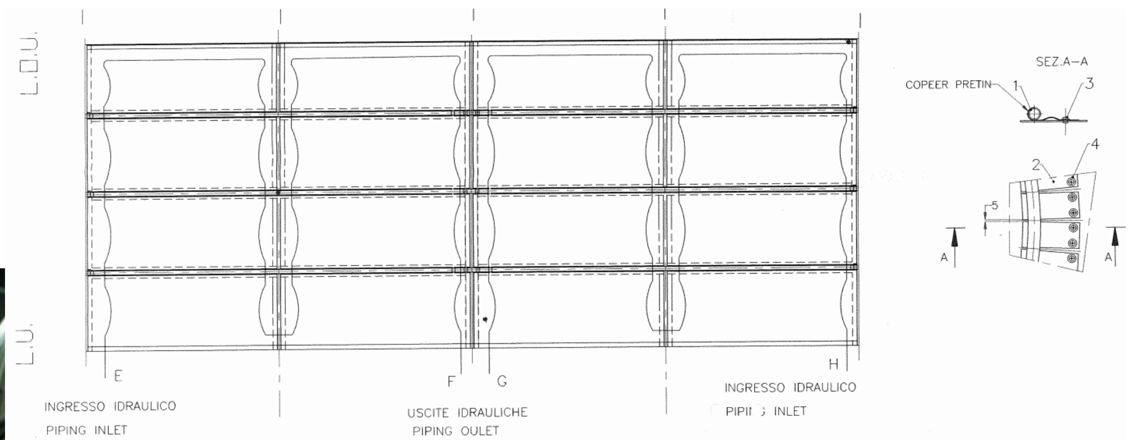
(parenthetic thought – perhaps we are fortunate that the valve box is removed. If desired, a test assembly can be designed and built to cool down the valve box independently and test to determine if the cold leak is in the magnet or valve box)

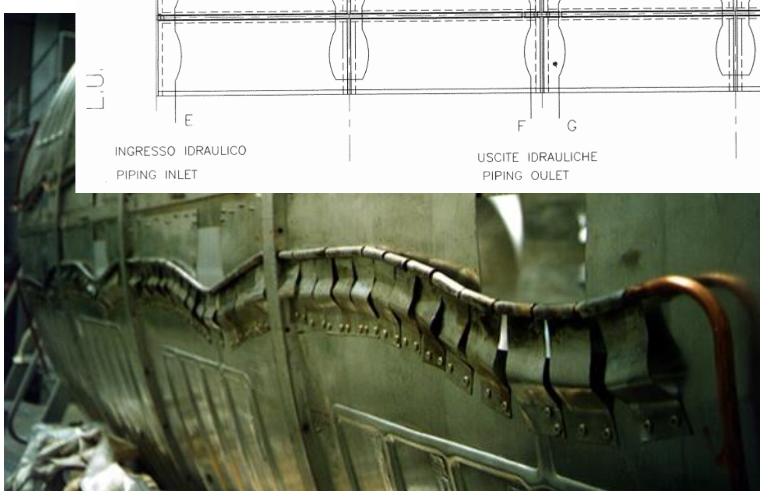
- From Dr. Pasquale Fabbricatore,

  "Only the chief technician, remembered that he dismounted the flanges and put blocks keeping the cold mass solidly anchored to the cryostat. The photos I found later confirmed that. Unfortunately, even if the magnet construction engineering is fully documented in detail, the transportation engineering is strangely missed. In particular I did not find any drawing of the transportation blocks."

# Thermal shield

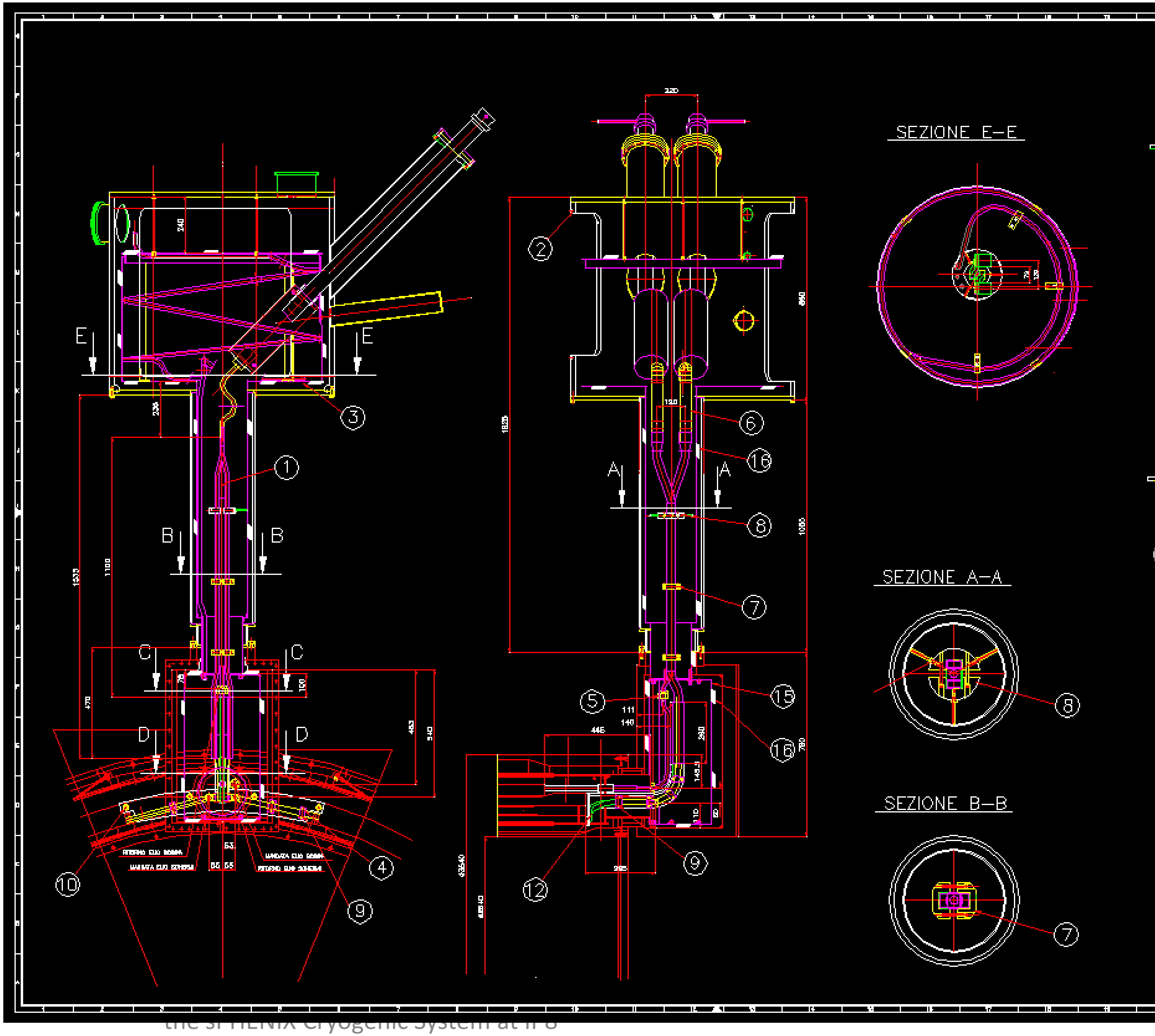
Inner and Outer shield. Forms an annular enclosure around solenoid
Material: Aluminum
Cooled by using 4.5K vapor from return flow from the separator
OUTER SHIELD
Shield panels: Cooling circuits 5 parallel headered together:
INNER SHIELD
Cooling line: strapped to shield surface

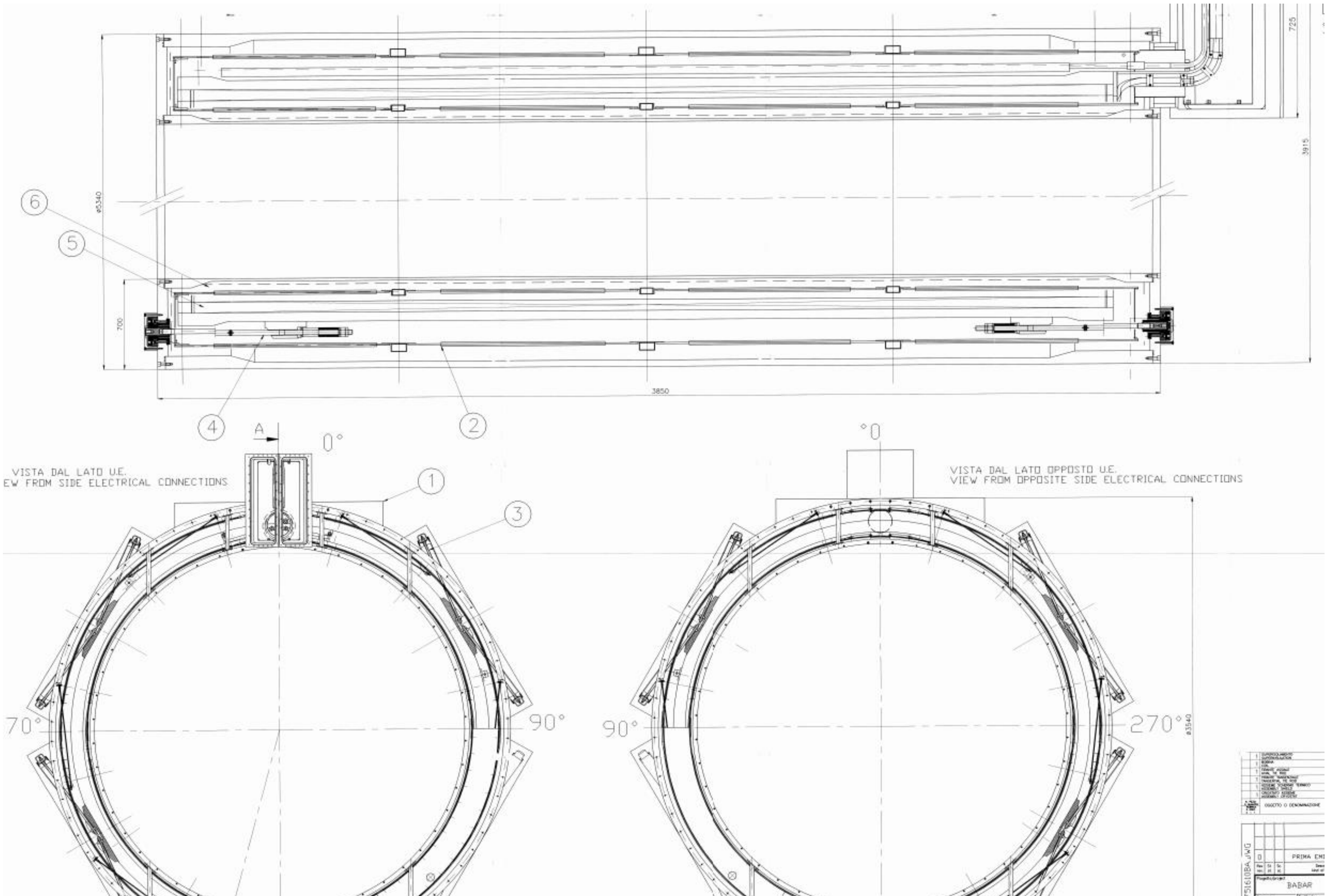


# Solenoid Valve & Current Lead box

2x 5000 A Copper Leads inside “lead pots”
Cryo valves
Cryo lines
Superconducting bus
Splice joints
Thermal shield




3850
725
3915
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700
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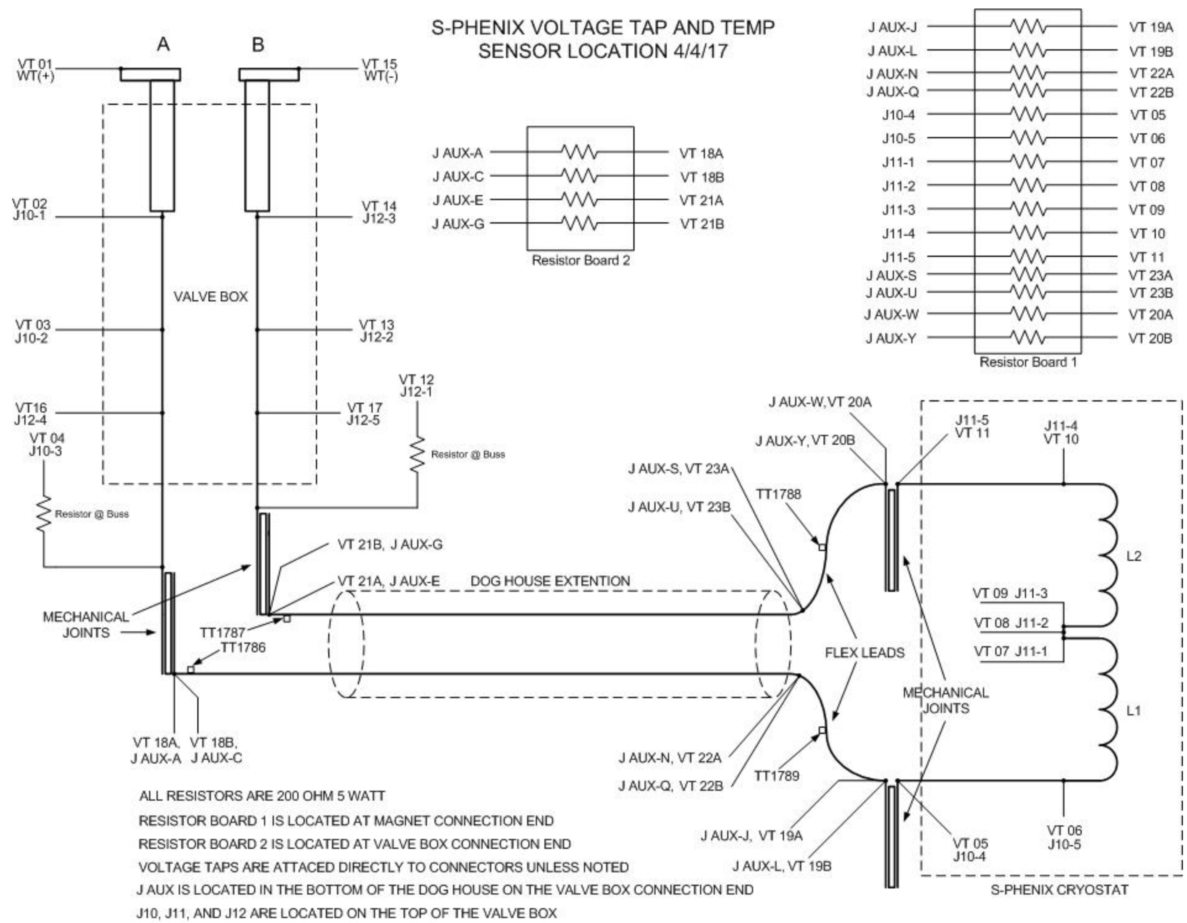
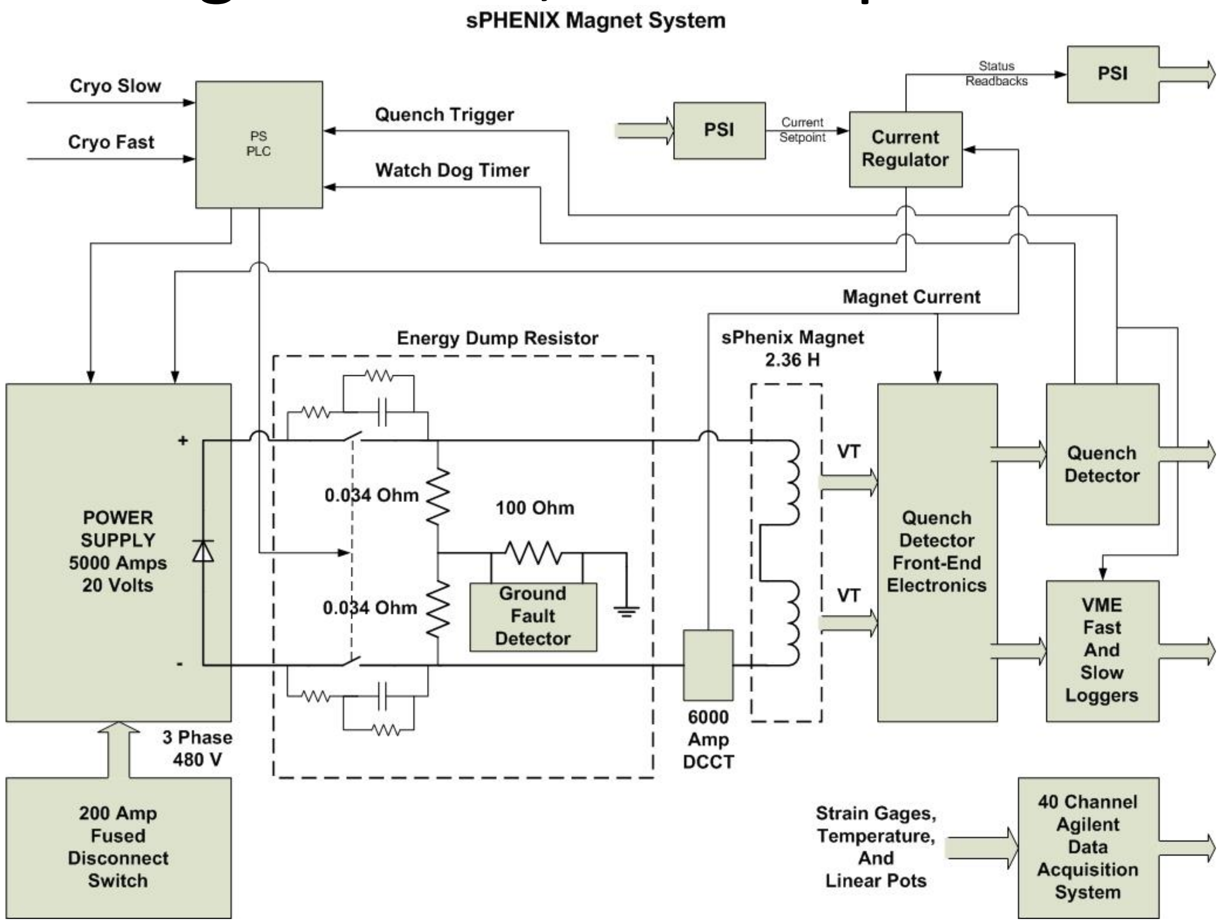
6
5
4
2
1
3
A
0°
VISTA DAL LATO U.E.
EW FROM SIDE ELECTRICAL CONNECTIONS
VISTA DAL LATO OPPOSTO U.E.
VIEW FROM OPPOSITE SIDE ELECTRICAL CONNECTIONS
70°
90°
90°
270°
OGGETTO O DENOMINAZIONE
BABAR
PRIMA EMI
751610BA.DWG

# Power supply: Voltage Tap Locations



# Power Supply: Quench Detector Block Diagram

- Slow discharge: >45 min
- Fast Discharge: 37 sec, causes quench back



# sPHENIX Magnet- JLab Risk Analysis

1. Coil Design
2. Coil Protection
3. Magnet Mechanical Support System
4. Magnet Cryogenics System and Current Leads

## Coil Design:

- The coil design is conservative.
- The magnet has had several thermal cycles however, to date, there is no evidence of this – i.e. no degrading quench behaviour which is a good sign.
- It is clear that eddy-current heating will occur if the magnet is ramped too quickly and that the magnet will quench as has happened a couple of times already during testing at BNL. Ramp rates determined as safe by BNL are: 0 to 2000 A at 2.5 A/s and then 1.5 A/s to 4830 A.
- There is also a question of whether the current leads have been over-stressed during the transport from SLAC to BNL – either the leads themselves or splices to the leads. However, there is no outward evidence of any deterioration of the leads at present.

# sPHENIX Magnet- JLab Risk Analysis

**Coil Protection-** The coil is protected with the usual method of an external resistor in parallel with the coil, which extracts approximately 75 % of the stored magnetic energy.

- The coil protection system is considered to be standard and works well and reliably as long as the breaker and resistor is serviced regularly. As the resistor and breaker are located externally to the coil itself, these items can be replaced easily if necessary.

  **Recommendation**: **Purchase new magnet power supply, breaker and resistor**
- The coil temperature rise is safe. The hot spot temperature could be twice as high as the average coil temperature rise but would still be considered safe by the usual design criteria of 150 K maximum temperature.

  **Recommendation: None**
- At least one critical voltage tap has been lost and another ne considered suspect. They have therefore been eliminated from the quench detection and protection system. There is a high likelihood that additional voltage taps could be lost or could malfunction in the future.

  **Recommendations: Fit additional voltage taps and check all the others. This requires disassembly of the magnet, and unfortunately this could introduce another risk to the magnet, that of causing damage to the conductor or insulation during the soldering and fitting of new voltage taps. So this remedial action should be carefully planned before execution.**

# sPHENIX Magnet- JLab Risk Analysis

**Magnet Mechanical Support System-** There are 6 axial and 16 radial Inconel 718 tie rods supporting the cold mass.

- The coil is placed inside a non-symmetric flux return yoke. This gives rise to axial offset forces. In order to have an offset force in one direction only (no inversion during the ramp up), the coil was positioned with ~30 mm axial displacement in the forward direction.
- The offset force is not equally shared by the three tie rods. The average strain in the three tie rods is 500 µm corresponding to 0.3 mm displacement.
- The net axial force is the difference of two large compressive forces of approximately 380 MT on the forward and backward ends of the coil. It is very sensitive to the axial location of the coil within the barrel.
- It is unlikely that the tie rods have been stressed beyond their elastic limit. However, the condition of the tie rods and spring washers remains as an unknown and therefore could pose some risk of damage for future operation.
- Several strain gauges (5) have been lost and at least one indicates a high reading and is subsequently ignored during magnet operation.

  **Recommendation: Fit new strain gauges. This will require disassembly of the magnet.**

- There is also a question of whether any of these mechanical components have been over-stressed during the transport from SLAC to BNL. However, there is no outward evidence of any deterioration of the internal mechanical support system at present.

# sPHENIX Magnet- JLab Risk Analysis

**Magnet Cryogenics System and Current Leads-**

- There is a potential hard touch between the inner thermal shield and helium vessel (observed by the temperature sensor on the inner shield reading 4.2 K).
- There also appears to be an internal leak when cold: $10^{-6}$ to $10^{-7}$ torr-liters/sec level – which is presently being managed by pumping during operation of the magnet. It is not clear whether this leak is within the magnet internal cryogenic system or within the valve box.
- There is some evidence (observed by BNL engineers who worked on other leaks on the magnet cryogenic system) that both Ansaldo and SLAC have struggled to repair leaks on cooling pipework in the past.
- There was a suggestion from an earlier review that the current lead flow may not have sufficient flow due to the return pressure. The proposed solution was to operate the solenoid bath at higher pressure, which means higher bath temperature.
- The existing internal leak (although small at present) and the potential for additional leaks is a concern.
- There is also a question of whether any of the internal cryogenic have been over-stressed during the transport from SLAC to BNL – e.g. welds between the cooling tubes and the coil support tube. However, there is no outward evidence of any deterioration of the internal cryogenic cooling system at present.