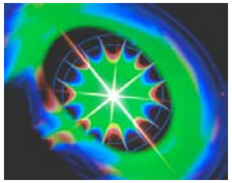

A one week course on

# Superconducting Accelerator Magnets

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US Particle Accelerator School
Arizona State University
Phoenix, Arizona
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# General Scope of This Course

Ramesh Gupta (Lecture Numbers):

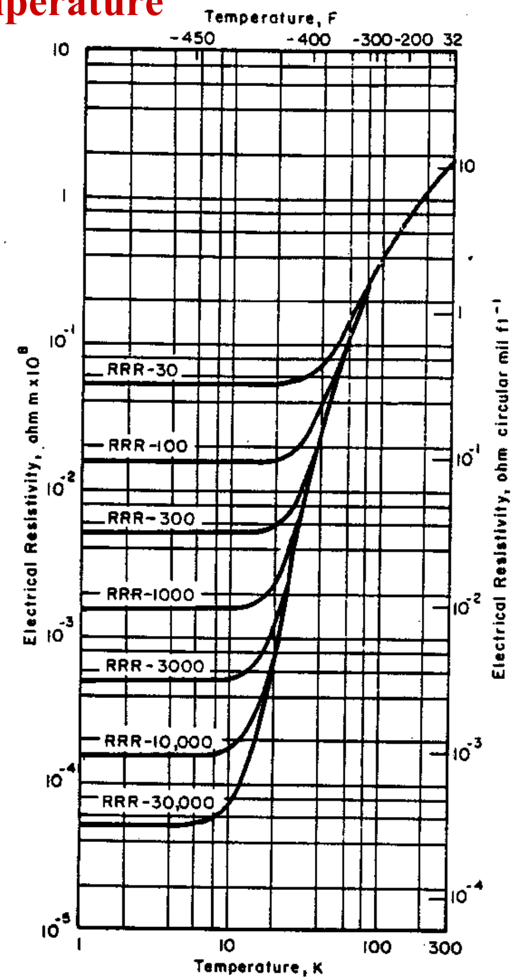
- Introduction to Superconducting Magnets (1)
- Superconductivity (2)
- Magnetic Design (3-6)
  - General Principles (3)
  - Coil Optimization (4)
  - Yoke Optimization (5)
  - Field Quality Adjustment After Initial Design (6)
- Field Errors and Their Estimates in Modern Superconducting Magnets (7)
- Field Quality as a Tool to Monitor Magnet Production (8)
- HTS Magnet Designs and Technology (9)
- Alternate Designs for Special Magnets (10)
- High Field Magnet Designs and Technology (11)

Animesh Jain:

- Magnet Theory and Magnetic Measurements

# Superconductivity

## Resistivity of Cu as a function of Temperature



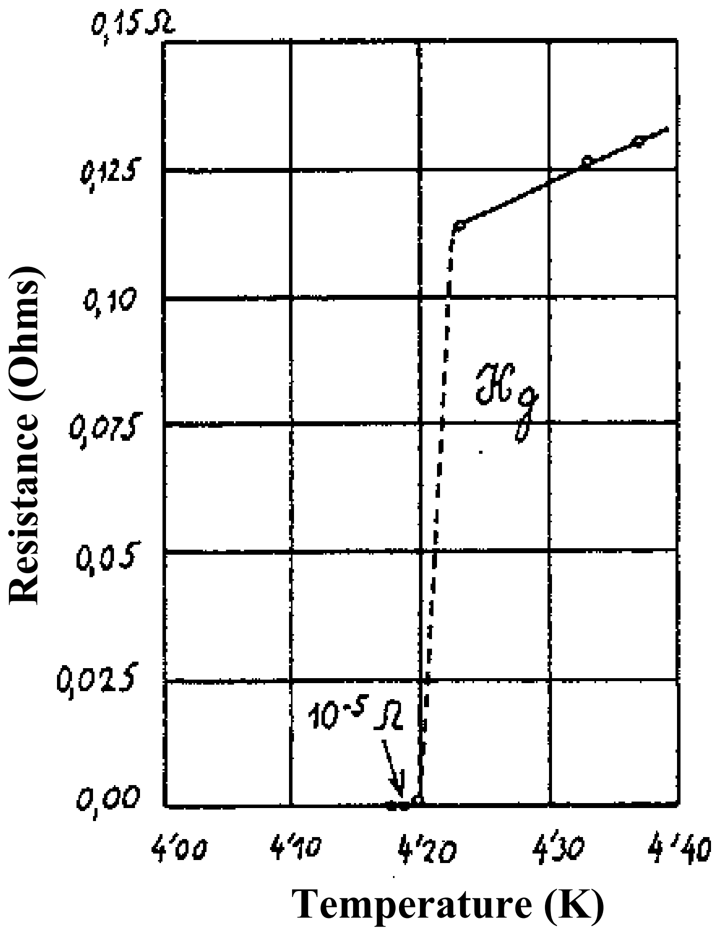

ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER

$RRR = \rho(273K)/\rho(\sim 4K)$

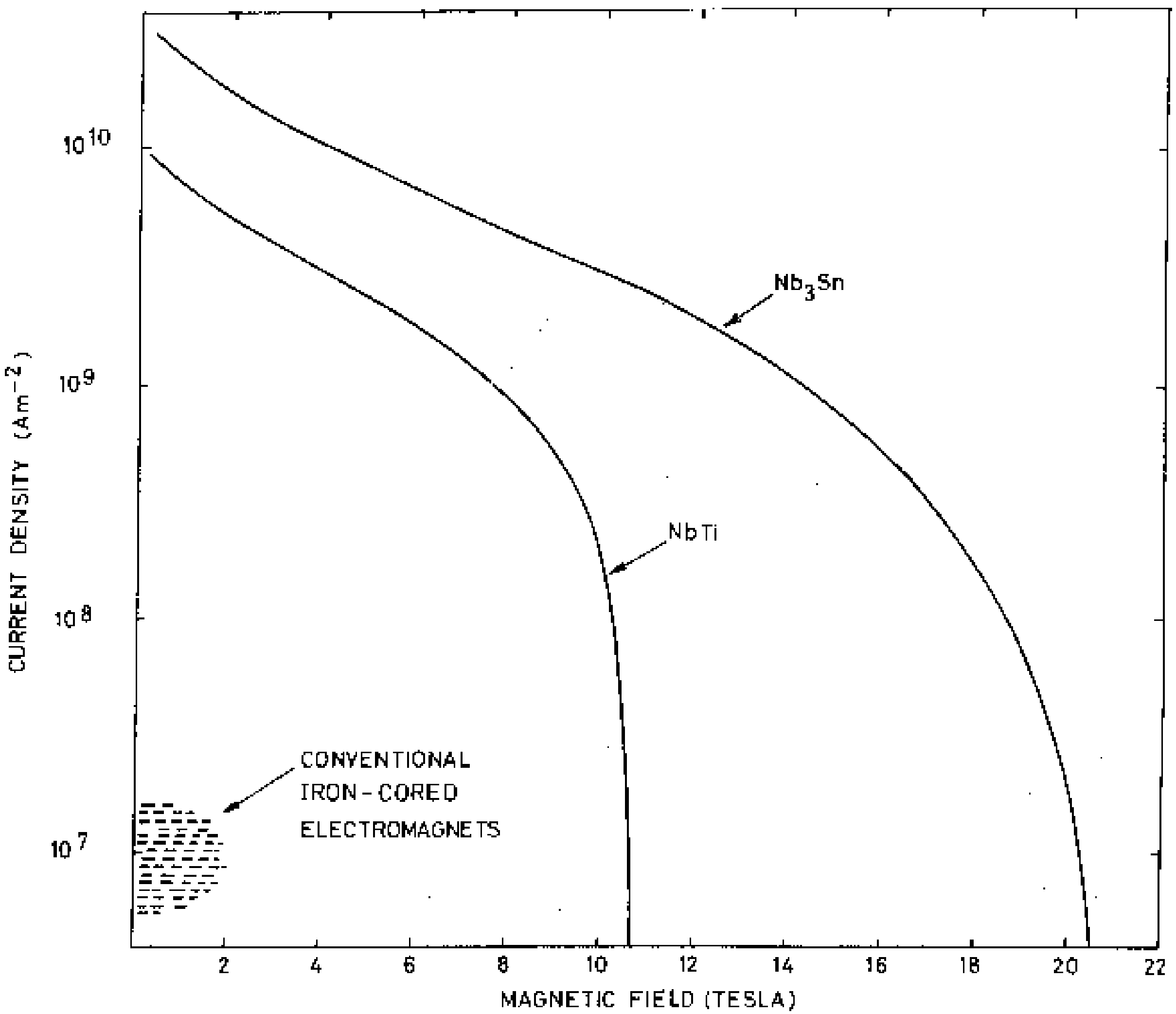
High purity copper has larger RRR

## First observation of "Superconductivity" by Onnes (1911)

**Resistance of Mercury falls suddenly below measurement accuracy at very low temperature**



# Why Use Superconducting Magnets in Accelerators?




Courtesy: Martin Wilson

Current density in copper coils of conventional magnets:

- Air cooled (max) ~1 A/mm$^2$ .
- Water cooled ~ 2-10 A/mm$^2$.

Typical fields: ~1.2 T.

**Question No. 1:**

**(Class test only, not counted for grades)**

- Why?
- Advantages?
- Disadvantages?

# Superconducting Magnets in Accelerators
## The Cost Issue

- In circular machines, the size of the machine is determined by the field in the magnet (Circumference $\propto$ 1/R).
- High field superconducting magnets may reduce the overall accelerator system cost (tunnel, facilities, vacuum system, etc.).
- Superconducting magnets may also reduce the operating cost as there is no Joule heating.
- But superconducting magnets themselves are much more expensive than conventional warm magnets. In addition, one must also consider the additional cryogenic costs (both installation and operational).

# Superconducting Magnets in Accelerators
## The Cost Issue (Contd.)

- However, even when superconducting (sc) magnets are used, the highest attainable field is often NOT the most cost effective solution.
- Moreover, in very high energy collider and storage rings, one must also consider synchrotron radiation. For example, using superconducting magnets would not be a good idea in a circular accelerator version of International Linear collider.

  Superconducting magnets, however, may play an important role in a few critical interaction region magnets at final focus.

- Use superconducting magnets only if there is a substantial savings, because they also bring complexities (magnet protection, cryogenic system, etc.).
- In high energy colliders (specially in hadron colliders), sc magnets tend to minimize the cost of building and operating the machine.

# A Typical High Energy Collider Chain

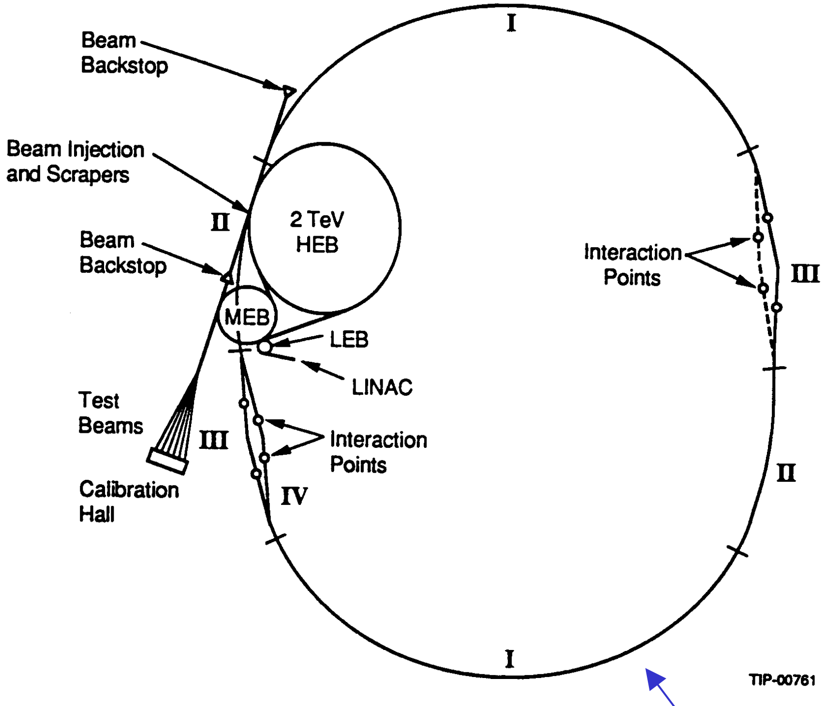


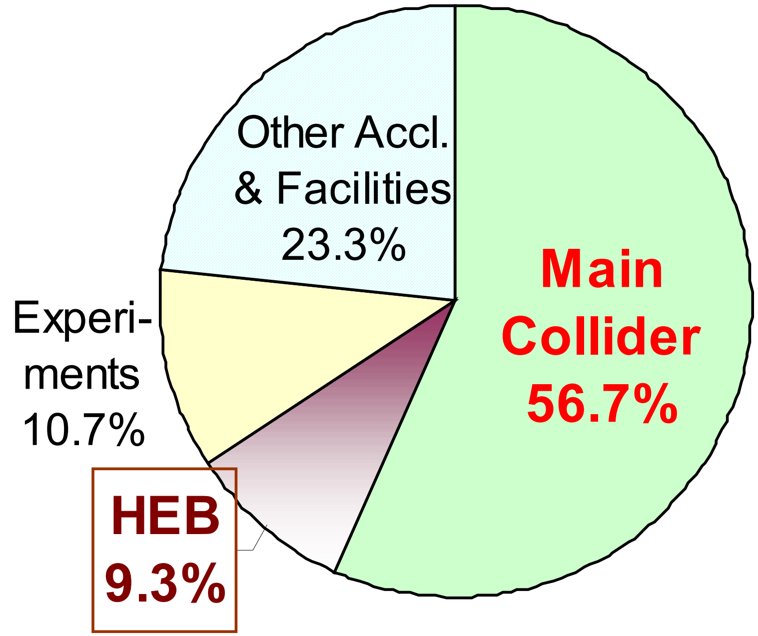
Figure 4.1.1.1-4. Schematic layout of SSC.

20 TeV SSC Main Ring

Schematic Layout of SSC

## Cost Distribution of Major Systems

(Reference SSC Cost: 1990 US $7,837 million)

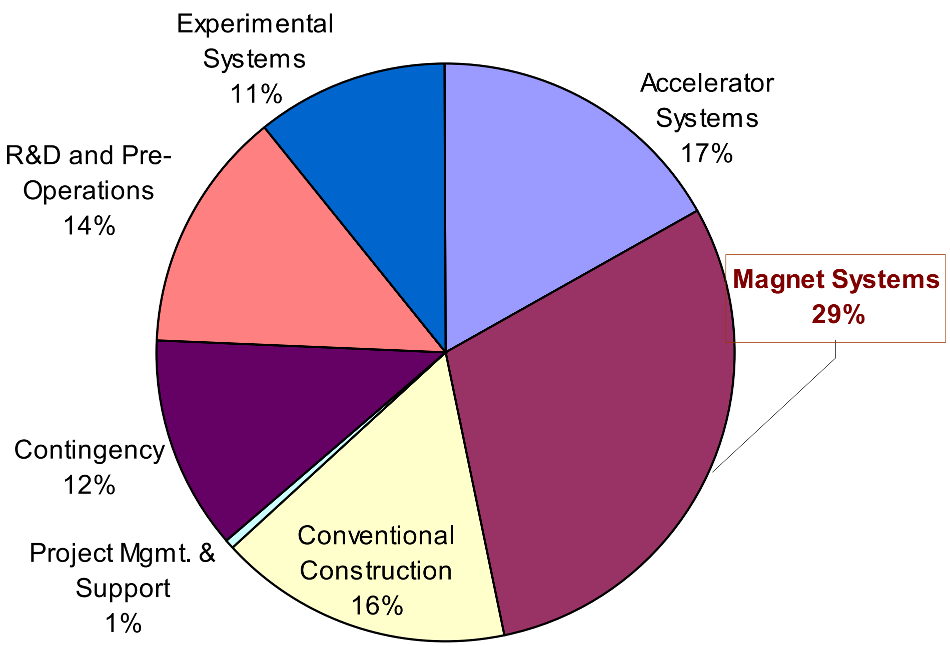



(Derived based on certain assumptions)

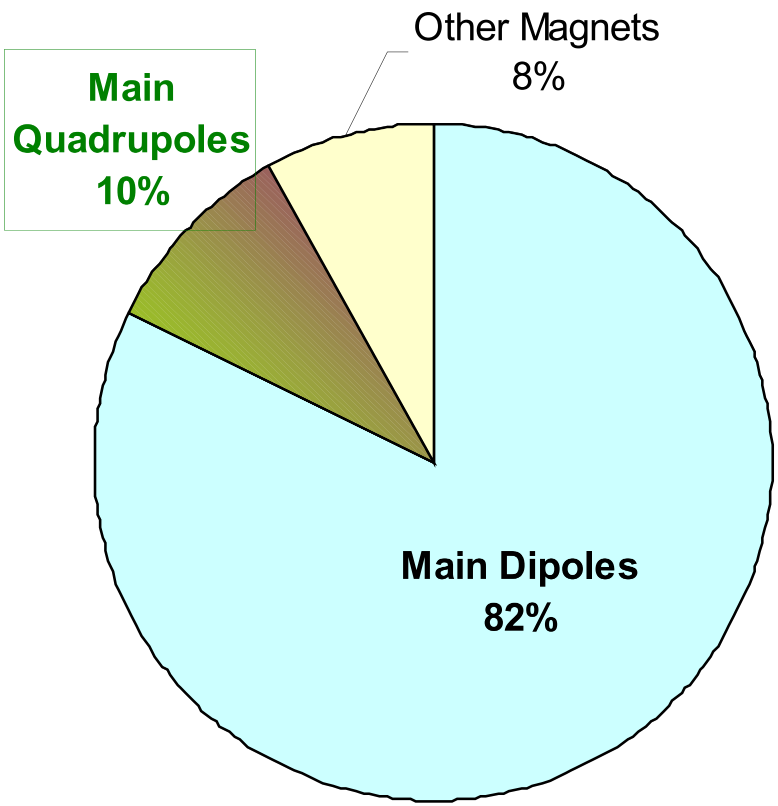
# Cost of the Main Components in a Modern High Energy Hadron Collider

**SSC Project Cost Distribution**

(Reference SSC Cost: 1990 US $7,837 million)




**Collider Ring Magnet Cost Distribution**




The dipole magnet system of the main ring is the cost driver.

But the cost of other magnets and systems is also important!

# Major Accelerator Projects with Superconducting Magnets

| Machine | Location | Energy | Circumference | Status |
|---|---|---|---|---|
| Tevatron | Fermilab, USA | 900 GeV (p) X 900 GeV (p-) | 6.3 km | Commisioned: 1983 |
| HERA | DESY, Germany | 820 GeV (p) X 30 GeV (e) | 6.4 km | Commisioned: 1990 |
| ~~SSC~~ | ~~SSCL, USA~~ | ~~20 TeV (p) X 20 TeV (p)~~ | ~~87 km~~ | ~~Cancelled: 1993~~ |
| ~~UNK~~ | ~~IHEP, Russia~~ | ~~3 TeV~~ | ~~21 km~~ | ~~Suspended~~ |
| RHIC | BNL, USA | 100 GeV/amu X 100 GeV/amu (proton: 250GeV X 250 GeV) | 3.8 km | Commisioned: 2000 |
| LHC | CERN, Europe | 7 TeV (p) X 7 TeV (p) | 27 km | Expected: 2007 |

| | Dipoles | | | | Quadrupoles | | | |
|---|---|---|---|---|---|---|---|---|
| Machine | B(T) | Aper(mm) | Length(m) | Number | Grad(T/m) | Aper(mm) | Length(m) | Number |
| Tevatron | 4 | 76.2 | 6.1 | 774 | 76 | 88.9 | 1.7 | 216 |
| HERA | 4.68 | 75 | 8.8 | 416 | 91.2 | 75 | 1.9 | 256 |
| ~~SSC~~ | ~~6.7~~ | ~~50~~ | ~~15~~ | ~~7944~~ | ~~194~~ | ~~40~~ | ~~5.7~~ | ~~1696~~ |
| ~~UNK~~ | ~~5~~ | ~~70~~ | ~~5.8~~ | ~~2168~~ | ~~70~~ | ~~70~~ | ~~3~~ | ~~322~~ |
| RHIC | 3.5 | 80 | 9.7 | 264 | 71 | 80 | 1.1 | 276 |
| LHC | 8.3 | 56 | 14.3 | 1232 | 223 | 56 | 3.1 | 386 |

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# Present Magnet Design and Technology (Main Dipole of Major Accelerator)

### Tevatron Dipole

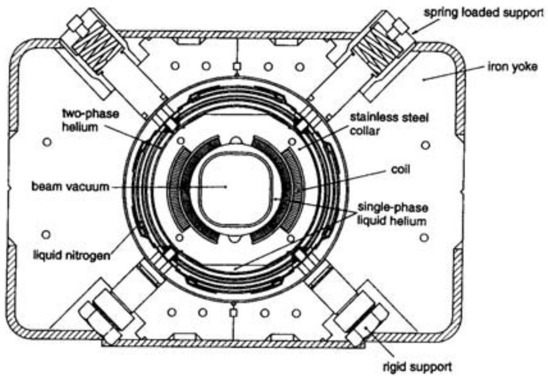
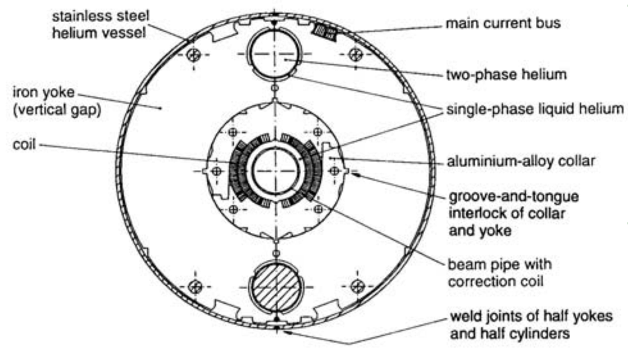
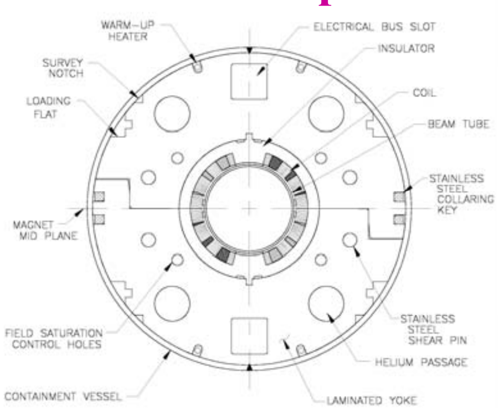



Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

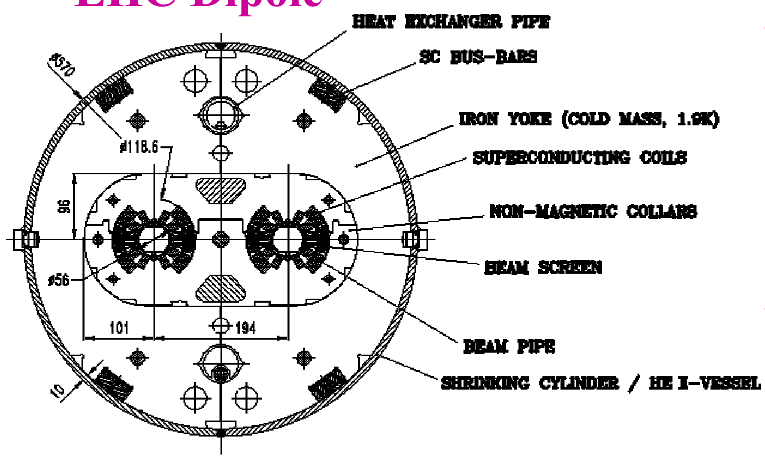
### HERA Dipole




### RHIC Dipole

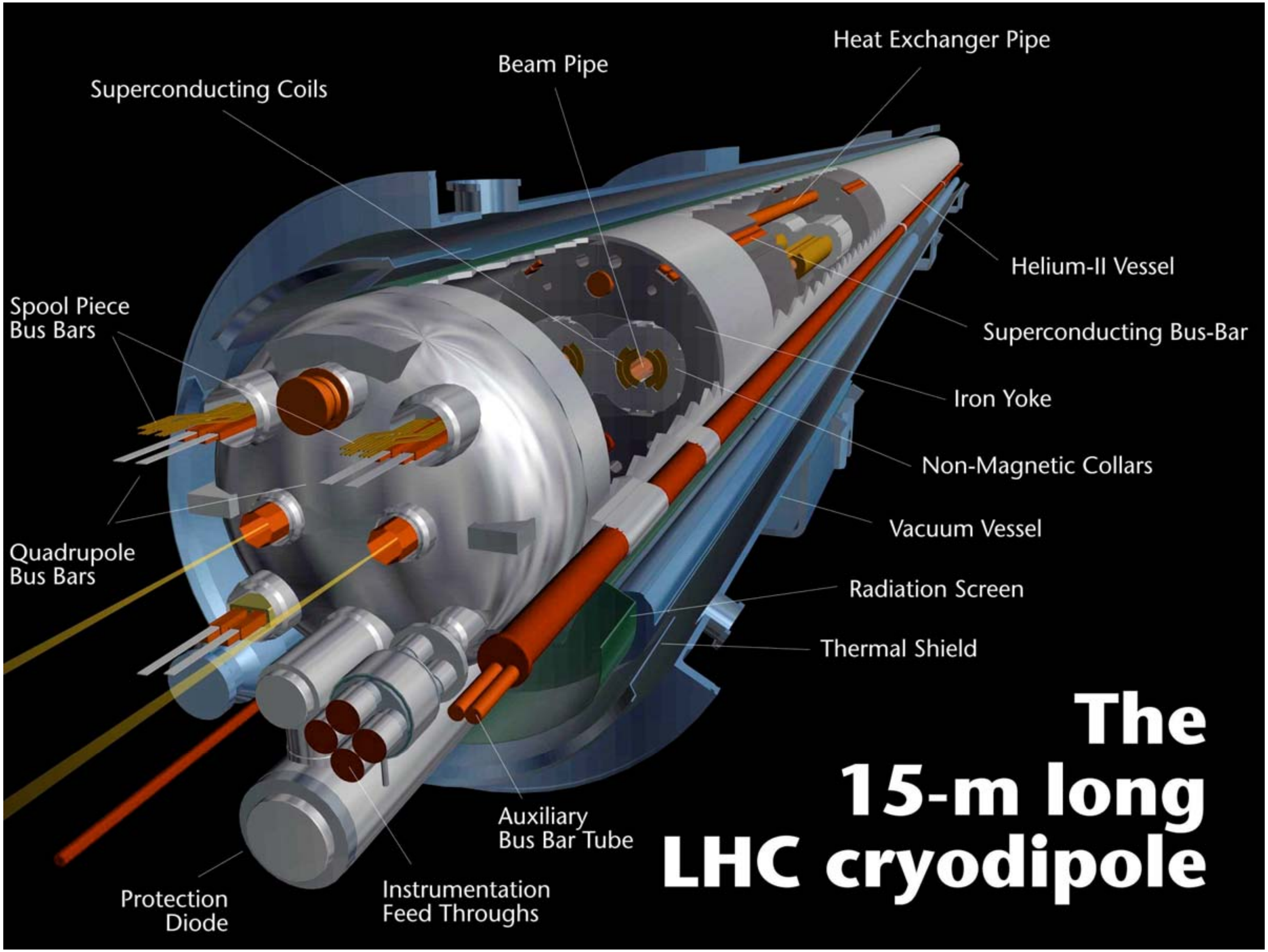



### LHC Dipole



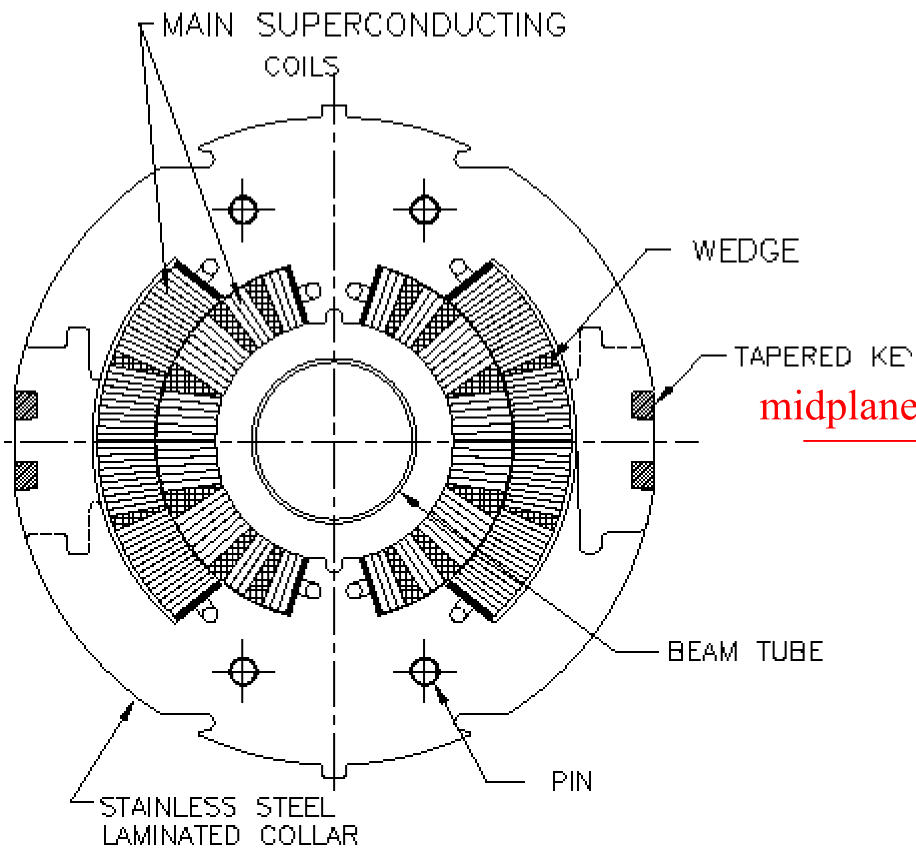

- All magnets use Nb-Ti Superconductor
- All designs use cosine theta coil geometry
- The technology has been in use for decades.
- The cost is unlikely to change significantly.

# Schematic of Twin Aperture LHC Dipole in Cryostat

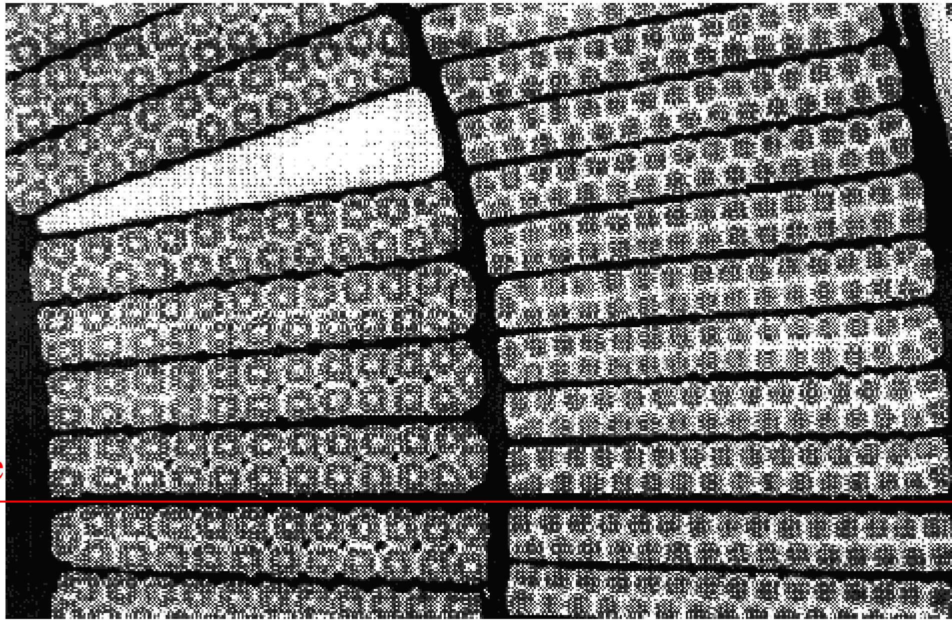


# Coil Cross-section of a SC Dipole (conductor dominated cosine theta design)

Most superconducting magnets are conductor dominated magnets.




SSC 50 mm dipole collared coil cross-section



Scanned and photo-enhanced image of a dissected SSC 40 mm Coil (still in collar). Inner and outer stands, wedge and insulation (dark) can be seen. One can determine the actual position of cable in a collared coil (warm).

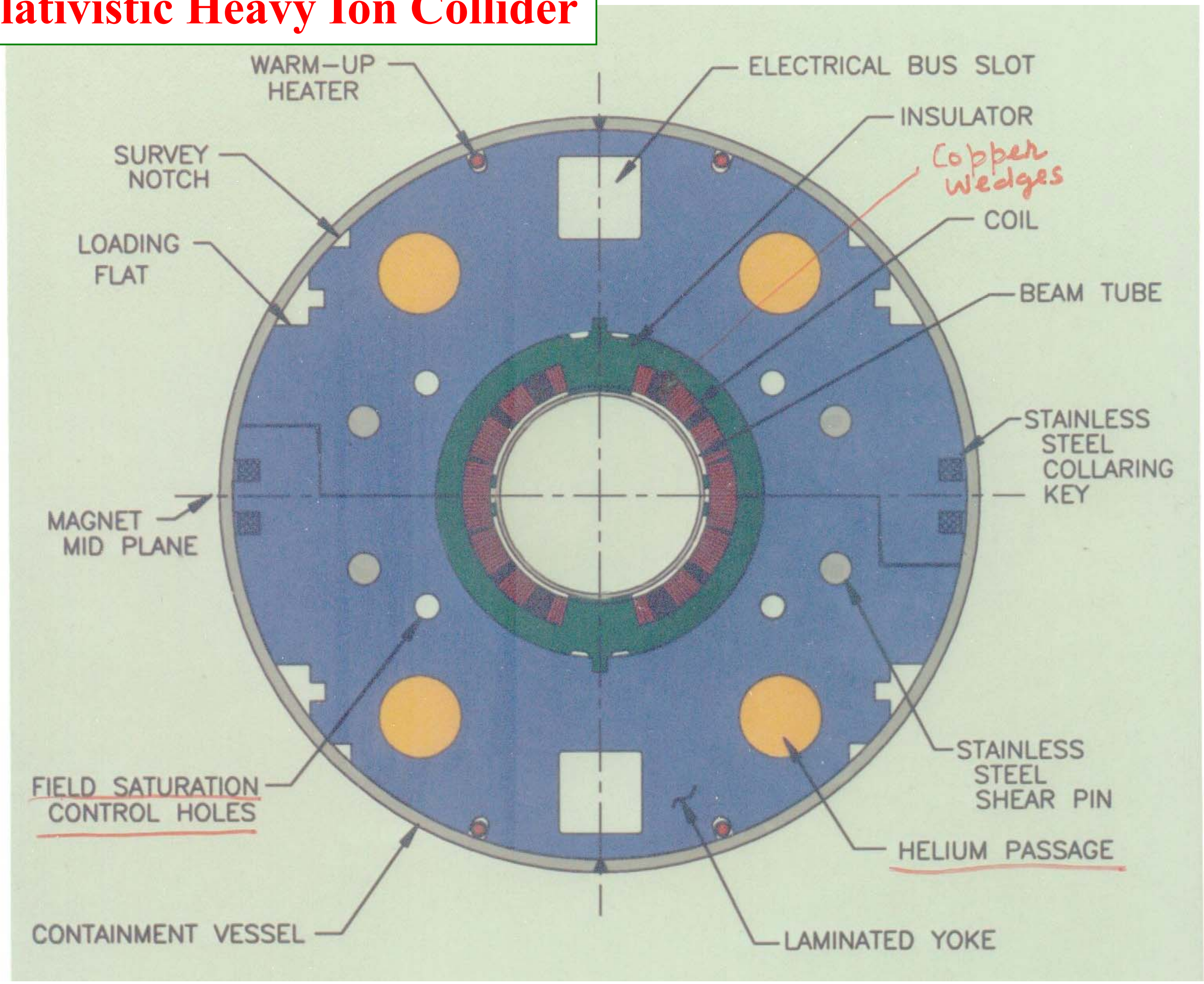
# RHIC Magnet Coldmass During Assembly

RHIC arc dipole coldmass during assembly

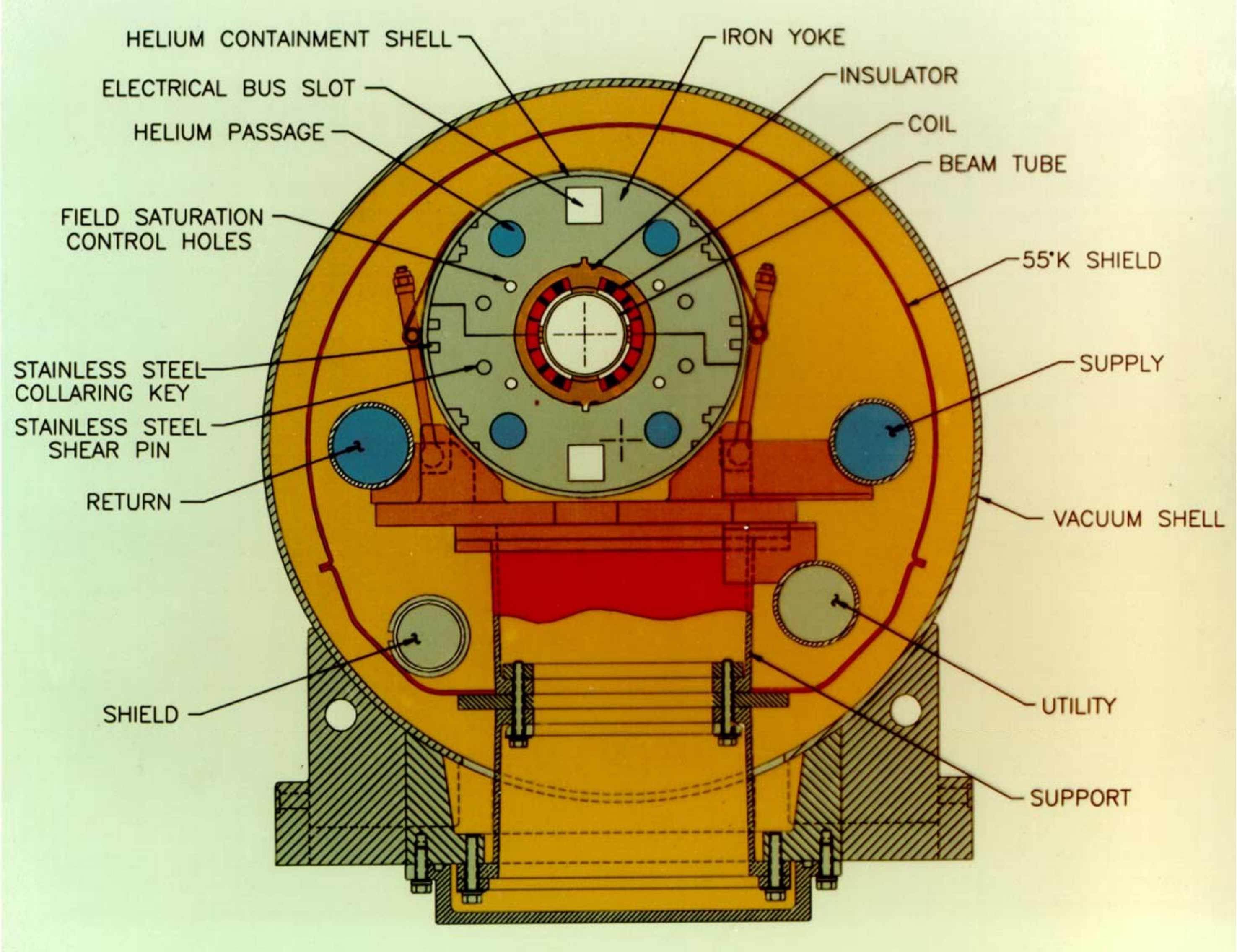
RHIC insertion quad coldmass during assembly

# RHIC Arc Dipole Coldmass

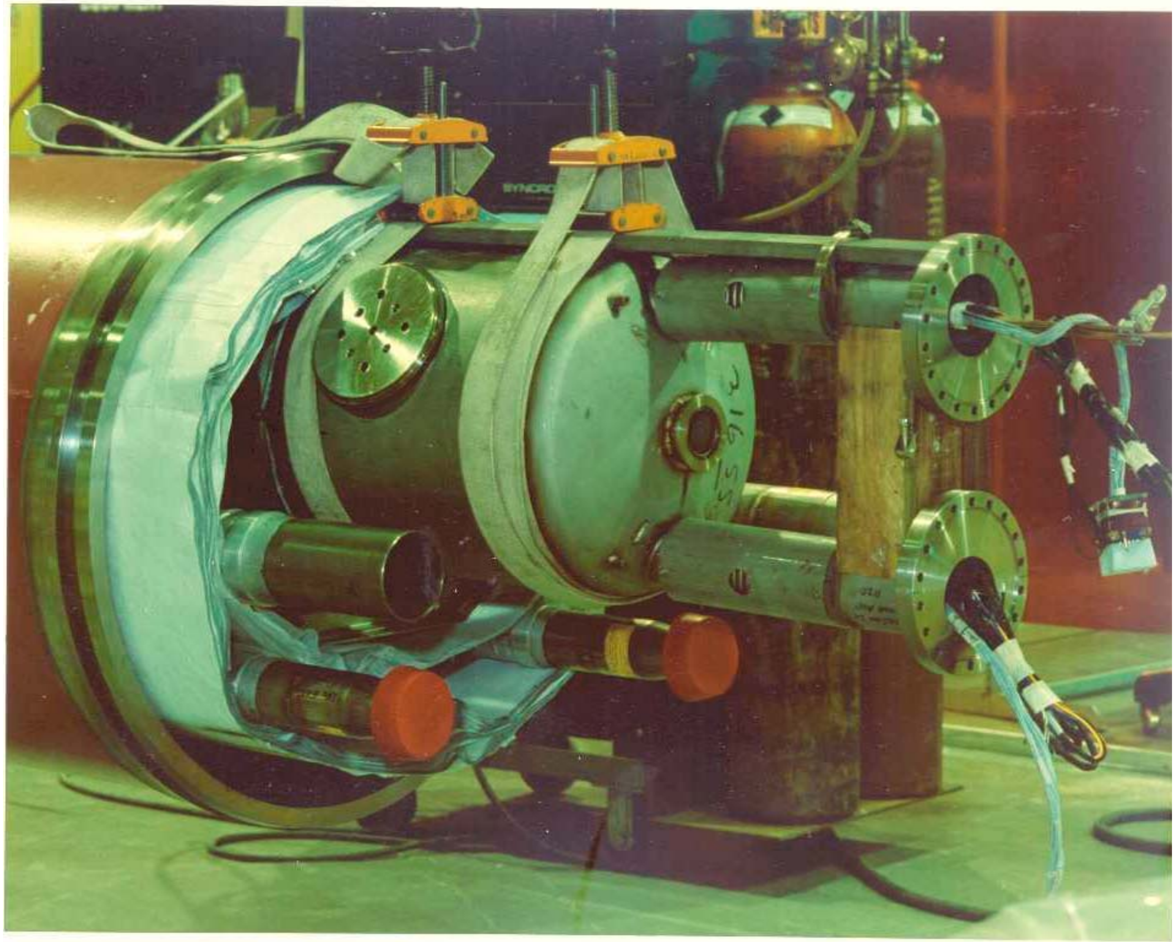
**RHIC: Relativistic Heavy Ion Collider**

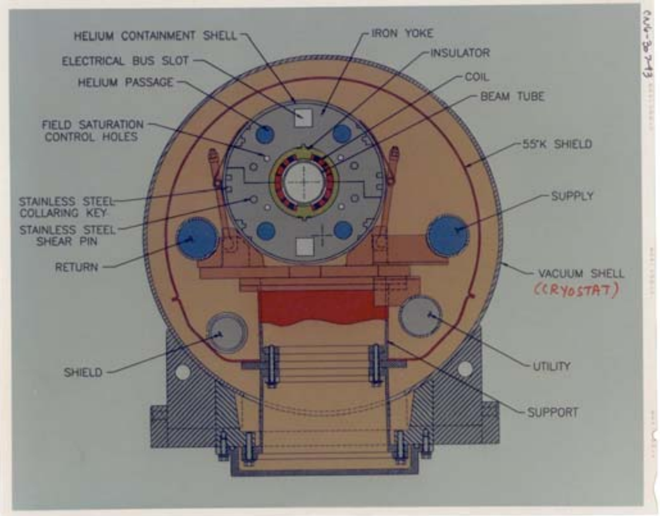


# RHIC Arc Dipole in Cryostat (schematic)



# Dipole Coldmass Being Assembled in Cryostat



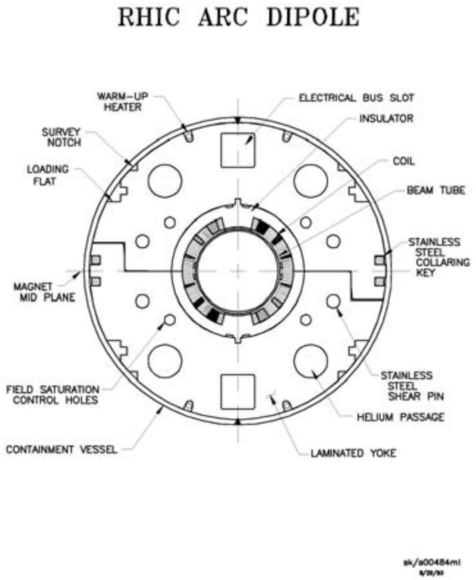


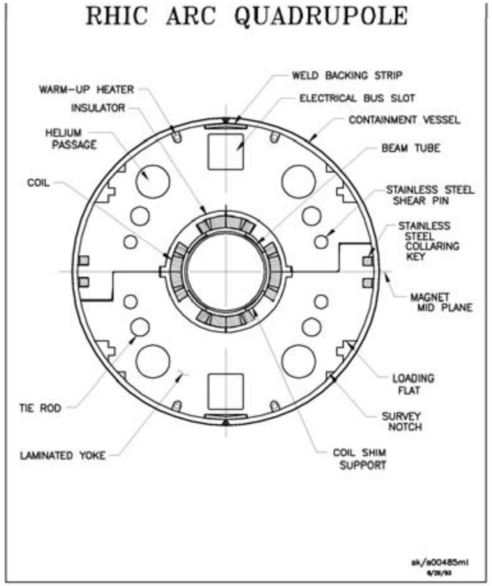

## Assignment:

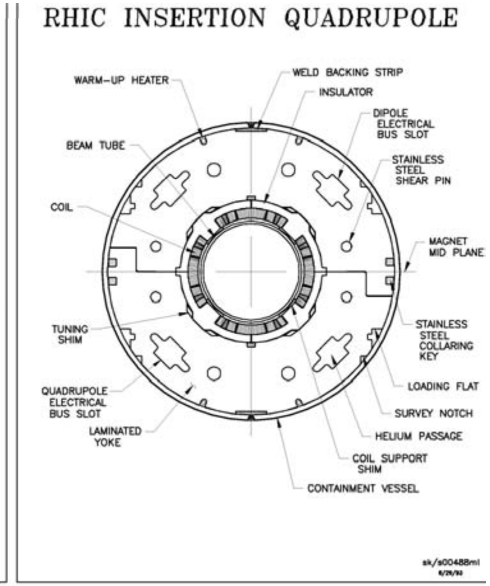
**Identify various components (use RHIC dipole in cryostat slide)**

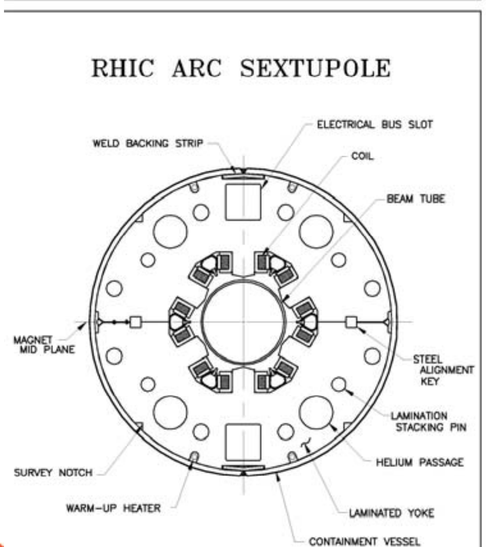
# SSC Magnets in Cryostat

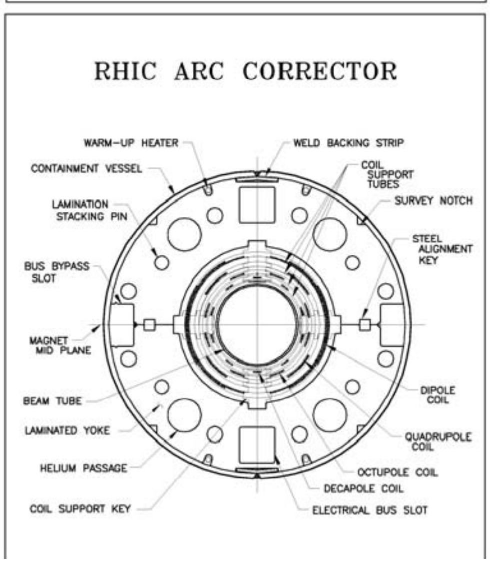
# Variety of Superconducting Magnets



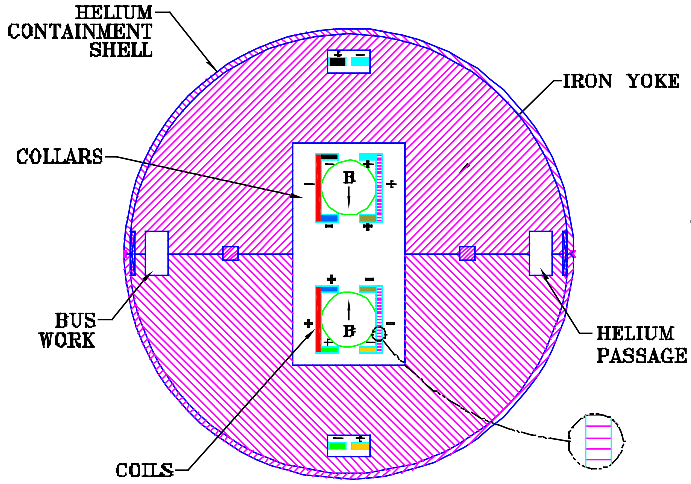



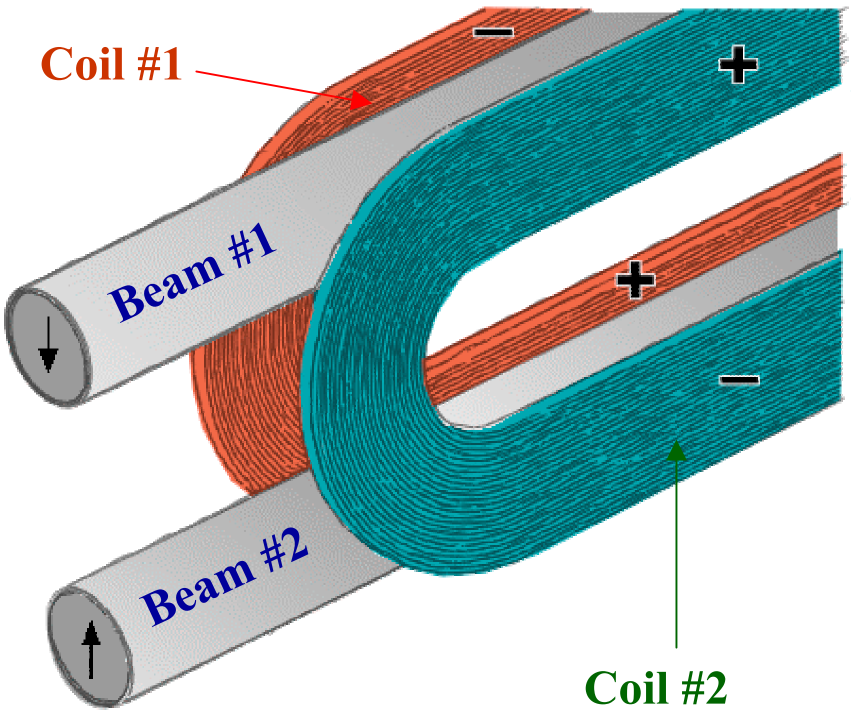




**Variety of superconducting magnets used in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), New York, USA**

# Common Coil Design
## (The Basic Concept)




- **Simple 2-d geometry with large bend radius (no complex 3-d ends)**
- **Conductor friendly (suitable for brittle materials - most high field conductors are brittle)**
- **Compact Design (much smaller in size as compared to two single aperture or other 2-in-1 dipoles)**
- **Block design (for large Lorentz forces at high fields)**
- **Efficient and methodical R&D due to simple & modular design**
- **Minimum requirements on big expensive tooling and labor**
- **Lower cost magnets expected**




**Main Coils of the *Common Coil Design***

## Magnet Cost for Large Scale Production:

- Material cost (superconductor, iron, stainless steel, etc.)
- Labor cost
- Associated component cost (quench protection, etc.)
- Infrastructure cost

## Magnet Cost for Small Production :

In a short production run, the R&D cost may exceed the material and labor cost.

Example: A few specialty magnets for large machines.

Try to use or adapt an existing design to meet machine requirements.

If a new design is needed, the cost optimization strategy would be different for a small scale production Vs. a large scale production.

- For example, assign a lower priority to minimizing conductor volume for a small scale magnet production.

# Superconducting Magnet Design (1)

## A few of many things that are involved in the overall design of a superconducting magnet

• The magnet should be designed in such a way that the conductor remains in the superconducting phase with a comfortable margin.

• Superconducting magnets should be well protected. If the magnet quenches (conductor loses its superconducting phase due to thermal, mechanical, beam load, etc.), then there should be enough copper in the cable to carry the current to avoid burn out.

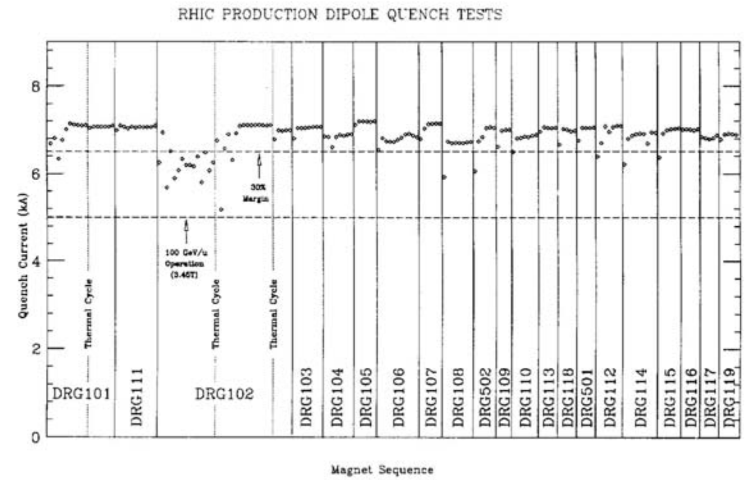
• The cryogenic system to cool and maintain the low temperature (roughly at 4 Kelvins) for the entire series of magnets in the machine. It should be able to handle heating caused by the beam, including that by synchrotron radiation or decay particles.

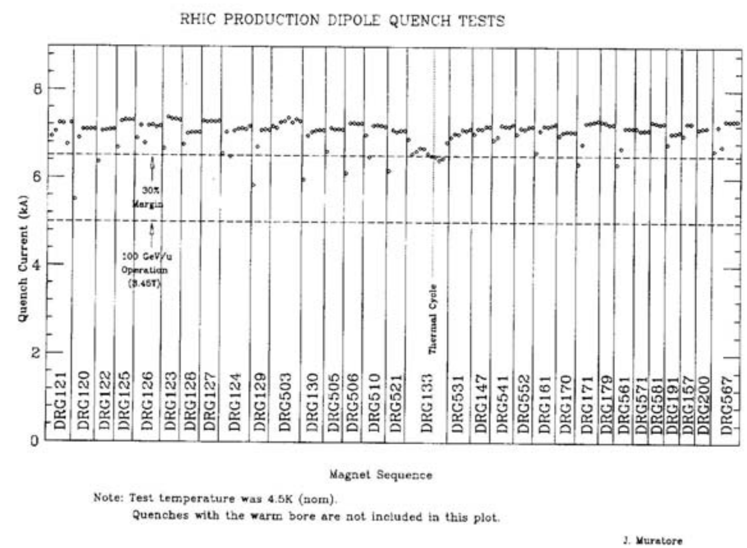
# Superconducting Magnet Design (2)

- The magnet cost should be minimized.
- There are very large Lorentz forces in superconducting magnets. They roughly increase as the square of the field. The coil should be contained in a well design support structure that can contain these large forces and minimize the motion of the conductor. In high field magnets, the design of the mechanical structure plays a major role.
- The magnets should be designed in such a way that it is easy to manufacture.
- It must meet the field quality (uniformity) requirements.

# Quench Performance of RHIC Production Magnets

- In a large series production, there could be some magnets that may not be able to reach the field as determined by the conductor spec/performance.
- Superconducting magnets for accelerators are, therefore, designed with some operating margin.
- RHIC magnets have over 30% margin. This means that theoretically, they are capable of producing over 30% of the required/design field.
- A successful design, engineering and production means that most magnets reach near the short sample current (as measured in the short sample of the cable) or field in a few quenches.
- Also, it is desirable that most reach the design operating field without any quench. Remember, the cost of cold test is high and it is desirable that we don't have to test all magnets cold.



# Why Is Field Quality So Important In Accelerator Magnets?

- The dipole magnets in a particle accelerator bend the beam.
- A field error translates in to a bend error like a wrong kick.
- In most modern high energy accelerator and storage rings, particles go around the machine billions of time.
- Those kicks may add in a systematic or resonant way (like that in harmonic accelerator), since machines have a periodic structure.
- Therefore, even small errors may add-up to eventually kick the beam out of the nominal orbit and some time out of the machine - an undesirable proposition.
- The requirement in relative field error in most modern machines is less than a few parts in 10,000 generally up to 2/3 of coil radius.

# Field Errors and Machine Cost/Performance

- **The field errors have a significant influence on the performance and cost of the machine**
  - **At injection: Main dipoles - large number**
    - impact performance, magnet aperture and hence the machine cost.
  - **At storage: Insertion quadrupoles - small number**
    - may determine ultimate luminosity performance.
- Corrector magnets + associated system
  - Ease of operation and overall machine cost.
- Tolerances in parts and manufacturing
  - Translates in to cost.

A proper understanding of various issues related to field quality is important for reducing the cost while assuring good machine performance.

# Evolution in Understanding of Field Quality

Conventional Thinking: Need 1 mil (25 μm) tolerances at most places

Results and analysis of SSC and RHIC magnets indicate that the influence of component errors may get reduced due to magnet symmetry and statistical cancellation of errors in magnet construction.

Such realization may reduce tolerance in parts and assembly (tolerances cost money) while maintaining good field quality.

A bonus from field quality

Field Quality as a tool to monitor production.

- Powerful, rapid feedback to manufacturer.

This tool was developed and used extensively during the RHIC magnet production.

# Sources of Field Errors (Systematic and Random)

- Magnetic Measurements
  - Both systematic and random. However, the advances in measurements system means that they don't limit the field quality performance in most cases.
- Magnetic Design
  - Primarily systematic
- Magnet Construction (tooling, parts & manufacturing)
  - Both systematic and random

- A good design will not only produce good field quality magnets on paper but will also anticipate deviations in parts during production and be flexible enough to accommodate them to produce good field quality magnets despite those errors.

  - **Magnet production generally can not stop just because an individual part is "a bit out of tolerance" ! So, better find a way to accommodate such scenarios.**

# A Few Topics To Be Covered on Magnetic Design & Analysis of Actual Magnets

**A concise tour of the magnetic design process**

- First come up with an overall design
- Then develop a detailed design

*Remember : Magnet design is an iterative process !*

**Field harmonics in superconducting magnets**

- What to expect?
- How to minimize them?
- What is the state of the art?

**Analysis of measured field harmonics**

- What do they tell us about the magnet construction?
- A tool to monitor magnet production.

# Setting-up A Magnetic Model With A Minimum Geometry

**To make efficient use of the computer resources and to get more accurate results in minimum time, set up the basic model with proper boundary conditions.**

**For example, for a dipole magnet, usually you need to model only a quadrant of the geometry, with the following boundary conditions:**

- field perpendicular boundary on the x-axis
- field parallel boundary on the y-axis
- infinite boundary condition on the other side(s), or else extend the other boundary far away so that the field near the end of boundary becomes very small.

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# Reasons for Using Superconducting Magnets in Accelerators

## Cost Advantage

Example: Main ring collider magnets

Modern hadron colliders use a large number of magnets.

Design should be driven by cost

Cost is determined by infrastructure, material and labor.

## Performance Advantage

Example: Insertion region magnets

The ultimate luminosity of modern high energy hadron colliders is determined by the performance of small number on magnets in interaction region (IR).

Design should be driven by the performance (can allow bigger cost per magnet)

The material and labor cost of the final magnets will be a small fraction of the overall cost that includes cost of carrying out magnet R&D.

⇒ There are many good arguments why different criteria and different design philosophies should apply to the two cases !

# SUMMARY

• This was a short introduction to superconducting magnets for particle accelerators.

• The next talk will be a brief introduction to superconductivity.

• Most of the lectures will be on magnetic design, measurements and analysis of superconducting magnets; primarily related to the field quality issues.

• The last few talks will be on the advanced designs and technology of HTS and high field magnets. There you will be exposed to the kind of thinking that goes in developing new R&D magnets at the cutting edge of the technology. You will get a feel on how to develop alternative design concepts.

• Maybe, you could develop a new revolutionary design concept during this course. (In that case you get $A^{+}$; No questions asked).

**Good luck and enjoy the rest of the course !!!**