

A one week course on

Superconducting Accelerator Magnets

By

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General Scope of This Course

Ramesh Gupta (Lecture No.):

- Introduction to Superconducting Magnets (1)
- Superconductivity (2)
- Magnetic Design (3-6)
- Field Errors and Analysis (7-8)
- High Field and Special Magnet Designs (9-10)
- Magnets with High Temperature Superconductors (11)

Animesh Jain:

Magnet Theory and Magnetic Measurements

A Future Vision of Mass Use of SC An Environment Friendly High Tech Village

From: International Superconductivity Technology Center, Japan
http://www.istec.or.jp/ISTEC_homepage/index-E.html



Assignment #1:
What is missing (or
hidden) in this picture?

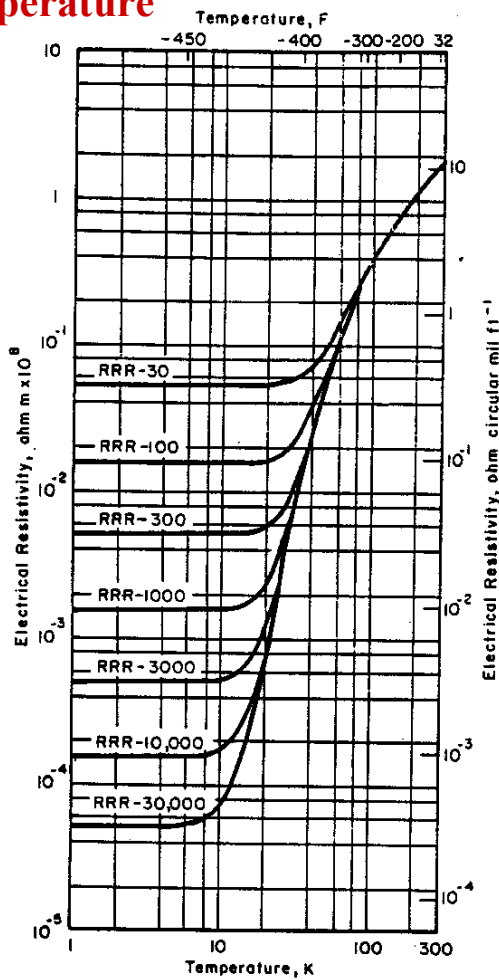
Answer:
A circular collider that uses superconducting magnets and RF Cavities.

The Superconductivity

**Superconducting
Magnet Division**

**Resistivity of Cu as a function
of Temperature**

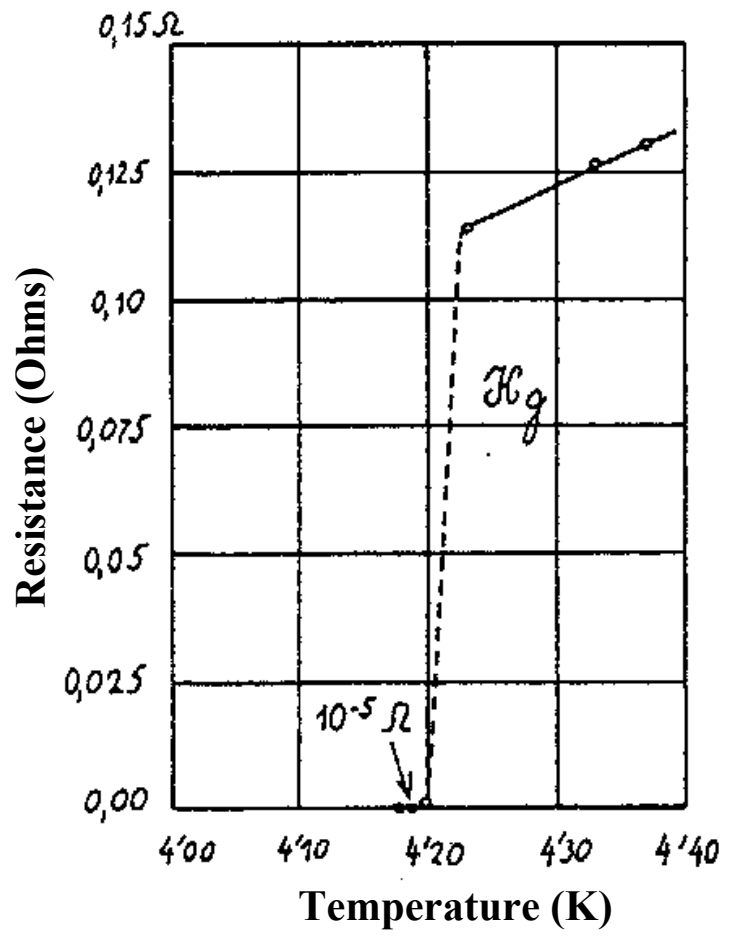
RRR = $\rho(273K) / \rho(\sim 4K)$
High purity copper has larger RRR



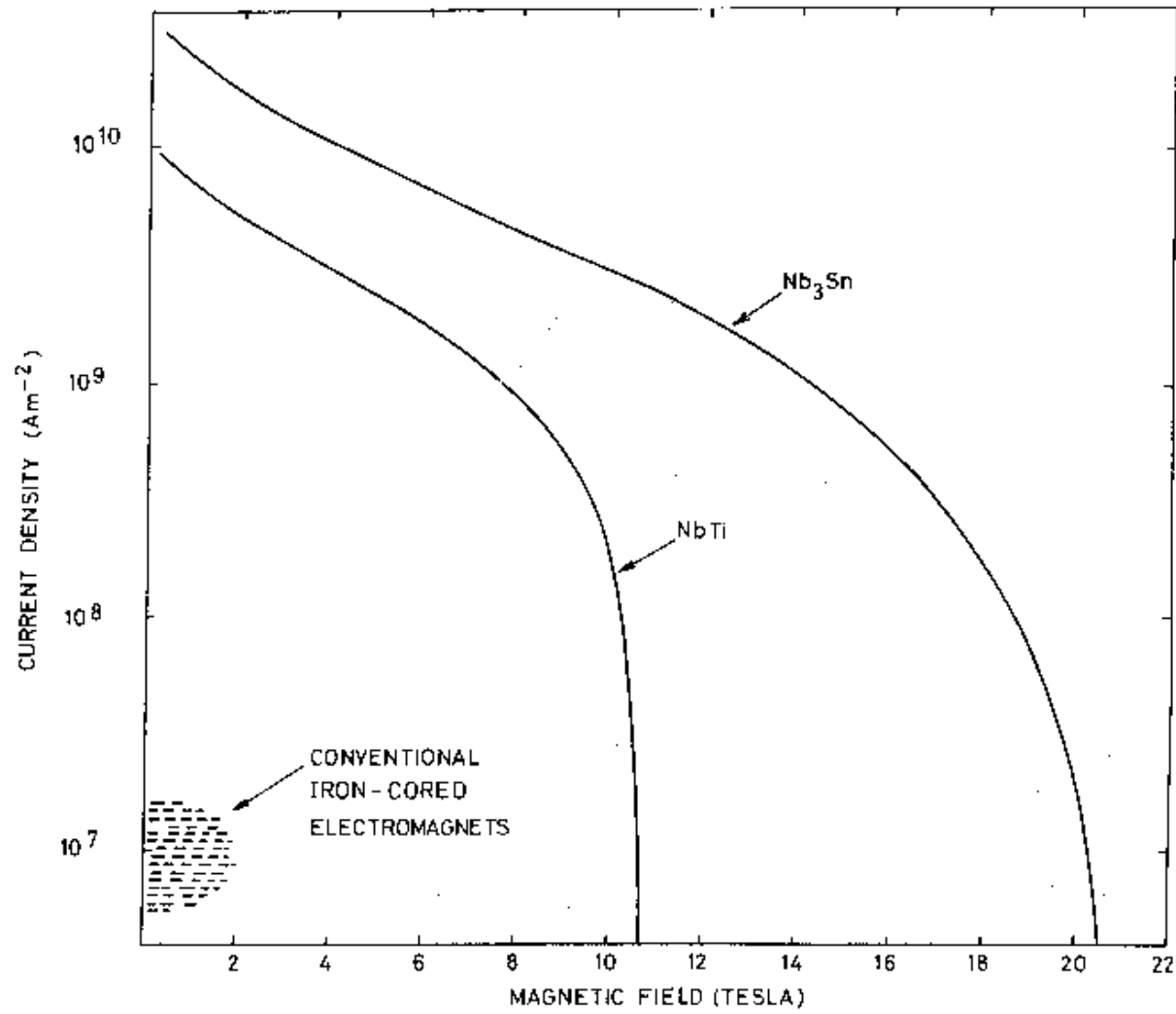
ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER

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

Question No. 1:
(Class test only, not counted for grades)

- Why?
- Advantages?
- Disadvantages?

Current density in the coils of conventional magnets: $\sim 10 A/mm^2$.

Typical fields: $\sim 1.2 T$.

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 the superconducting magnets themselves are much more expensive than the 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 the superconducting magnets are used, the highest attainable field is often NOT the most cost effective solution.
- Moreover, in very high energy collider and storage ring, one must also consider the synchrotron radiations. For example, using superconducting magnets is not an option for the proposed Next Linear collider (NLC).
- Use superconducting magnets only if there is a substantial savings, because they also bring the complexities (magnet protection, cryogenic system, etc.). In high energy colliders (specially in hadron colliders), the superconducting magnets tend to minimize the cost of building and operating the machine.

A Typical High Energy Collider Chain

Superconducting Magnet Division

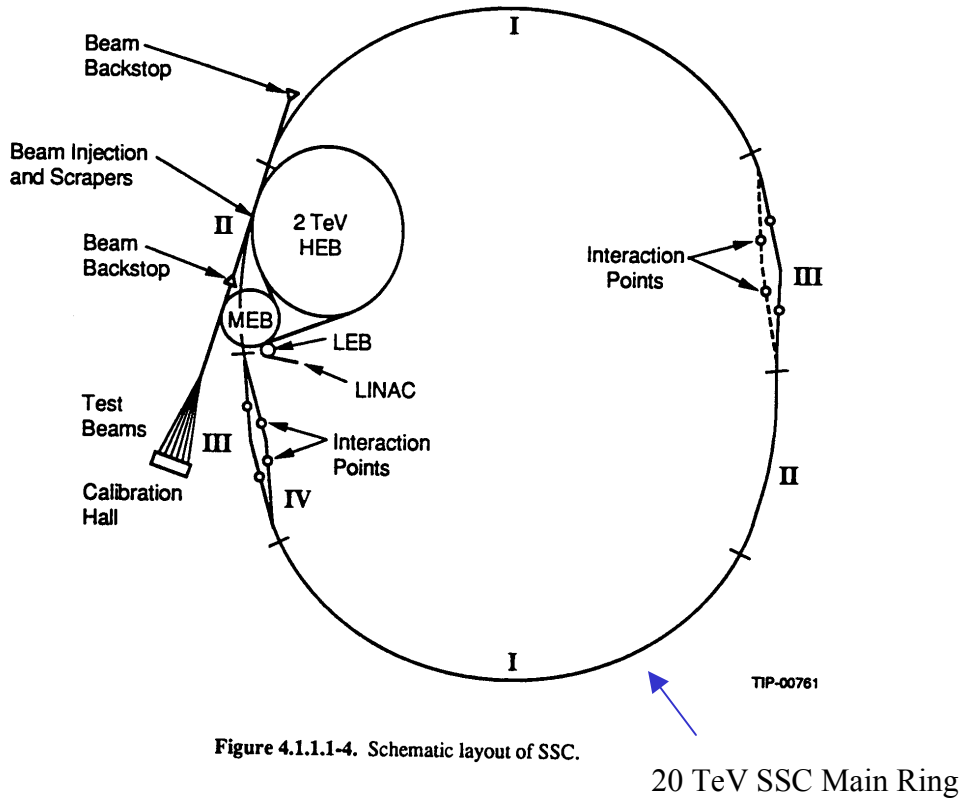
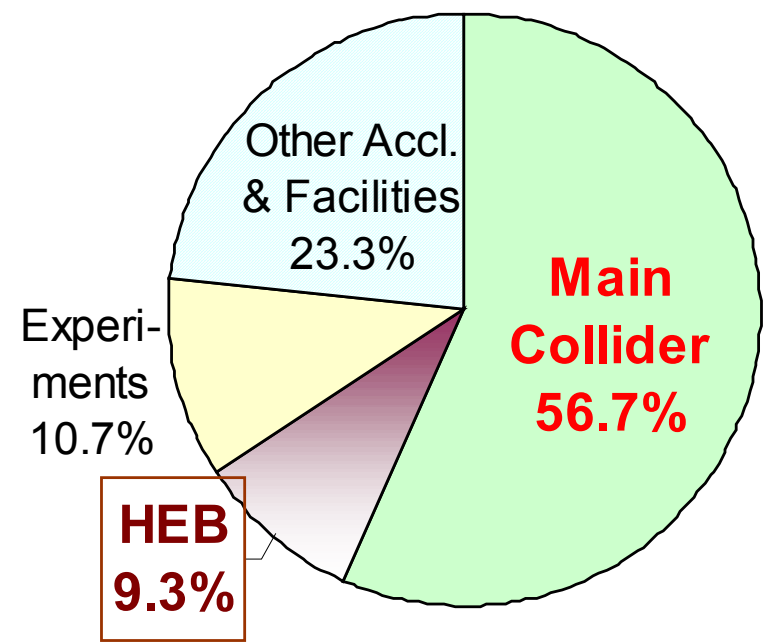


Figure 4.1.1.1-4. Schematic layout of SSC.

Schematic Layout of SSC

Cost Distribution of Major Systems

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

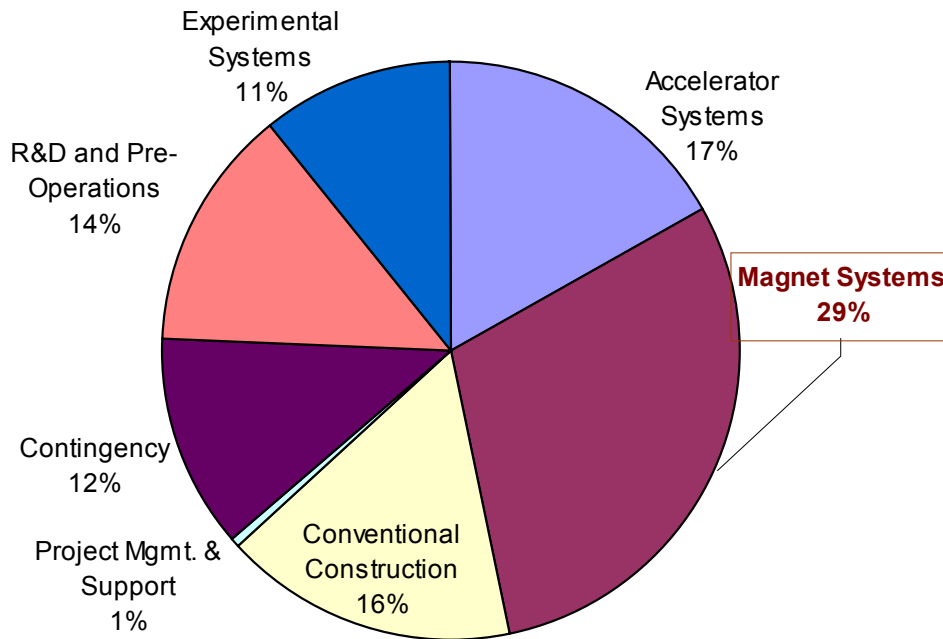


(Derived based on certain assumptions)

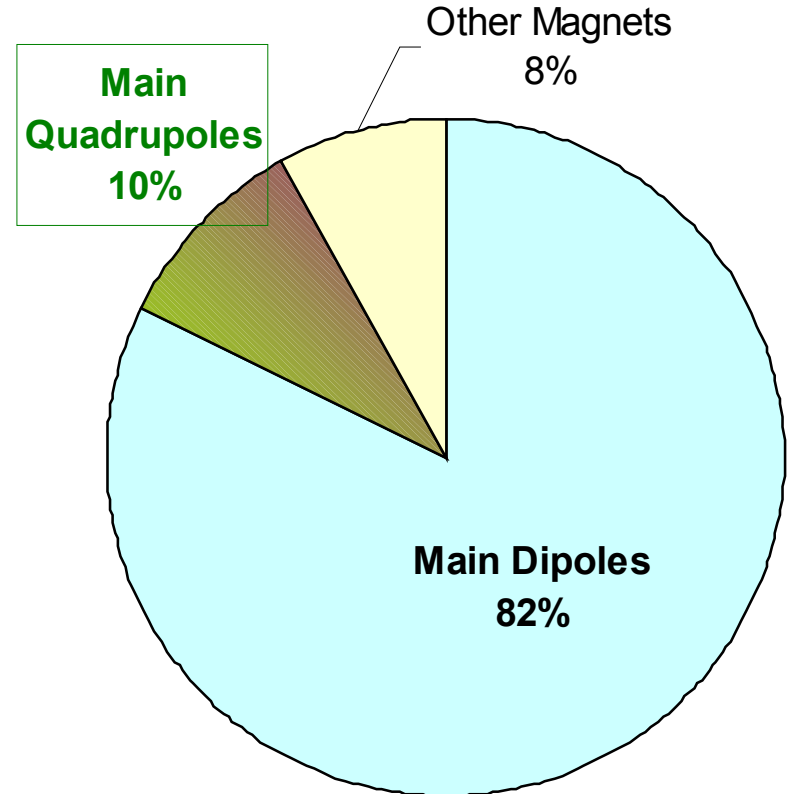
Cost of the Main Components in Modern High Energy Hadron Collider

SSC Project Cost Distribution

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



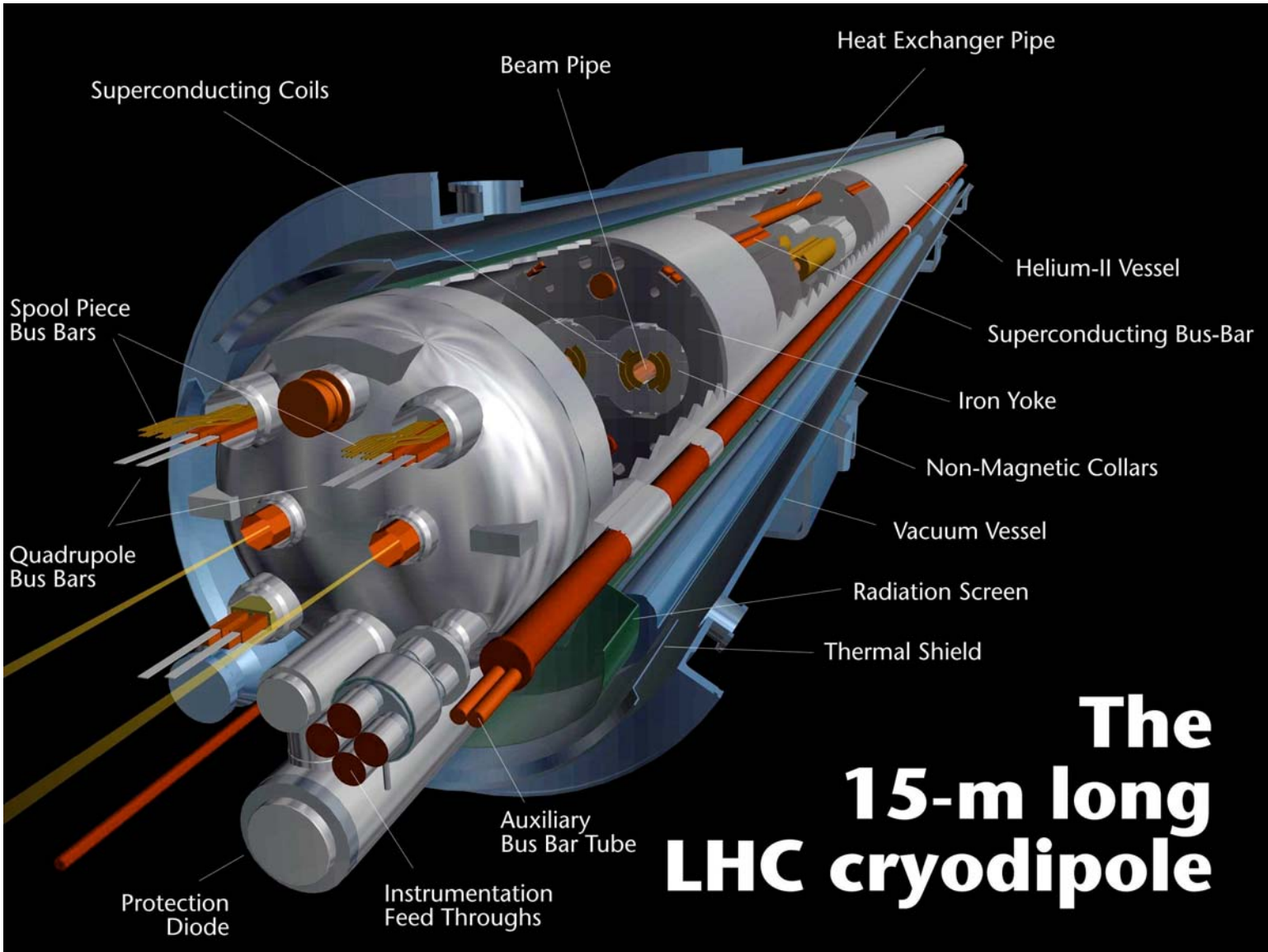
Collider Ring Magnet Cost Distribution



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

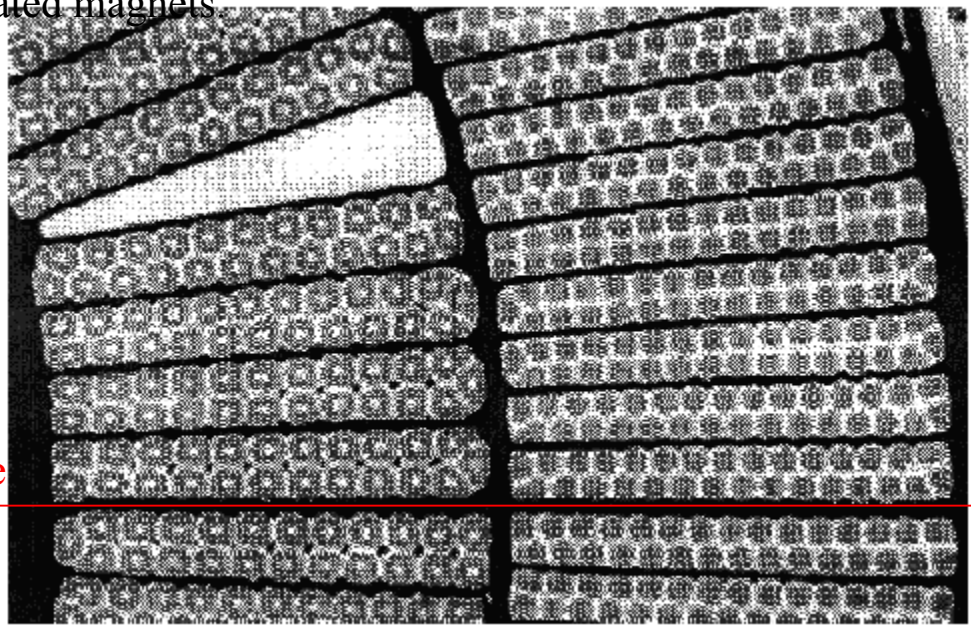
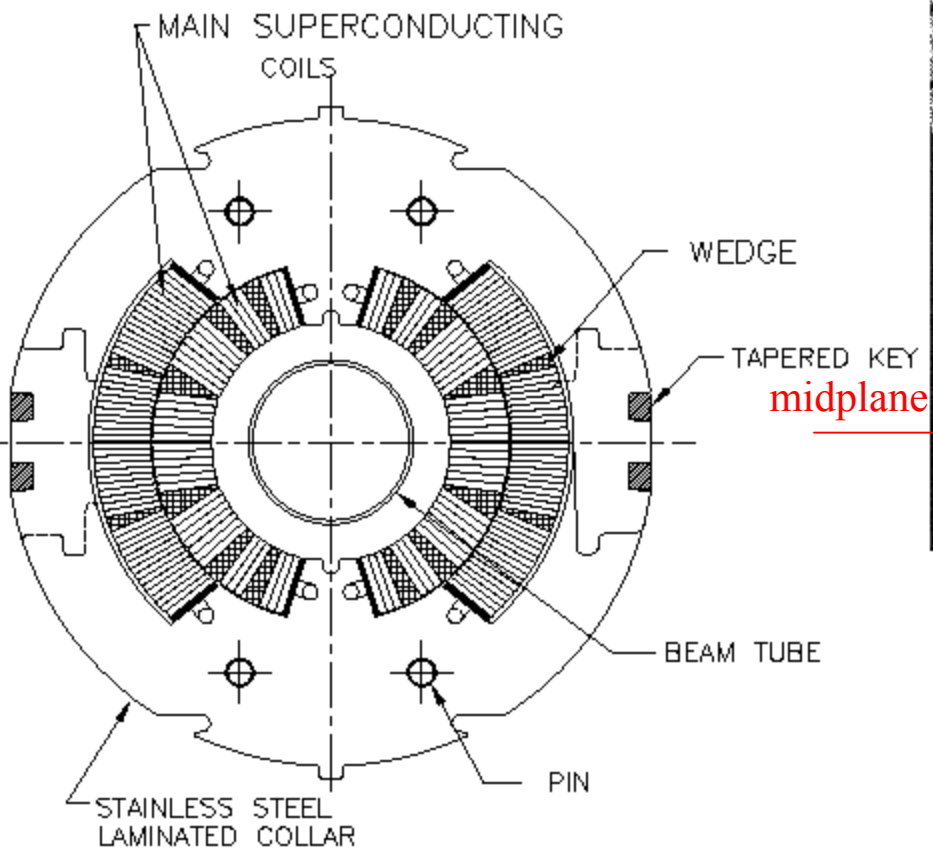
But the cost of other magnets and systems is also important!

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



Scanned and photo-enhanced image of a dissected SSC 40 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).

SSC 50 mm dipole collared coil cross-section

RHIC Magnet Coldmass During Assembly



RHIC dipole coldmass during assembly

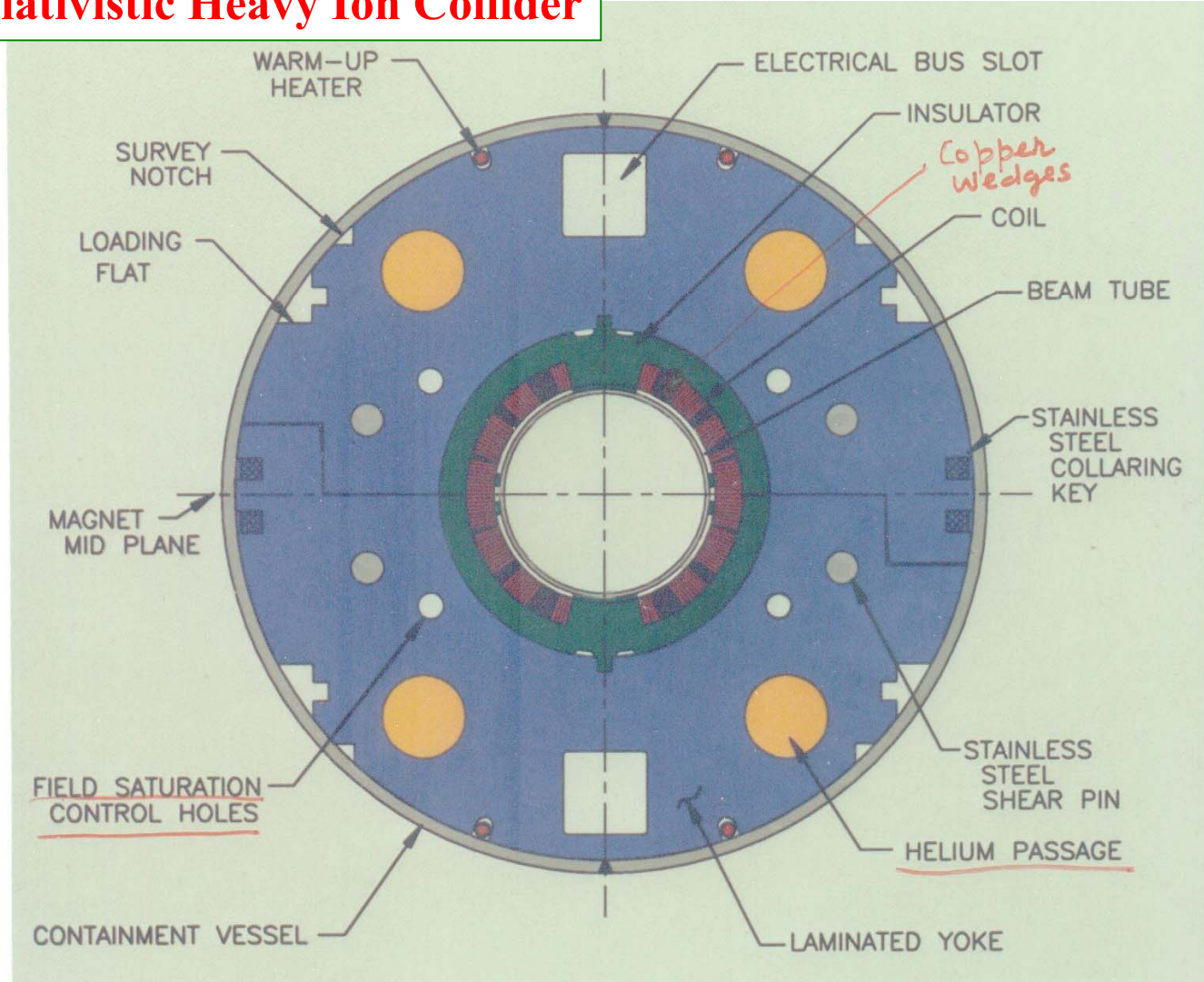


RHIC insertion quad coldmass during assembly

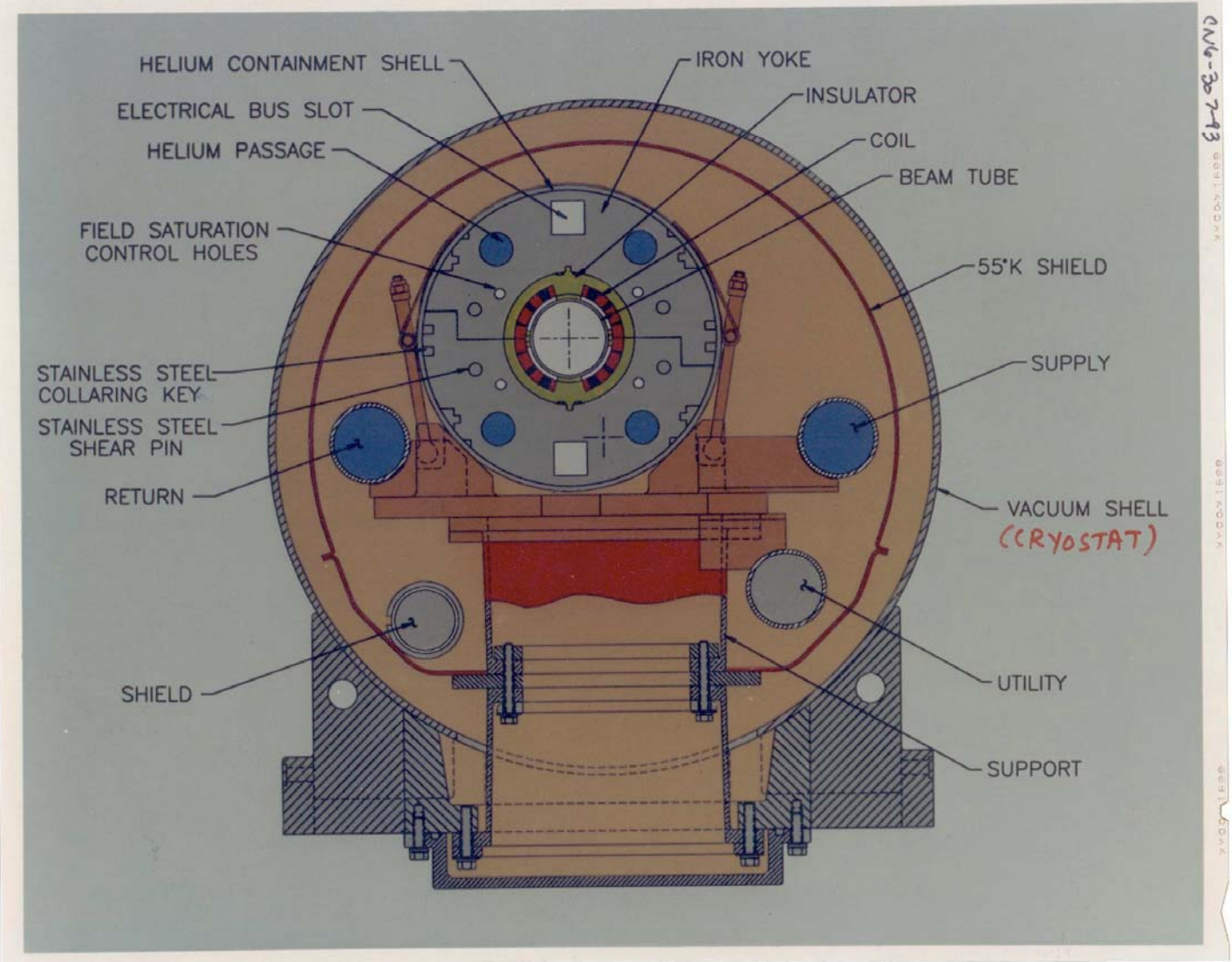
RHIC Dipole Coldmass

**Superconducting
Magnet Division**

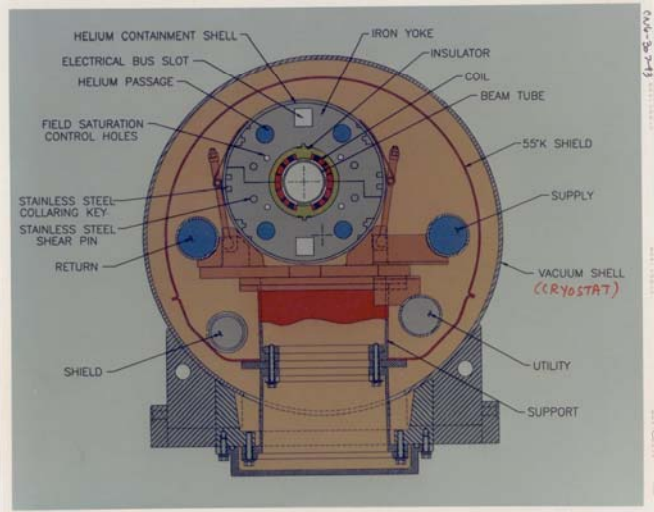
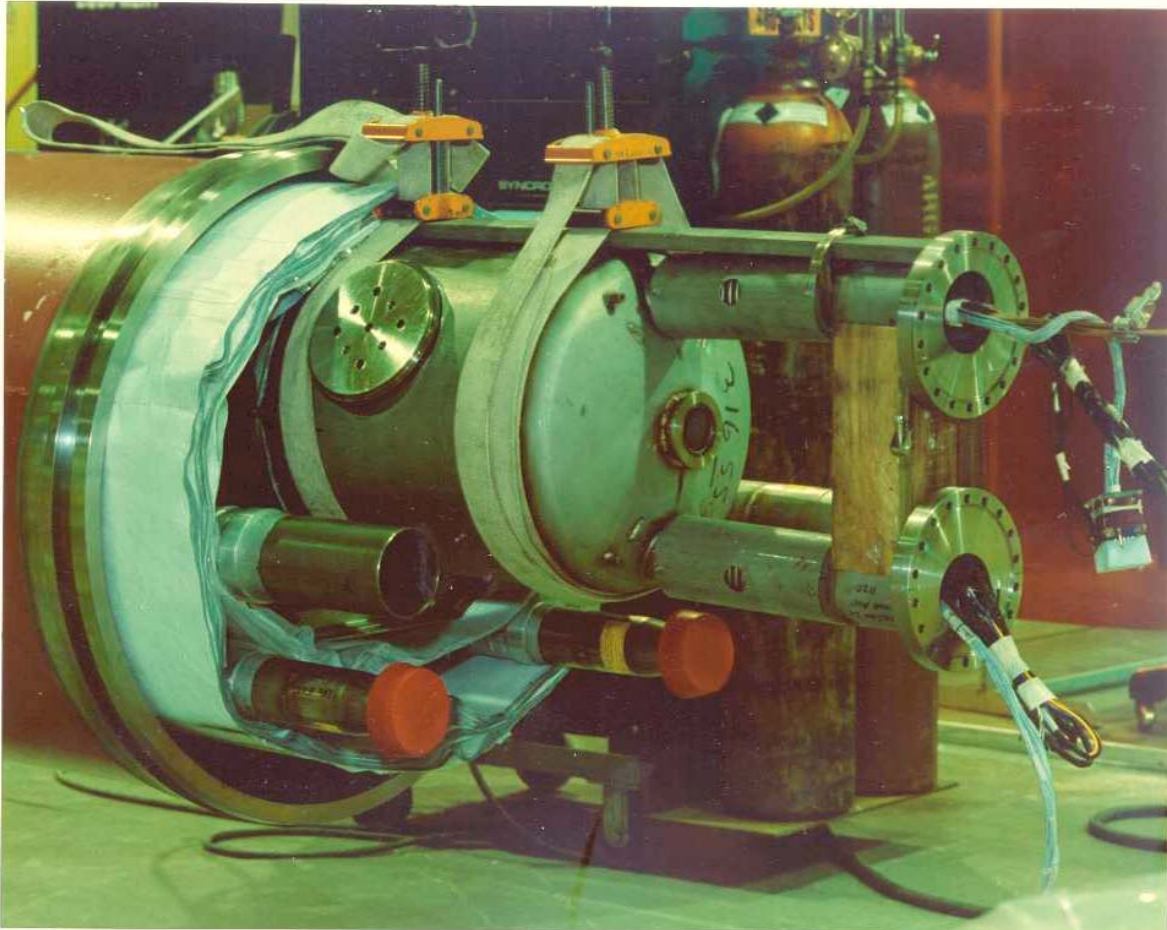
RHIC: Relativistic Heavy Ion Collider



RHIC Dipole in Cryostat (schematic)



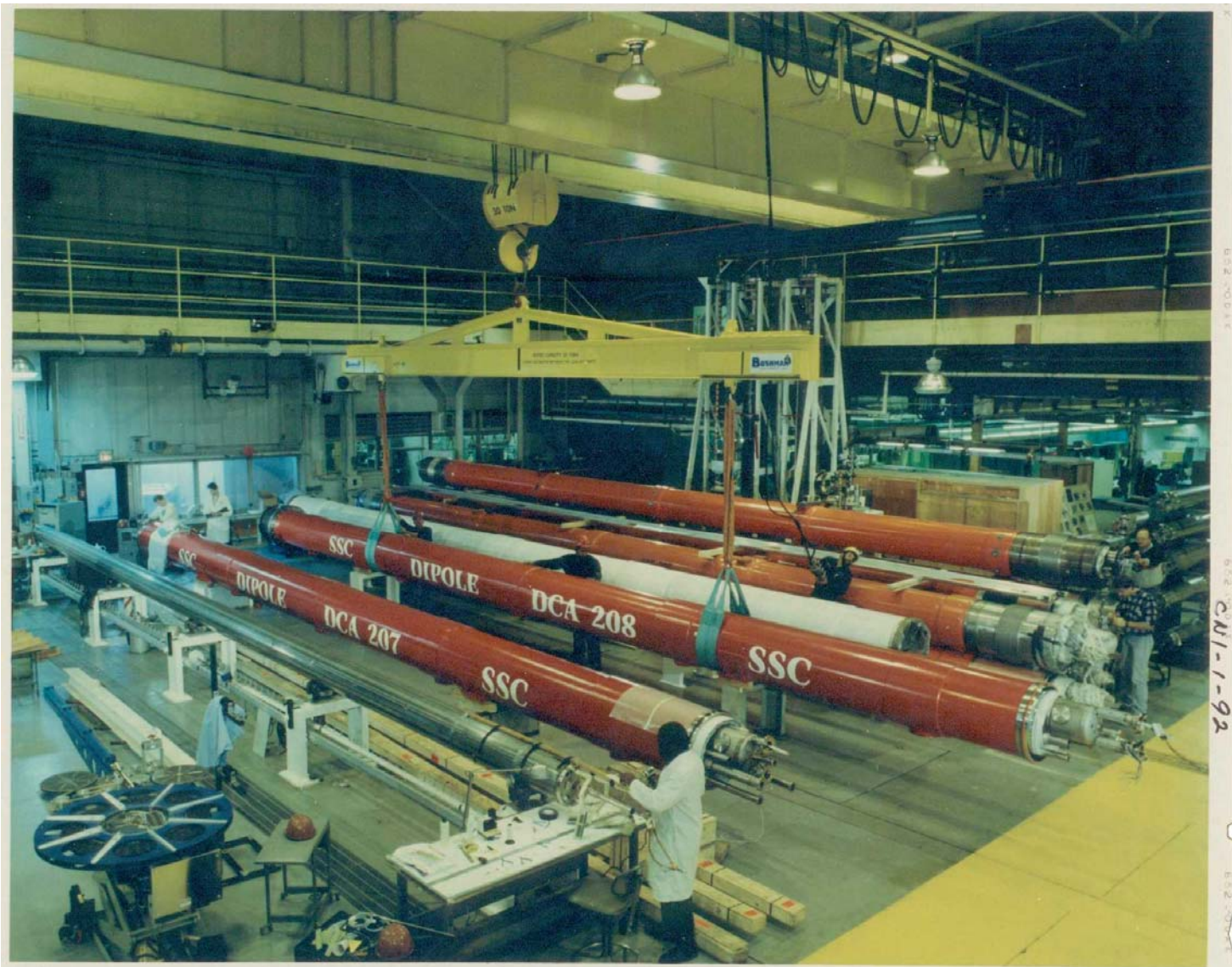
Dipole Coldmass Being Assembled in Cryostat



Assignment:

Identify various components (use RHIC dipole in cryostat slide)

SSC Magnets in Cryostat

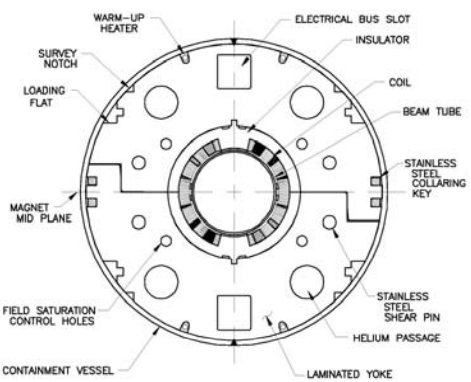


BNL-1-92

Variety of Superconducting Magnets

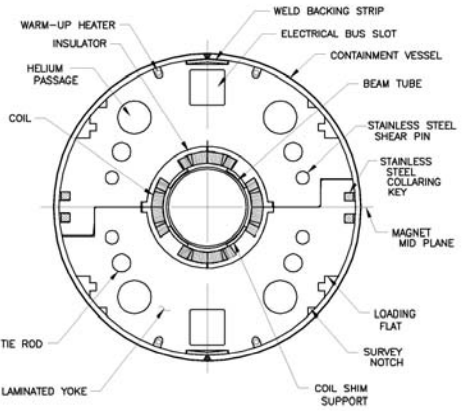
**Superconducting
Magnet Division**

RHIC ARC DIPOLE



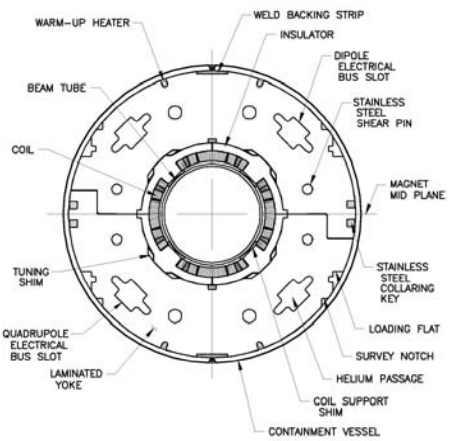
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RHIC ARC QUADRUPOLE



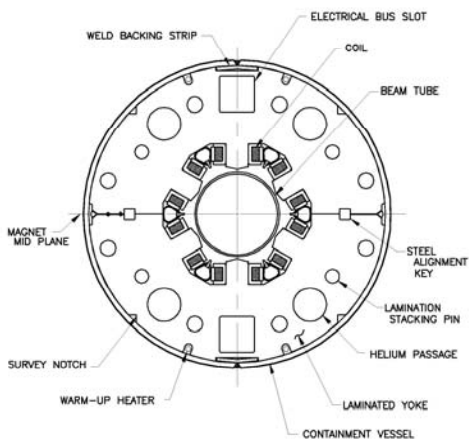
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RHIC INSERTION QUADRUPOLE

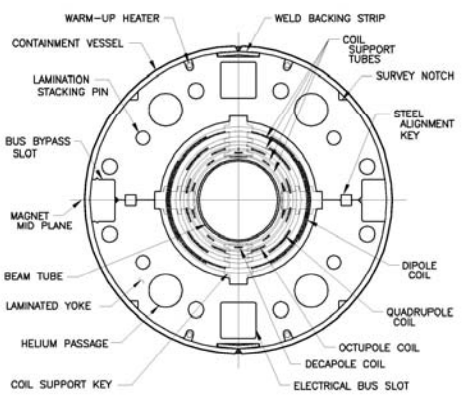


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RHIC ARC SEXTUPOLE



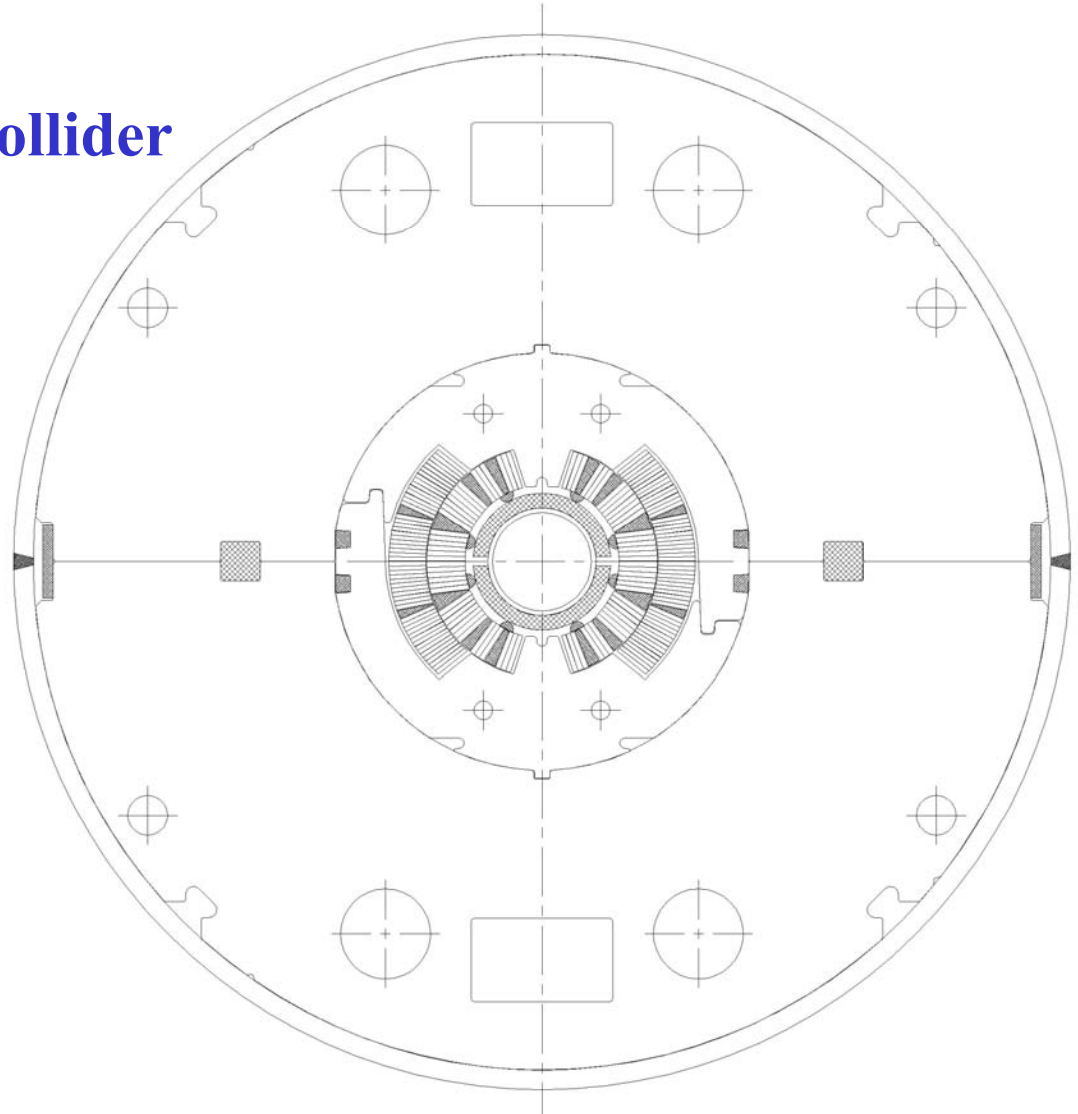
RHIC ARC CORRECTOR



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

SSC Dipole Coldmass

SSC:
Superconducting Supercollider



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: 2005 (?)

Machine	Dipoles				Quadrupoles			
	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

Present Magnet Design and Technology

Superconducting Magnet Division

Tevatron Dipole

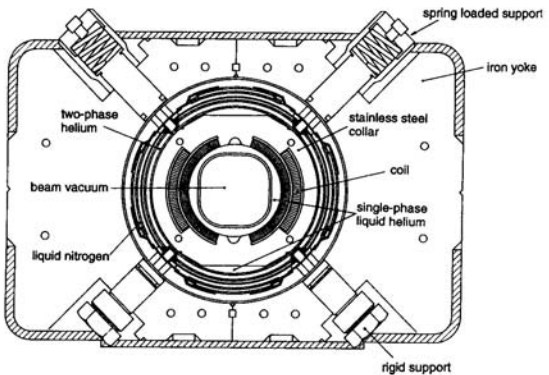
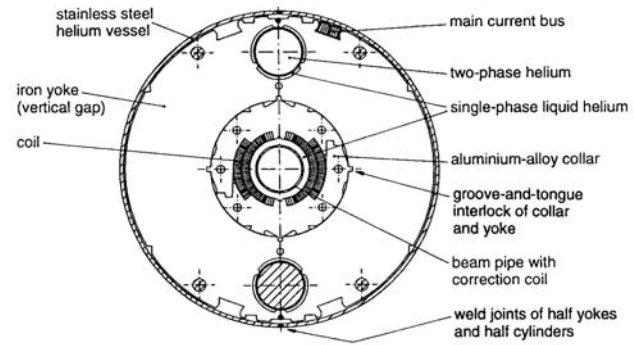
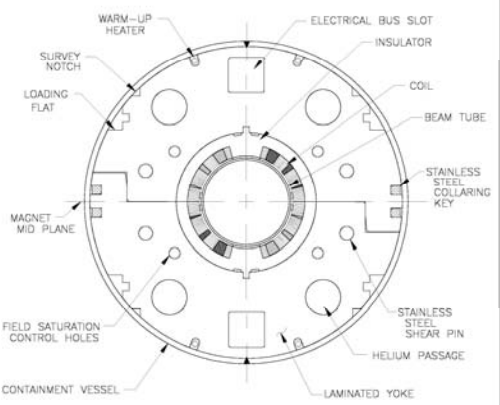


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

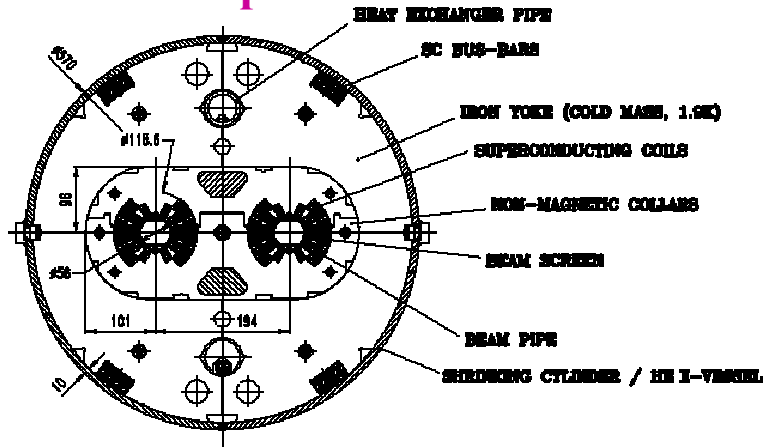
HERA Dipole



RHIC Dipole

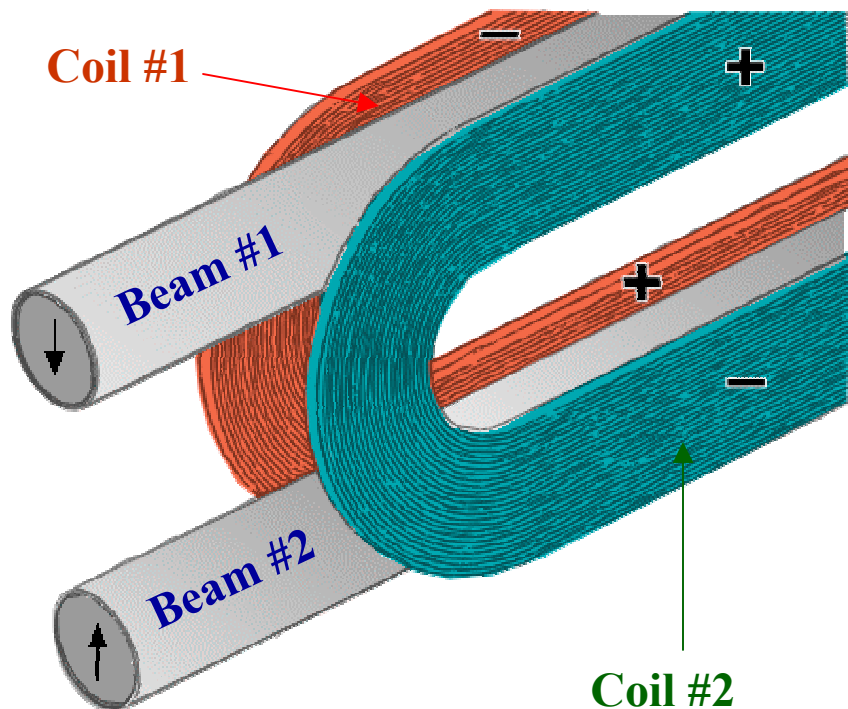
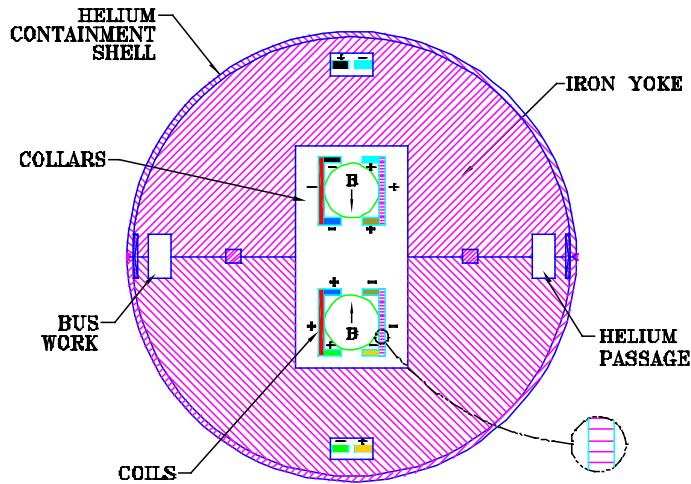


LHC Dipole



- 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 reduce significantly.

Common Coil Design (The Basic Concept)



Main Coils of the *Common Coil Design*

- **Simple 2-d geometry** with large bend radius (no complex 3-d ends)
- **Conductor friendly** (suitable for brittle materials - most are - Nb₃Sn, HTS tapes and HTS cables)
- **Compact** (compared to single aperture LBL's D20 magnet, half the yoke size for two apertures)
- **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

Superconducting Magnets in Accelerators

The Cost Issue

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 small production, 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 an overall design of the superconducting magnet

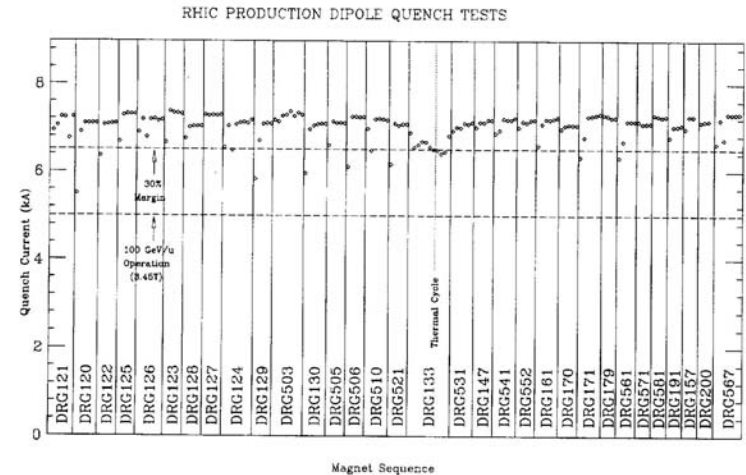
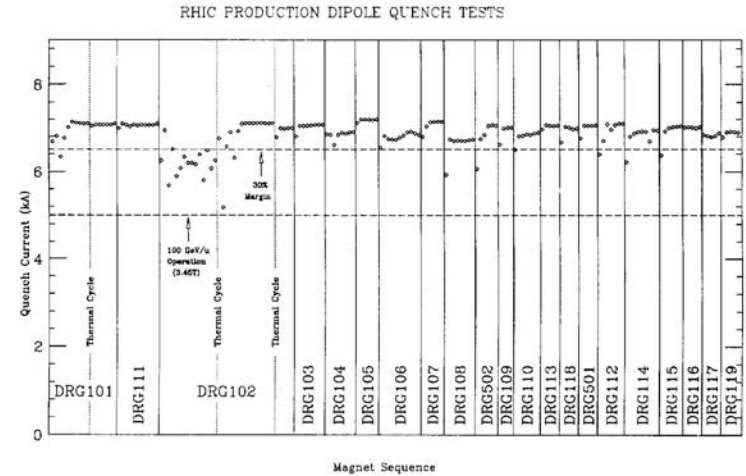
- The magnet should be designed in such a way that the conductor remains in superconducting phase with a comfortable margin.
- The superconducting magnets should be well protected. If the magnet quenches (conductor loses its superconducting phase due to thermal, mechanical, beam load, etc.), then there 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 Kelvin) for the entire series of magnets in the machine. It should be able to handle the heating caused by beam, including that by synchrotron radiations or decay particles.

Superconducting Magnet Design (2)

- The magnet cost should be minimized.
- There are very large Lorentz forces in the superconducting magnet. 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 conductor. In high field magnets, the design of mechanical structure plays a major role.
- The magnet should be designed in such a way that they are easy to manufacture.
- They must meet the field quality (uniformity) requirements.

Quench Performance of RHIC Production Magnets

- In a large series production, there will be some magnets, if not most, that will not be able to reach the ideal field performance (short sample).
- 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.



Note: Test temperature was 4.5K (nom).
Quenches with the warm bore are not included in this plot.

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

Luminosity of upcoming 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 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 !

Why Field Quality Is So Important In Accelerator Magnets?

- **The magnets in 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.**

Field Errors and Machine Cost/Performance

- **The field errors has 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 the field quality is important for reducing the cost while assuring a 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 many errors gets 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 a 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 would also anticipate deviations in parts during production and be flexible enough to accommodate them to produce good field quality magnets despite those errors.
 - The 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

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 on 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 magnet designs.
- May be, 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.