SUPERCONDUCTIVITY APPLIED TO PARTICLE ACCELERATOR MAGNETS

Arnaud Devred
CEA/Saclay

Technology School on Superconducting Magnets
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Contents

- Accelerator Magnet Technologies
- On the Use of Superconducting Magnets
- Review of Large Superconducting Particle Accelerators
- Prominent Features of Superconducting Accelerator Magnets
- Main Design Evolutions

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Magnet Technologies

- There are three main types of accelerator magnet technologies
  - permanent magnets,
  - resistive magnets,
  - superconducting magnets.

Permanent Magnets

- Permanent magnets are cheap, but can only provide a small and constant field (*e.g.,* ~0.15 T for strontium ferrite).
- They are well suited for storage ring operated at low and constant energy level *(see dedicated Technology Course).*

Example: 8-GeV, 3.3-km-circumference, antiproton recycler ring at Fermilab.

Resistive Magnets (1/2)

- Resistive magnets can be ramped in current, thereby enabling synchrotron-type operations.
- The most economical designs are iron-dominated.
- The upper field limit for iron-dominated magnets is ~2 T and is due to iron saturation.

Resistive Magnets (2/2)

- In practice, most resistive accelerator magnet rings are operated at low fields to limit power consumption (typically: ~0.15 T).

Example: electron ring accelerator at DESY, which has a 586.8 m bending radius, and achieves a maximum energy of 30 GeV with a bending field of 0.1638 T.

Superconducting Magnets (1/2)

- As we have seen, in a synchrotron-type accelerator, the particle energy is related to the product of the bending radius, χ, by the bending field strength, B.
- Hence, to operate at high energies, one must increase either χ or B (or both).

Superconducting Magnets (2/2)

- Increasing χ means a longer tunnel, while increasing B beyond standard values achieved on resistive magnets means relying on more costly and more difficult-to-build superconducting magnets.
- Since the late 70's, the trade-off between tunneling costs, magnet production costs, and accelerator operating costs is in favor of using superconducting magnets generating the highest possible fields and field gradients.

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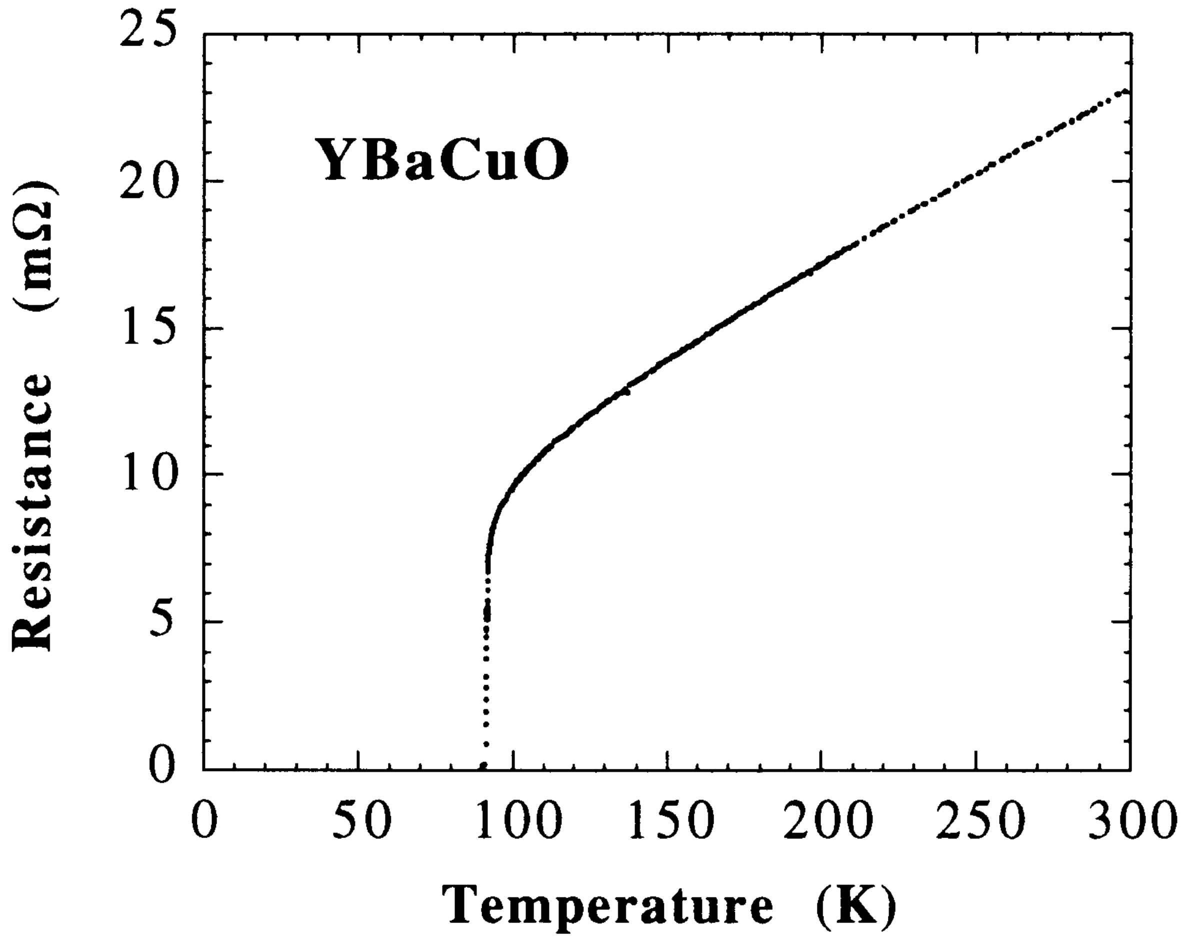
What is Superconductivity?

- Superconductivity is a unique property exhibited by some materials at low temperatures where the resistance drops to zero.
- As a result, materials in the superconducting state can transport current without power dissipation by the Joule effect.

Example: YBaCuO



(Courtesy P. Tixador)

Advantages of Superconductivity

- Superconductivity offers at least two advantages for large magnet systems
  - A significant reduction in electrical power consumption,
  - The possibility of relying on much higher overall current densities in the magnets coils.

Drawbacks of Superconductivity

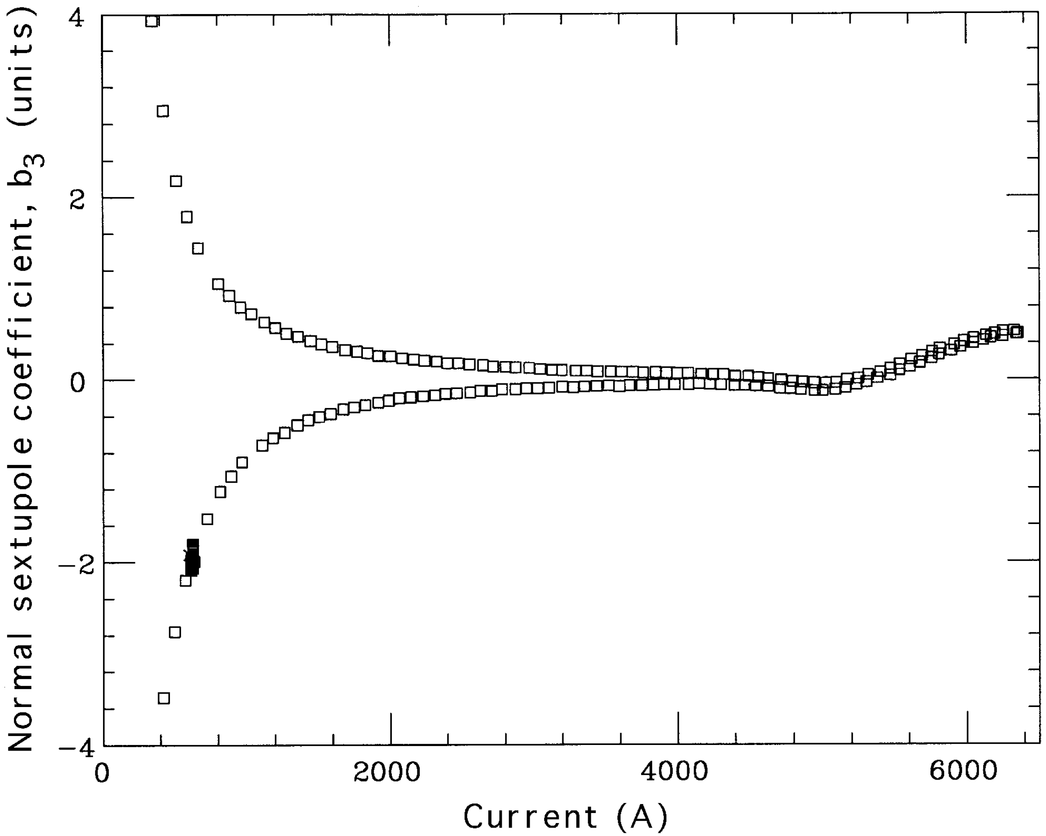
- There are at least three drawbacks in using superconducting magnets
  - cooling requirements,
  - magnetization effects,
  - risks of "quench".

Cooling

- To reach the superconducting state, the magnets must be cooled down and maintained at low temperatures.
- This requires large cryogenic systems usually based on liquid helium.

SSC Magnet Test Facility
at FNAL
(now dismantled)

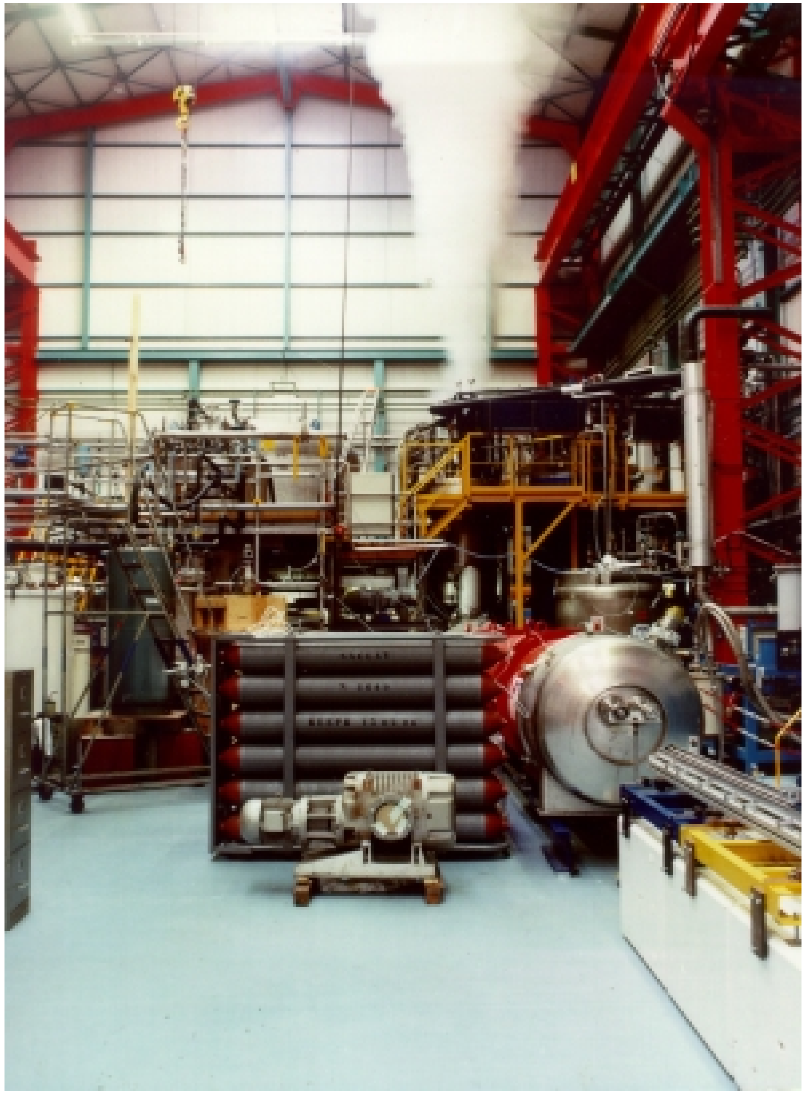
Magnetization Effects



Hysteresis Observed in the Sextupole Component of a SSC Dipole Magnet

- Superconductors generate magnetization effects which result in field distortions and can degrade performances.
- The field distortions of accelerator magnets must be corrected.

Quench (1/3)



- It can happen that an energized magnet, initially in the superconducting state, abruptly and irreversibly switches back to the normal resistive state.
- This phenomenon is referred to as a *quench*.

Quench of a LHC Dipole Magnet Prototype at CEA/Saclay

Quench (2/3)

- The occurrence of a quench causes an instantaneous disruption and requires that the magnet system be ramped down rapidly to limit conductor heating and prevent damages.
- Once the quenching magnet is discharged, it can be cooled down again and restored into the superconducting state, and the normal operation resumes.

Quench (3/3)

- A quench is seldom fatal, but it is always a serious disturbance.
- All must be done to prevent it from happening and all cautions must be taken to ensure the safety of the installation when it does happen.

On the Use of Superconducting Magnets

- In spite of these drawbacks, the use of superconducting magnet technology has been instrumental in the realization of today's giant particle accelerators.
- In return, high energy physics has become one of the driving forces in the development of applied superconductivity.

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Tevatron (1/2)

- The first large-scale application of superconductivity was the Tevatron.

Site:	FNAL, near Chicago, IL
Type:	proton/antiproton collider
Circumference:	6.3 km
Energy:	900 GeV per beam
Commissioning:	1983

Tevatron (2/2)

• The Tevatron arc dipole and quadrupole magnets were developed and built at FNAL.

Type:	single aperture
Aperture:	3″ (76.2 mm)
Dipole Field:	4 T
Dipole Length:	6.1 m
Total Number:	774

Tevatron Ring

Main Injector
and Recycler Ring

Tevatron Tunnel

Aerial View of FNAL

Tevatron Ring

HERA (1/2)

- The second large-scale particle accelerator to rely massively on superconducting magnets was HERA (Hadron Elektron Ring Anlage).

Site:	DESY, in Hamburg, Germany
Type:	electron/proton collider*
Circumference:	6.3 km
Energy:	30 GeV for electron beam and 920 GeV for proton beam
Commissioning:	1990

* Only proton ring relies on superconducting magnets.

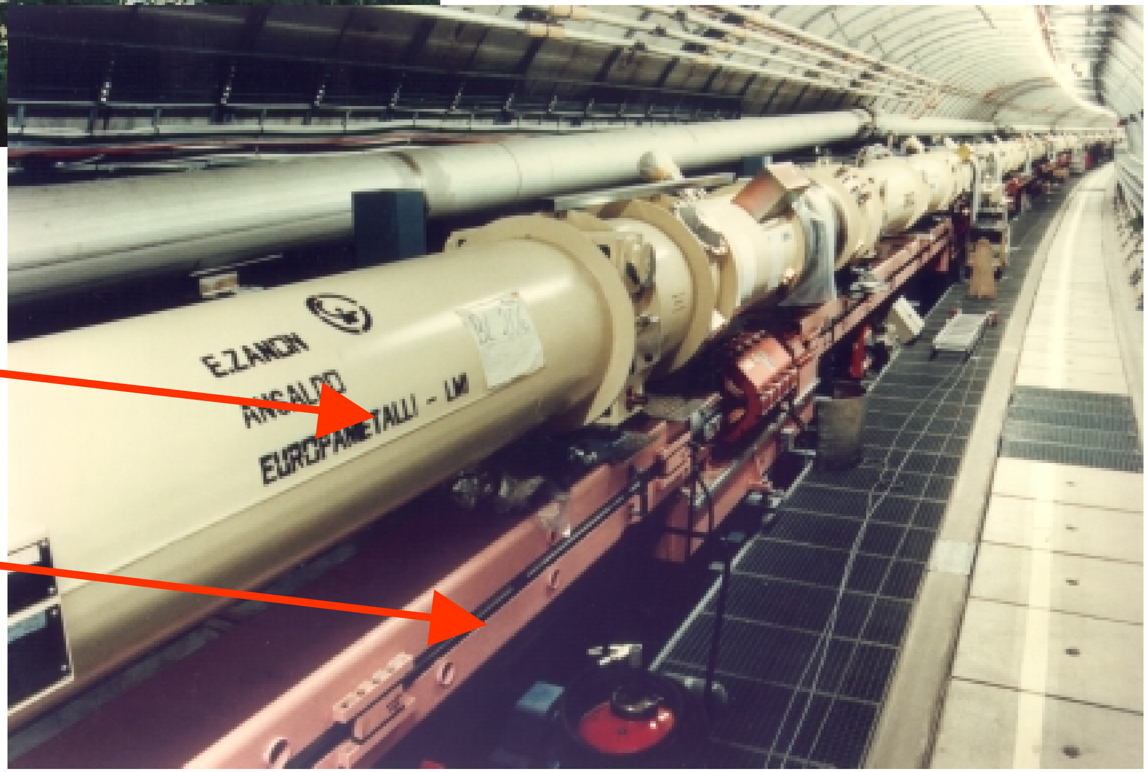
HERA (2/2)

- The HERA arc dipole magnets were developed at DESY while the arc quadrupole magnets were developed at CEA/Saclay. Both magnet types were mass-produced in industry.

Type:	single aperture
Aperture:	75 mm
Dipole Field:	5.2 T
Dipole Length:	8.8 m
Total Number:	416

Aerial View of DESY

HERA Tunnel



Superconducting p-Ring

Normal e-Ring

SSC (1/3)

- In the mid-80's, the USA started the Superconducting Super Collider (SSC) project.
- The last stage of the SSC complex would have been made up of two identical rings of superconducting magnets installed on top of each other.
- The project was canceled in October 1993 after 14.6 miles (~23.5 km) of tunnel were excavated and a successful magnet R&D program had been carried out.

SSC (2/3)

Site:	SSCL, near Dallas, TX
Type:	proton/proton collider
Circumference:	87 km
Energy:	20 Tev per beam
Commissioning:	Cancelled in 1993

NB: the last injector to the SSC main ring, called the High Energy Booster (HEB), would have relied also on superconducting magnets operated in a bipolar mode.

SSC (3/3)

- The arc dipole magnets of the SSC main ring were developed by a collaboration between SSCL, BNL and FNAL, while the arc quadrupole magnets were developed by a collaboration between SSCL and LBNL. Both magnet types would have been mass-produced in industry.

Type:	single aperture
Aperture:	50 mm
Dipole Field:	6.79 T
Dipole Length:	15 m
Total Number:	7944

Aerial View of N-15 Construction Site Near Waxahatchie, TX

Bottom View of Main Shaft to SSC Tunnel

LHC (1/2)

- In December 1994, CERN has approved the construction in its existing tunnel of the Large Hadron Collider (LHC).

Site:	CERN, at the Swiss/French border, near Geneva
Type:	proton/proton collider
Circumference:	27 km
Energy:	7 TeV per beam
Commissioning:	2005

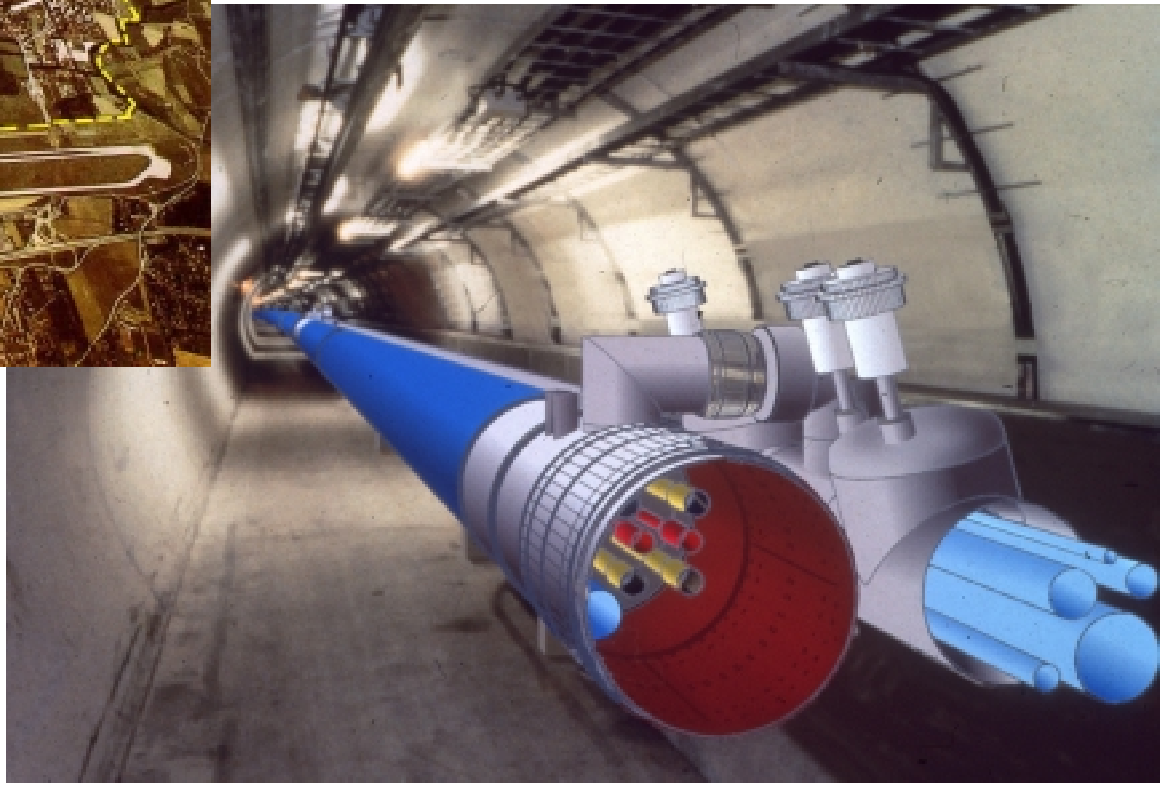
LHC (2/2)

• The LHC arc dipole magnets were developed by CERN in collaboration with industry, while the arc quadrupole magnets were developed at CEA/Saclay. The industrial production of both magnet types is underway.

Type:	twin aperture
Aperture:	56 mm
Dipole Field:	8.4 T
Dipole Length:	14.2 m
Total Number:	1232

CERN Aerial View

Artist View of LHC Tunnel



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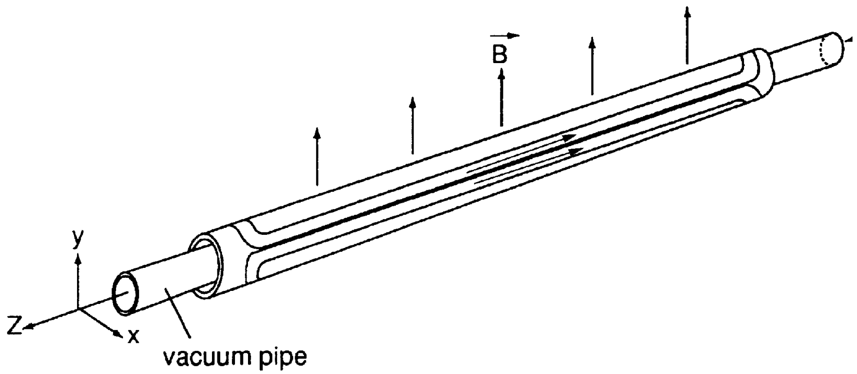
Magnet Design

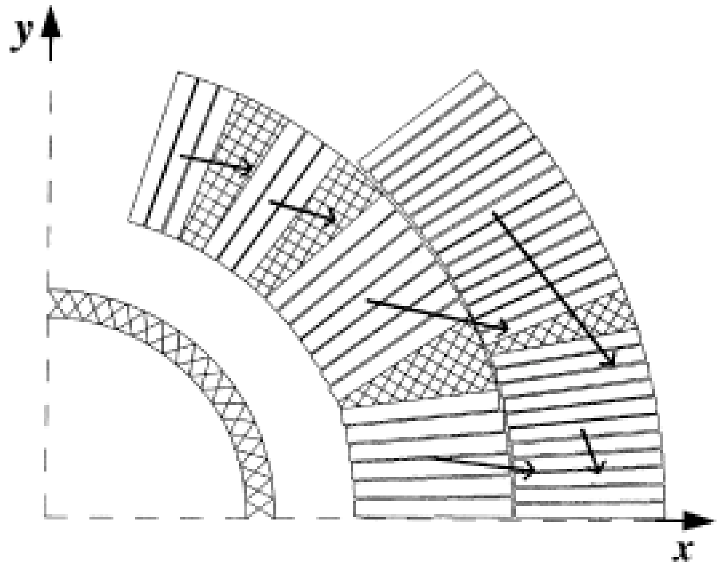
- Most dipole and quadrupole magnets built up to now (Tevatron, HERA, SSC, LHC…) rely on similar design concepts.
- These concepts were pioneered in the late 70's for the Tevatron at Fermilab.
- Improvements in superconductor and magnet fabrication have led to more than double the field over the last 20 years.

Magnetic Design

- Field is produced by saddle-shape coils, which, in their long straight sections, approximate cosθ or cos2θ conductor distributions.



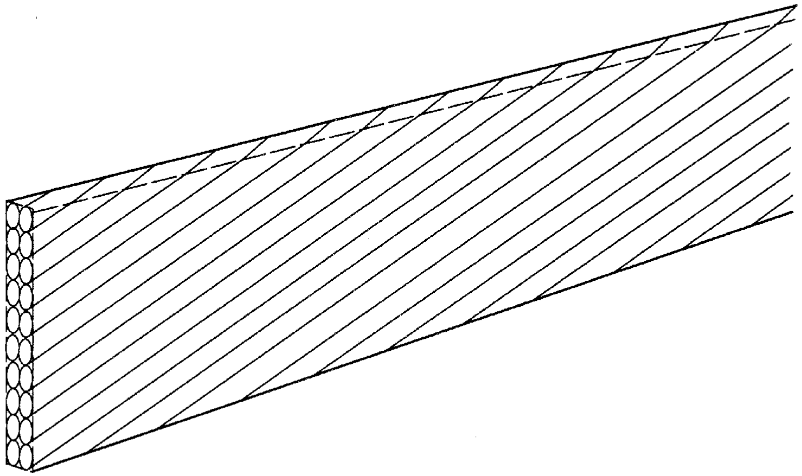
Saddle-Shape Coil Assembly for a Dipole Magnet



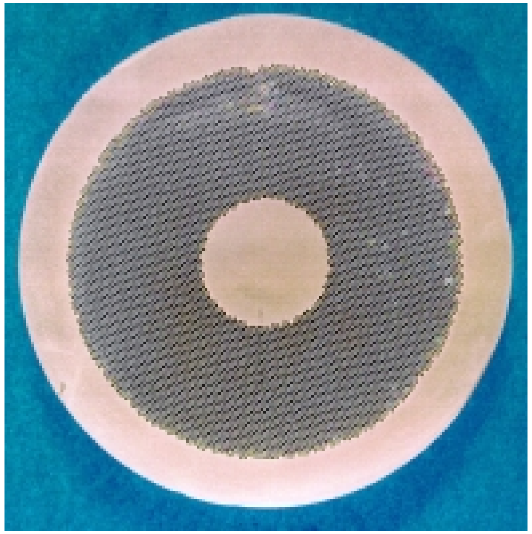
Cosθ Conductor Distribution in a Dipole Coil Assembly Quadrant (Courtesy R. Gupta)

Rutherford-Type Cable

- Coils are wound from flat, two-layer Rutherford-type cables, made up of NbTi multifilamentary composite strands.

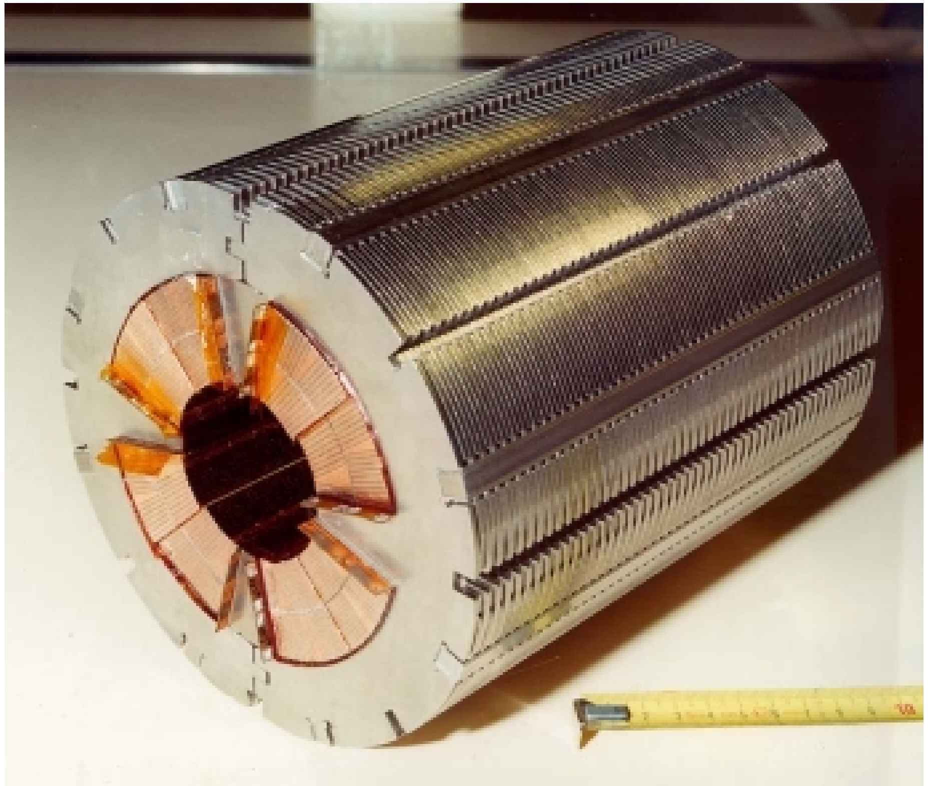


Rutherford-Type Cable
(Courtesy T. Ogitsu)



NbTi Strand for Accelerator Magnet Application
(Courtesy Alstom/MSA)

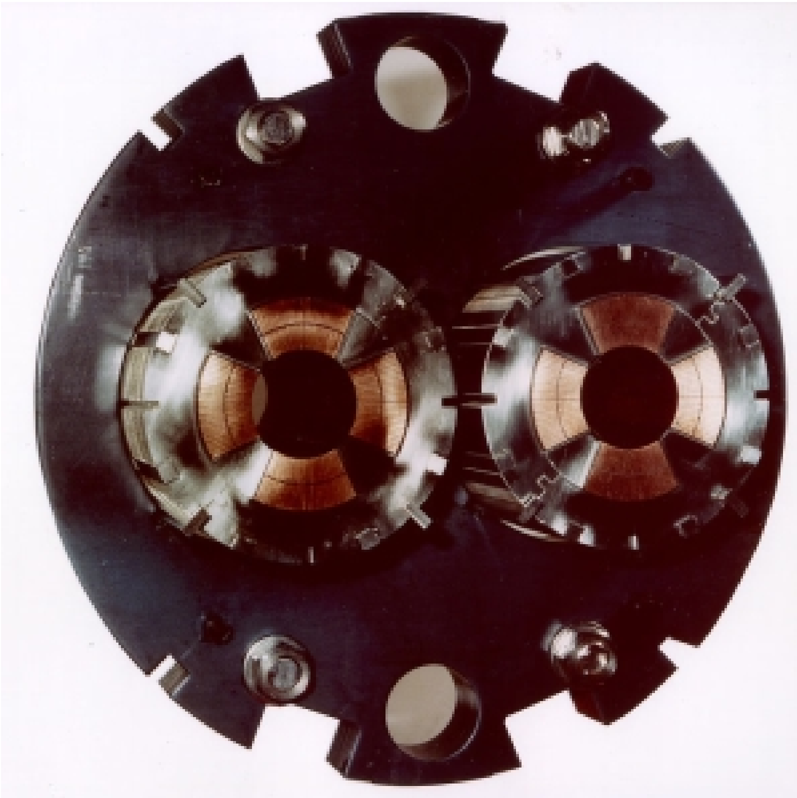
Mechanical Design



Collared-Coil Assembly Section
of LHC Arc Quadrupole Magnet
Developed at CEA/Saclay

- Coils are restrained mechanically by means of laminated collars, locked together by keys or tie rods.

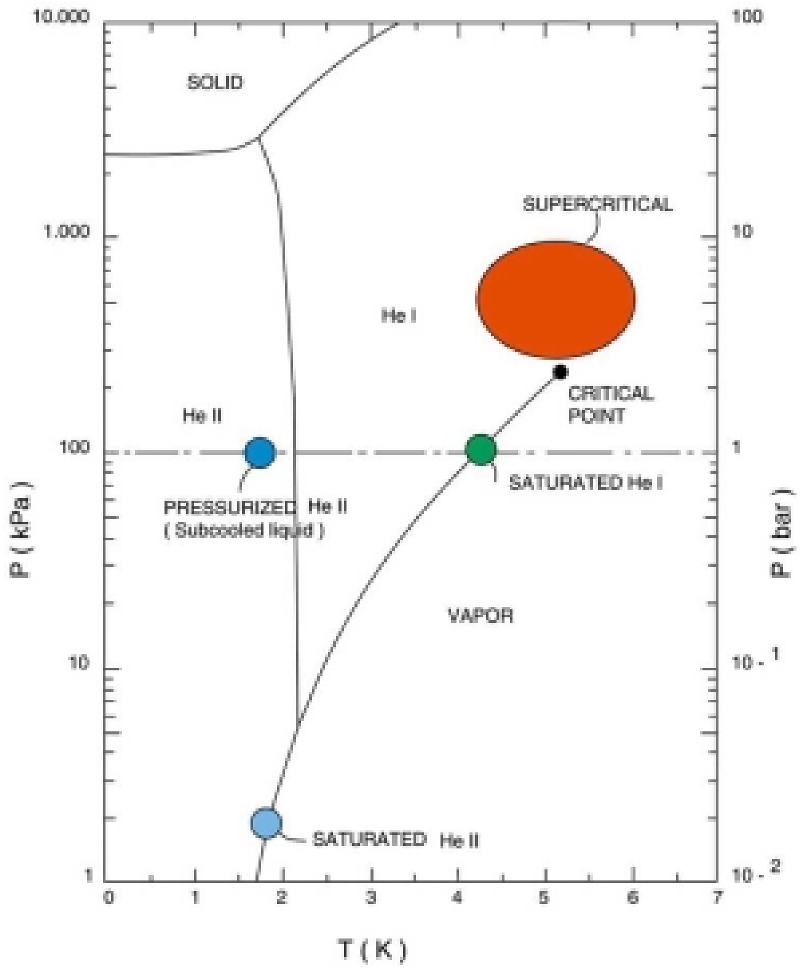
Iron Yoke



Twin-Aperture, LHC Arc
Quadrupole Magnet Design
Developed at CEA/Saclay

- Collared-coil(s) is(are) surrounded by an iron yoke providing a return path for the magnetic flux.
- In some designs, the yoke contributes to the mechanical support.

Magnet Cooling

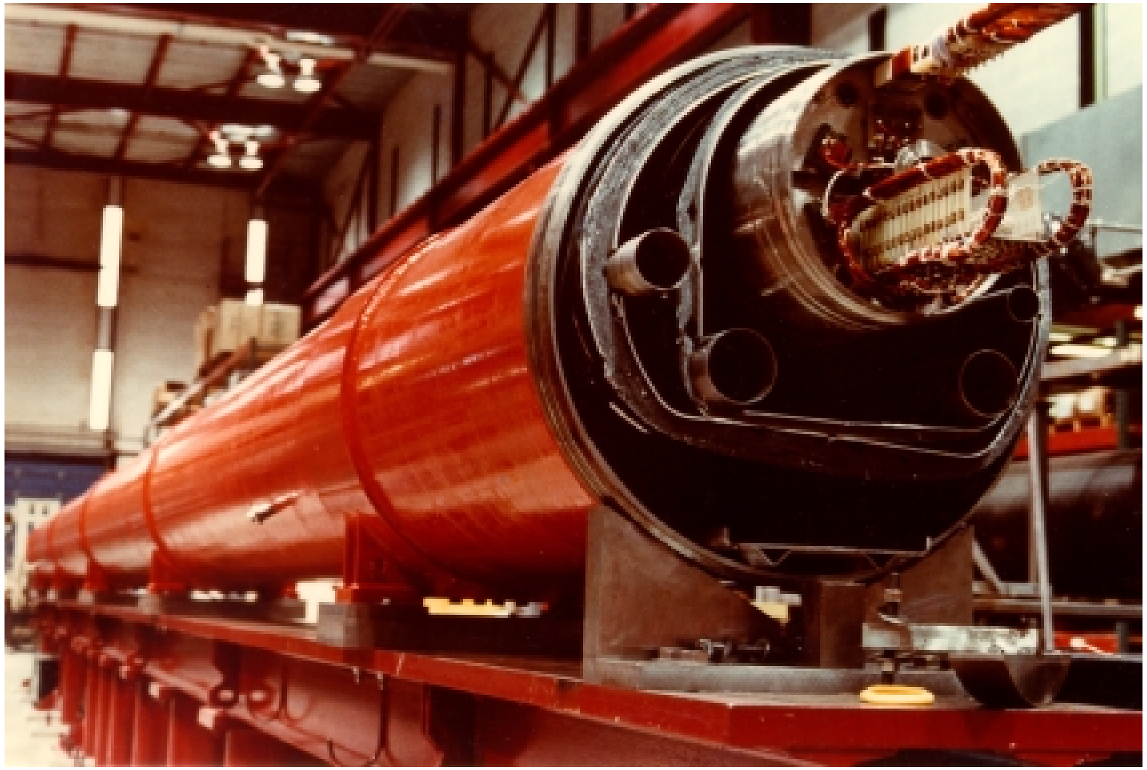


He Phase Diagram (courtesy P. Lebrun)

- Tevatron, HERA, UNK, SSC and RHIC magnets are cooled by boiling helium at 1 atmosphere (4.2 K) or supercritical helium helium at 3 to 5 atmosphere (between 4.5 K and 5 K).
- LHC magnets are cooled by superfluid helium at 1.9 K.

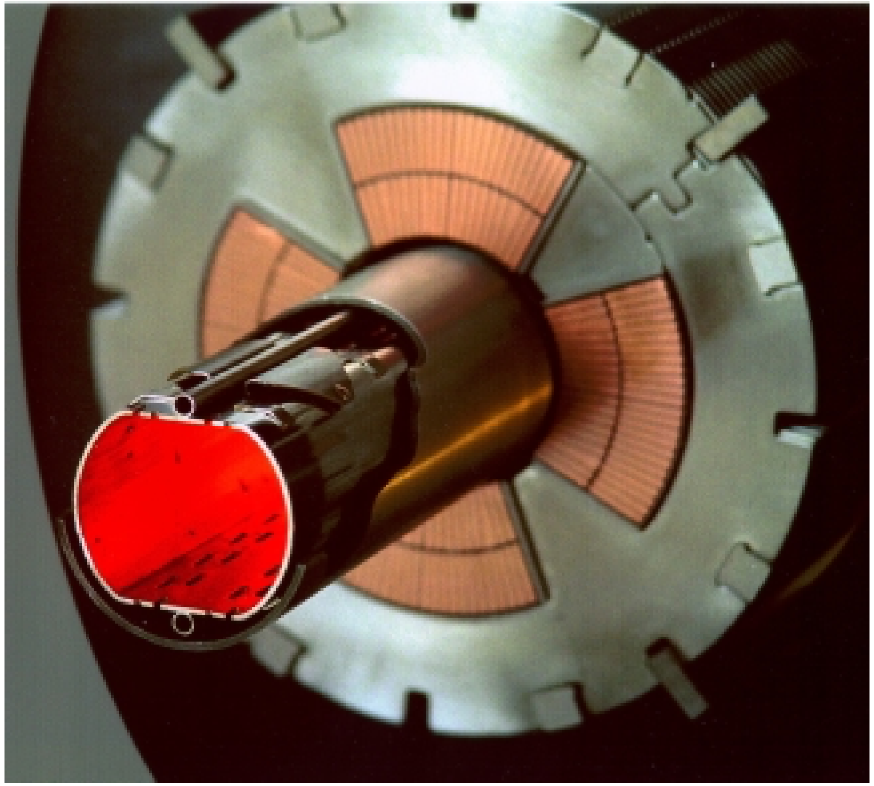
Cryostat

- The magnet cold mass is surrounded by a helium containment vessel and is mounted inside a cryostat to reduce heat losses.



SSC Dipole Magnet Cryostat

Beam Pipe



Beam Screen and Beam Pipe
Under Development
for LHC magnets

- The particle beams are circulated within a vacuum chamber inserted into the magnet coil apertures.
- The vacuum chamber, usually referred to as *beam pipe*, is cooled by the helium bathing the magnet coil.

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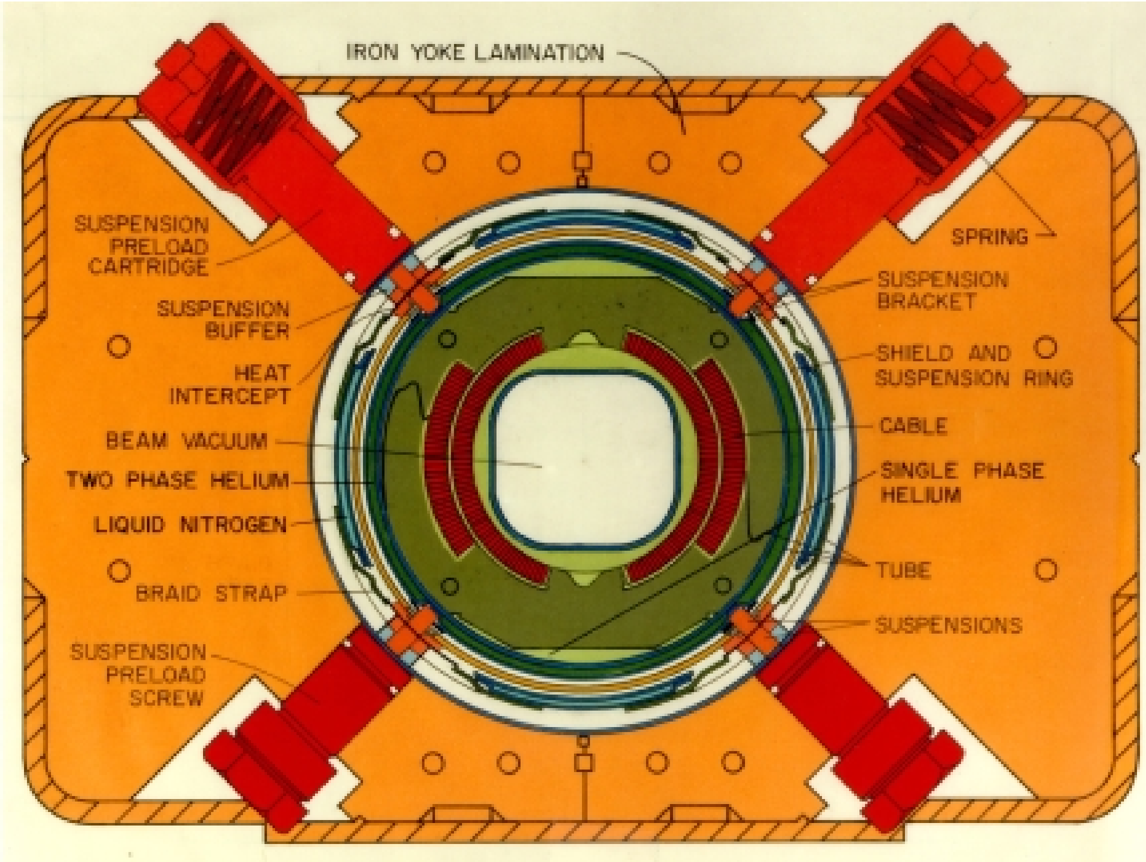
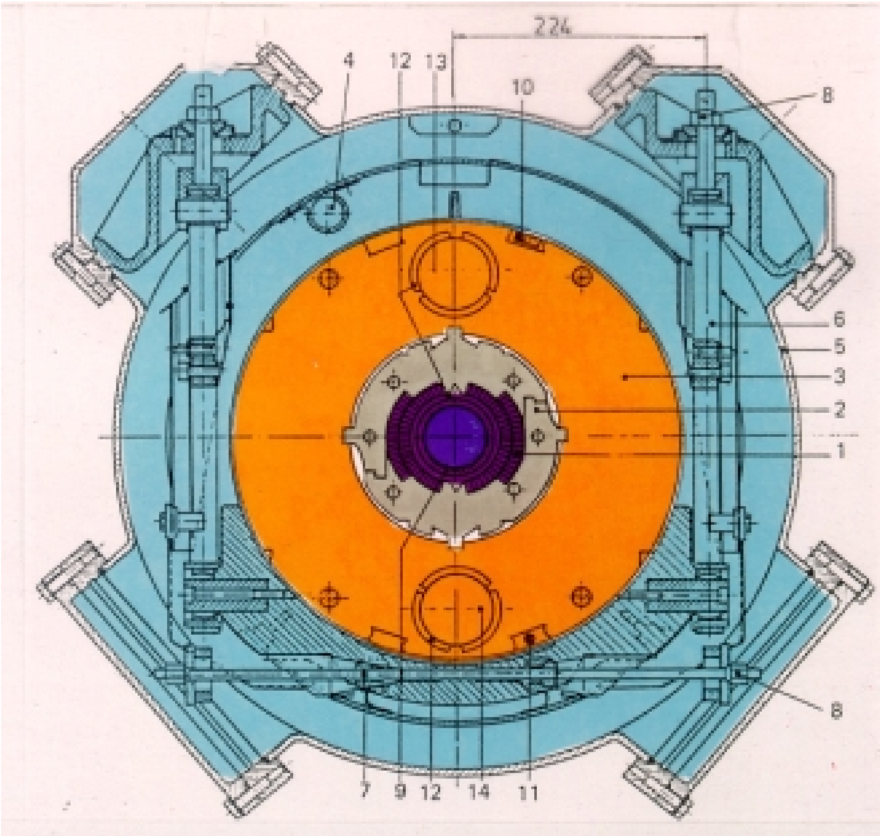
Tevatron

- The Tevatron dipole magnets rely on a warm iron yoke and are operated reliably since 1983 at a field of 4 T.

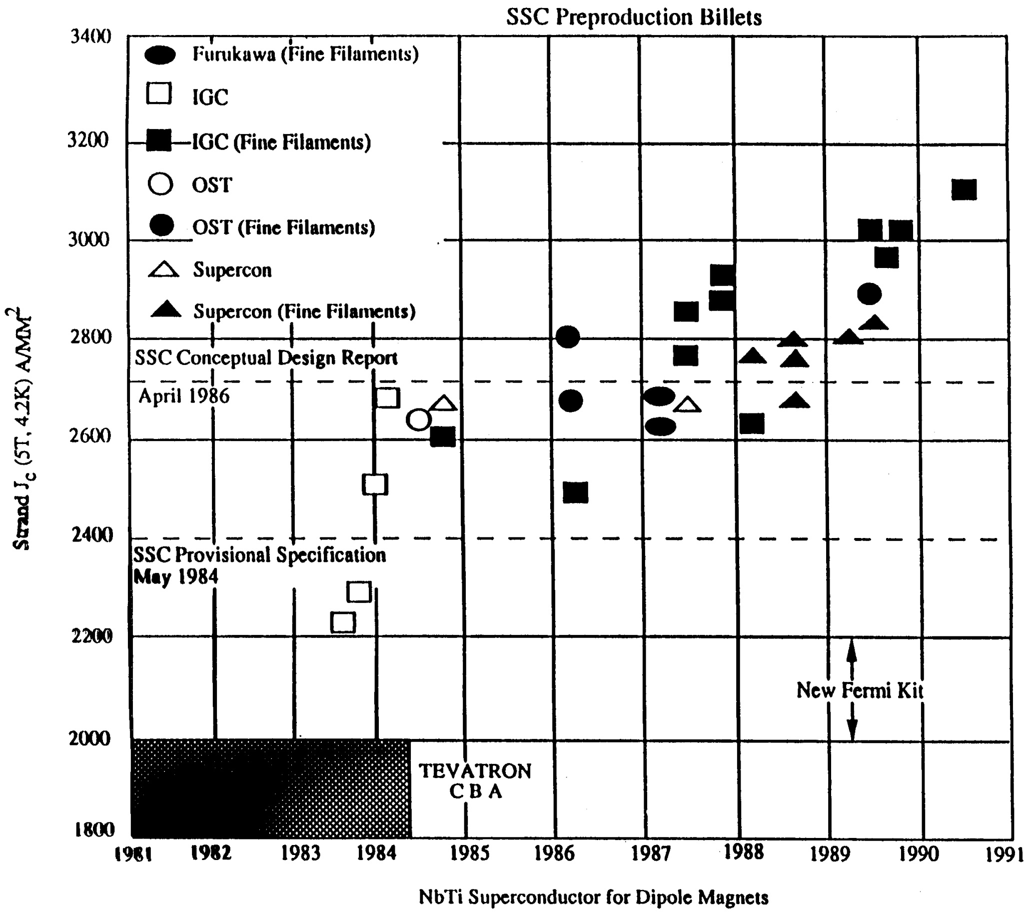


HERA



- Starting with HERA, the iron yoke is included in the cold mass.
- HERA was commissioned in 1990 and the dipole magnets are operated at 5.23 T (12% above original design field).

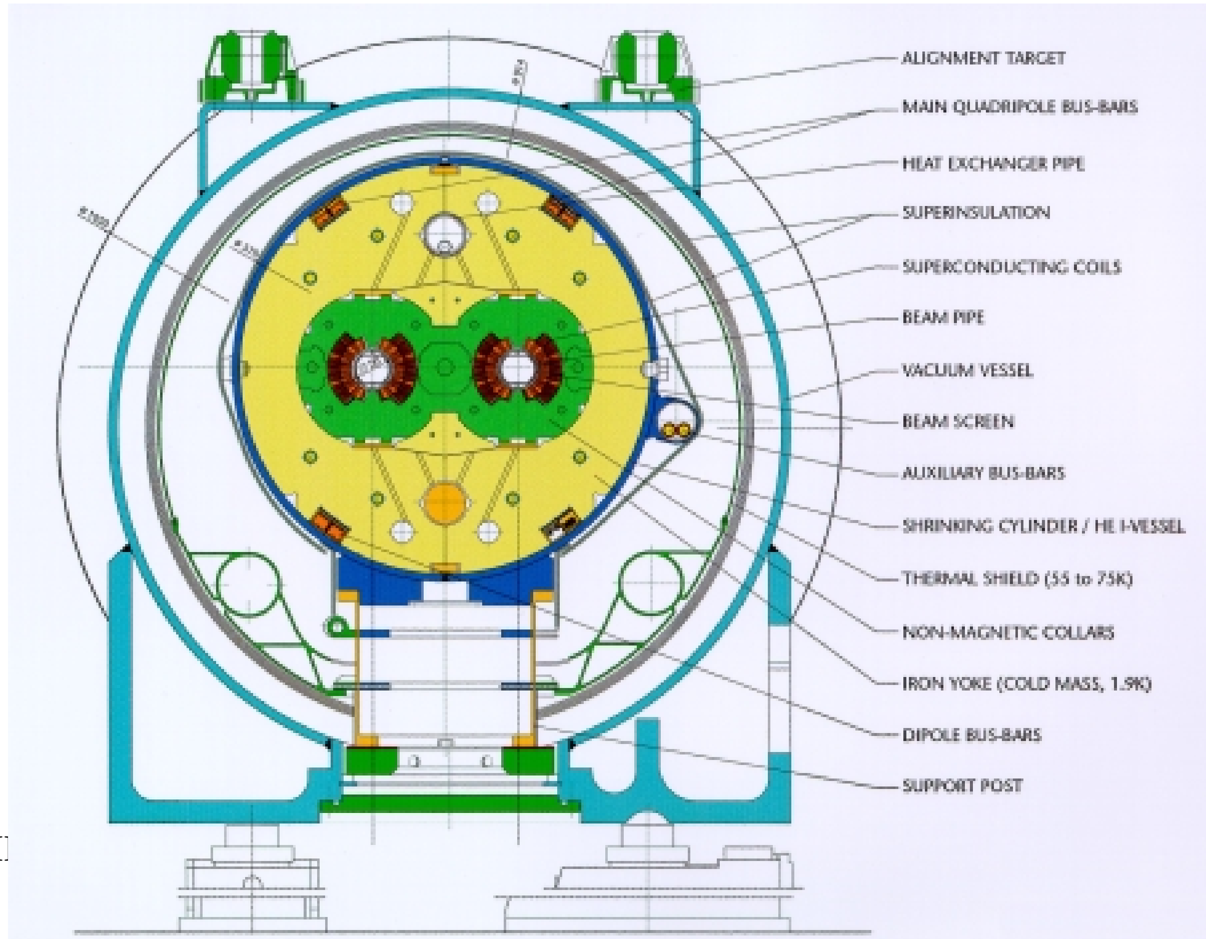
SSC



- The SSC magnet R&D program has allowed significant improvements in the performances and production costs of NbTi wires.

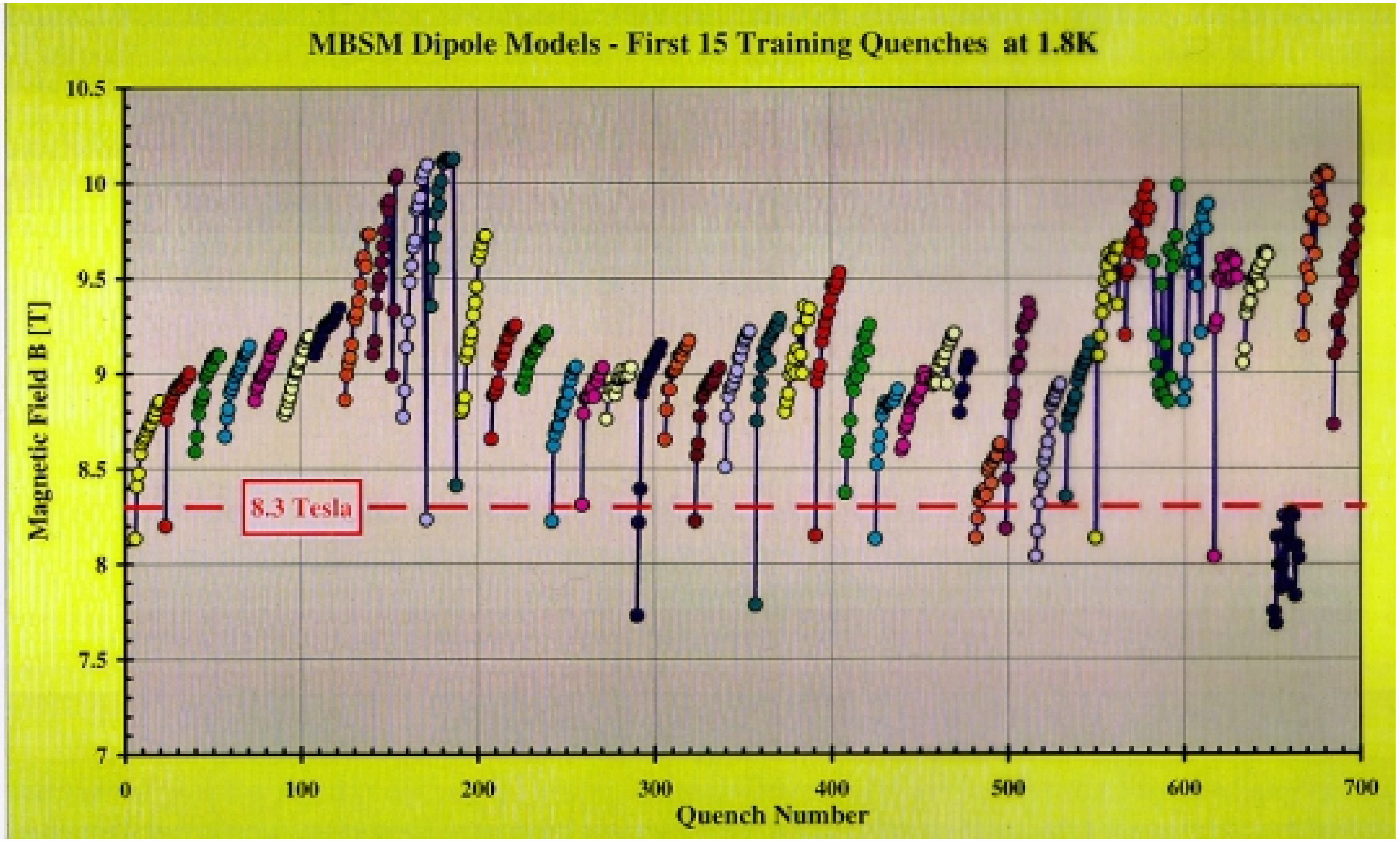
LHC

- LHC will rely on twin-aperture magnets operated in superfluid helium at 1.9 K.



LHC (Cont.)

• The LHC magnet R&D program shows that the 1.9-K limit of NbTi cosθ magnets could be between 9 and 10 T.



(Courtesy A. Siemko)

Perspectives

- The present NbTi-based, Tevatron-originated accelerator magnet design seems at its limit.
- Hence, to go beyond LHC, one must perform a technological jump.
- This jump involves necessarily a change in superconducting material.
- It can involve also a calling into question of the $\cos\theta$ design.

$\Rightarrow$ Providing a reasonable funding level, these could be exciting times for magnet developers.