SUPERCONDUCTIVITY APPLIED TO PARTICLE ACCELERATOR MAGNETS

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Snowmass Lectures on Magnets, Revisited
July 2001

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

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.

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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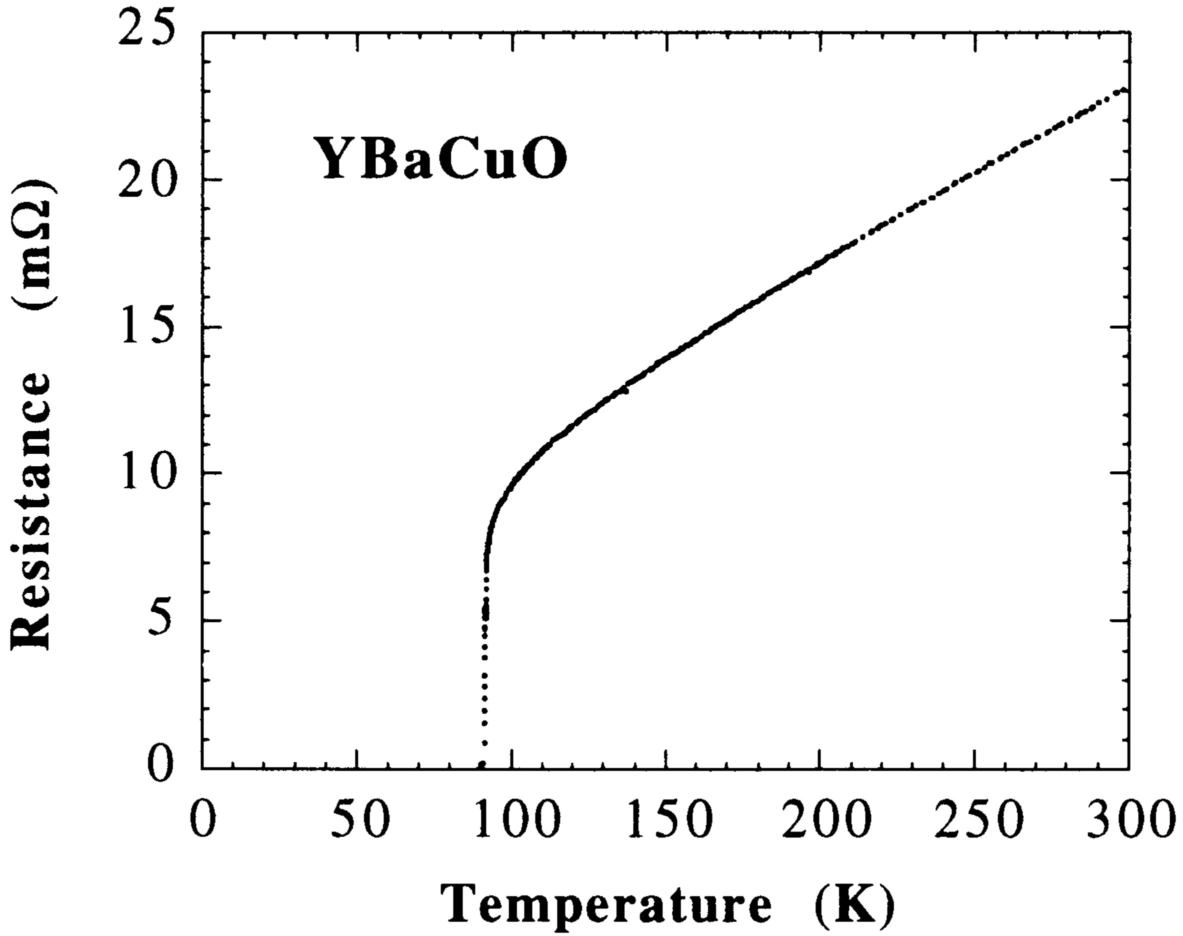
What is Superconductivity?

- 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

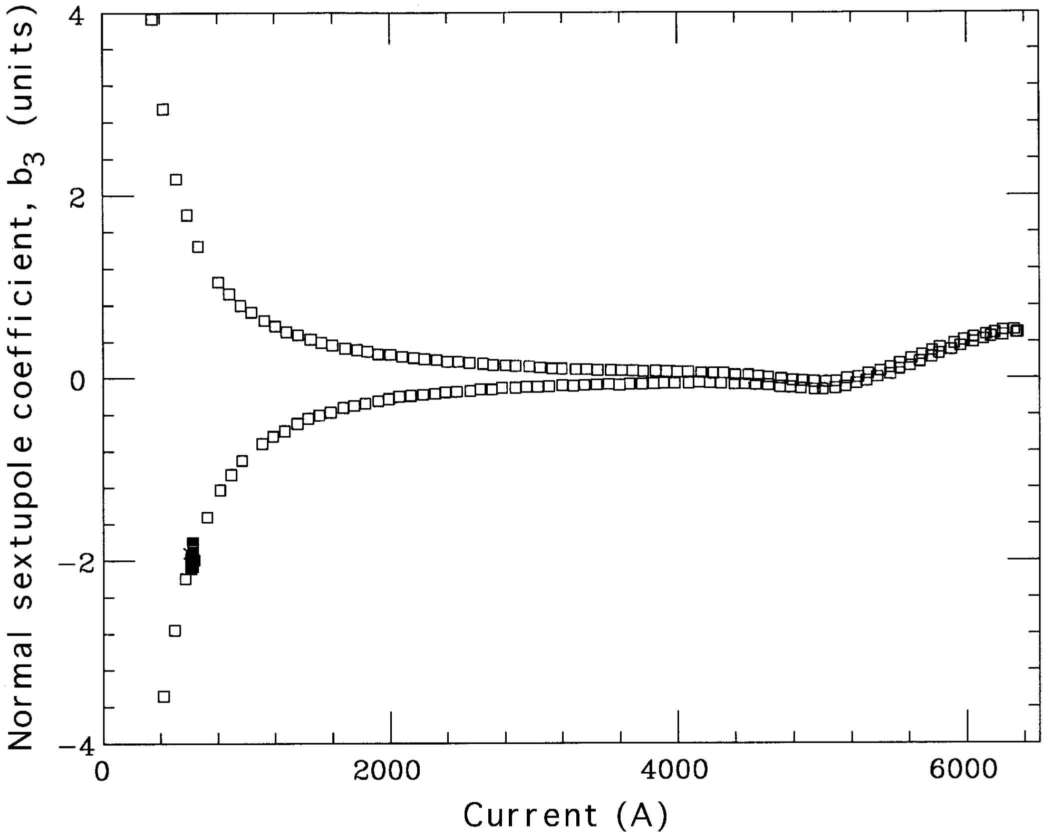
- There are at least three drawbacks in using superconducting magnets
    - cooling requirements,
    - magnetization effects,
    - risks of “quench”.

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)

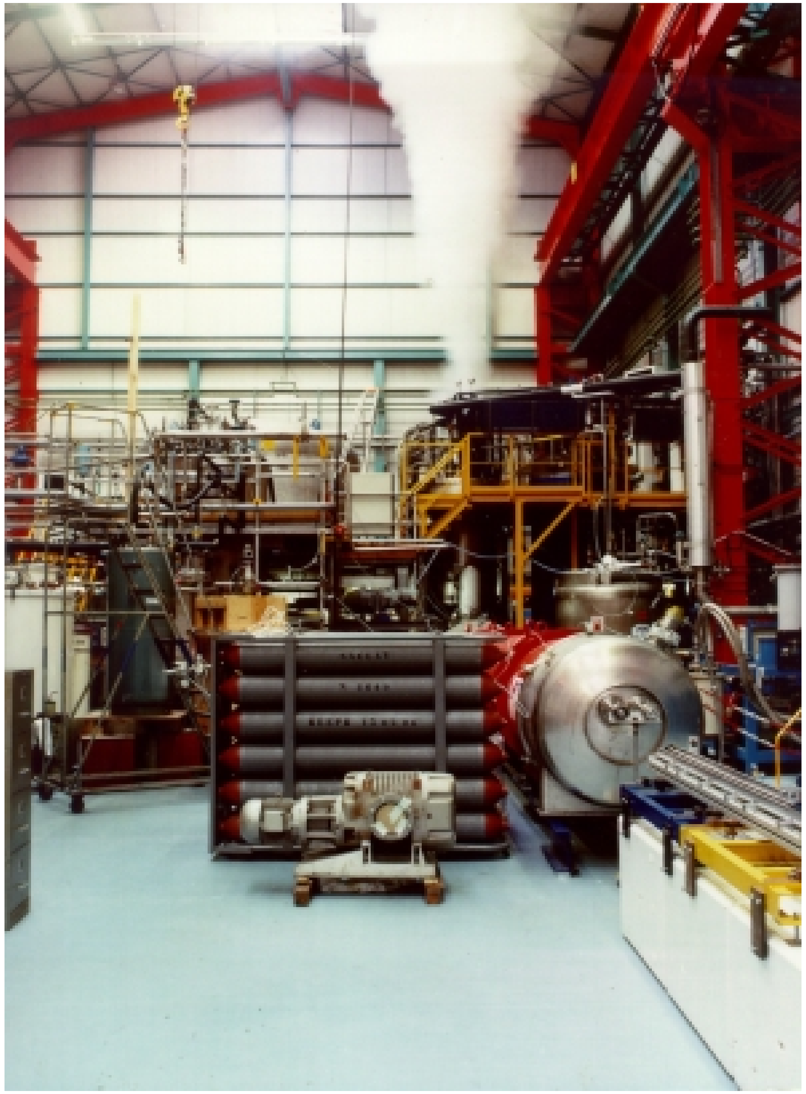
Magnetization Effects



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.

Tevatron Parameters

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 relies on a single ring of superconducting magnets developed and built at FNAL.

Arc Dipole Magnet Parameters

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

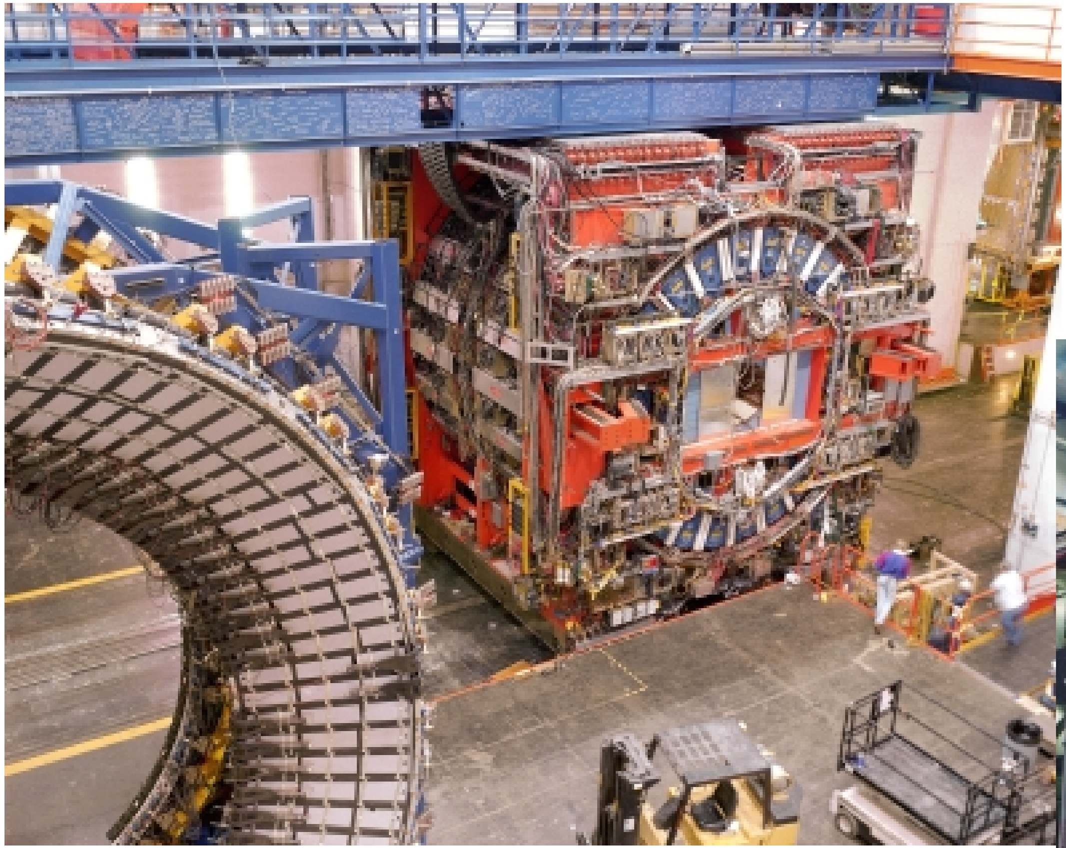
Aerial View of FNAL

Tevatron Tunnel

Tevatron Ring

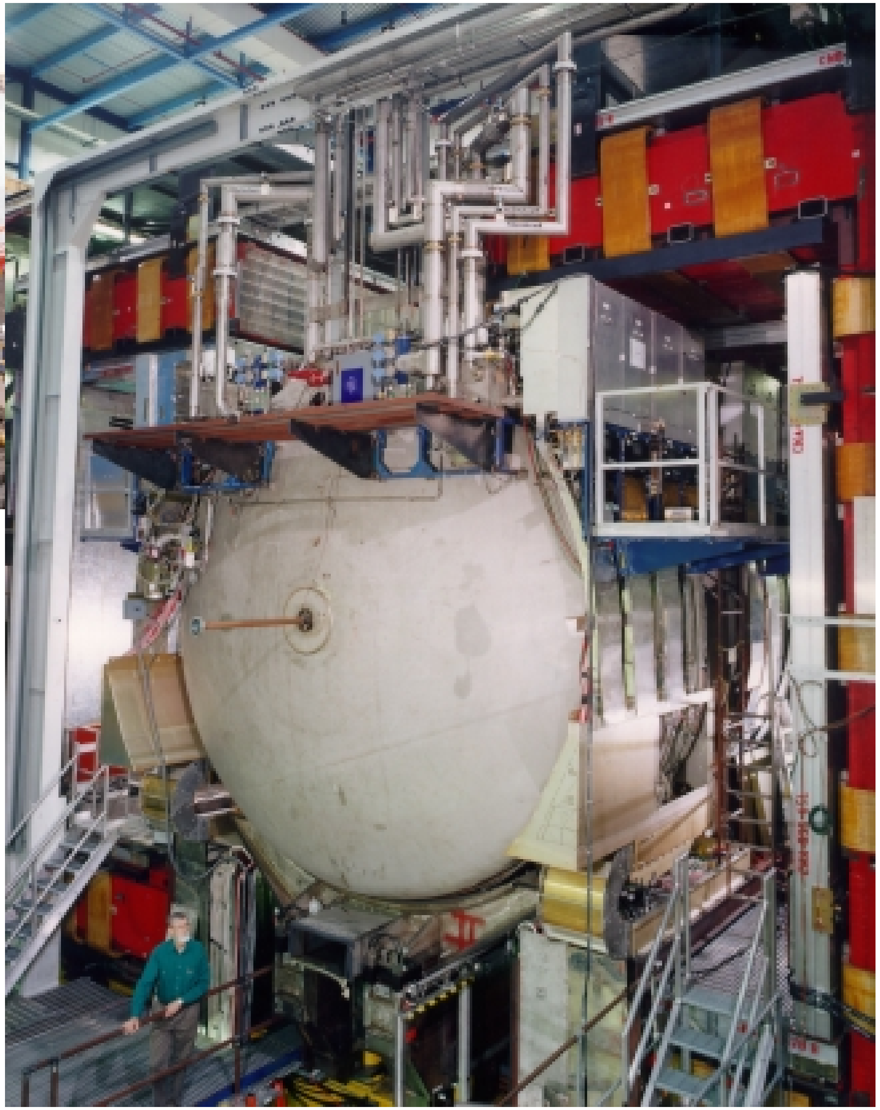
Tevatron Experiments

- There are two main physics experiments at the Tevatron: the Collider Detector experiment at Fermilab (CDF) and D0.
- Both experiments include a large superconducting solenoid embedded in the detector array.



CDF

D0



HERA (1/2)

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

HERA Parameters

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

HERA (2/2)

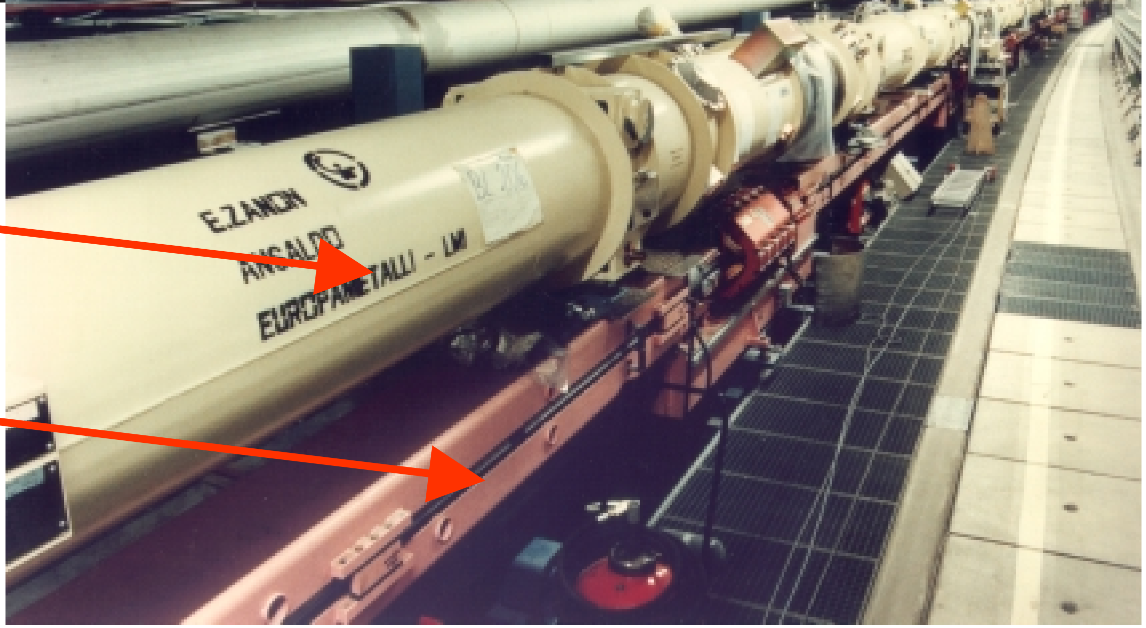
- HERA relies on two magnet rings mounted on top of each other: one conventional magnet ring for electrons and one superconducting magnet ring for protons.
- The superconducting arc dipole magnets were developed at DESY while the quadrupole magnets were developed at CEA/Saclay; both magnet types were mass-produced in industry.

Arc Dipole Magnet Parameters

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

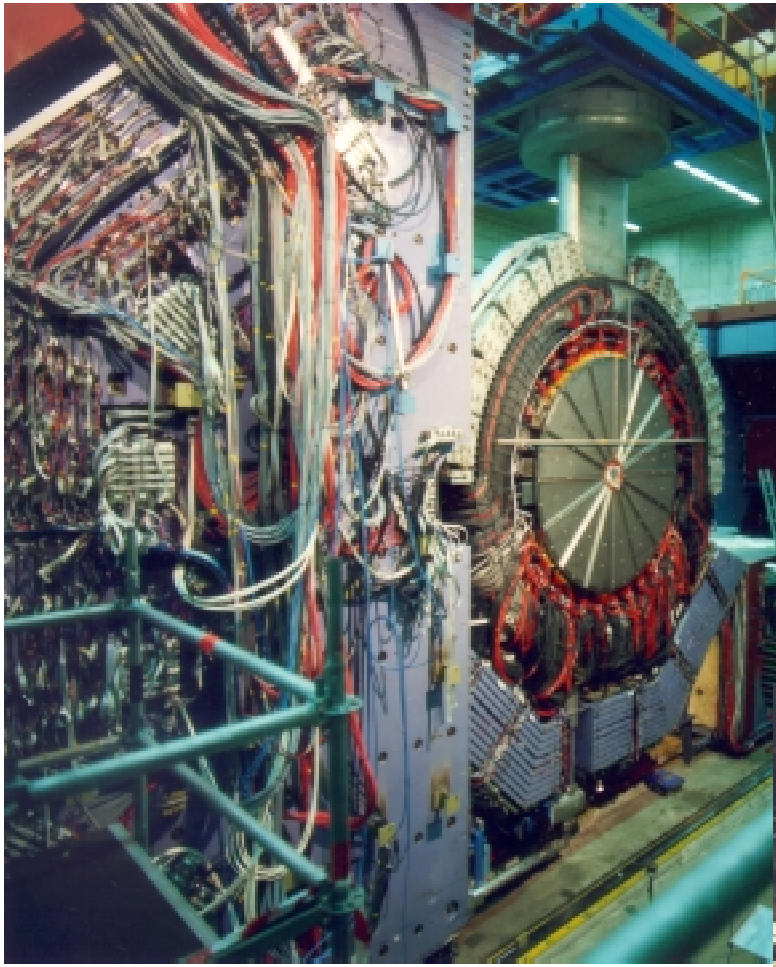


Superconducting p-Ring

Normal e-Ring

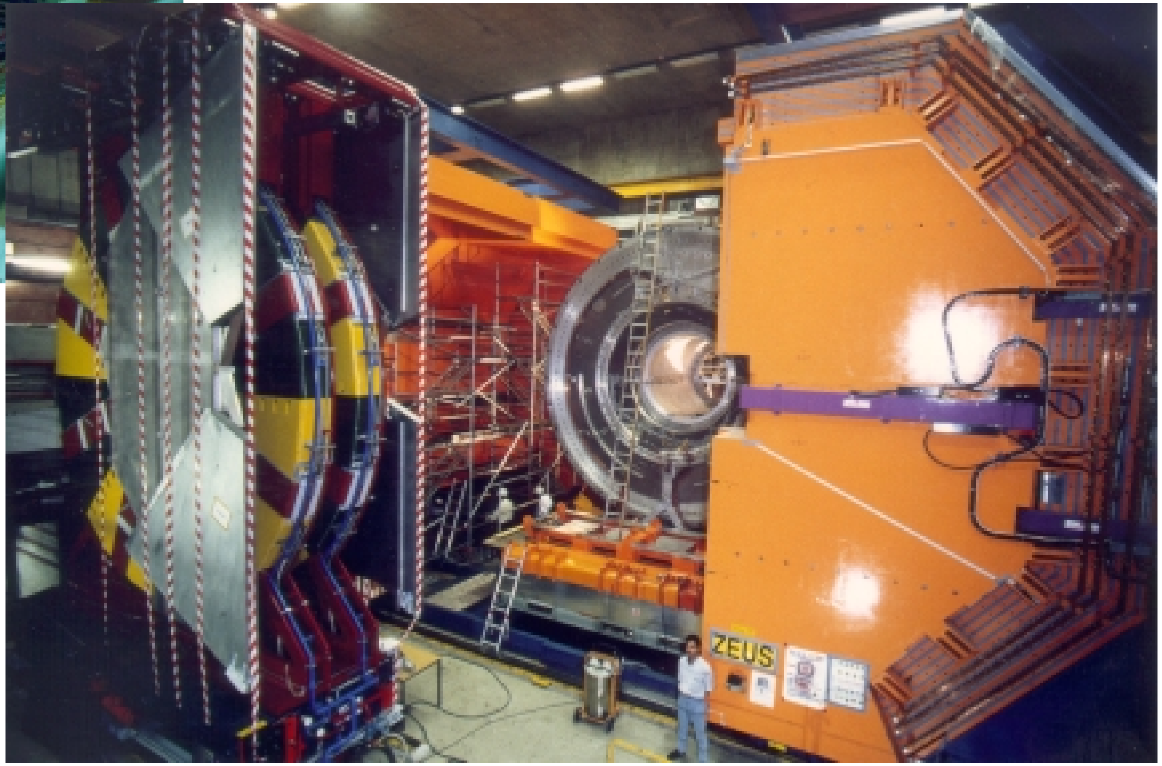
HERA Experiments

- There are two colliding-beam physics experiments at HERA: H1 and ZEUS, and two fixed-target experiment: HERMES and HERA-B.
- H1 and ZEUS include a large superconducting solenoid embedded in the detector array.



H1

ZEUS



UNK (1/3)

- Since the early 1980’s, the Russian Institute for High Energy Physics (IHEP) is working on a project of proton accelerator named UNK.

UNK Parameters

Site	IHEP, in Protvino, Russian Federation
Type	proton synchrotron
Circumference	21 km
Energy	3 TeV in fixed target mode
Status	undecided

UNK (2/3)

- UNK is designed to rely on a single ring of superconducting magnets.
- A number of dipole and quadrupole magnet prototypes have been built and cold tested at IHEP.

Arc Dipole Magnet Parameters

Type	single aperture
Aperture	70 mm
Dipole Field	5.0 T
Dipole Length	5.8 m
Total Number	2168

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)

SSC Parameters

Site	SSCL, near Dallas, TX
Type	proton/proton collider
Circumference	87 km
Energy	20 Tev per beam
Status	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.

Arc Dipole Magnet Parameters

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

RHIC (1/2)

- BNL has completed in 1999 the construction on its site of the Relativistic Heavy Ion Collider (RHIC).

RHIC Parameters

Site	BNL, on Long Island, New York
Type	heavy ion collider
Circumference	2.4 miles (3.8 km)
Energy	100 GeV/amu per beam for ions, and 250 GeV per beam for protons
Commissioning	1999-2000

RHIC (2/2)

- RHIC relies on two side-by-side superconducting magnet rings.
- The arc dipole and quadrupole magnets were developed at BNL and mass-produced in industry.

Arc Dipole Magnet Parameters

Type	single aperture
Aperture	80 mm
Dipole Field	3.4 T
Dipole Length	9.7 m
Total Number	264

BNL Aerial View

RHIC Tunnel

RHIC Experiments

- There are two large physics experiments at RHIC: PHENIX and STAR (which stands for Solenoid Tracker At RHIC), and two smaller ones: PHOBOS and BRAHMS (which stands for Broad RAnge Hadron Magnetic Spectrometer).

PHENIX

STAR

LHC (1/2)

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

LHC Parameters

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)

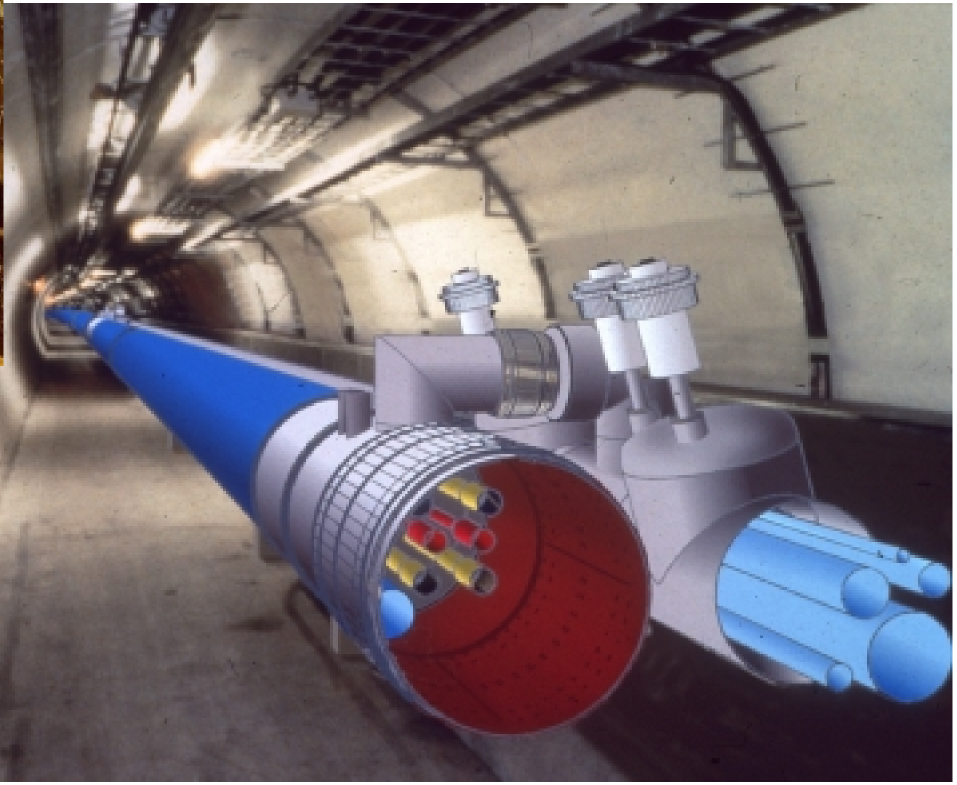
- LHC will rely on a single ring of twin-aperture, superconducting magnets.
- The LHC arc dipole magnets were developed by CERN in collaboration with industry, while the arc quadrupole magnets were developed by CEA/Saclay.
- The industrial production of both magnet types is underway.

Arc Dipole Magnet Parameters

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

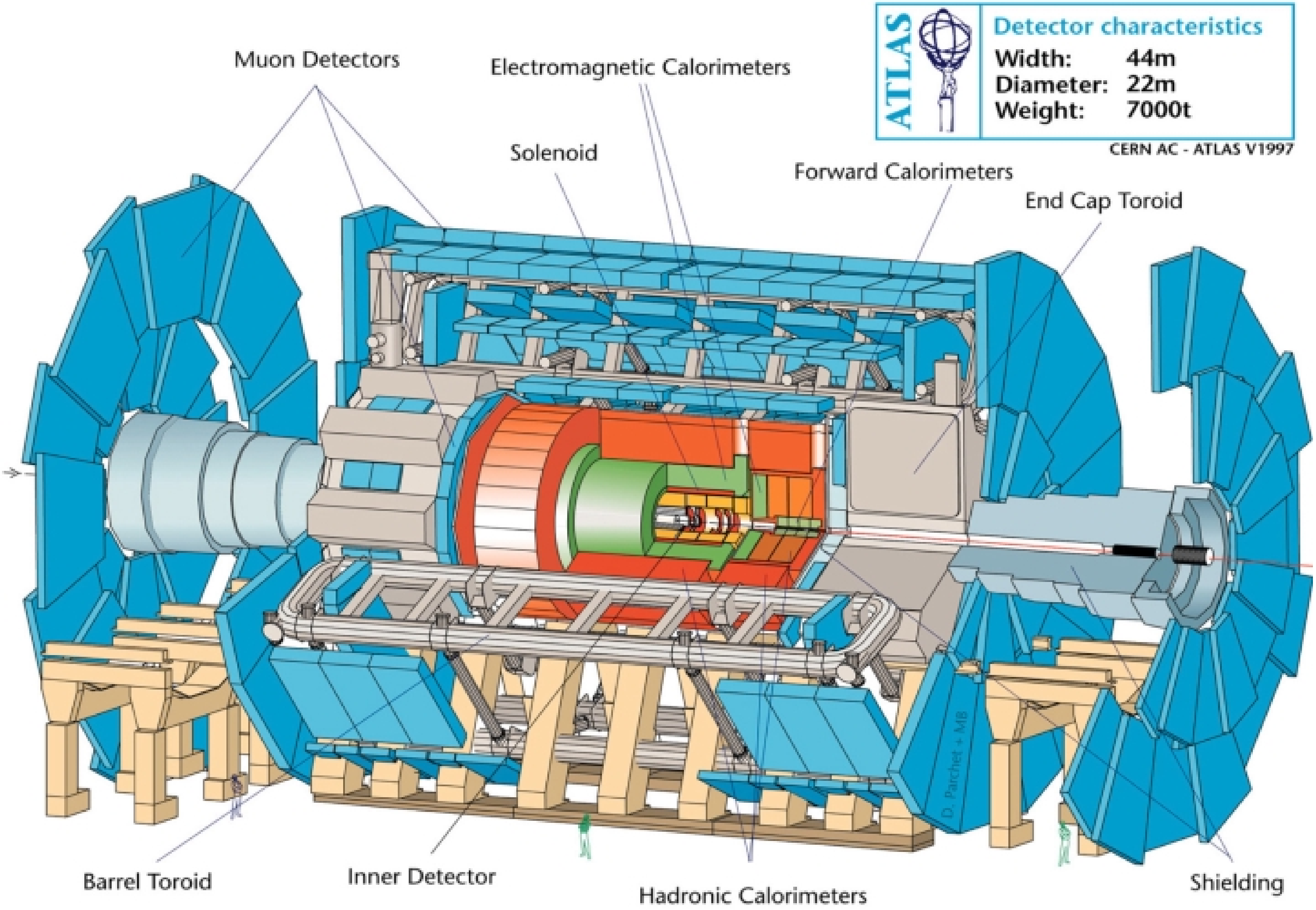
CERN Aerial View

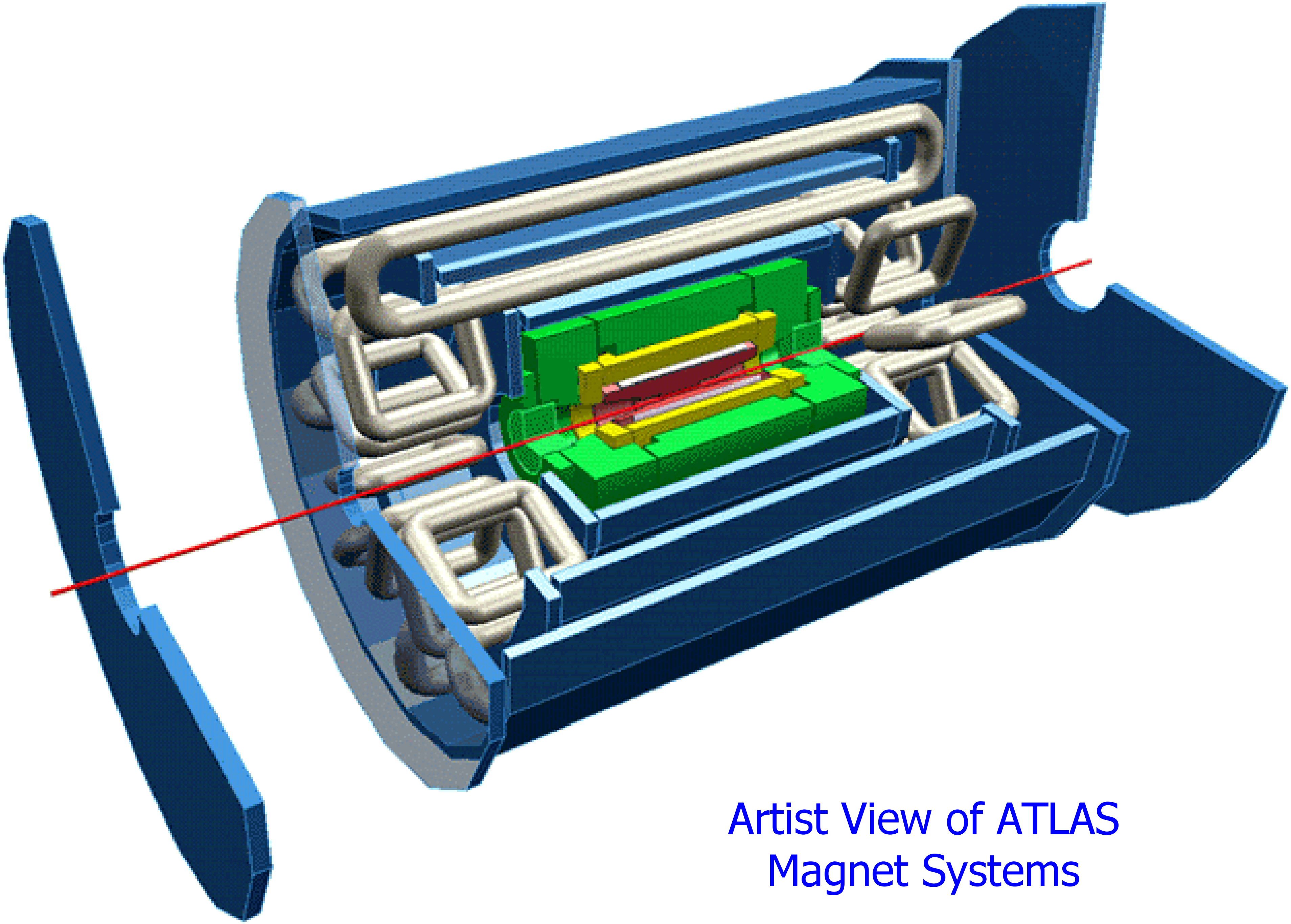
Artist View of LHC Tunnel



LHC Experiments

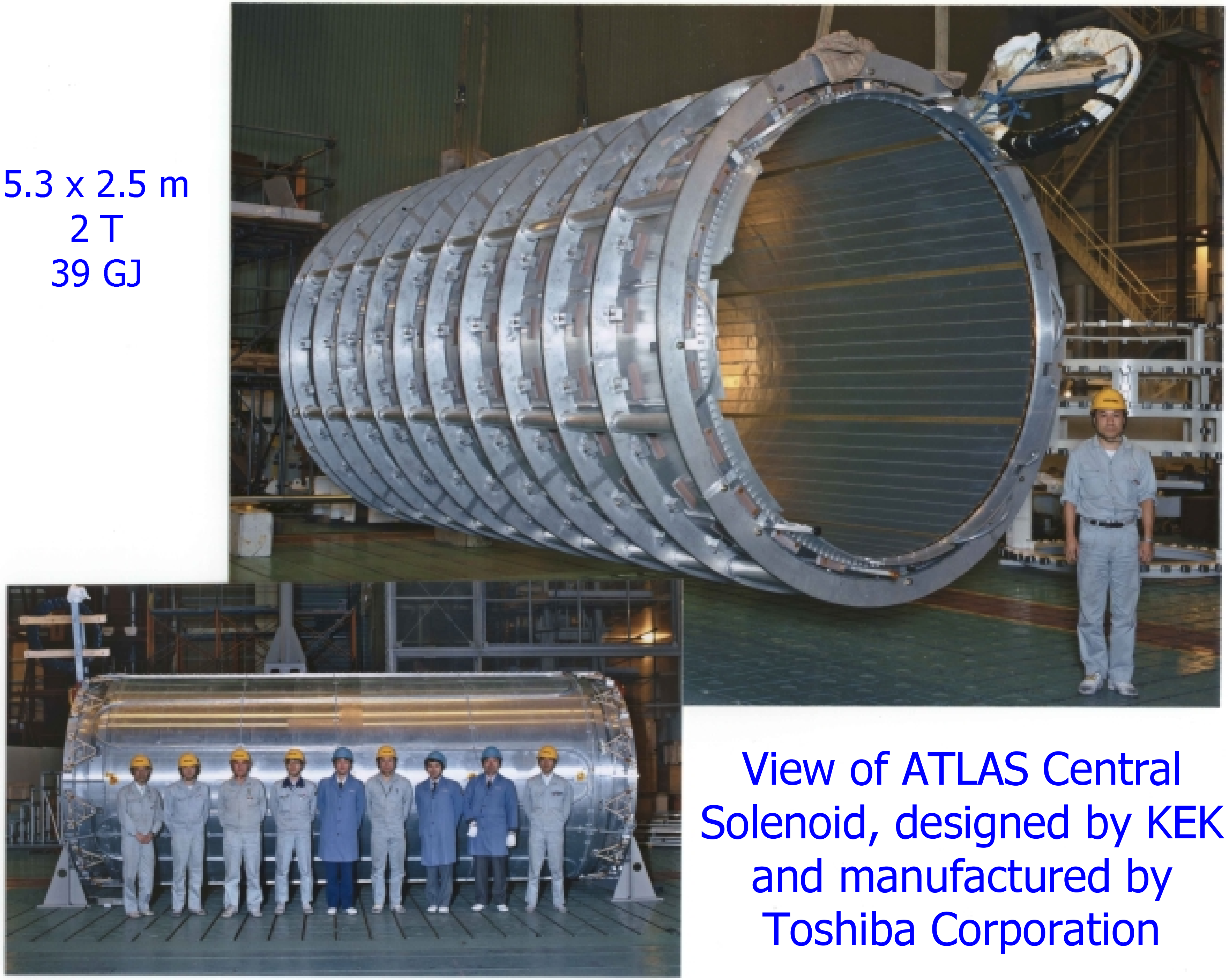
- At present (2001), two high-energy physics experiments are being developed for LHC: ATLAS (which stands for Air core Toroid for Large Acceptance Spectrometer), and CMS (which stands for Compact Muon Solenoid).
- ATLAS include four superconducting magnet systems: a Central Solenoid (CS), a Barrel Toroid (BT) and two End-Cap Toroids (ECT).
- CMS include one large superconducting solenoid.


ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

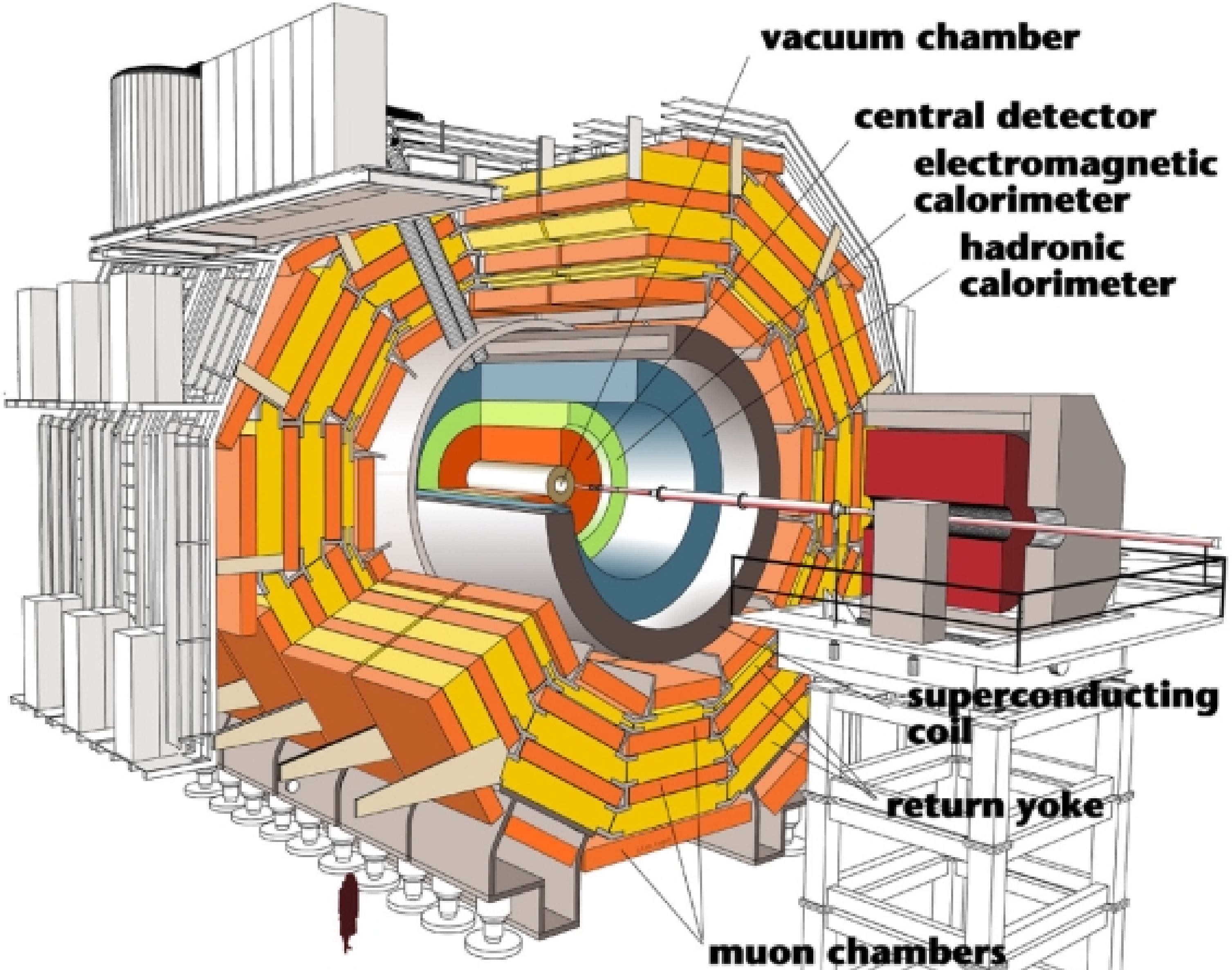


Artist View of ATLAS Magnet Systems

5.3 x 2.5 m
2 T
39 GJ



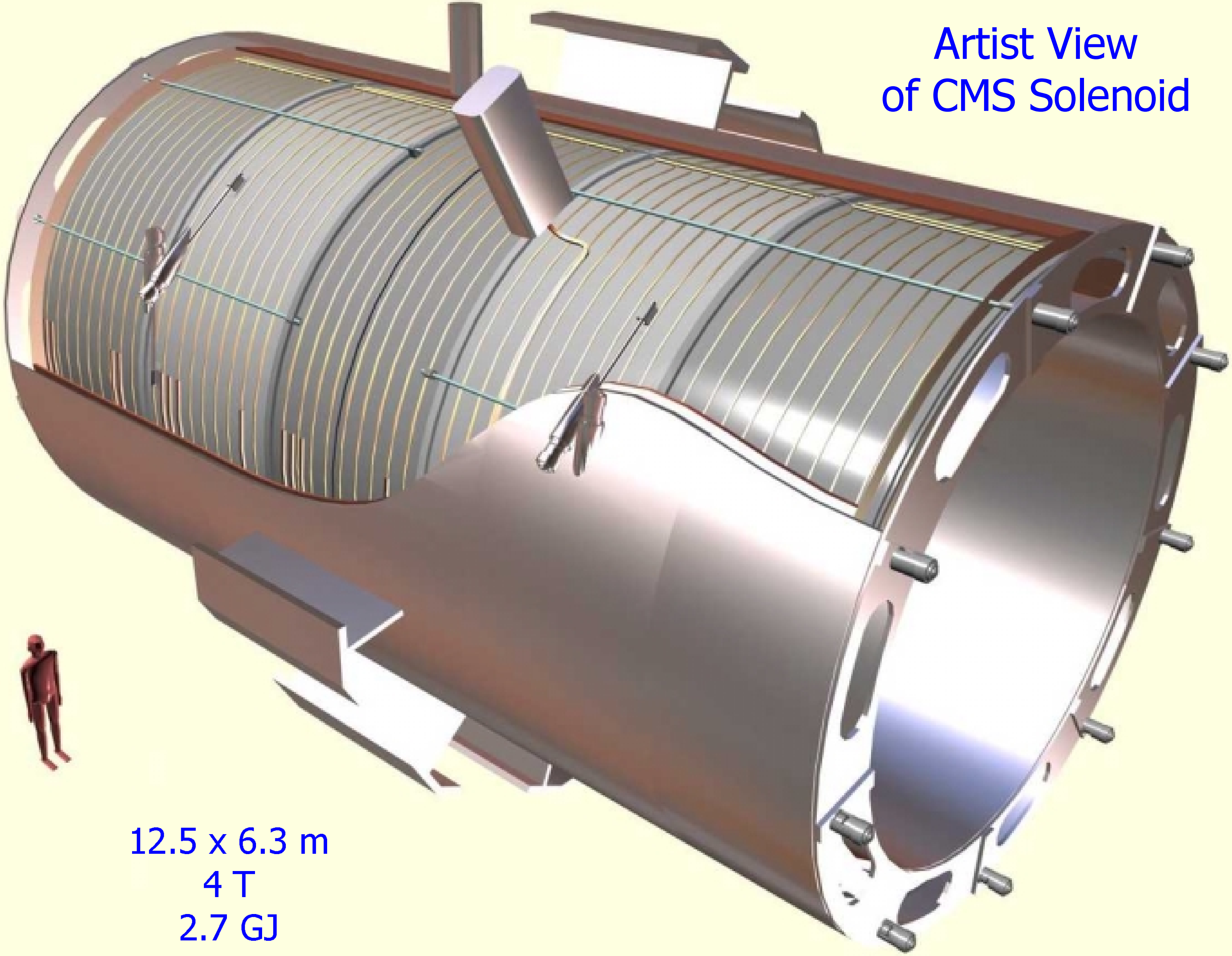
View of ATLAS Central Solenoid, designed by KEK and manufactured by Toshiba Corporation



Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

Artist View of CMS Solenoid



12.5 x 6.3 m
4 T
2.7 GJ

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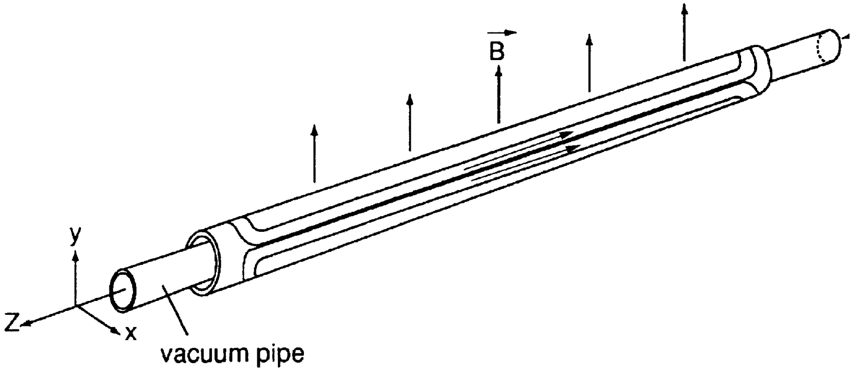
Magnet Design

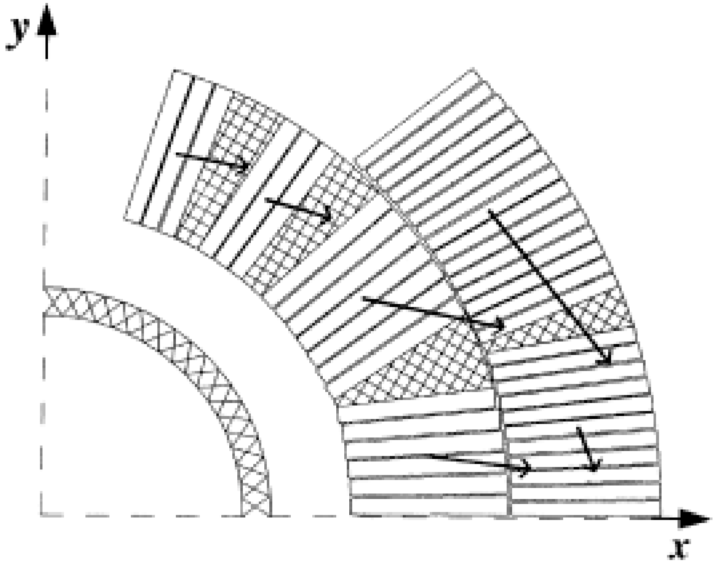
- Most dipole and quadrupole magnets built up to now (Tevatron, HERA, SSC, LHC…) rely on similar design concepts.
- These concepts were pioneered in the late 70's for the Tevatron at Fermilab.
- Improvements in superconductor and magnet fabrication have led to a doubling of the field over the last 20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

Magnetic Design

- Field is produced by saddle-shape coils, which, in their long straight sections, approximate $\cos\theta$ or $\cos 2\theta$ conductor distributions.



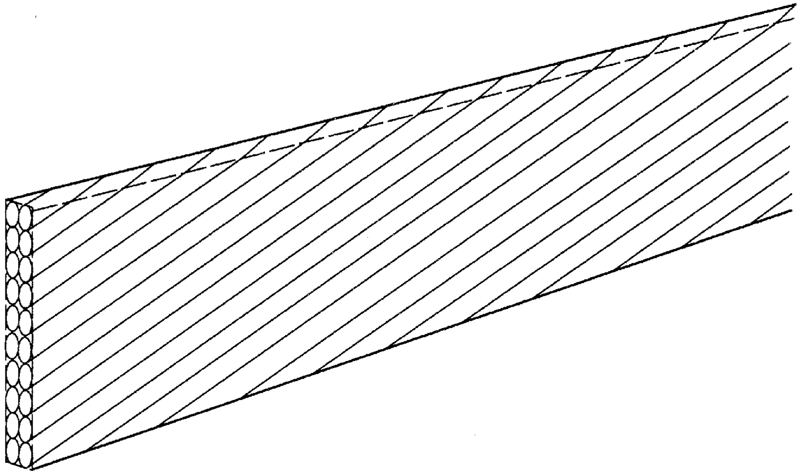
Saddle-Shape Coil Assembly for a Dipole Magnet



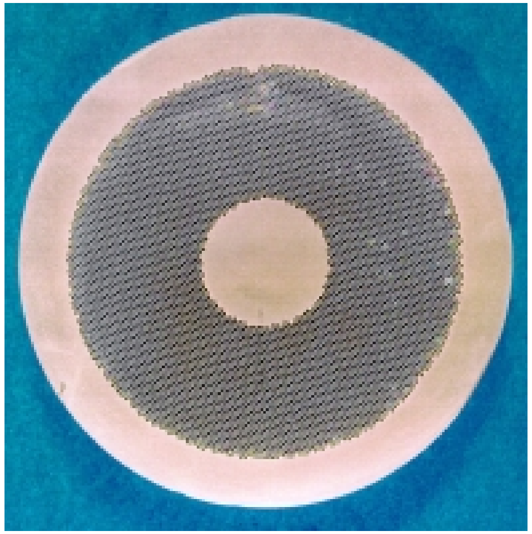
$\mathrm{Cos}\,\theta$ Conductor Distribution in a Dipole Coil Assembly Quadrant (Courtesy R. Gupta)

Rutherford-Type Cable

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

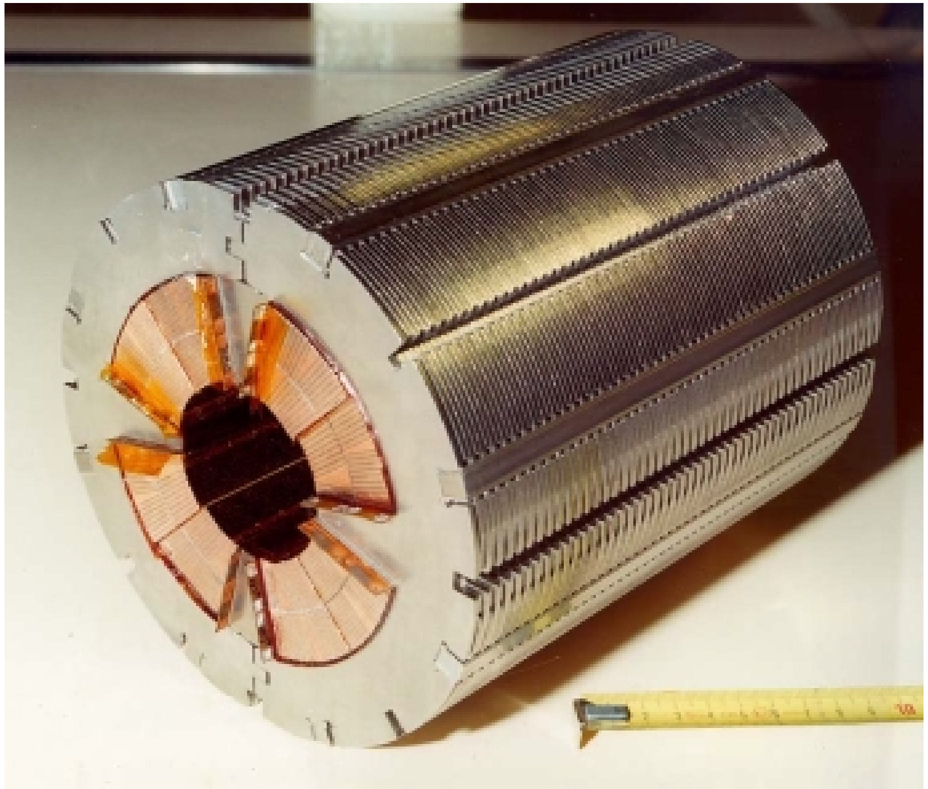


Rutherford-Type Cable
(Courtesy T. Ogitsu)



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

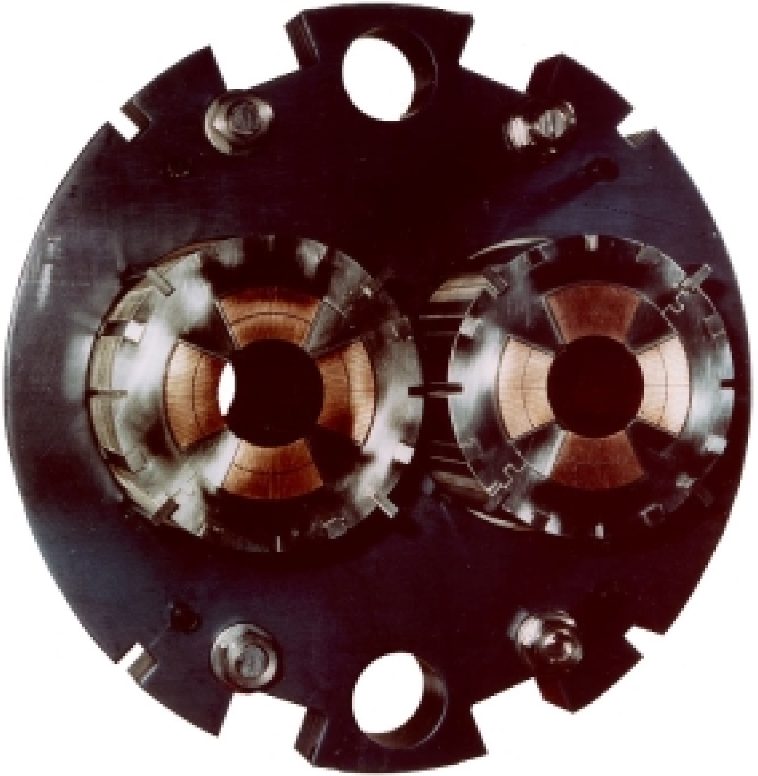
Mechanical Design



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.

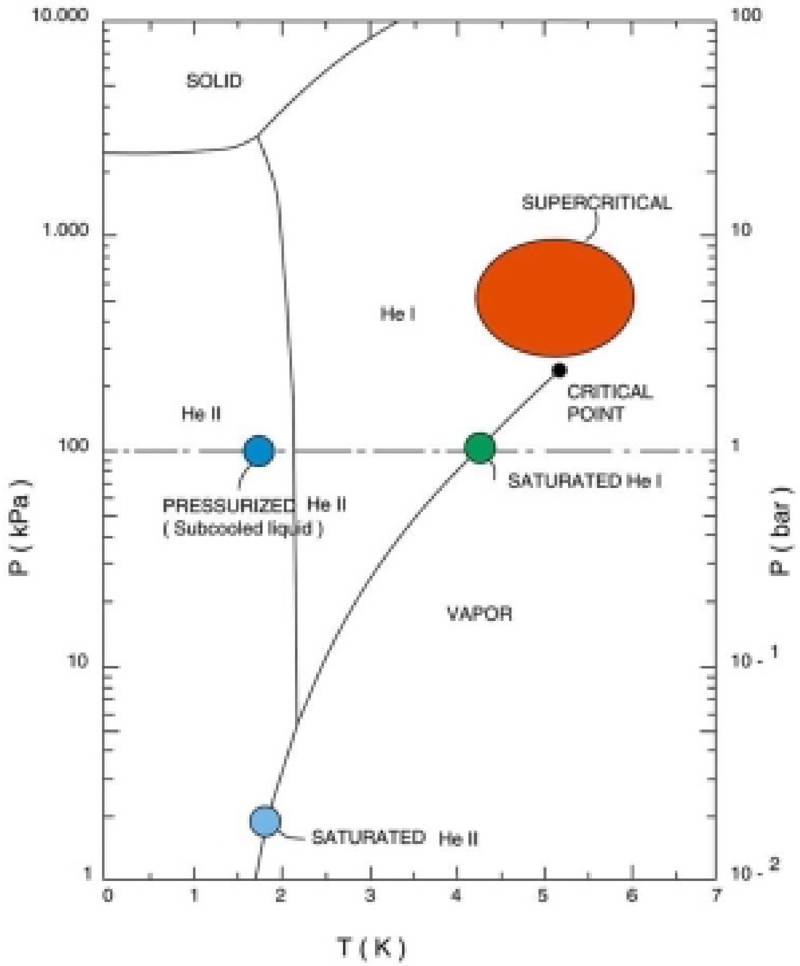
Iron Yoke



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

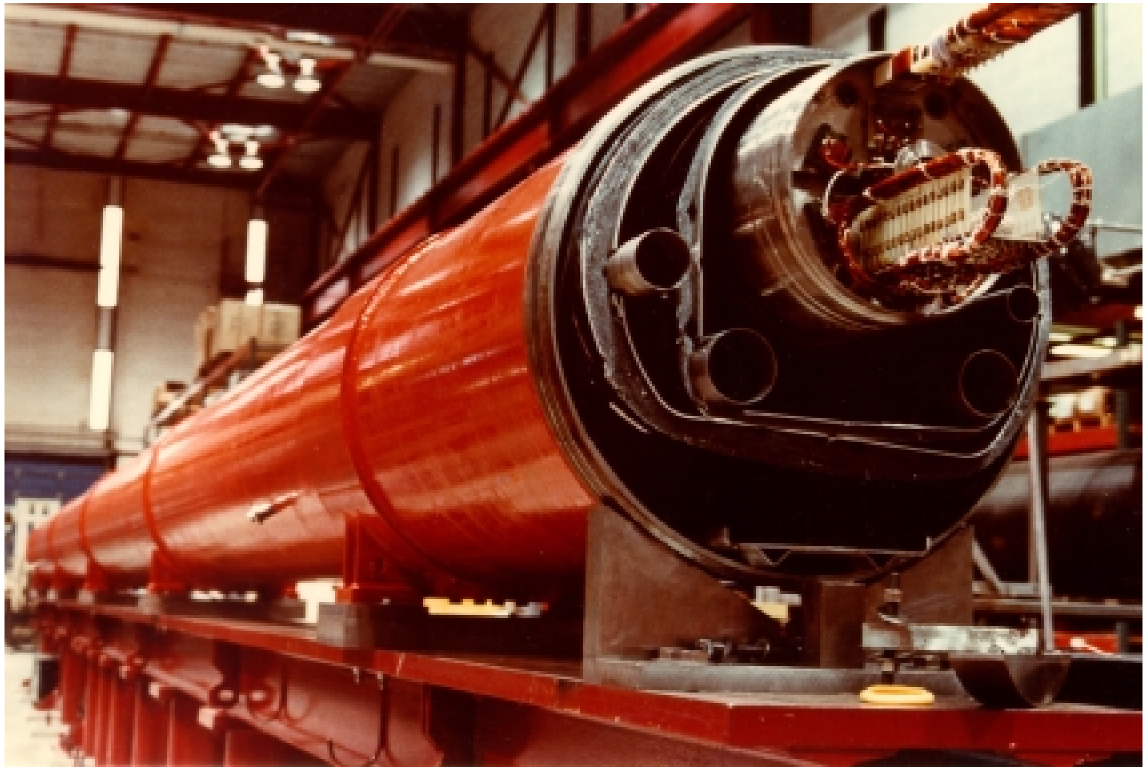


He Phase Diagram
(courtesy P. Lebrun)

- 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.

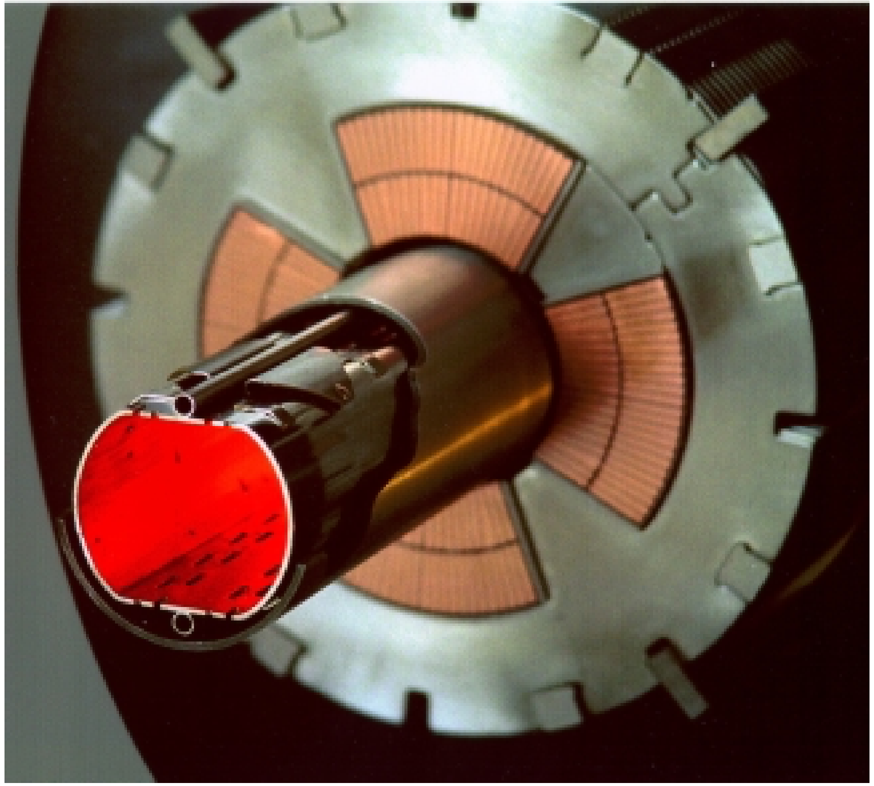
Cryostat

- 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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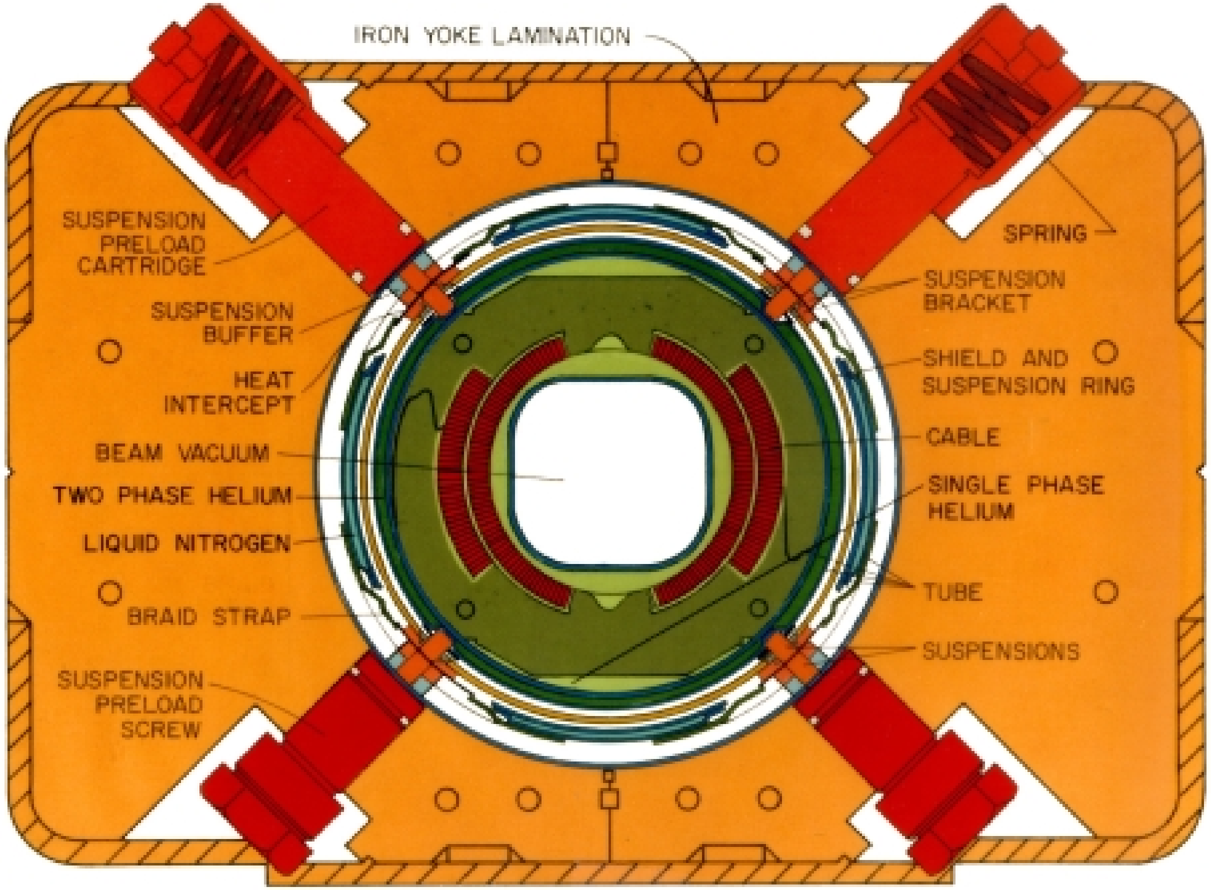
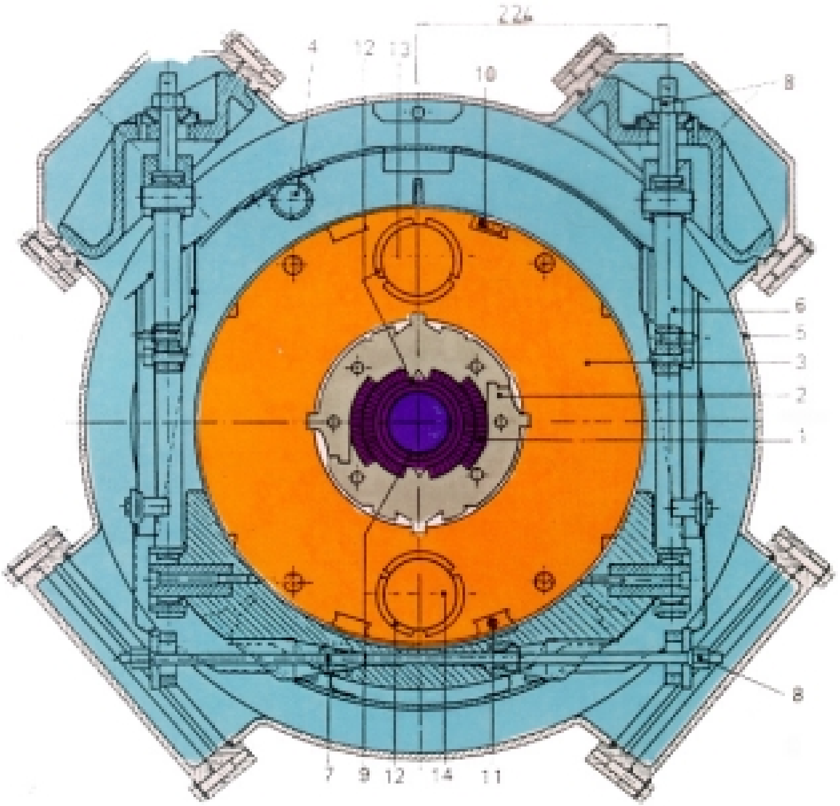
Tevatron

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

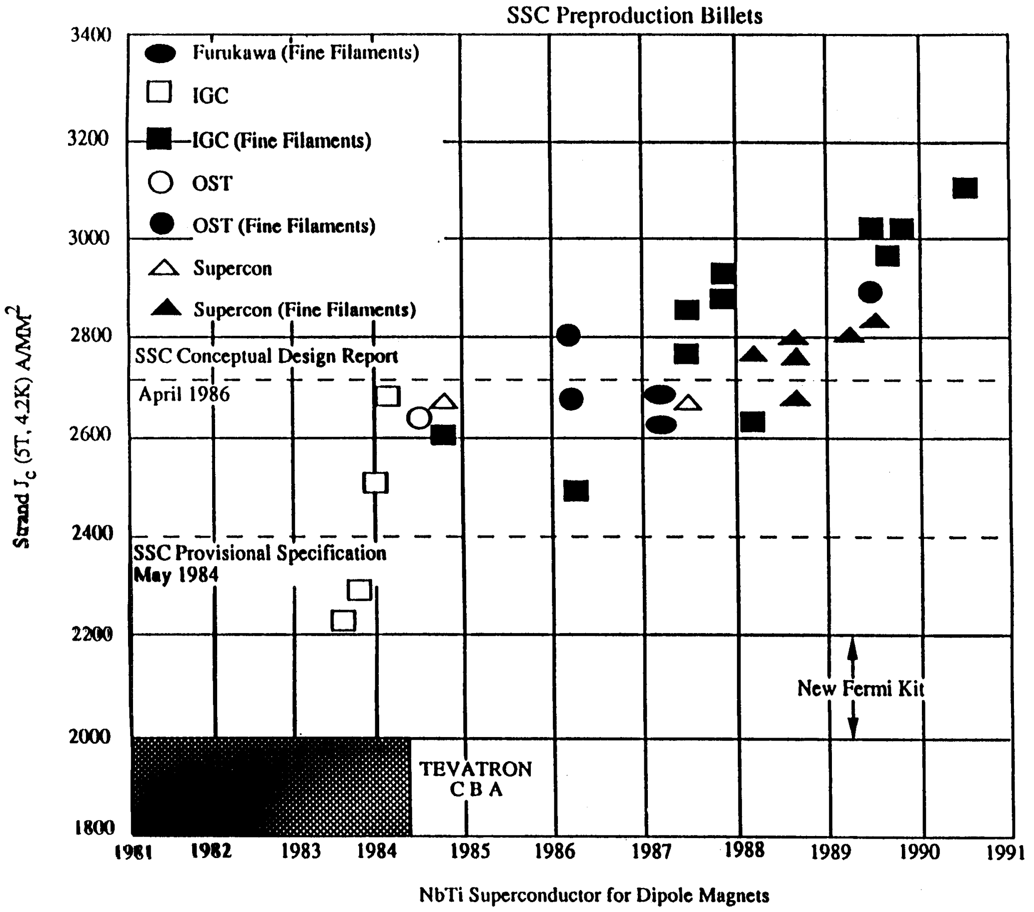


HERA



- 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).

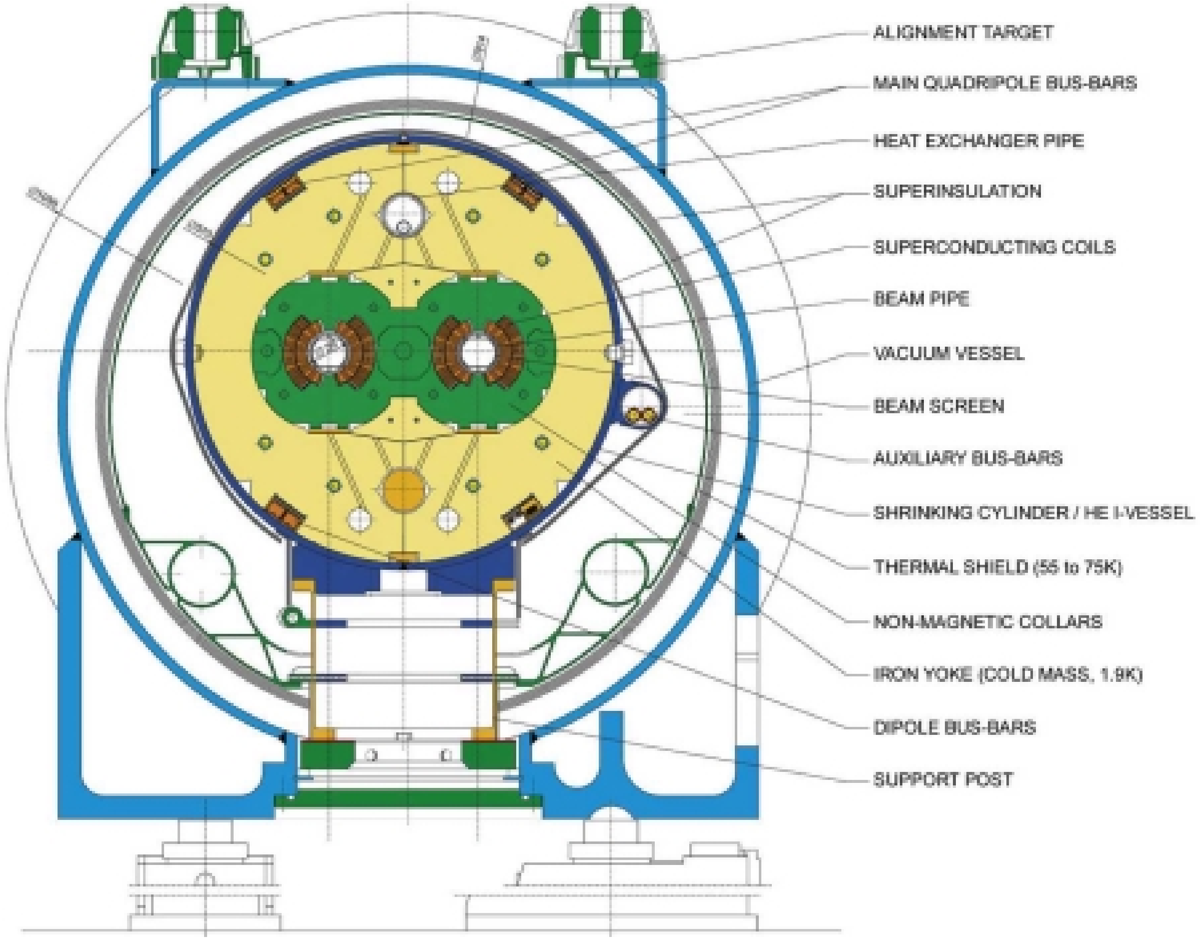
SSC



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

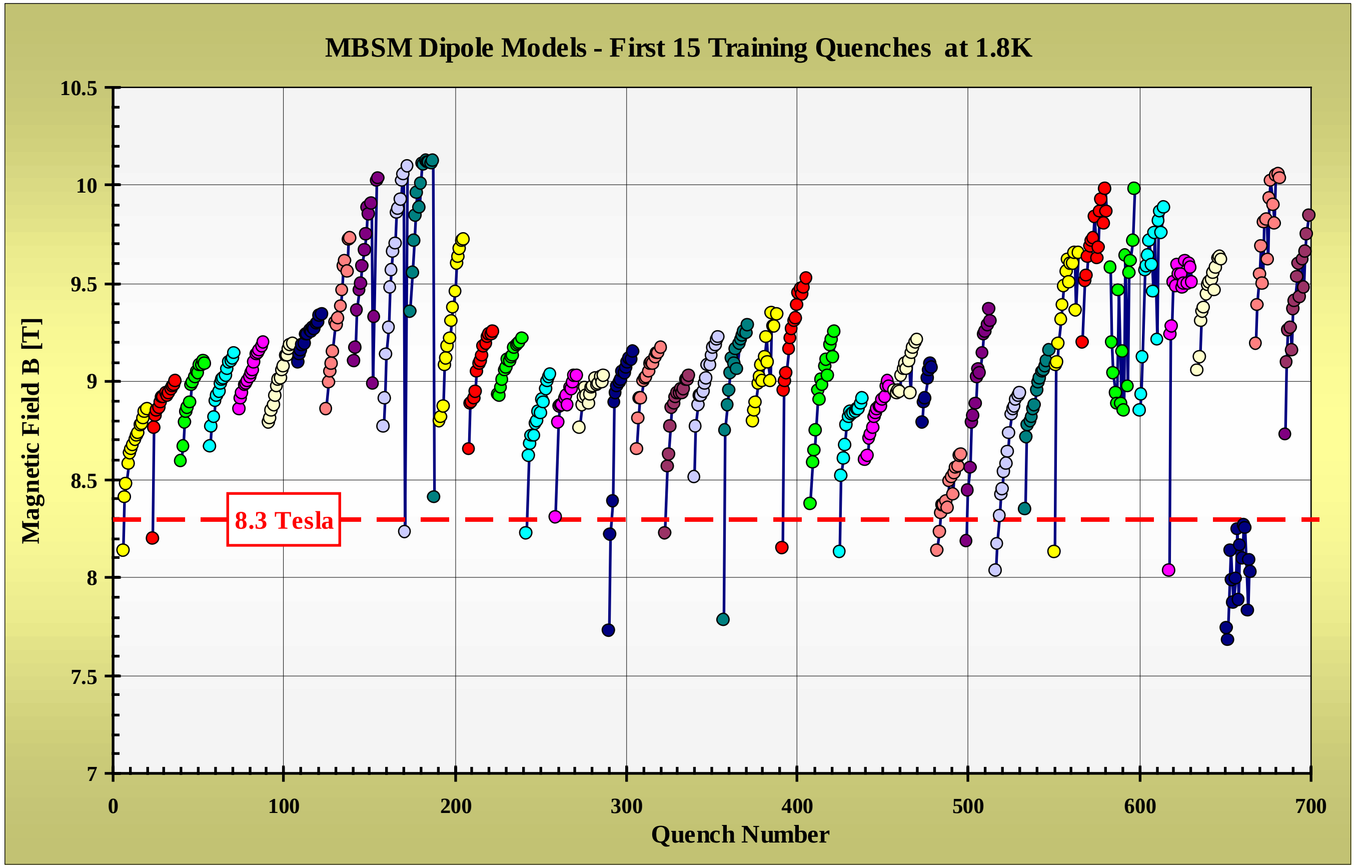
LHC (1/2)

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



LHC (2/2)

- 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

- As we have seen, 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.