MAGNET SYSTEMS FOR LARGE PARTICLE ACCELERATORS

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Snowmass Lectures on Magnets, Revisited
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Contents

The Goals of Particle Physics

- Nuclear and high-energy physics have at least two main goals
  - studying the ultimate components of matter and their modes of interaction,
  - understanding the universe origin and its early evolution.

Particle Smashing (1/2)

- The research is carried out by breaking into pieces what are known to be non-elementary particles (such as ions or protons) and by analyzing the nature and properties of the pieces.
- It is done also by producing interactions between what are thought to be elementary particles (such as electrons or muons) at energy levels which only existed right after the big bang.

Particle Smashing (2/2)

- The interactions are produced by accelerating the particles to high momenta and either by blasting them against a fixed target or by colliding them among themselves.

Particle Beam

- To gather statistically significant data sample and achieve high event rates, the particles are bunched together and are formatted into high intensity beams.

Example: once filled up, each LHC ring will contain 2835 bunches made up of 1.05 10^{11} protons.
(When circulated at a velocity near that of light around a circumference of ~27 km, this corresponds to an effective beam current of 0.53 A.)

The Tools of Particle Physics

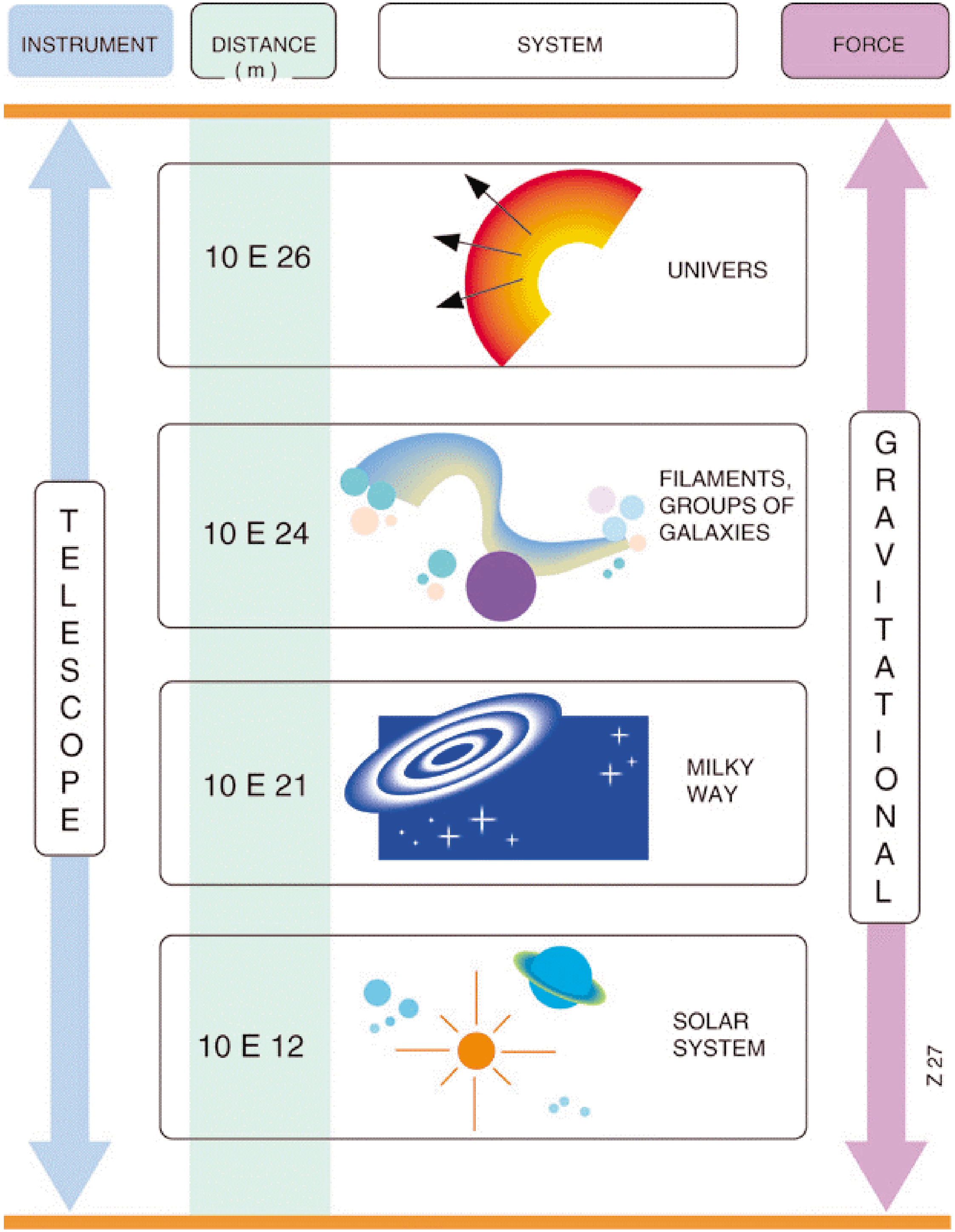
- The main tools required for particle physics experiments are
  - sources, from which the particles of interest are extracted and captured,
  - accelerators, which are used to prepare particle beams, raise their energy and direct them towards interaction points,
  - detectors, which surround the interaction points and are designed to observe and identify interaction products.

On the Need of High-Energy Accelerators

- The more elementary the particles, the higher the energy needed to smash them.
- Experiments at the proton scale require beam energies of the order of 1 TeV or more. (1 TeV = 10^{12} eV ≈ 1.6 10^{-7} J.)

Review of Physics Instruments

- The next three slides illustrate the role played by particle accelerators in the array of instruments used by physicists in their investigations from the infinitely large to the infinitely small.



INSTRUMENT
DISTANCE (m)
SYSTEM
FORCE

TELESCOPE

10 E 26 UNIVERS

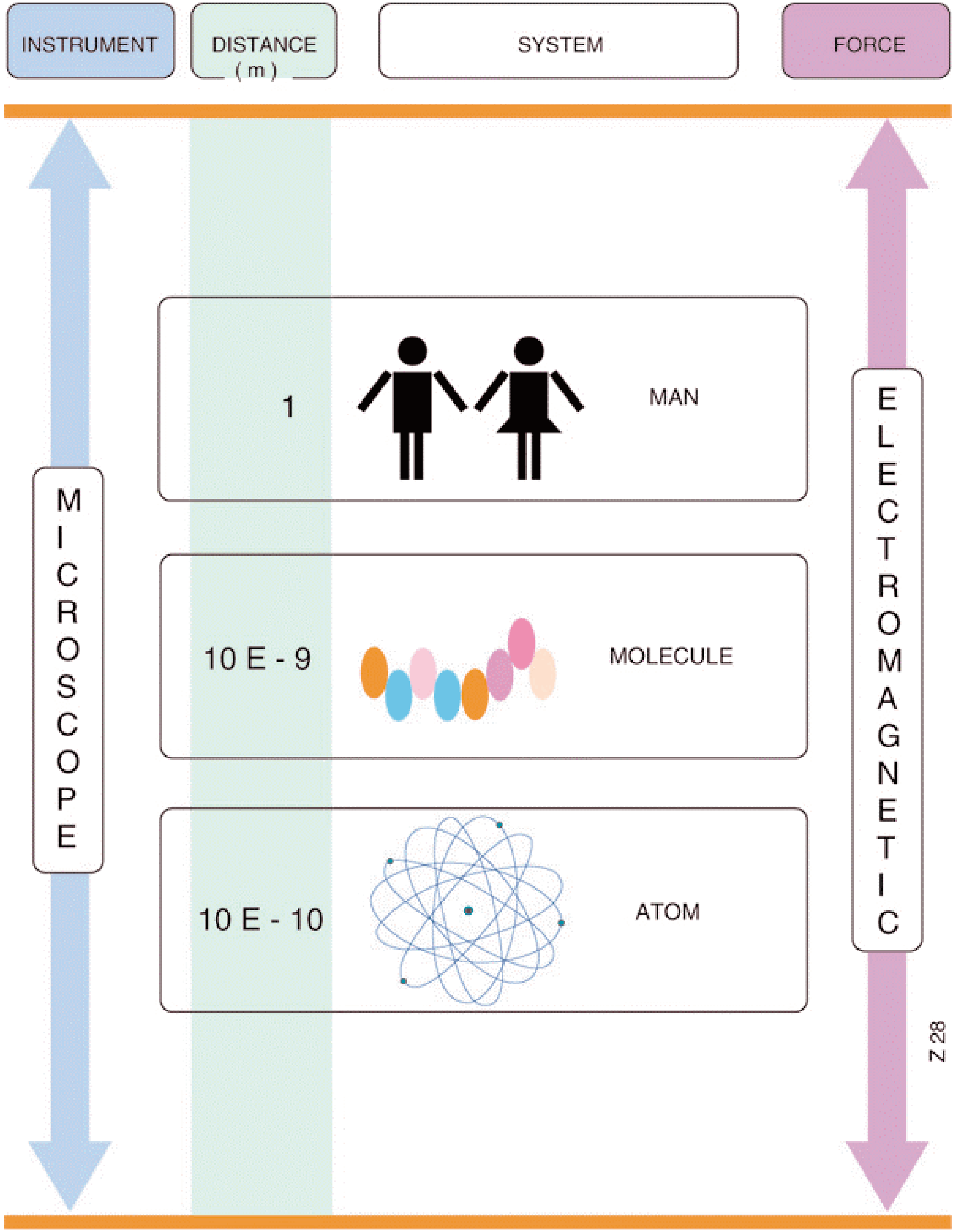
10 E 24 FILAMENTS, GROUPS OF GALAXIES

10 E 21 MILKY WAY

10 E 12 SOLAR SYSTEM

GRAVITATIONAL

Z 27


INSTRUMENT
DISTANCE
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SYSTEM
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MAN
10 E - 9
MOLECULE
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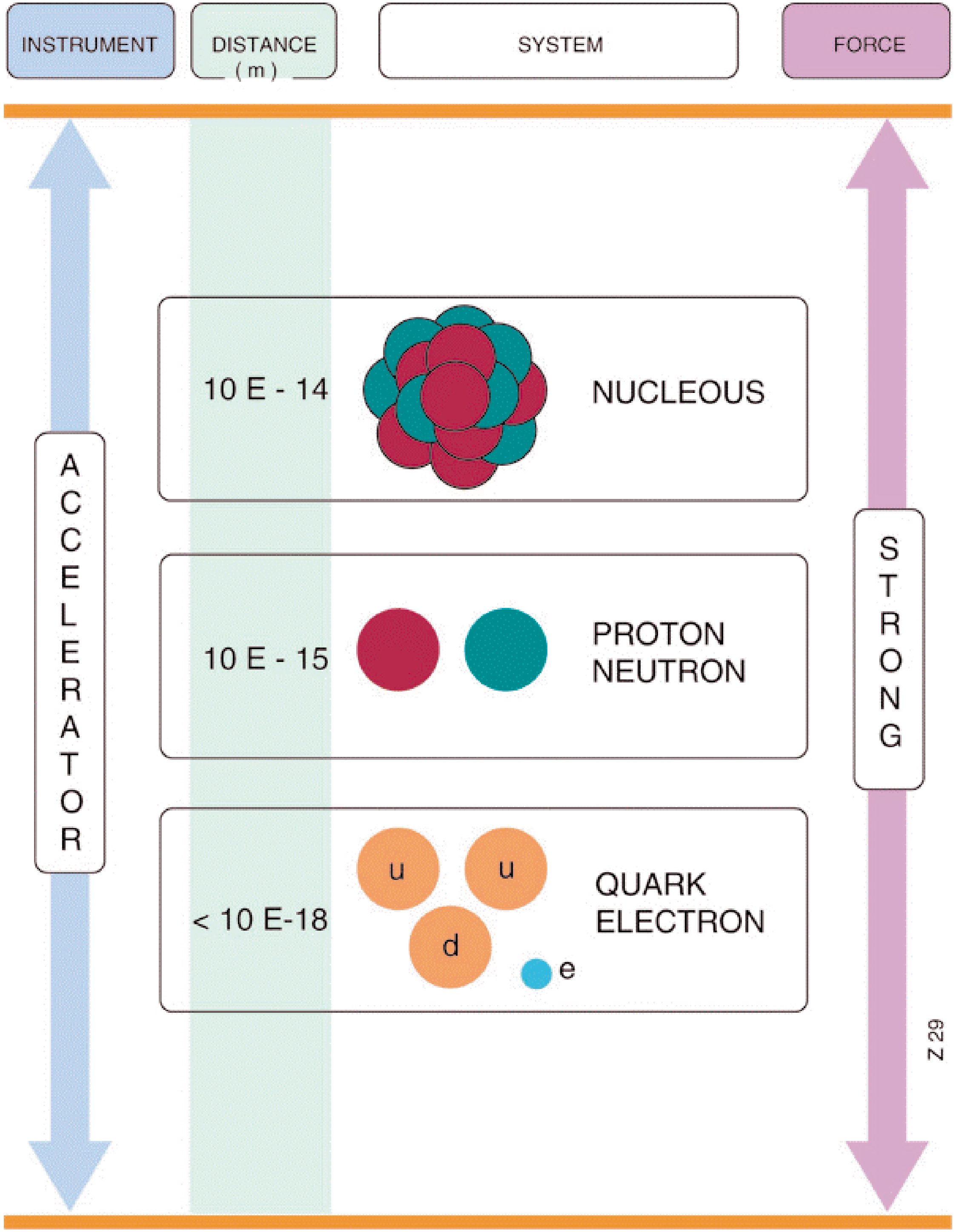
ATOM
ELECTROMAGNETIC
Z 28



INSTRUMENT

DISTANCE (m)

SYSTEM

FORCE

ACCELERATOR

10 E - 14 NUCLEOUS

10 E - 15 PROTON NEUTRON

< 10 E-18 QUARK ELECTRON

STRONG

Z 29

Contents

- Tools of Particle Physics
- **Accelerator Types**
- Accelerator Components
- Synchrotron-Type Accelerators
- Types of Magnet Systems
- Dipole and Quadrupole Magnets

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- **Accelerator Types**
    - **Classification**
    - Linear Accelerators
    - Circular Accelerators
    - Accelerator Complex

Accelerator Types

- There is a large number of accelerator configurations.
- The most commonly used are
  - linear accelerators,
  - circular accelerators.

Contents

- **Accelerator Types**
  - Classification
  - **Linear Accelerators**
  - Circular Accelerators
  - Accelerator Complex

Linear Accelerators

- In a linear accelerator, also referred to as *linac*, the particle bunches travel along a mostly straight trajectory.

Pros of Linear Accelerators

- A linear accelerator has two main advantages
    - it only requires a limited number of trajectory-bending elements,
    - the level of electromagnetic radiation emitted by the particles, referred to as *synchrotron radiation,* is low.

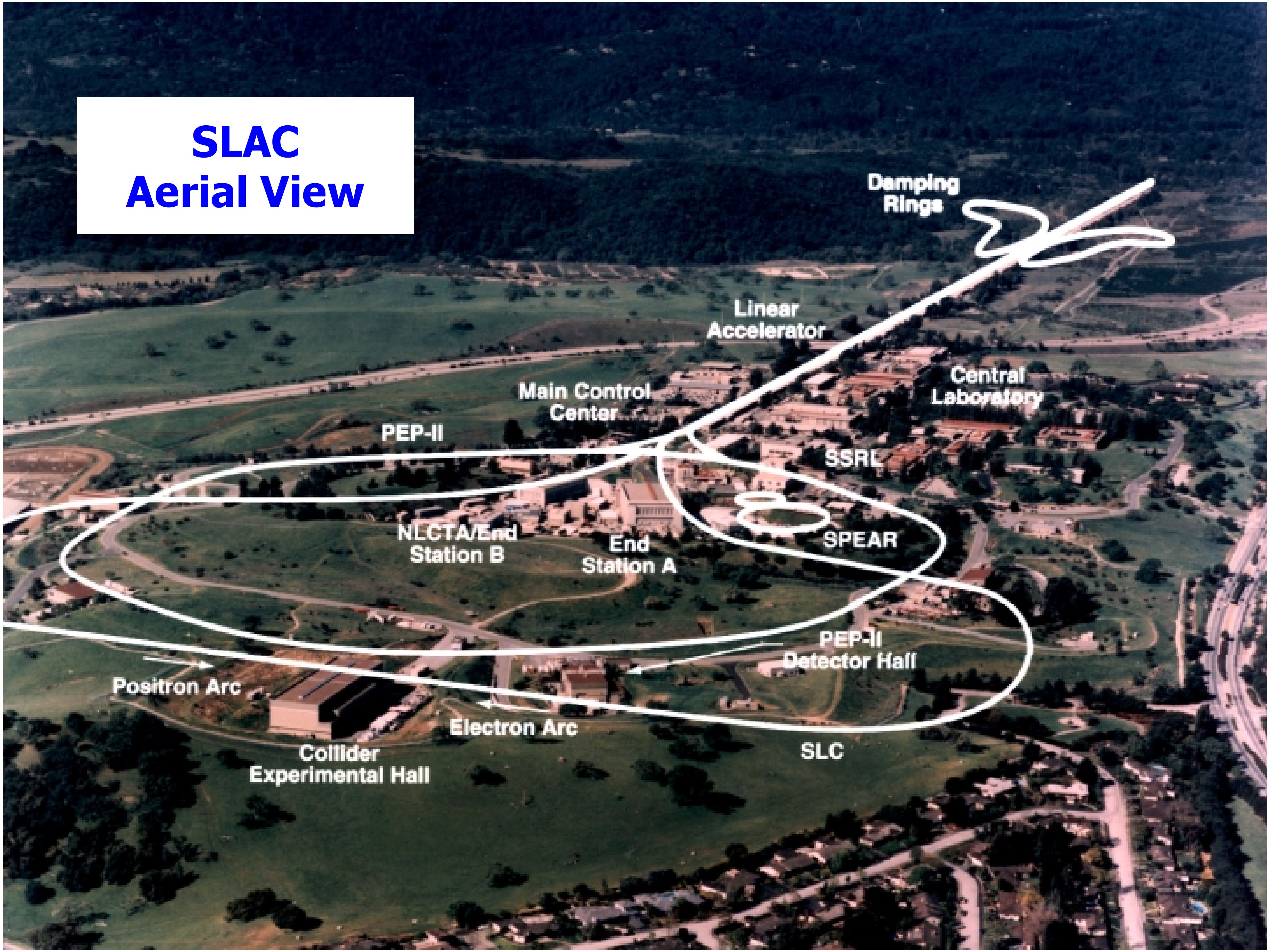
Cons of Linear Accelerators

- A linear accelerator has two main disadvantages
  - the particle bunches travel only once through the machine and cannot be re-circulated,
  - to achieve high momenta, the particles must go successively through a large number of accelerating stations.

Example of Linear Accelerator

- As of today (2001), the longest linear accelerator is that of the Stanford Linear Collider (SLC), implemented at the Standford Linear Accelerator Center (SLAC), near Palo Alto, California.
- It is 2 miles (3.2 km) long and is capable of accelerating electron and positron beams up to 50 GeV.

SLAC
Aerial View



Contents

- **Accelerator Types**
  - Classification
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  - Accelerator Complex

Circular Accelerators

- In a circular accelerator, the beam is circulated many times around a closed orbit.

Pros of Circular Accelerators

- A circular accelerator has at least two advantages
  - the particle bunches can be stored in the accelerator ring,
  - it only requires a few accelerating stations, through which the particles go at every turn.

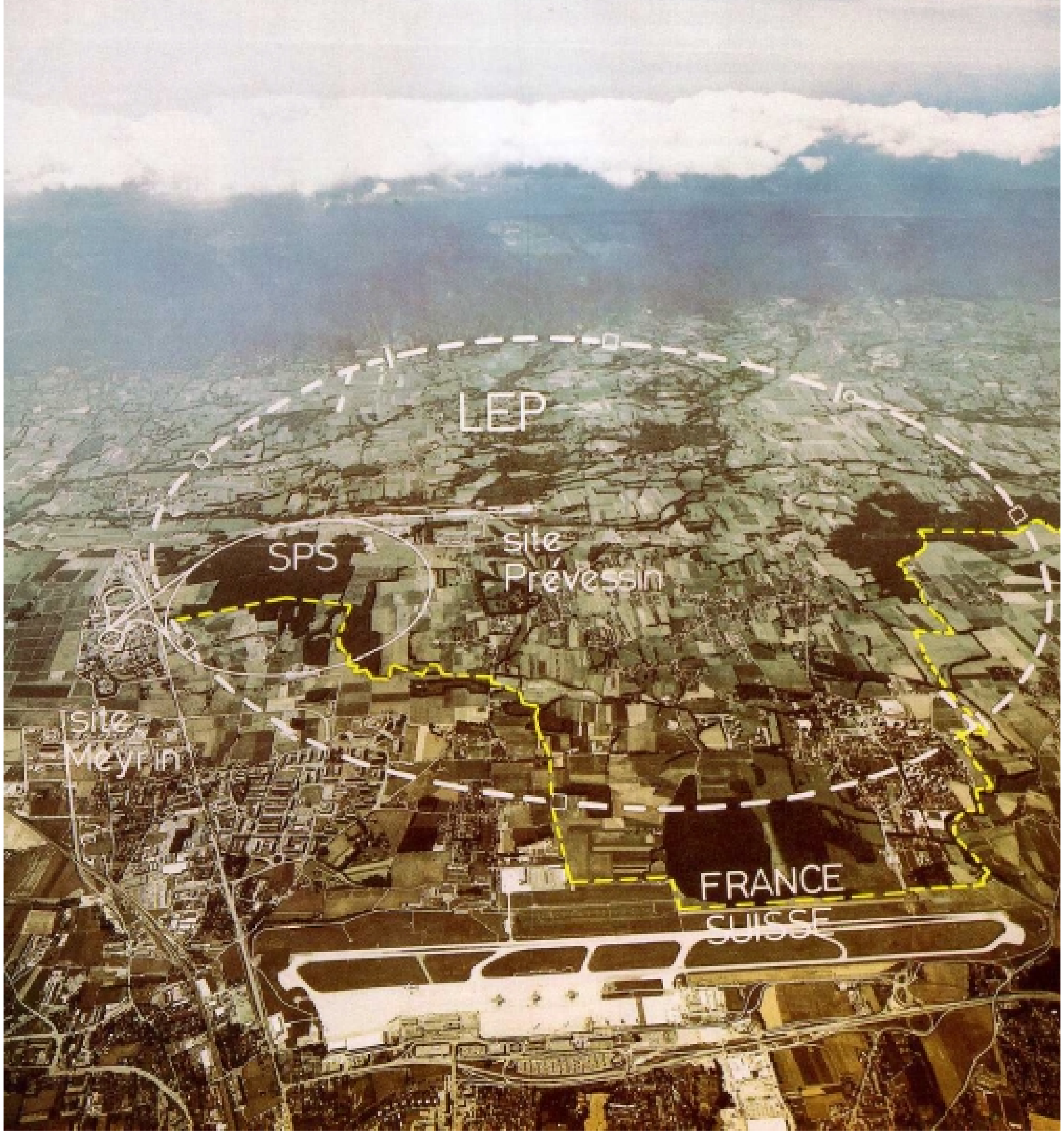
Cons of Circular Accelerators

- A circular accelerator has tow main disadvantages
  - it calls for a large number of trajectory-bending elements distributed over the accelerator arcs,
  - the level of synchrotron radiation can be very high, especially for light particles such as electrons, resulting in large energy losses which must be compensated.

Example of Circular Accelerator

- Until November 2000, the largest circular accelerator in operation was the Large Electron Positron (LEP) collider, implemented at the European Laboratory for Particle Physics (CERN).
- It had a total circumference of 27 km and was capable of accelerating electron and positron beams up to about 100 GeV.

CERN Aerial View



Contents

- **Accelerator Types**
  - Classification
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  - **Accelerator Complex**

Accelerator Complex

- The most powerful machines are made up of several stages, which progressively raise beam energy.
- Each stage is a fully-fledged accelerator, which can be of either types.
- The beam prepared in the accelerator chain is then used to produce interactions.

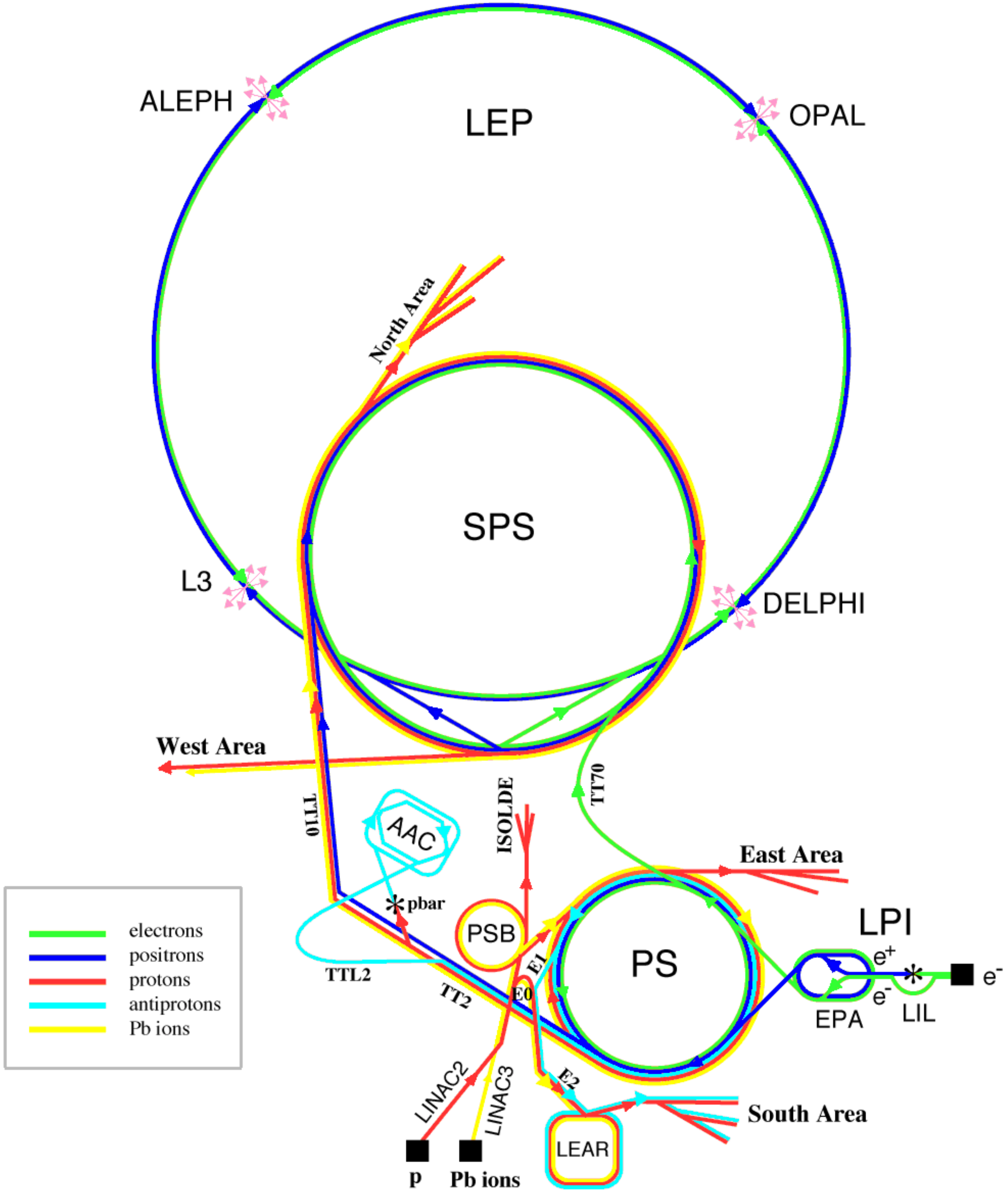
Collider

- A collider is a machine where two beams are prepared in parallel, either in linear or in circular accelerators, and are brought into head-on collisions at the last stage.
- This offers the advantage of doubling the interaction energy in a reference frame tied up to the center of mass of the colliding particles.

CERN Accelerator Complex

- Proton Synchrotron Booster (PSB)
  - Circumference: 50 m (aboveground)
  - Maximum proton energy: 1 GeV
- Proton Synchrotron (PS)
  - Diameter: 200 m (aboveground)
  - Maximum proton energy: 26 GeV
  - Commissioning: 1959
- Super Proton Synchrotron (SPS)
  - Circumference: 6.9 km
  - Tunnel depth: 25 to 65 m
  - Maximum proton energy: 450 GeV
  - Commissioning: 1976
- Large Electron Positron (LEP) Collider

CERN Accelerator Complex



Contents

- Tools of Particle Physics
- Accelerator Types
- **Accelerator Components**
- Synchrotron-Type Accelerators
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Contents

- **Accelerator Components**
  - **Classification**
  - Accelerating Stations
  - Guiding Elements

Accelerator Components

- The only particles we know how to capture, guide and accelerate are charged particles.
- Charged particle accelerators rely on two main types of components
  - accelerating stations, designed to raise particle energy to desired energy level,
  - guiding elements, designed to control particle trajectory.

Contents

- **Accelerator Components**
  - Classification
  - **Accelerating Stations**
  - Guiding Elements

Particle Acceleration

- Charged particles are accelerated by means of electric fields.
- The force, $\overrightarrow{F_{Cb}}$, exerted by an electric field, $\vec{E}$, on a charge, q, is given by Coulomb's law

$$\overrightarrow{F_{Cb}} = q\,\vec{E}$$

- $\overrightarrow{F_{Cb}}$ results in an acceleration parallel to $\vec{E}$.

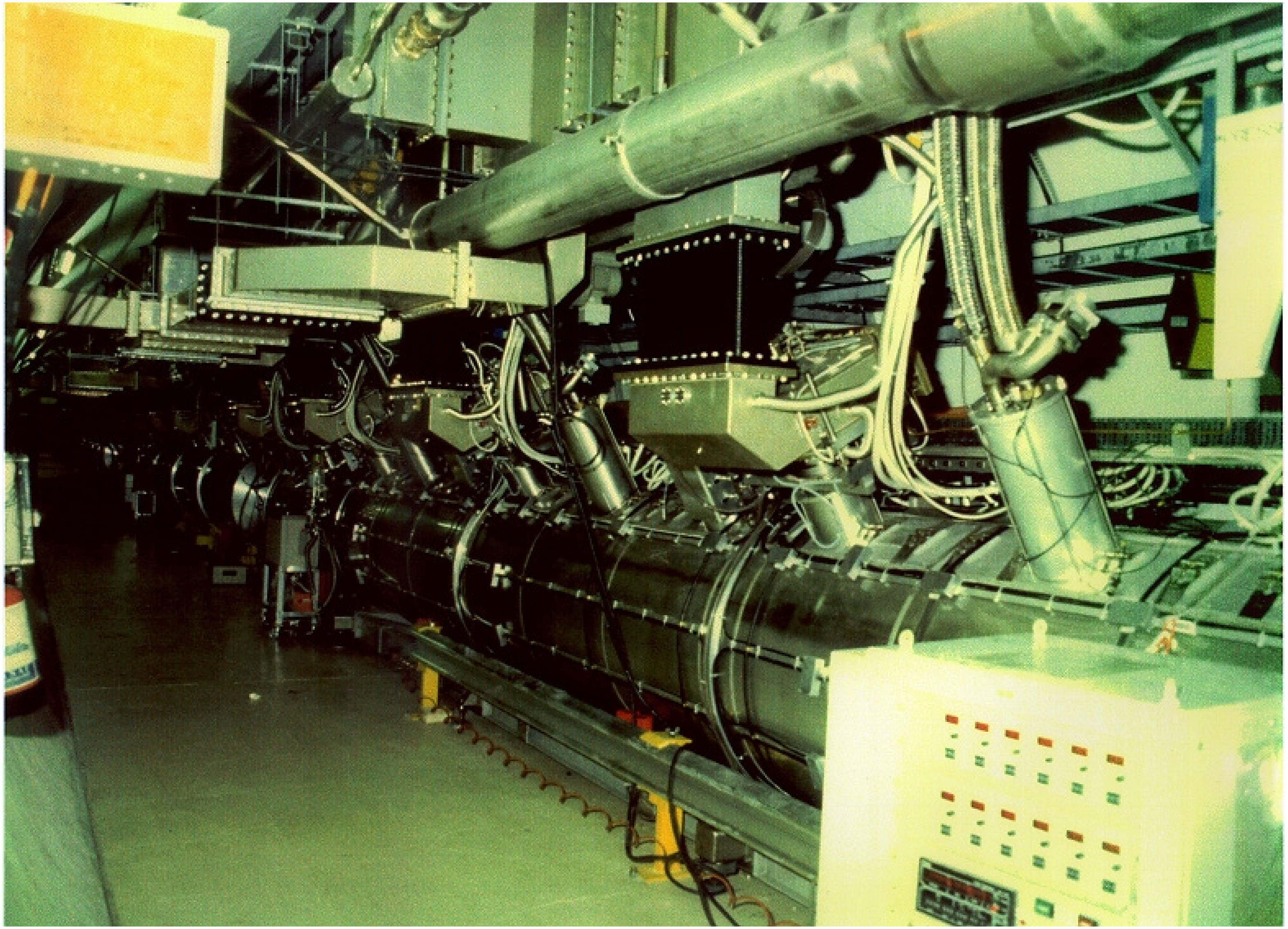
RF Cavities

- In most particle accelerators, the accelerating stations are made-up of Radio Frequency (RF) cavities, which can be superconducting.
- RF cavities determine the size of *linear accelerators,* where particle bunches travel only once through the machine.

LEP2 RF System (1/2)

- LEP2 relied on 272 superconducting cavities, providing a nominal RF voltage of 2800 MV (which corresponds to an active length of the order of 462 m).
- The cavities were made-up of four half-wavelength quasi-spherical cells, operated at 352.209 MHz and delivering a nominal average electric field of 6 MV/m.
- They were grouped by four in 12.5-m long cryostats.

LEP2 RF System (2/2)



LHC RF System

- LHC will rely on two separate RF systems (one for each beam) designed to provide a maximum RF voltage of 16 MV per beam.
- Each system will be made up of 8 single-cell, superconducting cavities, operated at 400.8 MHz and delivering a nominal average electric field of 5.3 MV/m.
- The cavities will be grouped by four in 6.5-m-long modules.

State of the Art in Superconducting RF Cavities

- Average electric fields of 25 MV/m are now routinely achieved in 9-cell, 1.3 GHz superconducting RF cavities developed as part of the R&D efforts for the Tera Electron volts Superconducting Linear Accelerator (TESLA).
- Values as high as 40 MV/m have been obtained in experimental prototypes.

Contents

- **Accelerator Components**
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Particle Guiding (1/2)

- Charged particles are guided by means of magnetic flux densities.
- The force, $\overrightarrow{F_L}$, exerted by a magnetic flux density, $\vec{B}$, on a charge, *q*, traveling at a velocity, $\vec{v}_q$, is given by Lorentz' law

$$\overrightarrow{F_L} = q\,\vec{v}_q \times \vec{B}$$

- $\overrightarrow{F_L}$ is perpendicular to the direction of $\vec{v}_q$ and $\vec{B}$, and its only action is to deflect particle trajectory.

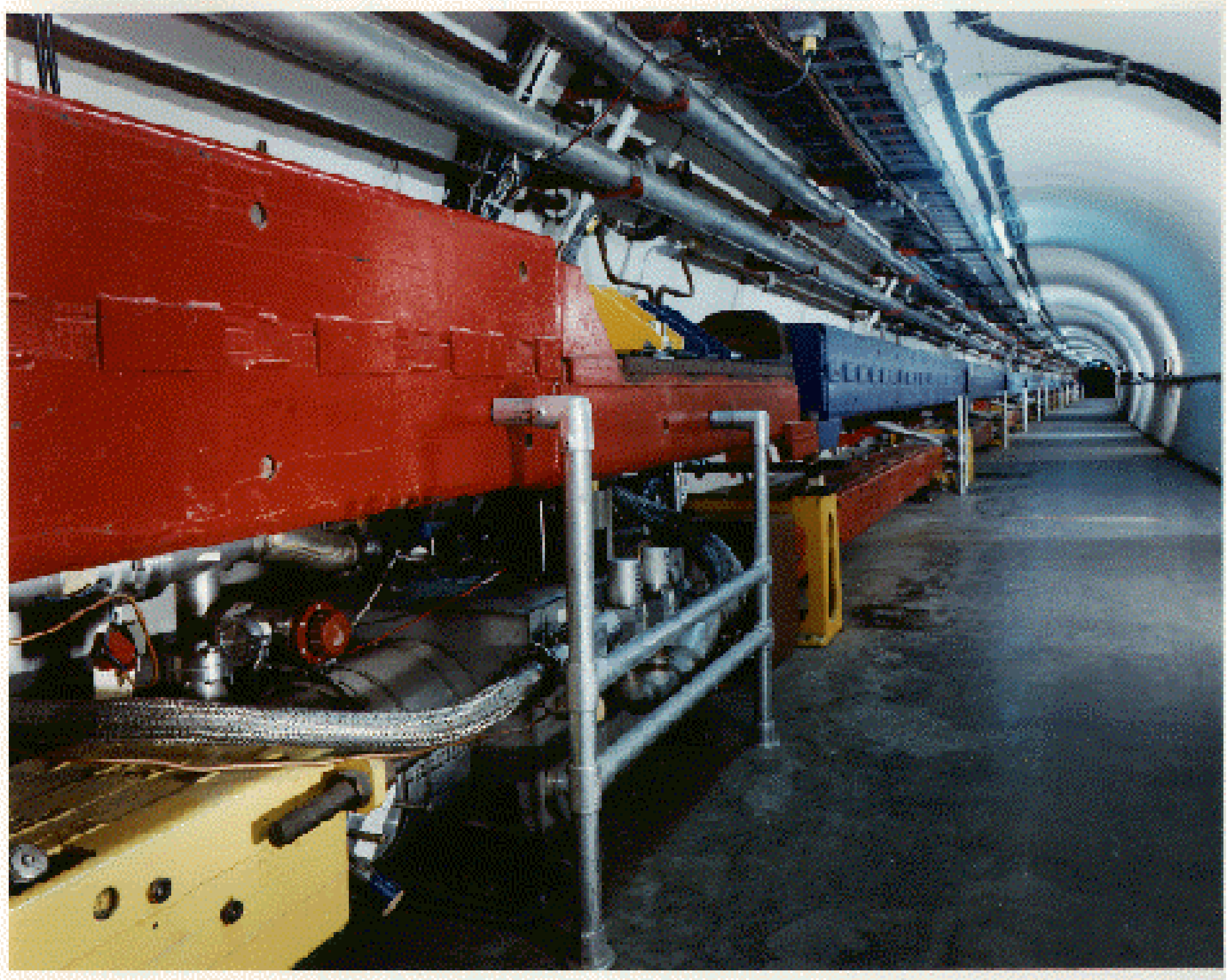
Particle Guiding (2/2)

- Particle accelerators rely on various types of magnets, designed to fulfill specific functions, such as trajectory bending and beam focusing.
- Bending and focusing magnets are crucial components of *synchrotron-type accelerators,* where particle bunches are circulated many times around a close and constant orbit.

Tevatron Magnet Ring (1/2)

- The 900 GeV proton/antiproton collider at Fermi National Accelerator Laboratory (FNAL), referred to as *Tevatron,* relies on
  - 774 6.1-m-long superconducting dipole magnets (delivering of to 4 T),
  - 216 1.7-m-long superconducting quadrupole magnets (delivering up to 76 T/m).
- The magnets are distributed around a 6.3-km-circumference ring.

Tevatron Magnet Ring (2/2)



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Synchrotron-Type Accelerators

- A synchrotron-type accelerator is made up of several arcs separated by quasi-straight insertion regions.
- It includes a small number of accelerating stations located in one insertion region, through which the particles go at every turn.
- It includes a large number of guiding magnets distributed over the ring arcs, to bend particle trajectory and close beam orbit.

Bending Radius (1/3)

- Let us consider a particle of charge, *q*, traveling at a velocity, $\vec{\mathrm{v}}_{\mathrm{q}}$, in a region immersed in a magnetic flux density, $\vec{\mathrm{B}}$.
- Let us further assume that $\vec{\mathrm{B}}$ is uniform and perpendicular to $\vec{\mathrm{v}}_{\mathrm{q}}$.
- It can be shown that the particle trajectory is a circle located in a plane perpendicular to $\vec{\mathrm{B}}$ and of radius, χ, given by

$$\chi = \frac{m_{\mathrm{q}}\gamma_{\mathrm{q}}v_{\mathrm{q}}}{qB}$$

where, m_{q} is the particle mass at rest, v_{q} and B are the amplitudes of $\vec{\mathrm{v}}_{\mathrm{q}}$ and $\vec{\mathrm{B}}$, and γ_{q} is the lorentz factor.

Bending Radius (2/3)

- Let us recall that the lorentz factor, γ_q, is defined as

$$\gamma_q = \frac{1}{\sqrt{1 - \frac{v_q^2}{c^2}}}$$

where c = 299 792 458 km/s is the speed of light in free space.

Bending Radius (3/3)

- Assuming that the particle total energy, $E_q = m_q \gamma_q c^2$, is far greater than its energy at rest, $E_{q,0} = m_q c^2$, the previous equation can be recast in the simpler form

$$\chi \approx \frac{E_q}{c\, q\, B} \approx \frac{\varepsilon_{\mathrm{GeV}}}{0.3\, q_e\, B}$$

where χ is in meters, B is in teslas, q_e is in units of electron charge, and $\varepsilon_{\mathrm{GeV}}$ is in giga electron volts (GeV).

- The above equation shows that to keep χ constant, $\varepsilon_{\mathrm{GeV}}$ and B must be varied in proportion, thereby requiring a perfect synchronization of accelerating stations and arc magnets.

Dimensioning
a Circular Accelerator (1/2)

- Let us use the previous equation to dimension a circular proton accelerator with a maximum energy of 100 TeV.

B	χ	$(2\pi\chi)$
2 T	167 km	1047 km
8 T	42 km	262 km
12 T	28 km	174 km

Dimensioning a Circular Accelerator (2/2)

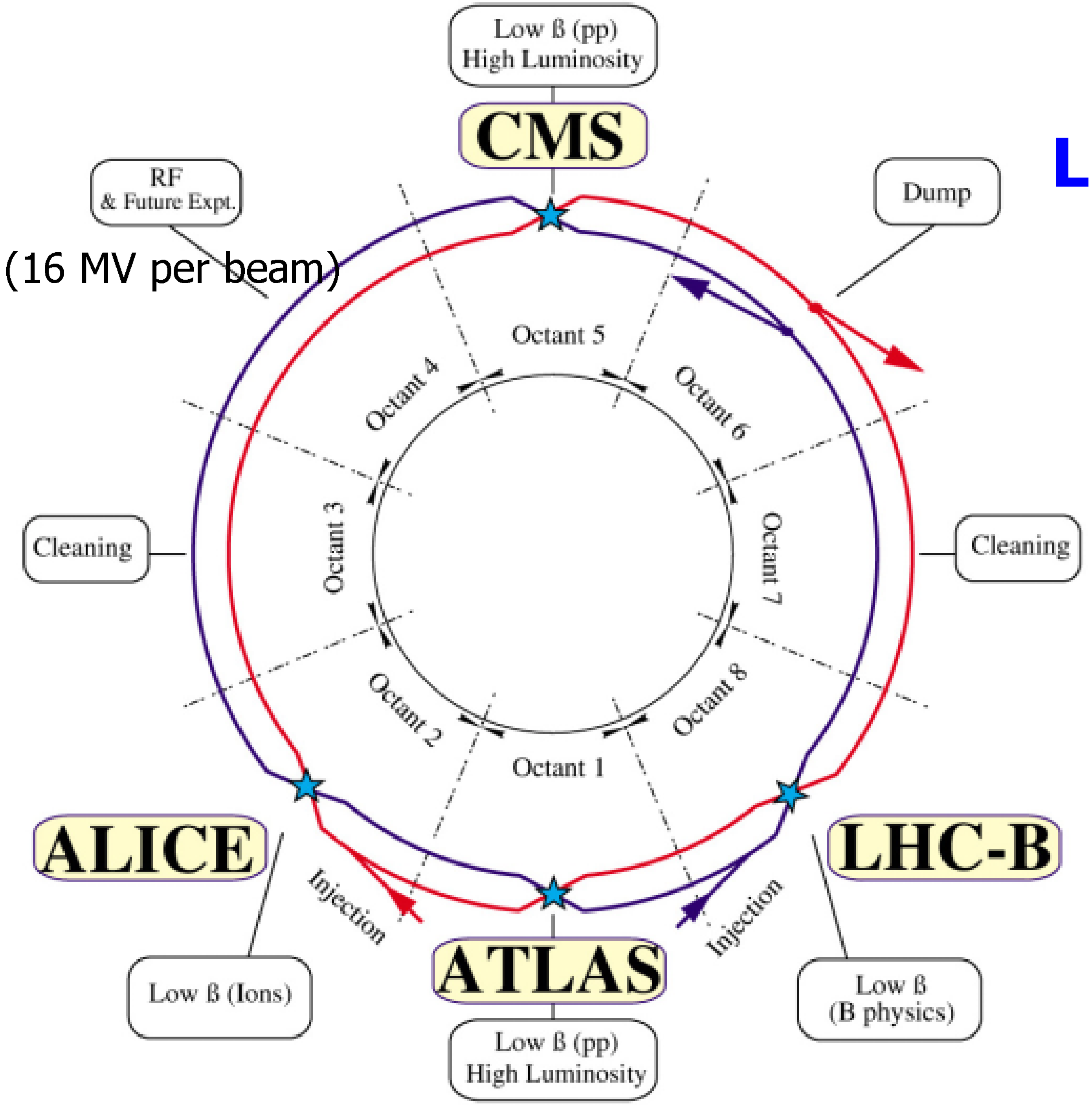
- The previous table shows that, when dimensioning a circular accelerator, a trade-off must be found between
  - – the availability of land and the tunneling costs,
  - – the feasibility and costs of electromagnets.

Note that the total circumference of an accelerator ring is usually greater than $(2\pi\chi)$, for the bending elements are interleaved with focusing elements, and the ring arcs are separated by insertion regions housing utilities and physics experiments.

Example: LHC at CERN (1/3)

- In December 1994, CERN has approved the construction in the LEP tunnel of the Large Hadron Collider (LHC).
- LHC is a proton/proton collider with a maximum energy of 7 TeV per beam that will use the PSB, PS and SPS as injector chain.
- It is divided into 8 bending arcs, separated by 8 ~530-m-long insertion regions, and has a total circumference of ~27 km.
- The two counter-rotating proton beams will be circulated around the eight arcs and will cross at the middle of four insertion regions.

Example: LHC at CERN (2/3)



(16 MV per beam)

Example: LHC at CERN (3/3)

- The LHC bending magnets are designed to operate with a maximum magnetic flux density of 8.386 T and the bending radius is set to 2784.32 m (yellow book design).
- It follows that the maximum beam energy will be

$$E_{\mathrm{q}} = \mathrm{c}\, q\, B\, \chi = 7000\,\mathrm{GeV}$$

- Commissioning is scheduled for 2005.

Synchrotron Radiation (1/4)

- The power, P_{sync}, radiated in the laboratory frame by a relativistic particle of charge, q, undergoing an acceleration, a_{q}, perpendicular to its direction can be estimated as

$$P_{\text{sync}} \approx \frac{1}{6\pi\varepsilon_0} \frac{q^2 a_{\text{q}}^2}{c^3} \gamma_{\text{q}}^4$$

where ε_0 is the permittivity of free space, c is the speed of light, and γ_{q} is the particle lorentz factor.

Synchrotron Radiation (2/4)

- Assuming that a_q corresponds to a centripetal acceleration on a trajectory of bending radius, χ, we have

$$a_q \approx \frac{c^2}{\chi}$$

and the previous equation can be recast in the form

$$P_{\text{sync}} \approx \frac{1}{6\pi\varepsilon_0} \frac{q^2}{m_q^4 c^7} \frac{E_q^4}{\chi^2}$$

where m_q is the particle mass at rest and $E_q = m_q \gamma_q c^2$ is the particle total energy.

Synchrotron Radiation (3/4)

- Assuming further that the particle trajectory is circular and that its velocity is near that of light, the revolution time, τ_{q}, can be estimated as

$$\tau_{\mathrm{q}} \approx \frac{2\pi\chi}{\mathrm{c}}$$

and the energy loss per turn, ΔE_{q}, is given by

$$\Delta E_{\mathrm{q}} \approx \frac{1}{3\varepsilon_0}\frac{q^2}{m_{\mathrm{q}}^4\mathrm{c}^8}\frac{E_{\mathrm{q}}^4}{\chi}$$

Synchrotron Radiation (4/4)

- The previous equation can be rewritten

$$\Delta\varepsilon_{\mathrm{GeV}} \approx 88.5\,10^{-6}\,\frac{q_{\mathrm{e}}^{2}\varepsilon_{\mathrm{GeV}}^{4}}{m_{\mathrm{e}}^{4}\chi}$$

where q_e is the particle charge in units of electron charge, m_e is the particle mass at rest in units of electron mass at rest, and $\varepsilon_{\mathrm{GeV}}$ and $\Delta\varepsilon_{\mathrm{GeV}}$ are the particle total energy and the energy loss per turn in giga electron volts (GeV).

Synchrotron Radiation at LEP2

- In the case of LEP2, we had: $q_e = m_e = 1$, and χ = 3096.175 m. Taking E = 100 GeV, we get

$$\Delta\varepsilon_{\mathrm{GeV}} \approx 2.9\,\mathrm{GeV}$$

- The energy loss by synchrotron radiation was quite large and the RF system was dimensioned to compensate it.
- The total RF voltage installed at LEP2 was in excess of 2.8 GV, and center-of-mass energies up to 209 GeV were achieved in April 2000.

Synchrotron Radiation at LHC

- In the case of LHC (yellow book design), we have: $q_e = 1$, $m_e = 1836.1$, and $\chi = 2784.36$ m. Taking E = 7000 GeV, we get

$$\Delta\varepsilon_{\mathrm{GeV}} \approx 6.7\,10^{-6}\ \mathrm{GeV}$$

- In spite of the fact that the energy is 70 times greater than for LEP2, the proton mass is such that the energy loss per turn is reduced by a factor of ~435 000.

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- **Types of Magnet Systems**
  - **Classification**
  - Arc Magnets
  - Insertion Magnets
  - Corrector Magnets
  - Detector Magnets
  - Special-Function Magnets

Magnet Types

- Five main types of magnet systems can be found in synchrotron-type accelerators or storage rings
  - arc magnets
    (to control beam trajectory in accelerator arcs),
  - insertion and final-focusing magnets
    (to handle beam near injection, extraction and interaction points),
  - corrector magnets
    (to fine-tune beam optics and correct field distortions of main magnets),
  - detector magnets
    (embedded in detector arrays surrounding targets or collision points),
  - special-function magnets
    (for synchrotron radiation or beam polarization).

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- **Types of Magnet Systems**
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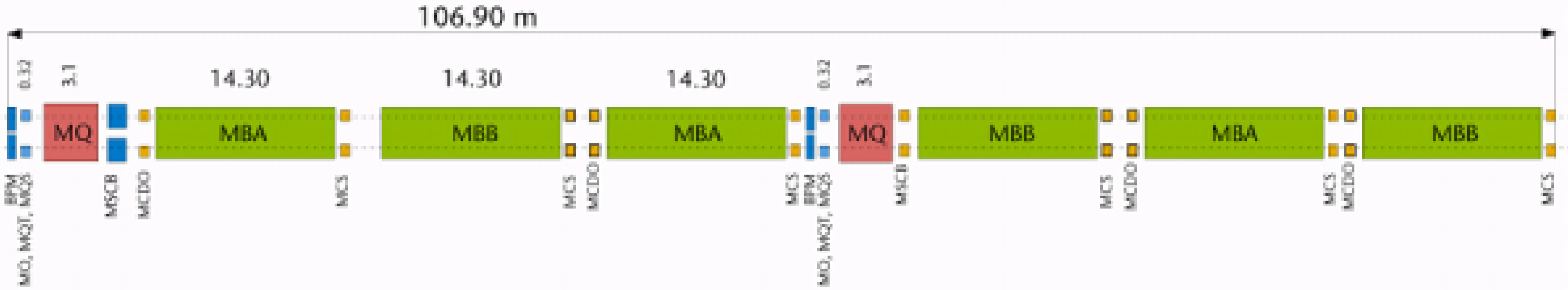
Arc Magnets (1/3)

- The magnets distributed over the ring arcs have two main functions
  - bending of beam around a close and constant orbit,
  - focusing of beam to achieve proper size and intensity.
- In large machines, the bending and focusing functions are separated: the former is provided by dipole magnets, while the latter is provided by quadrupole magnets.

Arc Magnets (2/3)

- The arc magnets are usually arranged in a regular lattice of cells, made up of a focusing quadrupole, a string of bending dipoles, a defocusing quadrupole and another string of bending dipoles.



MQ: Lattice Quadrupole
MO: Skew Quadrupole
MQT: Landau Octupole
MQS: Tuning Quadrupole
MSCB: Combined Lattice Sextupole (MS) or skeco sextupole (MMS) and Orbit Corrector (MCB)
BPM: Beam position monitor
MBA: Dipole magnet Type 1
MBB: Dipole magnet Type 2
MCS: Local Sextupole corrector
MCDO: Local combined decapole and octupole corrector

Cell of the Proposed Magnet Lattice For LHC Arcs
(LHC counts 8 arcs made up of 23 such cells)

Arc Magnets (3/3)

- Large circular machines require a large number of arc magnets (*e.g.*, 1232 dipole magnets and 386 quadrupole magnets for LHC).
- They must be mass-produced in industry.
- They are the most expensive components of the machine.

⇒ Any new circular machine beyond LHC will require significant value-engineering efforts to improve magnet performance and limit costs.

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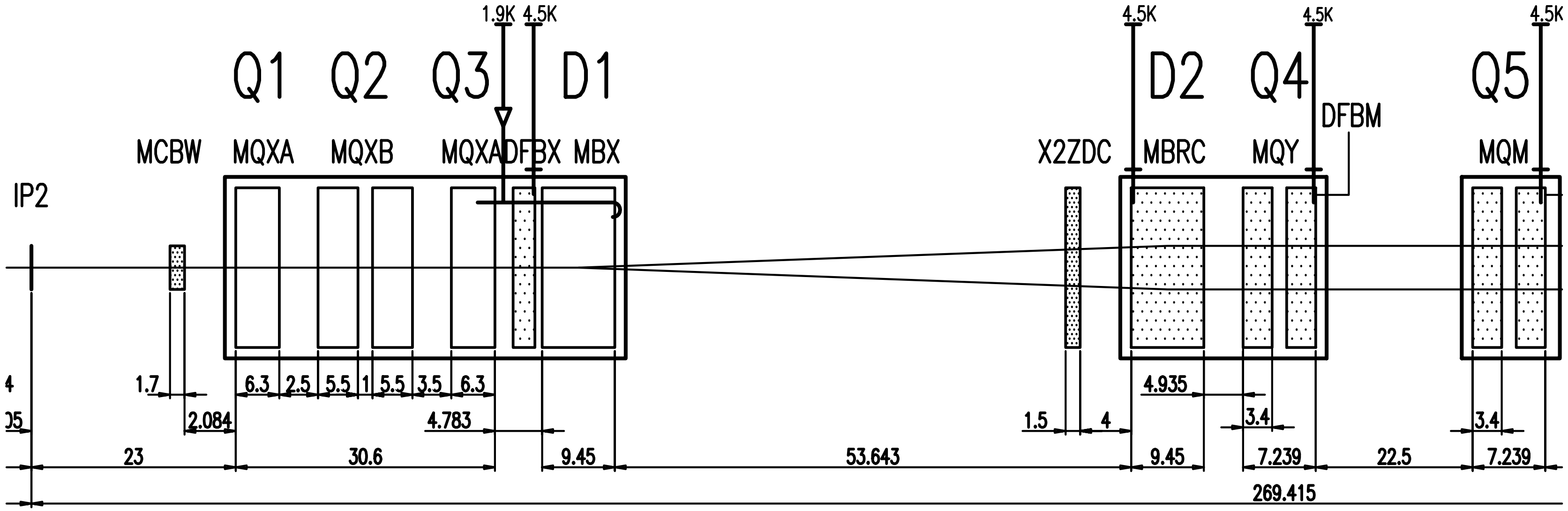
Insertion Magnets (1/4)

- Circular and linear accelerators require sets of special magnets implemented in the insertion regions for at least two reasons
  - beam transport near injection and extraction point,
  - steering and final focusing of beam(s) near interaction points.

Insertion Magnets (2/4)

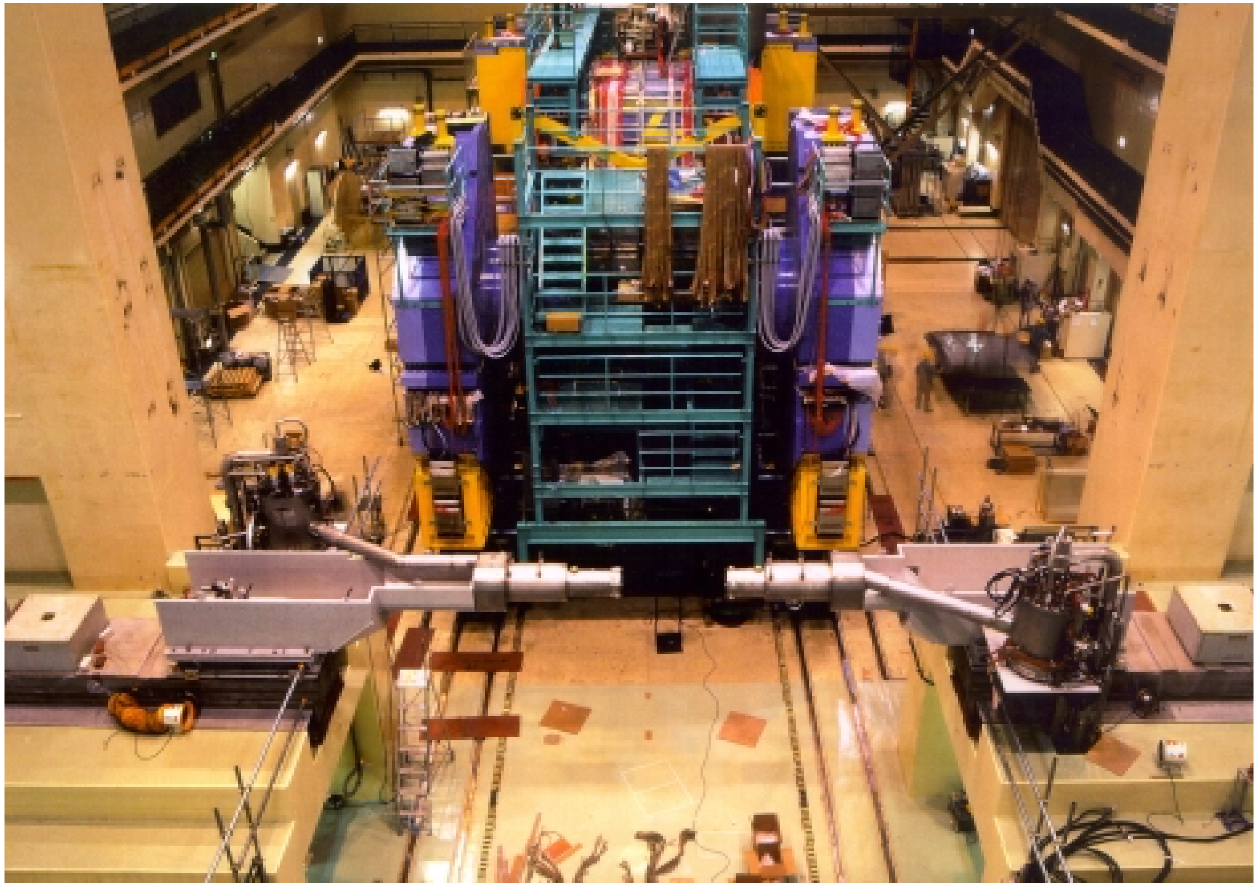


Proposed Magnet Lattice For the Right-Hand Side of #2 Interaction Point of LHC, showing from left to right:

- quadrupole magnet inner triplet (Q1, Q2 and Q3),
- single-aperture beam-separation dipole (D1),
- twin-aperture beam-separation dipole (D2),
- first two elements of quadrupole magnet outer triplet (Q4 and Q5).

Insertion Magnets (3/4)

- Beam optics can require that final focusing quadrupole magnets be implemented at the extremities or inside the physics experiments and sustain the stray field of detector magnet.



Implementation of Final-Focusing Magnets for KEK-B Factory.

The magnets are shown in front of the BELLE detector, which has been railed back from its normal position.

Insertion Magnets (4/4)

- The insertion magnets are in limited number.
- They must be customized to their crowded environment.
- The requirements for the final-focusing quadrupole magnets can be very stringent (high field gradient in a large aperture, good field quality, high heat load from beam losses, sizeable background field, ...).

⇒ They can be used as a test bench for more innovative designs.

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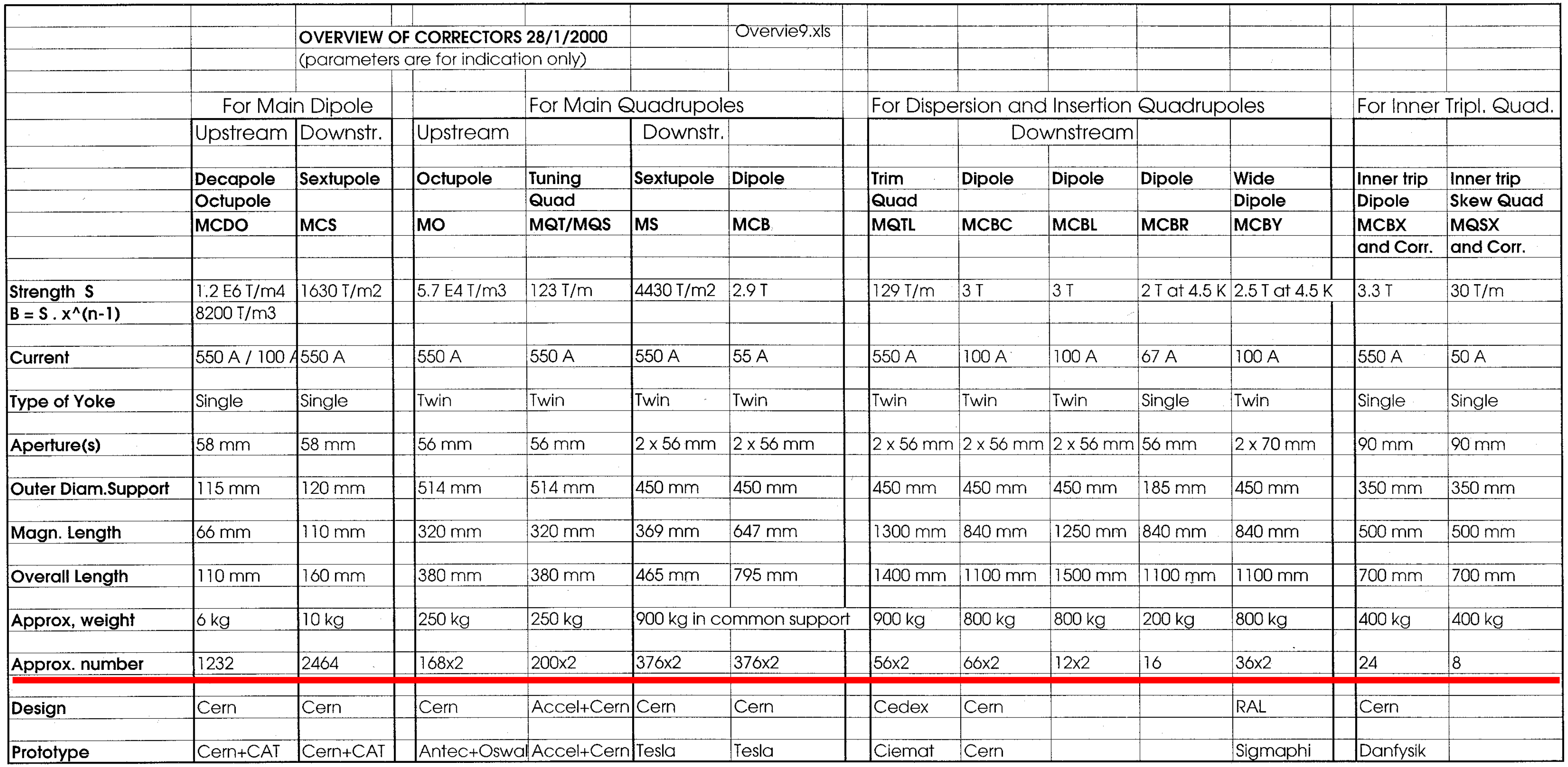
Corrector Magnets

- Large machines require a large number of corrector magnets.
- These magnets are needed for two main reasons
  - fine tuning of beam optics,
  - local or global corrections of alignment and field errors of main magnets.
- They are small in size and cost, and can be mass-produced in industry.

LHC Magnet Corrector List



		OVERVIEW OF CORRECTORS 28/1/2000				Overvie9.xls							
		(parameters are for indication only)											
	For Main Dipole			For Main Quadrupoles			For Dispersion and Insertion Quadrupoles					For Inner Tripl. Quad.	
	Upstream	Downstr.	Upstream		Downstr.			Downstream					
	Decapole Octupole	**Sextupole**	**Octupole**	**Tuning Quad**	**Sextupole**	**Dipole**	**Trim Quad**	**Dipole**	**Dipole**	**Dipole**	**Wide Dipole**	**Inner trip Dipole**	**Inner trip Skew Quad**
	MCDO	**MCS**	**MO**	**MQT/MQS**	**MS**	**MCB**	**MQTL**	**MCBC**	**MCBL**	**MCBR**	**MCBY**	**MCBX and Corr.**	**MQSX and Corr.**
Strength S	1.2 E6 T/m4	1630 T/m2	5.7 E4 T/m3	123 T/m	4430 T/m2	2.9 T	129 T/m	3 T	3 T	2 T at 4.5 K	2.5 T at 4.5 K	3.3 T	30 T/m
B = S . x^(n-1)	8200 T/m3												
Current	550 A / 100 A	550 A	550 A	550 A	550 A	55 A	550 A	100 A	100 A	67 A	100 A	550 A	50 A
Type of Yoke	Single	Single	Twin	Twin	Twin	Twin	Twin	Twin	Twin	Single	Twin	Single	Single
Aperture(s)	58 mm	58 mm	56 mm	56 mm	2 x 56 mm	2 x 56 mm	2 x 56 mm	2 x 56 mm	2 x 56 mm	56 mm	2 x 70 mm	90 mm	90 mm
Outer Diam.Support	115 mm	120 mm	514 mm	514 mm	450 mm	450 mm	450 mm	450 mm	450 mm	185 mm	450 mm	350 mm	350 mm
Magn. Length	66 mm	110 mm	320 mm	320 mm	369 mm	647 mm	1300 mm	840 mm	1250 mm	840 mm	840 mm	500 mm	500 mm
Overall Length	110 mm	160 mm	380 mm	380 mm	465 mm	795 mm	1400 mm	1100 mm	1500 mm	1100 mm	1100 mm	700 mm	700 mm
Approx, weight	6 kg	10 kg	250 kg	250 kg	900 kg in common support		900 kg	800 kg	800 kg	200 kg	800 kg	400 kg	400 kg
Approx. number	1232	2464	168x2	200x2	376x2	376x2	56x2	66x2	12x2	16	36x2	24	8
Design	Cern	Cern	Cern	Accel+Cern	Cern	Cern	Cedex	Cern			RAL	Cern	
Prototype	Cern+CAT	Cern+CAT	Antec+Oswal	Accel+Cern	Tesla	Tesla	Ciemat	Cern			Sigmaphi	Danfysik	

For LHC, the number of corrector magnets far exceed the number of arc and insertion magnets.

Contents

- **Types of Magnet Systems**
  - Classification
  - Arc Magnets
  - Insertion Magnets
  - Corrector Magnets
  - **Detector Magnets**
  - Special-Function Magnets

Detector Magnets (1/2)

- Particle physics experiments are made up of various kinds of detectors, which measure the energy and determine the trajectories of interaction products.

- They usually include a large magnet system embedded in the detector array, which produces a strong magnetic flux density (a few teslas) in a large volume (up to tens of cubic meters) around the interaction point.

- This magnetic flux density causes a bending of the charged particles’ trajectories, with radii of curvature which are directly proportional to the particles’ charge and energy.

- The detection of such bending and the determination of its parameters provide additional informations on the nature of interaction products and on their kinematics.

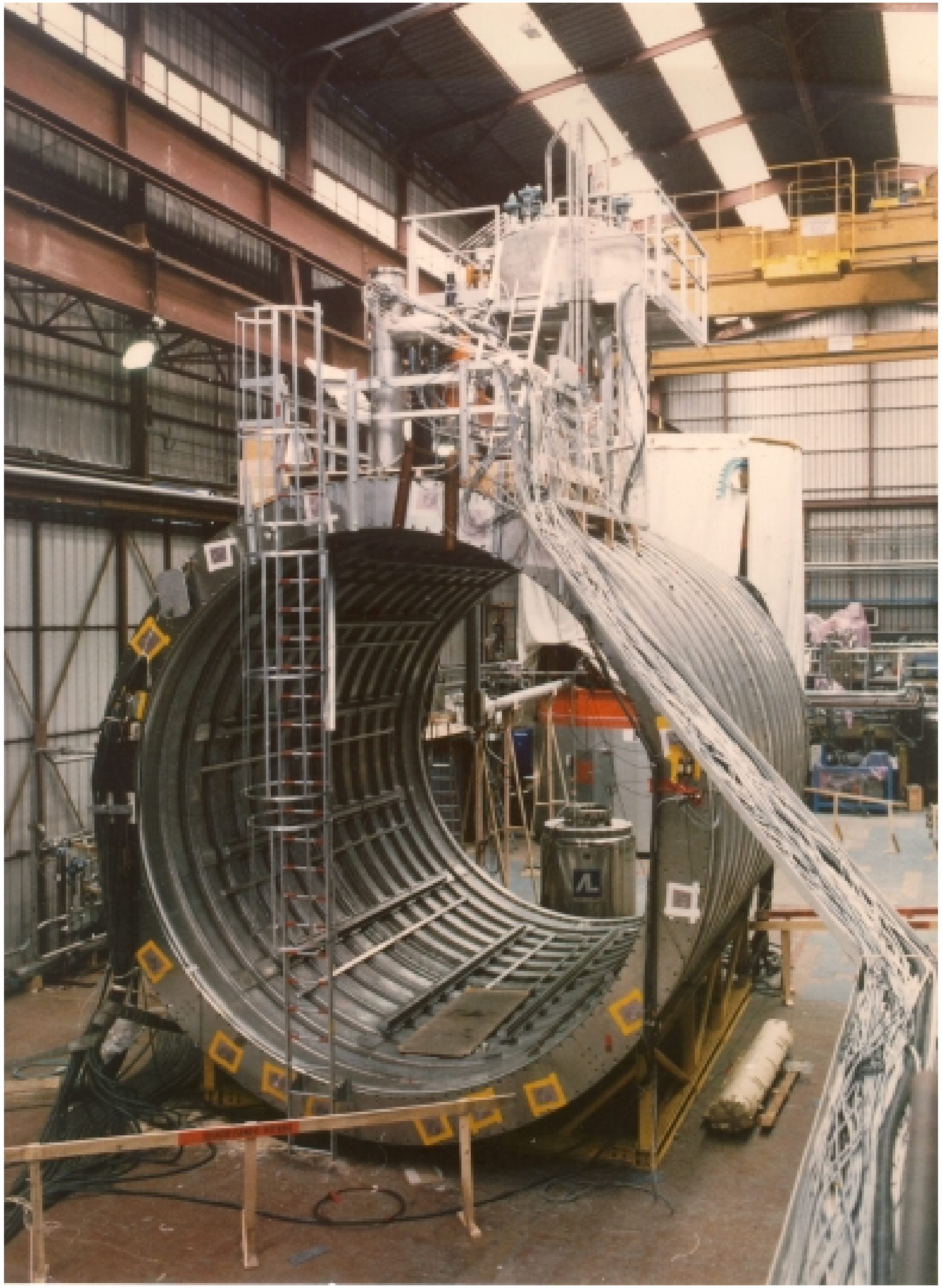
Detector Magnets (2/2)

- Most often, detector magnet systems are based on a solenoid, but they can rely also on a toroid or a large dipole magnet.
- The magnet structure must be minimized to save space and reduce interactions with particles.
- The large dimensions of detector magnets require special manufacturing, handling and transportation techniques.
- Once buried in the detector array, the magnet system is no longer accessible for repair and maintenance, and it must be engineered to operate safely and reliably.

Example: ALEPH Solenoid

- The oncoming slides present a series of photographs illustrating the fabrication, transportation and installation of the superconducting solenoid for the ALEPH experiment at CERN.
- The solenoid was designed and built at CEA/Saclay, and was subsequently delivered to CERN.
- Its main parameters were: an overall length of 7 m, an inner bore of 5 m, a central field of 1.5 T and a stored energy of 160 MJ.

Winding of ALEPH Solenoid at CEA/Saclay.

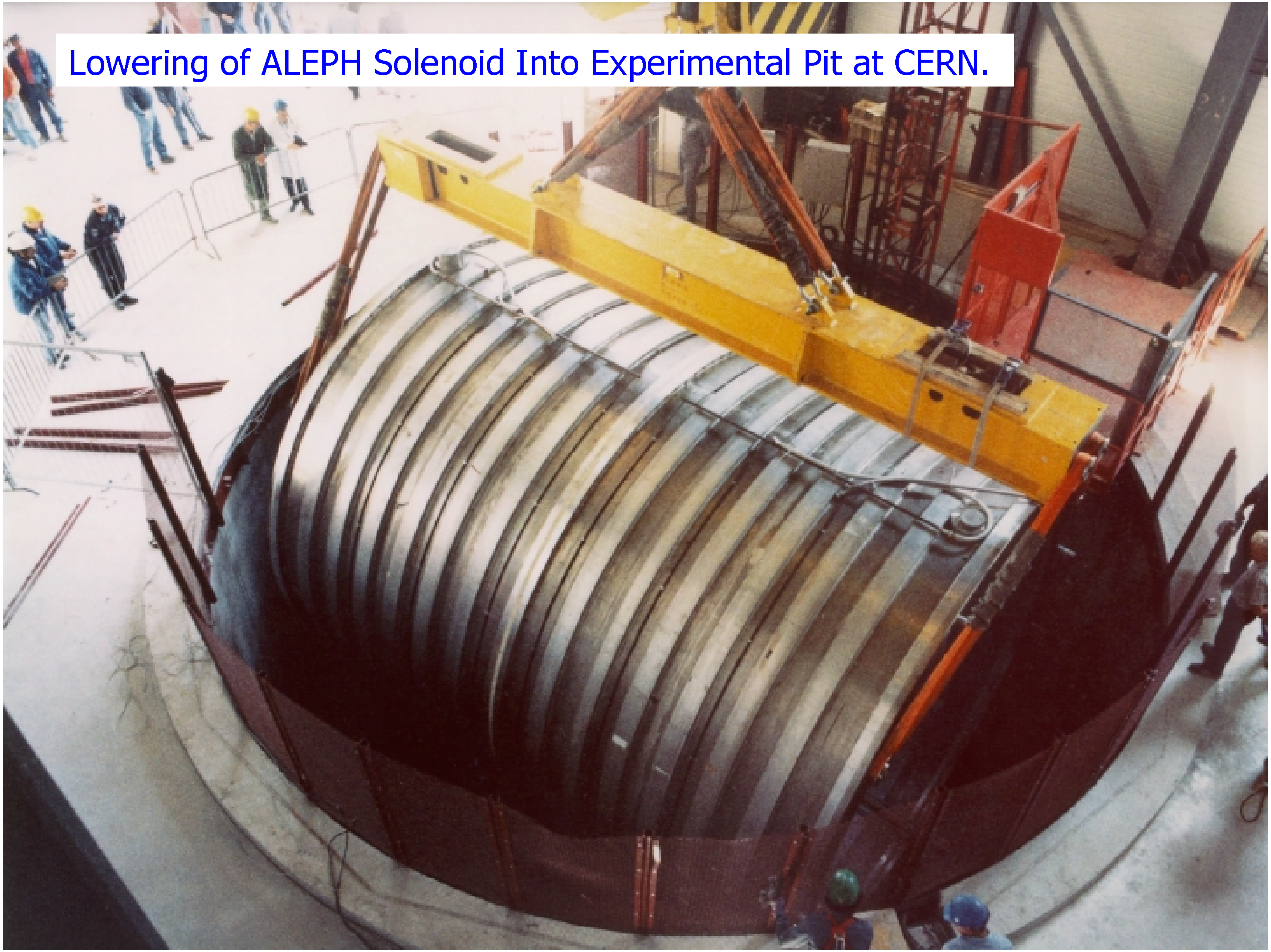


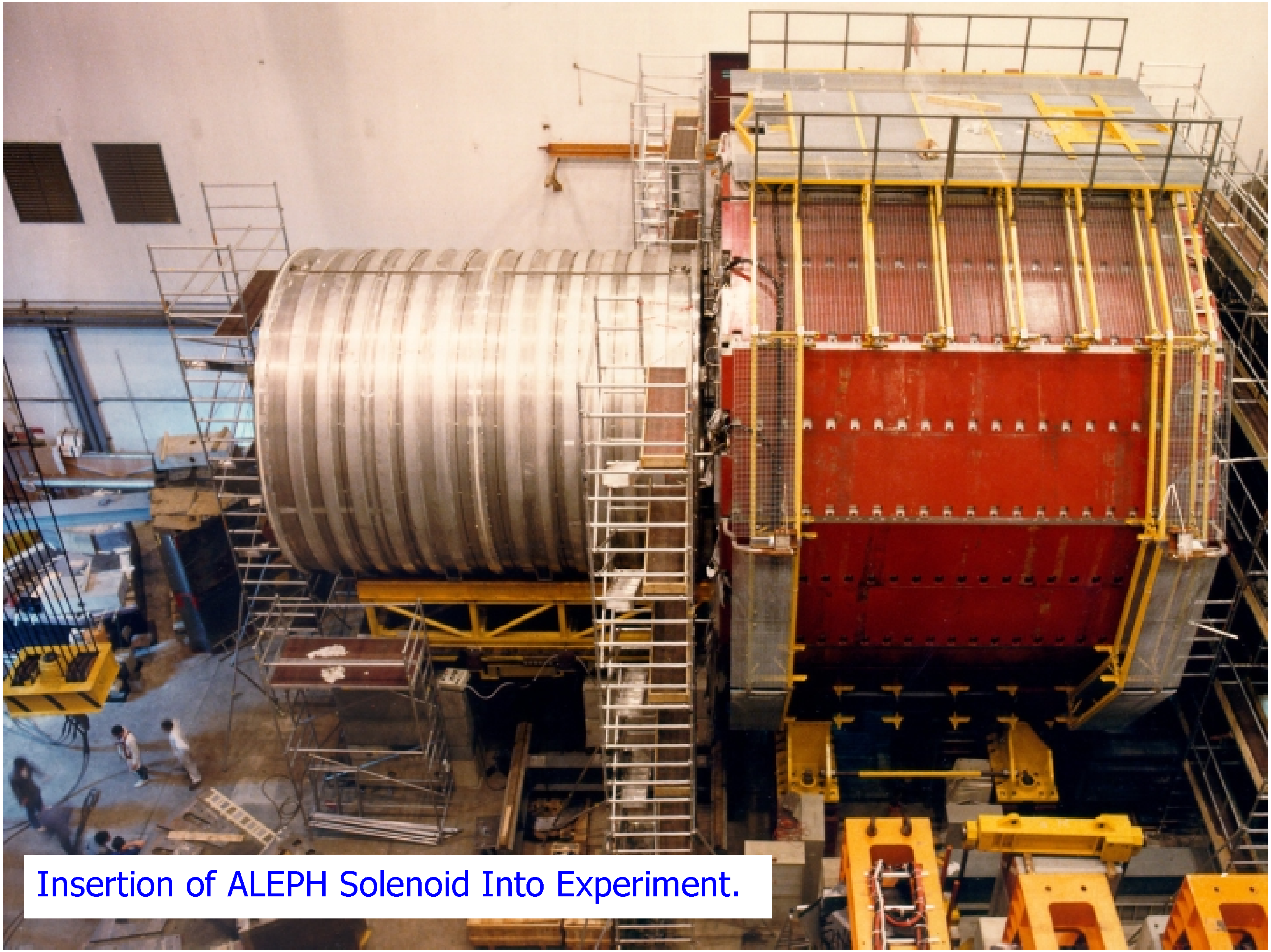
ALEPH Solenoid Undergoing
Cold Tests at CEA/Saclay.

ALEPH Solenoid Upon its Departure From CEA/Saclay.

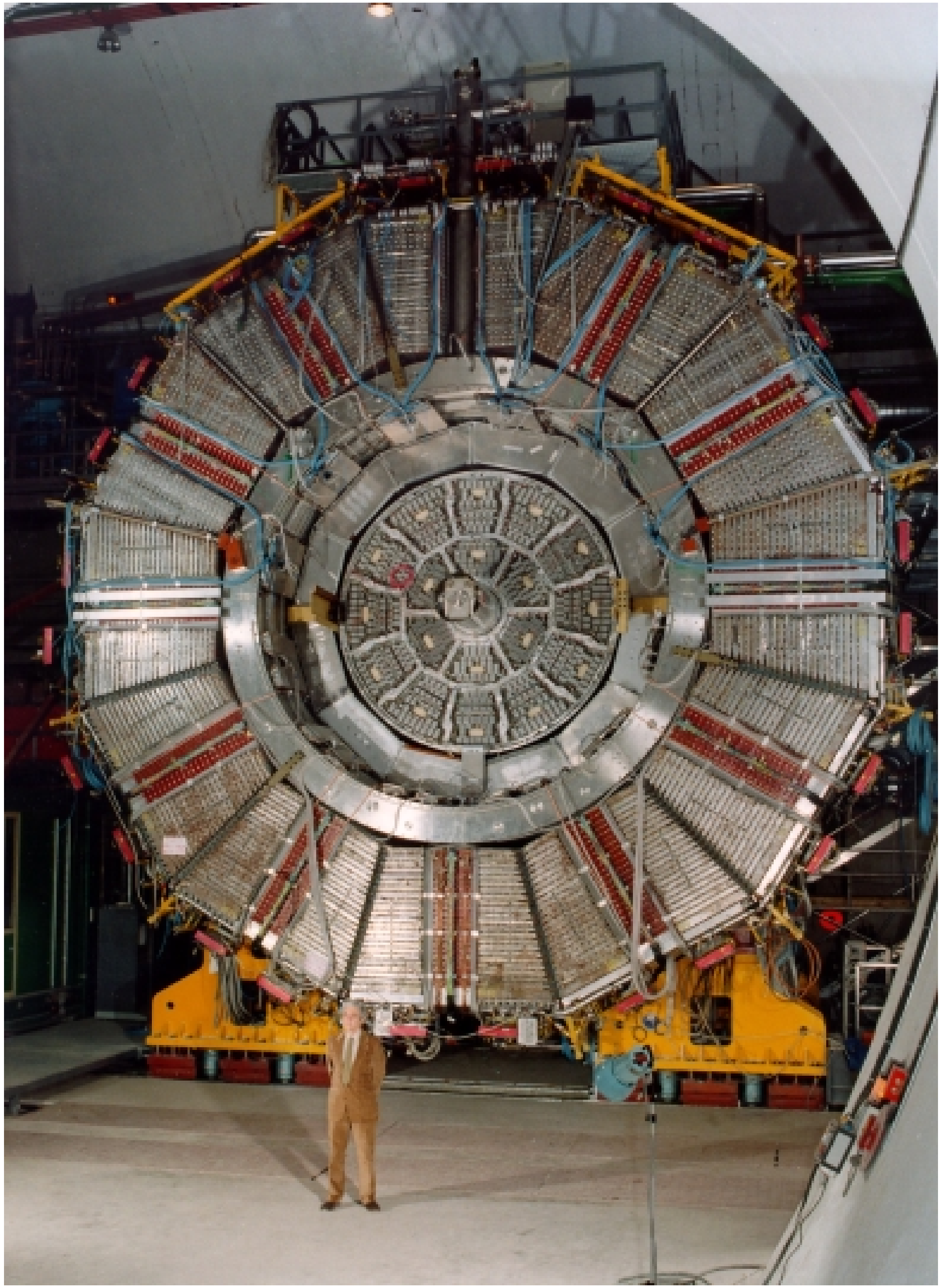
ALEPH Solenoid En Route to CERN.

Lowering of ALEPH Solenoid Into Experimental Pit at CERN.





Insertion of ALEPH Solenoid Into Experiment.



ALEPH Solenoid Embedded in Detector Array.

Contents

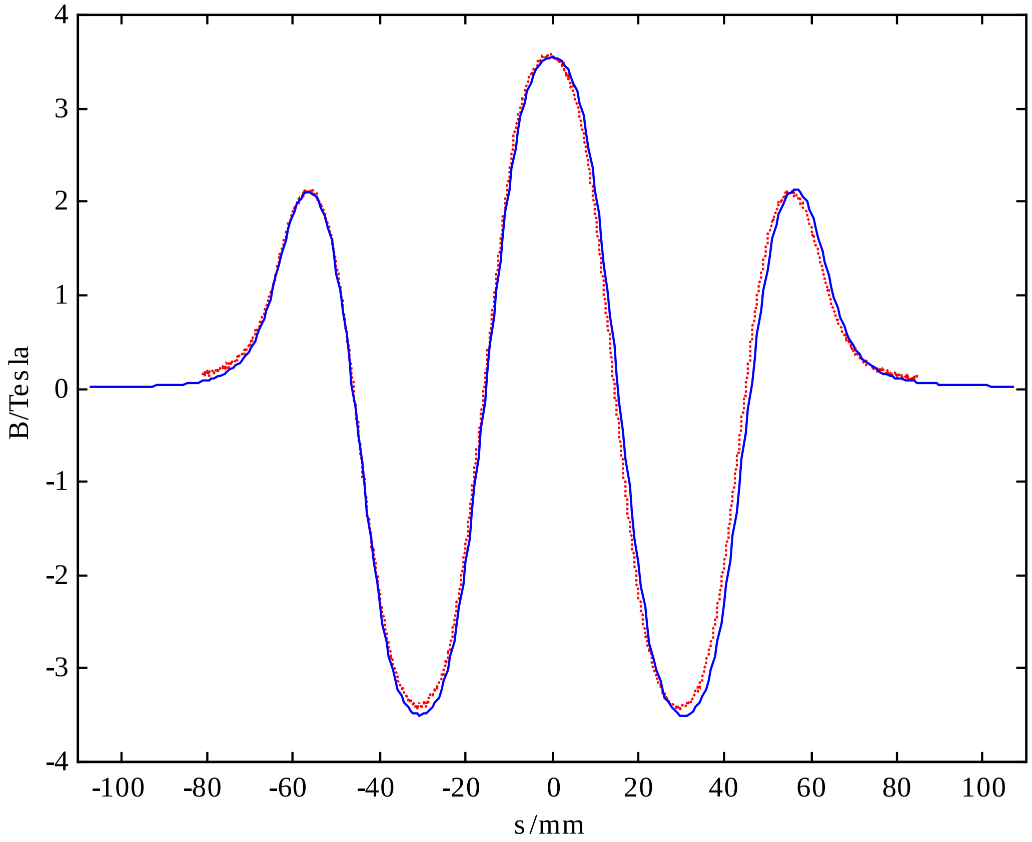
- **Types of Magnet Systems**
  - Classification
  - Arc Magnets
  - Insertion Magnets
  - Corrector Magnets
  - Detector Magnets
  - **Special-Function Magnets**

Special-Function Magnets

- In addition to multipole and detector magnets, particle accelerators and storage rings can also require special magnet systems dedicated to specific functions.
- Among them are wiggler magnets, used in electron machines to produce synchrotron radiation, and helicoidal magnets, used to polarize proton beams.
- The special-function magnets are usually implemented in the insertion regions.

Wiggler Magnets (1/4)

- A wiggler magnet is designed to produce a normal dipole field that oscillates like a sine function along the magnet axis.



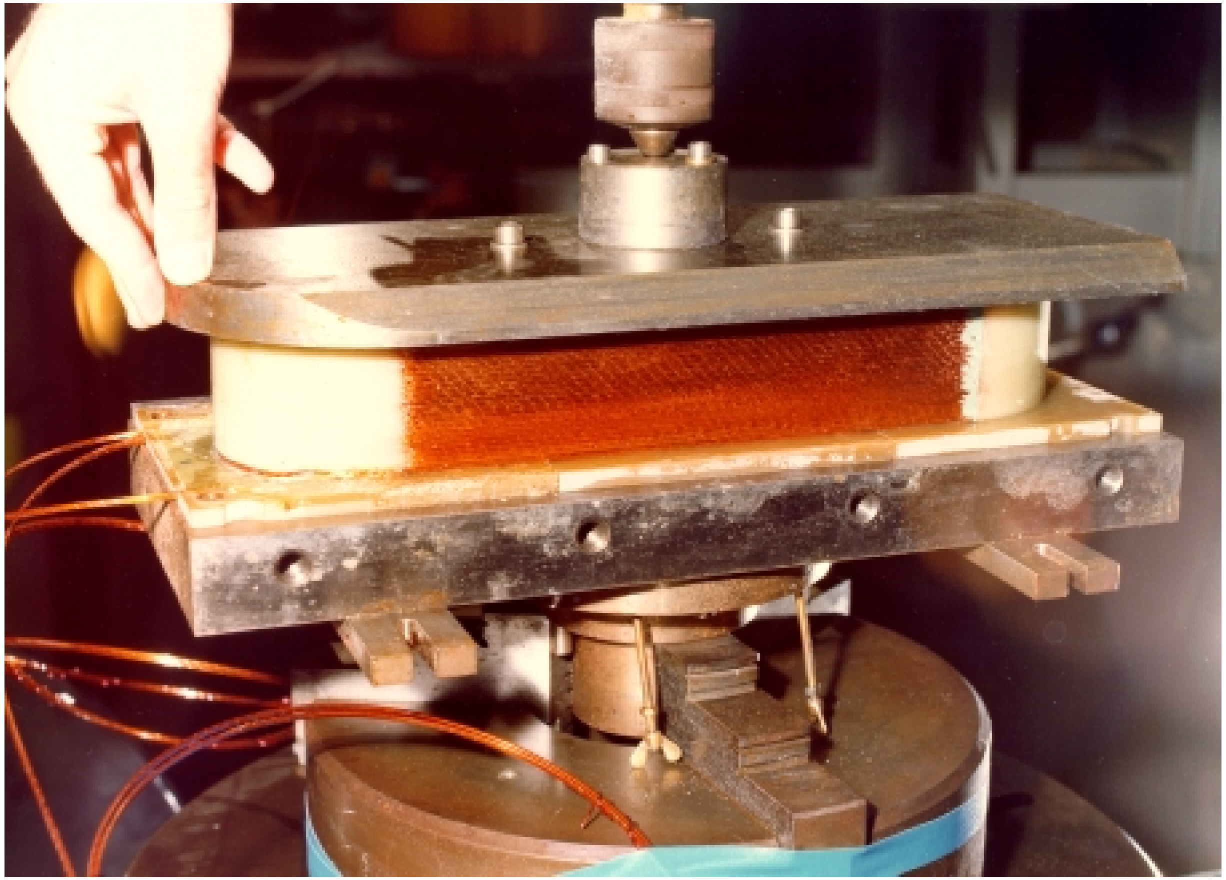
Field Oscillation Along the Axis of a 5-Pole Wiggler (Courtesy G. LeBlanc)

Wiggler Magnets (2/4)

- The vertical field oscillation results in an horizontal oscillation of charged particles’ trajectories.
- In the case of electrons, the trajectories’ oscillations result in large synchrotron radiation in the horizontal plane.
- The synchrotron radiation can be used as X-ray source or as a mean to control critical beam optics parameters.

Wiggler Magnets (3/4)

- Most superconducting wiggler magnets rely on pairs of horizontal racetrack-type coils wound around iron poles.

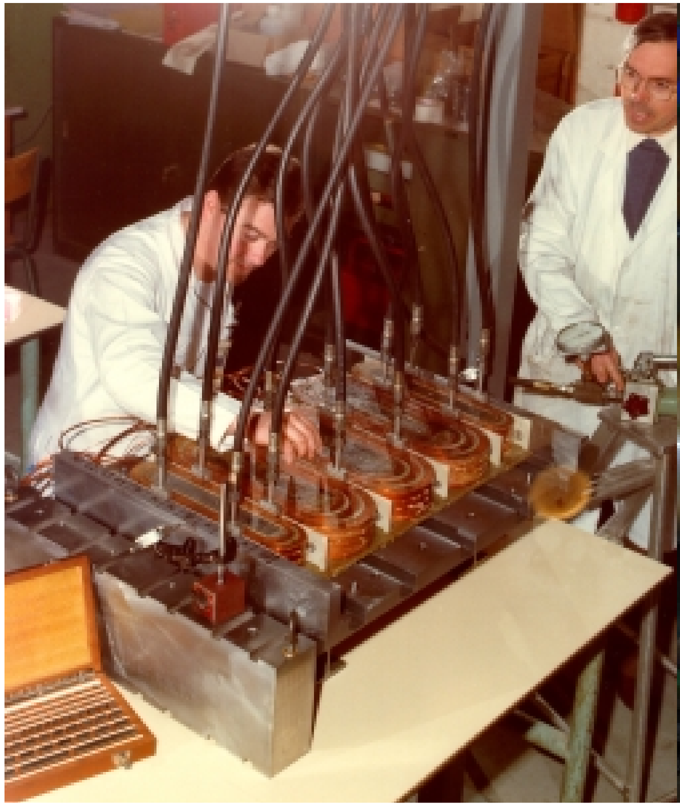


Winding of a Wiggler Coil at CEA/Saclay (Courtesy J. Pérot)

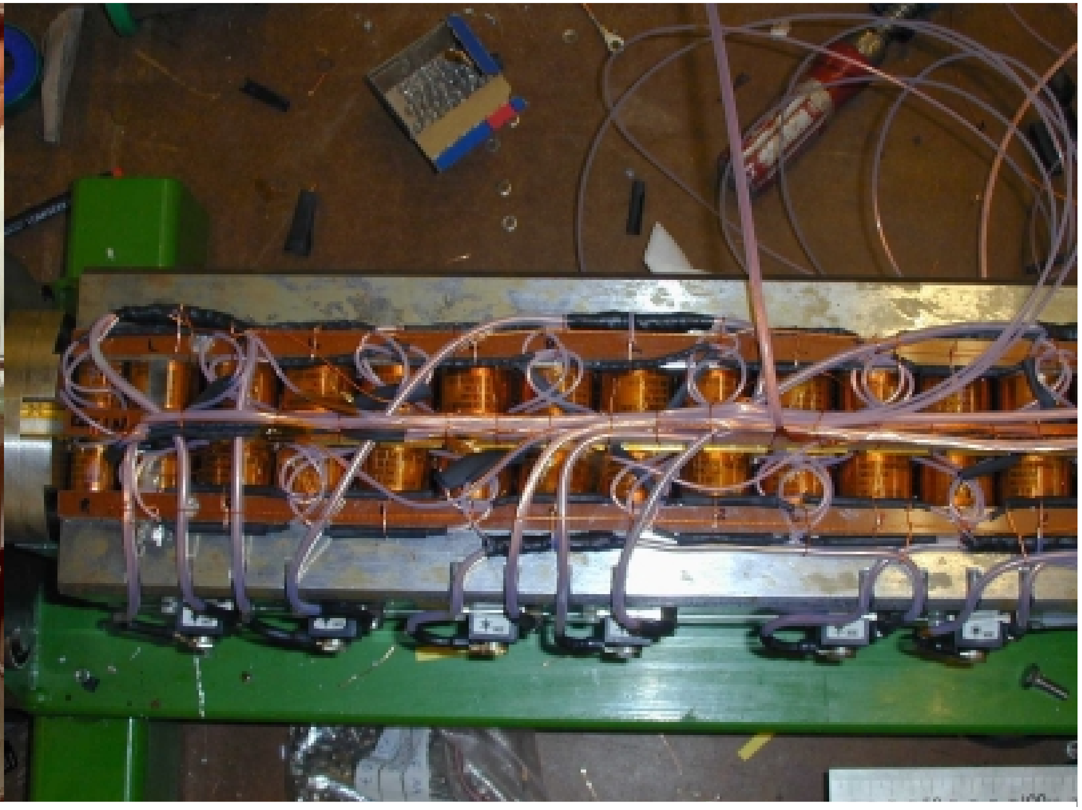
Wiggler Magnets (4/4)

- The coils of a given pair are mounted symmetrically on top and bottom of the beam tube with their main axes perpendicular to the beam axis.
- The coils of adjacent pairs are supplied with currents of opposite polarity to produce the sine-like field.

Examples of Wiggler Magnets



Top (or Bottom) Coil
Assembly of 5-Pole
Wiggler for LURE
(Courtesy J. Pérot)



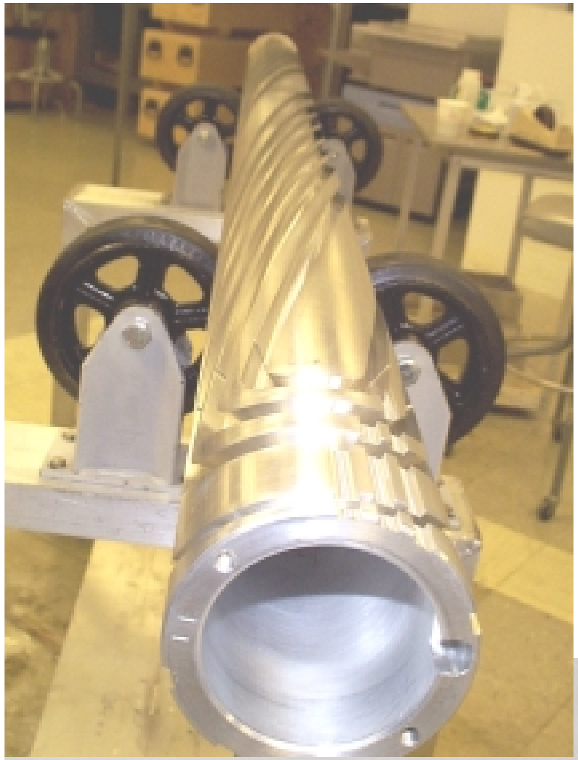
Partial View of 49-Pole
Wiggler for MAX-II
(Courtesy G. LeBlanc)

Helicoidal Magnets

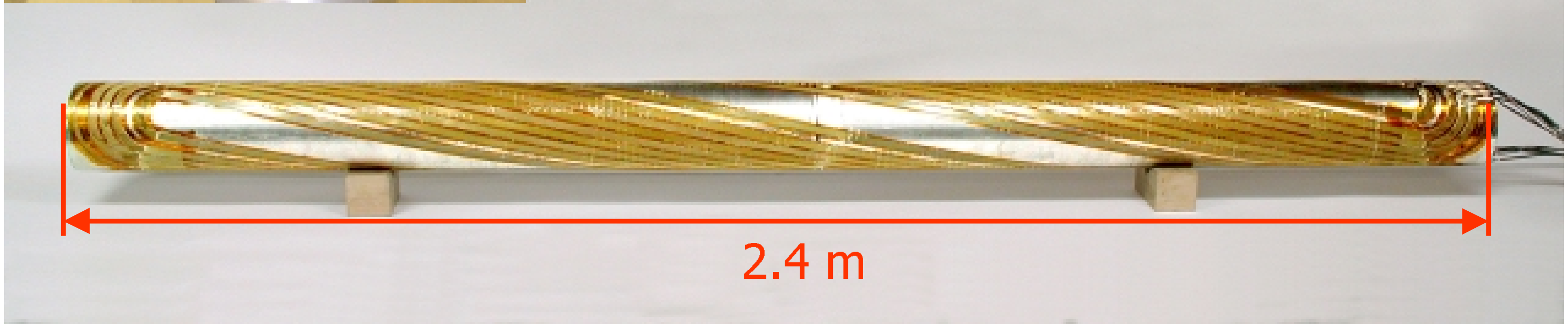
- An helicoidal magnet is designed to produce a dipole field that rotates in the vertical plane by 360° over a given distance along the magnet axis.
- In the case of protons, the field rotation results in a polarization of the protons' spins, that is useful for certain types of experiments.
- The production of a rotating field requires sophisticated design algorithms and manufacturing procedures.

RHIC Helicoidal Magnets

- In the case of the superconducting helicoidal magnets built for the Relativistic Heavy Ion Collider (RHIC), the conductors are wound into grooves precisely machined in a cylindrical mandrel positioned around the beam tube.



(Courtesy E. Willen)

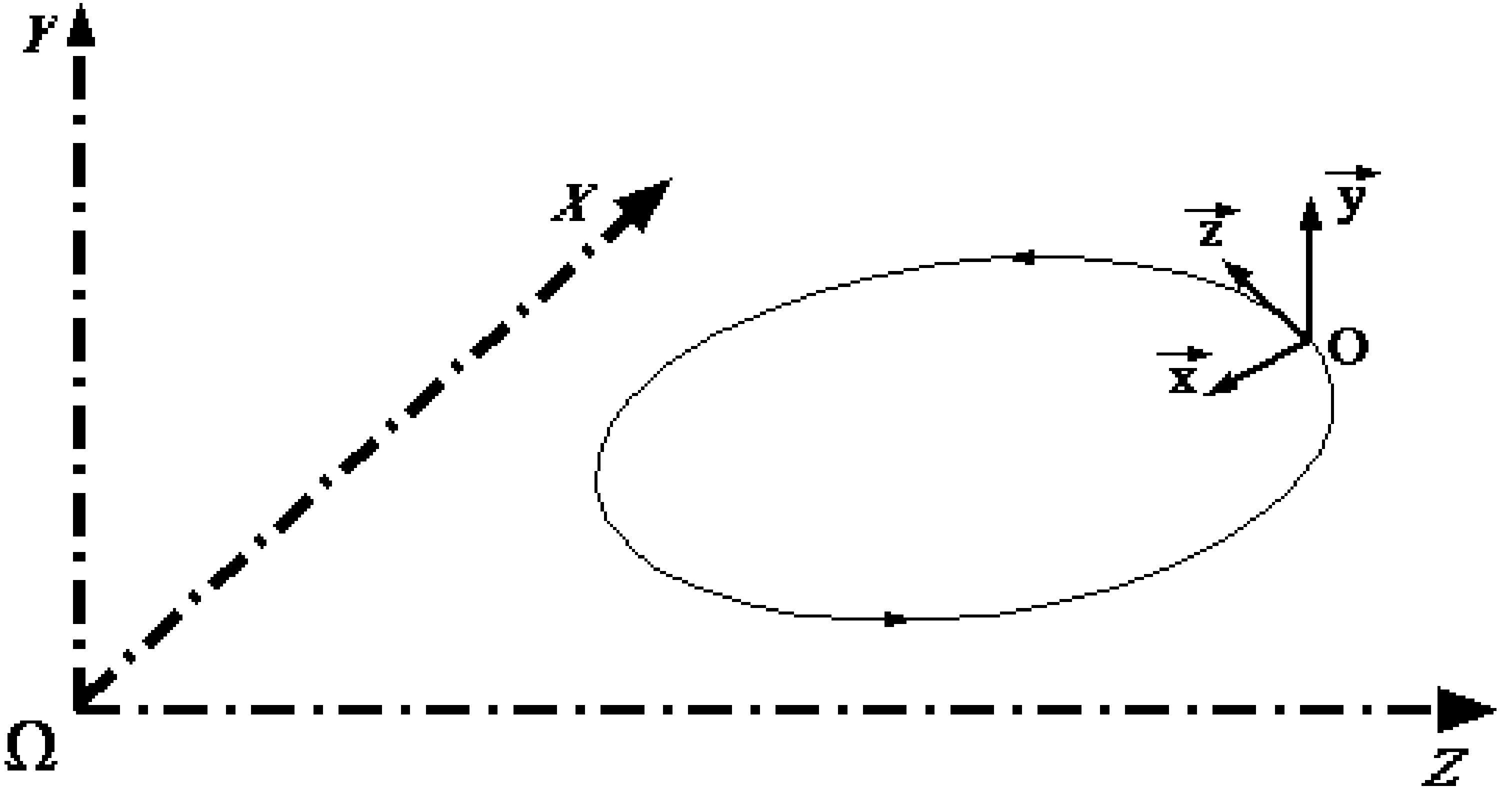


Contents

Contents

- **Dipole and Quadrupole Magnets**
  - **Coordinate Systems**
  - **Dipole Magnets**
  - **Quadrupole Magnets**

Coordinate Systems



- The *x*-axis defines the horizontal direction.
- The *y*-axis defines the vertical direction.
- The *z*-axis corresponds to the main direction of particle motion.

Contents

- **Dipole and Quadrupole Magnets**
    - Coordinate Systems
    - **Dipole Magnets**
    - Quadrupole Magnets

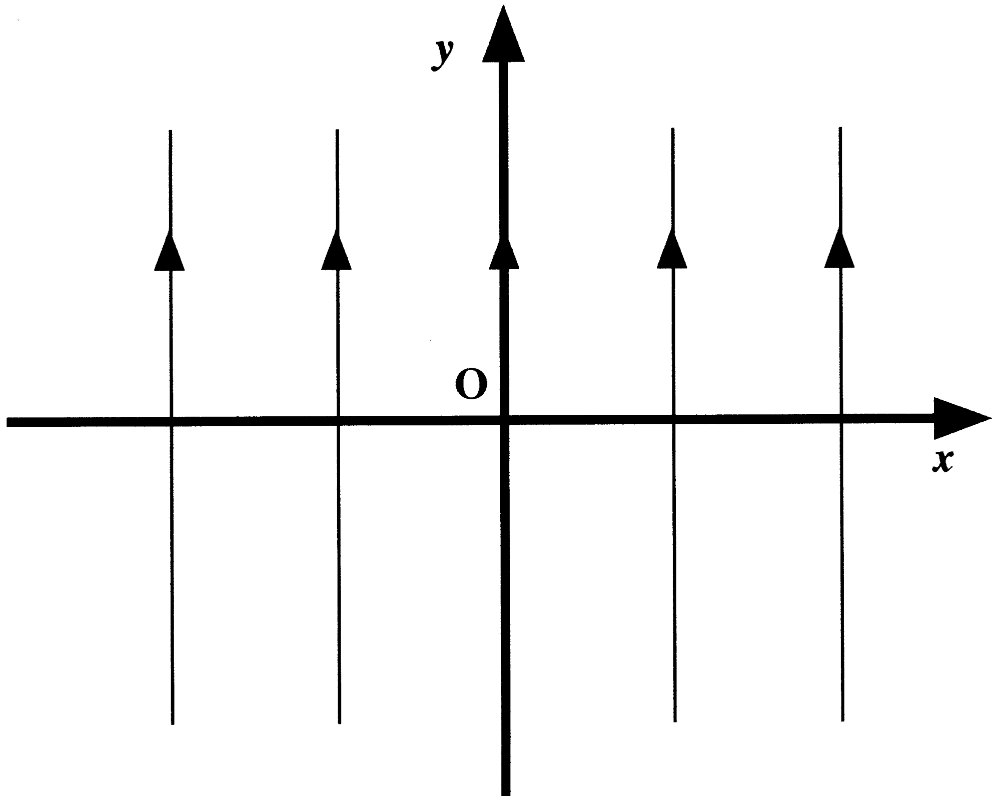
Definition

- An ideal normal dipole magnet whose center is positioned at O is a magnet, which, within its aperture produces an uniform magnetic flux density parallel to the *y*-axis and such that

$$B_x = 0 \qquad B_y = B_1 \qquad \text{and} \qquad B_z = 0$$

where B_x, B_y and B_z are the *x*-, *y*- and *z*-components of the magnetic flux density, and B_1 is a constant referred to as the *dipole field strength.*

Field Lines



- The field lines of an ideal normal dipole magnet are straight lines parallel to the *y*-axis.

Effects on Beam

- A charged particle traveling along the direction of the *z*-axis through the aperture of a normal dipole magnet of length, l_{dip}, describes an arc of circle parallel to the horizontal $(\vec{\mathrm{x}},\vec{\mathrm{z}})$ plane, and of radius of curvature, χ.
- The angular deflection, ϕ_{dip}, of the particle trajectory can be estimated as

$$\phi_{\text{dip}} \approx \frac{l_{\text{dip}}}{\chi}$$

Here, ϕ_{dip} is in radians, and l_{dip} and χ are in meters.

Example: LHC Dipole Magnets

- The effect of a dipole magnet on a beam of charged particles can be compared to the effect of a prism on a light ray.
- For the storage/collision phase of LHC, we have

  $l_{\text{dip}} = 14.2$ m and $\chi = 2784.32$ m

  (yellow book design).

  It follows that

  $\phi_{\text{dip}} \approx 5.1$ mrad.

  Hence, a full (2π) rotation requires a total of

  $2\pi/\phi_{\text{dip}} \approx 1232$

  arc dipole magnets.

Contents

- **Dipole and Quadrupole Magnets**
  - Coordinate Systems
  - Dipole Magnets
  - **Quadrupole Magnets**

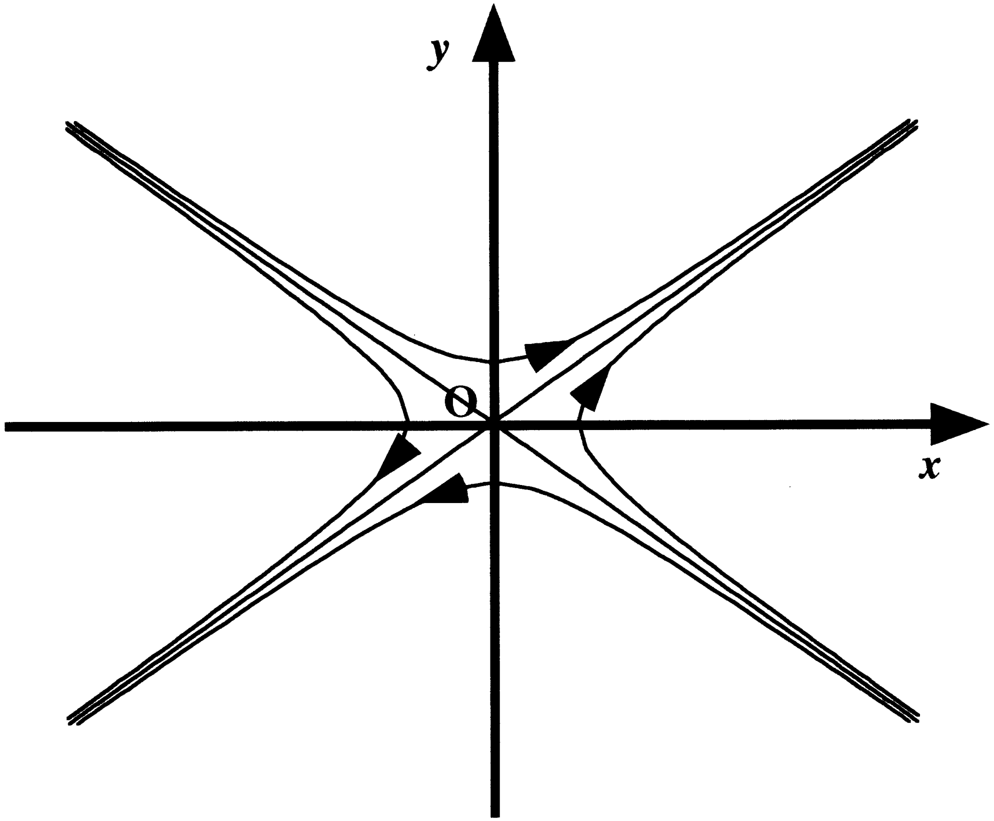
Definition

- An ideal normal quadrupole magnet whose center is positioned at O is a magnet, which, within its aperture produces a two dimensional magnetic flux density parallel to the $(\vec{x}, \vec{y})$ plane and such that

$$B_x = g\,y \qquad B_y = g\,x \quad \text{and} \quad B_z = 0$$

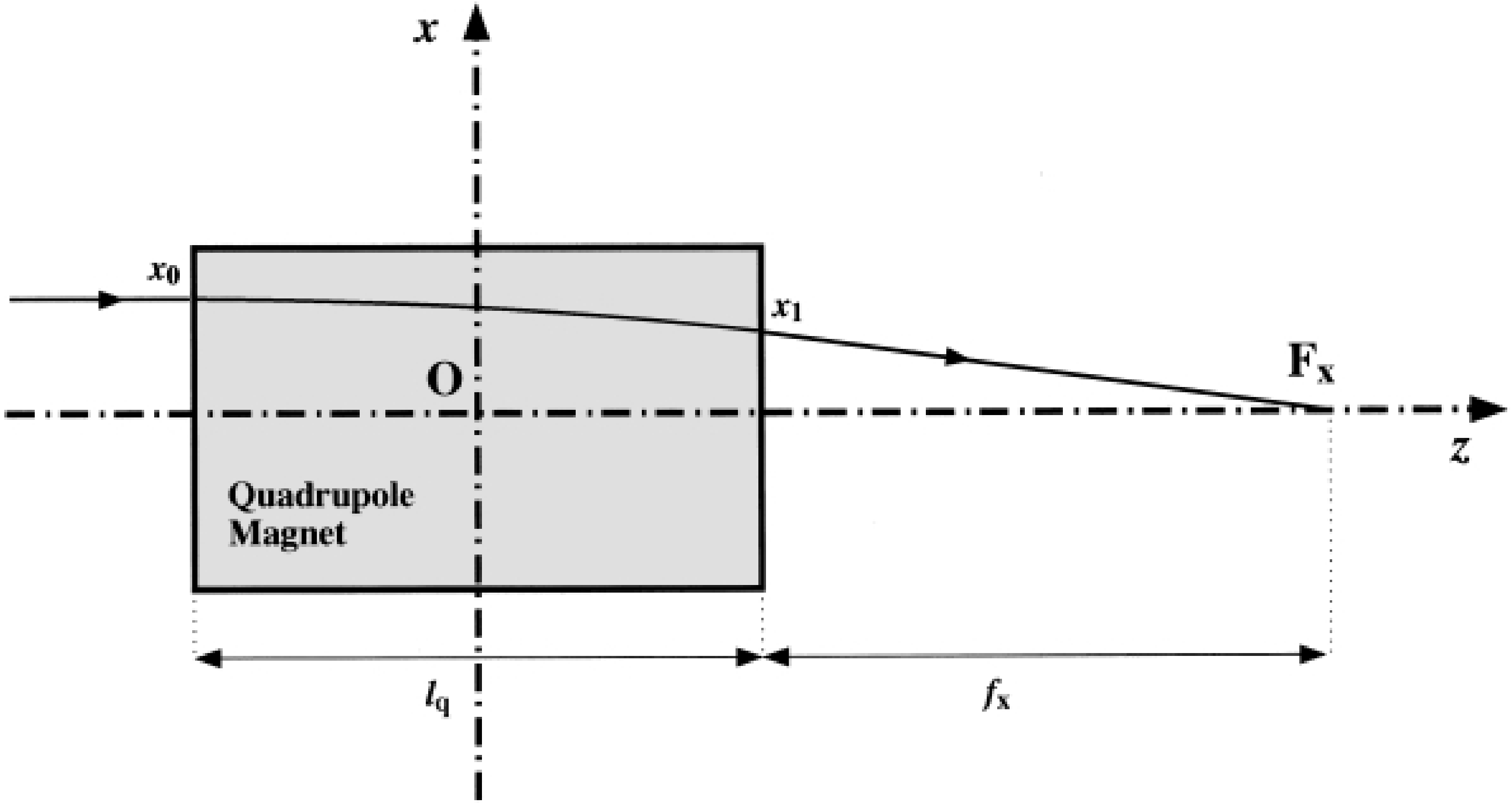
where B_x, B_y and B_z are the *x*-, *y*- and *z*-components of the magnetic flux density, and *g* is a constant referred to as the *quadrupole field gradient (T/m).*

Field Lines



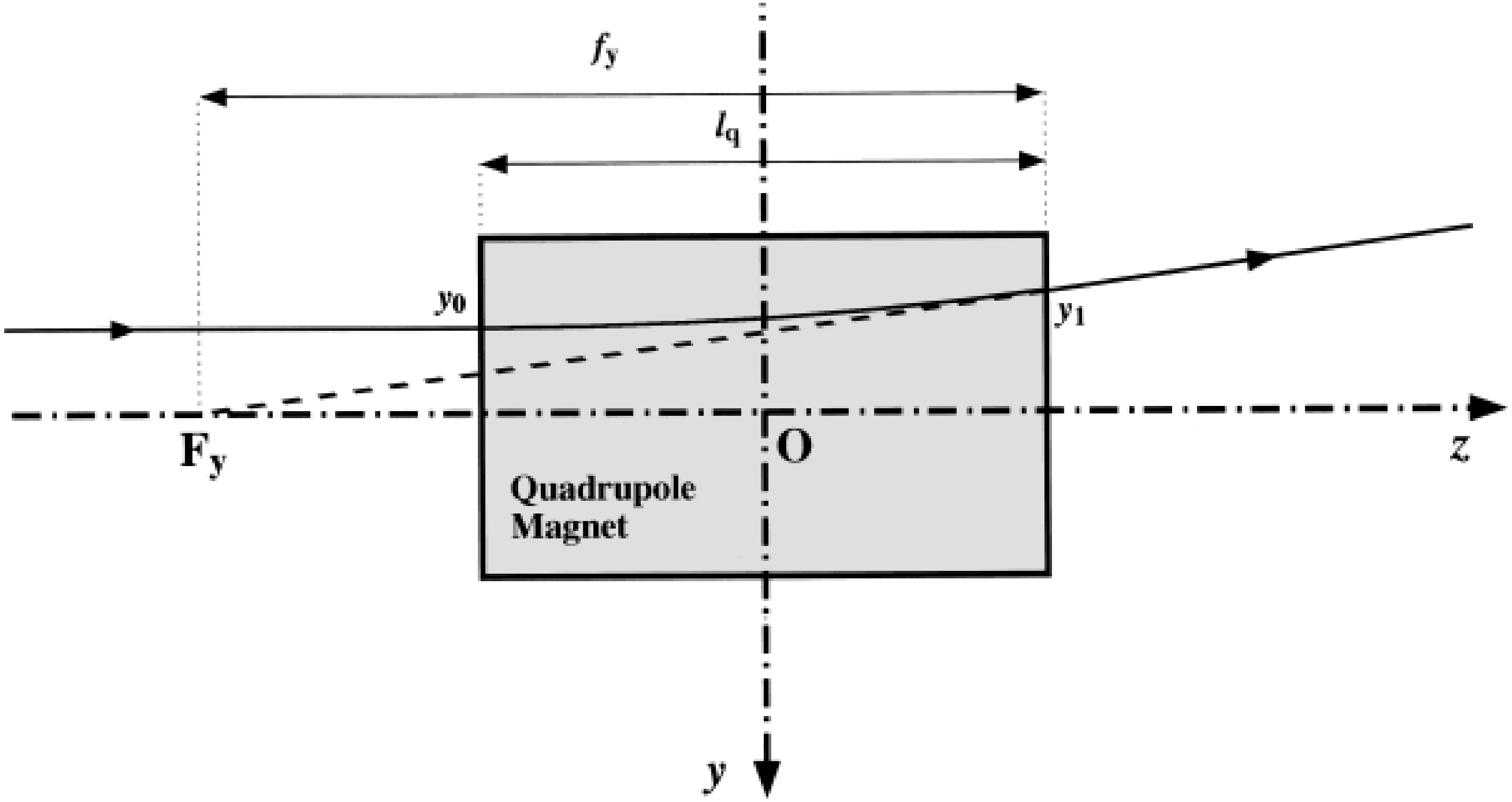
- The field lines of an ideal normal quadrupole magnet are hyperbolae of center O whose asymptotes are parallel to the first and second bisectors.

Effects on Beam (1/4)



- A beam of positively charged particles traveling along the direction of the *z*-axis through the aperture of a normal quadrupole magnet is horizontally focused and vertically defocused when *g* is positive.

Effects on Beam (2/4)



- Conversely, the beam is vertically focused and horizontally defocused when *g* is negative.

Effects on Beam (3/4)

- In reference to its action along the *x*-axis (on a beam of positively charged particles traveling along the positive *z*-direction), a magnet with a positive gradient is called a *focusing* quadrupole magnet, while a magnet with a negative gradient is called a *defocusing* quadrupole magnet.
- To obtain a net focusing effect along both *x*- and *y*-axes, focusing and defocusing quadrupole magnets must be alternated in the magnet lattice.

Effects on Beam (4/4)

- The effects of focusing/defocusing quadrupole magnets on a beam of charged particles are similar to those of convex/concave lenses on a light ray.

Focal Lengths (1/2)

- By analogy with optical lenses, the focusing effect of a normal quadrupole magnet of length, l_{quad}, can be characterized by the focal length, f_{x}, given by

$$f_{\mathrm{x}} \approx \frac{1}{\sqrt{\kappa_{\mathrm{g}}}} \cot\left(\sqrt{\kappa_{\mathrm{g}}}\, l_{\mathrm{quad}}\right)$$

where κ_{g} is the normalized gradient defined as

$$\kappa_{\mathrm{g}} = \frac{q_{\mathrm{e}}\, g}{m_{\mathrm{q}}\, \gamma_{\mathrm{q}}\, v_{\mathrm{q}}} \approx \frac{0.3\, q_{\mathrm{e}}\, g}{\varepsilon_{\mathrm{Gev}}}$$

Here κ_{g} is in (rad/m)^2, q_{e} is in units of electron charge, g is in teslas per meters and $\varepsilon_{\mathrm{GeV}}$ is in GeV.

Focal Lengths (2/2)

- Similarly, the defocusing effect of a normal quadrupole magnet can be characterized by the focal length, f_y, given by

$$f_{\mathrm{y}} \approx \frac{-1}{\sqrt{\kappa_{\mathrm{g}}}} \coth\left(\sqrt{\kappa_{\mathrm{g}}}\, l_{\mathrm{quad}}\right)$$

Note that f_x and f_y are computed from the magnet end where the beam exits.

Example: LHC Quadrupoles

- For the storage/collision phase of LHC we have

  $g = 223$ T/m, $l_{\mathrm{quad}} = 3.1$ m, and $\varepsilon_{\mathrm{GeV}} = 7000$
  (yellow book design).

  It follows that

  $\kappa_{\mathrm{g}} \approx 0.01\ (\mathrm{rad/m})^2$

  $f_{\mathrm{x}} \approx 32.7\ \mathrm{m}$
  $f_{\mathrm{y}} \approx -34.8\ \mathrm{m}$

- The LHC arcs count a total number of 386 quadrupole magnets.