MAGNET SYSTEMS FOR LARGE PARTICLE ACCELERATORS

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Contents

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

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Accelerator Components

- 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.

Particle Acceleration (1/2)

- 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 $\vec{E}$.

Particle Acceleration (2/2)

- In most particle accelerators, the accelerating stations are made-up of Radio Frequency (RF) cavities, which can be superconducting *(see dedicated Technology Course*).
- RF cavities are crucial components of *linear accelerators,* where particle bunches travel only once through the machine along a mostly straight trajectory.

Particle Guiding (1/2)

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

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

- $\vec{F_L}$ 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.

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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.

Basic Equations (1/3)

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

$$\chi = \frac{m_q \gamma_q v_q}{qB}$$

where, m_q is the particle mass at rest, v_q and B are the amplitudes of $\vec{v}_q$ and $\vec{B}$, and γ_q is the lorentz factor.

Basic Equations (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.

Basic Equations (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

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

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

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

Bending Radius vs. Bending Field

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

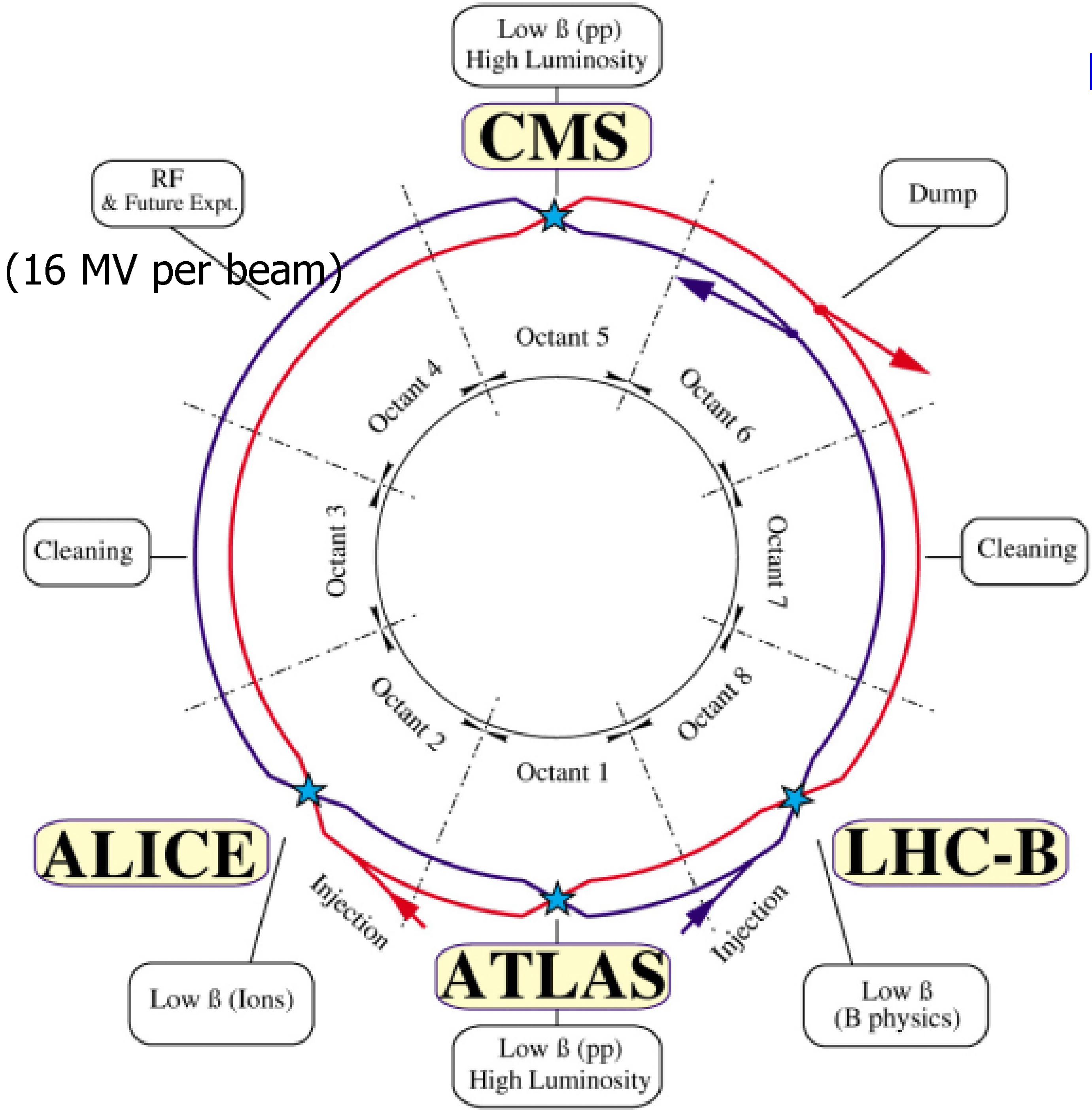
B	χ	Circumference
2 T	167 km	1047 km
8 T	42 km	262 km
12 T	28 km	174 km

- It appears that, when dimensioning a circular accelerator, a trade-off must be found between the availability of land and the tunneling costs, on one hand, and the feasibility and the costs of the electromagnets, on the other hand.

Example: LHC at CERN (1/2)

- LHC is a proton-proton collider under construction at CERN.
- It will be installed in an existing underground tunnel with a circumference of ~27 km.
- It will be divided into 8 bending arcs, separated by 8 ~530-m-long insertion regions.
- Two counter-rotating proton beams will be circulated around the eight arcs and will cross at the middle of four insertion regions.

Layout of Large Hadron Collider (LHC) at CERN



Example: LHC at CERN (2/2)

- The 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

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

- Commissioning is scheduled for 2005.

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Magnet Types

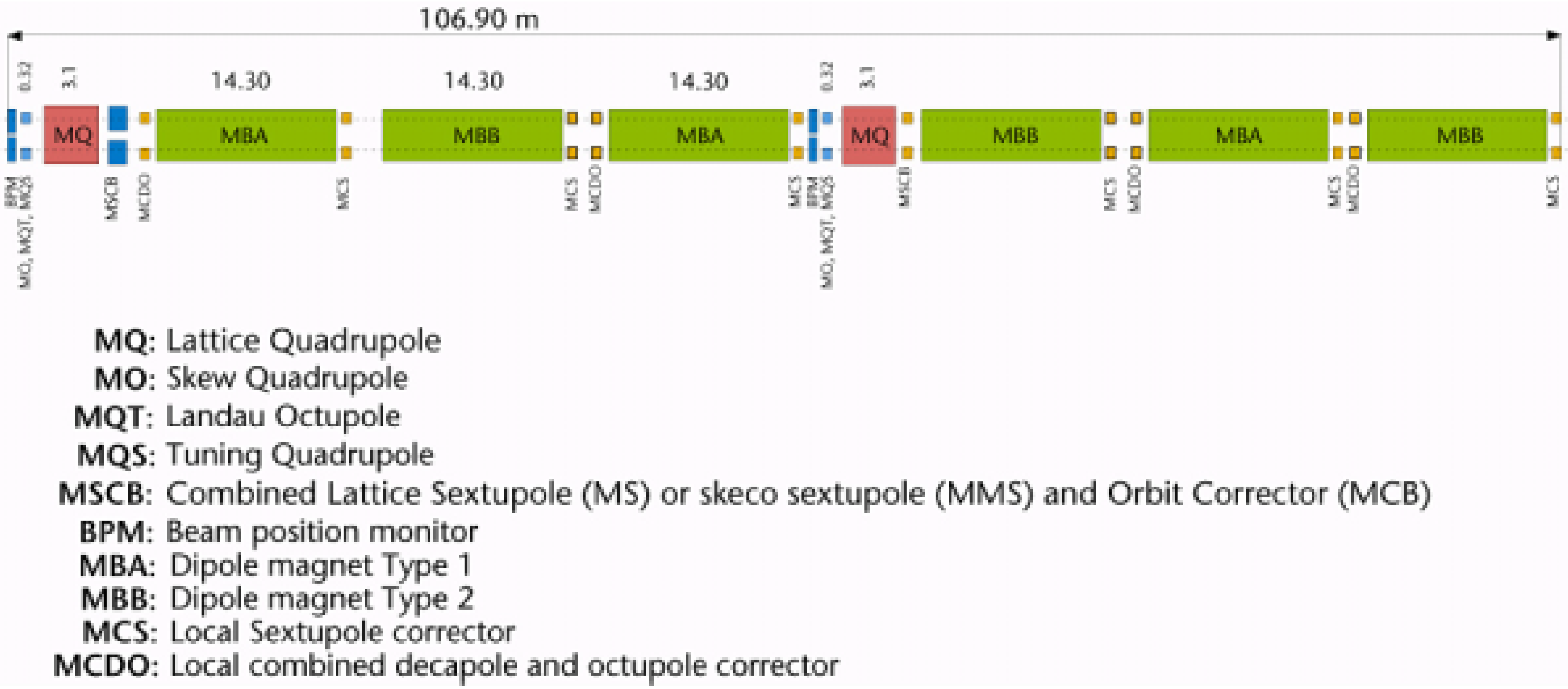
- Four types of magnet systems can be found in large particle accelerators
  - arc magnets
    (to control beam trajectory in accelerator arcs),
  - insertion and final-focusing magnets
    (to handle beam near injection, extraction and interaction points),
  - corrector magnets
    (to fine-tune beam optics and correct field distortions of main magnets),
  - detector magnets
    (embedded in detector arrays surrounding targets or collision points).

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.



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

Arc Magnets (3/3)

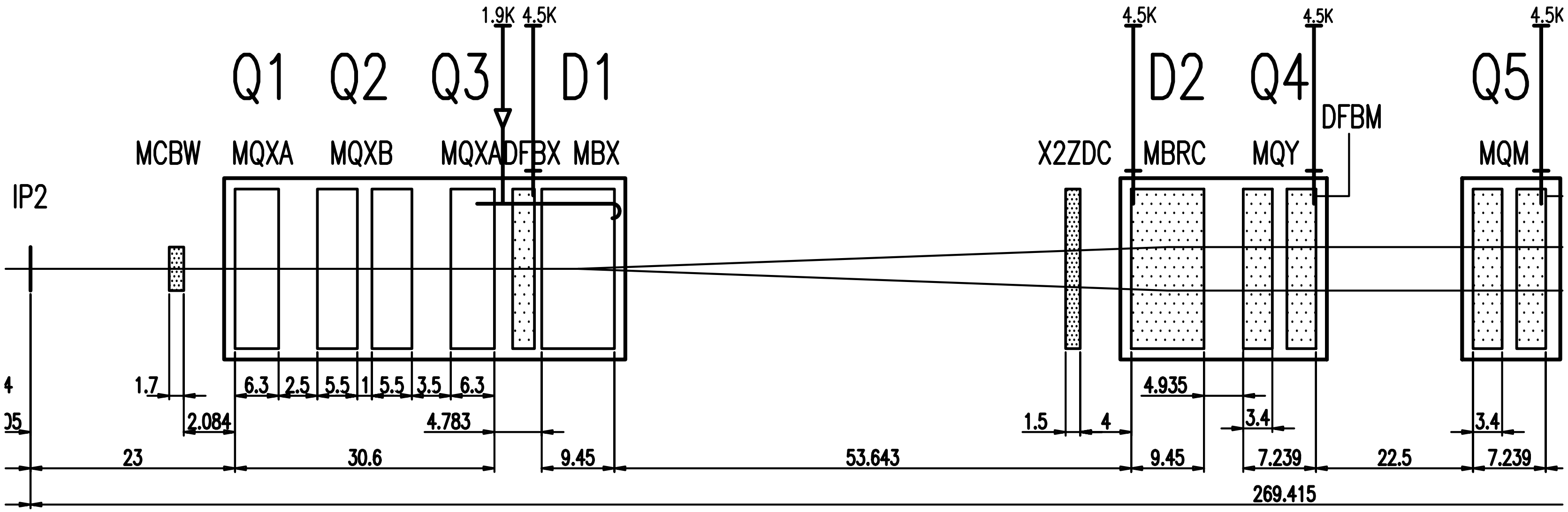
- Large circular machines require a large number of arc magnets (*e.g.*, 1232 dipole magnets and 386 quadrupole magnets for LHC).
- They must be mass-produced in industry.
- They are the most expensive components of the machine.

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

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)

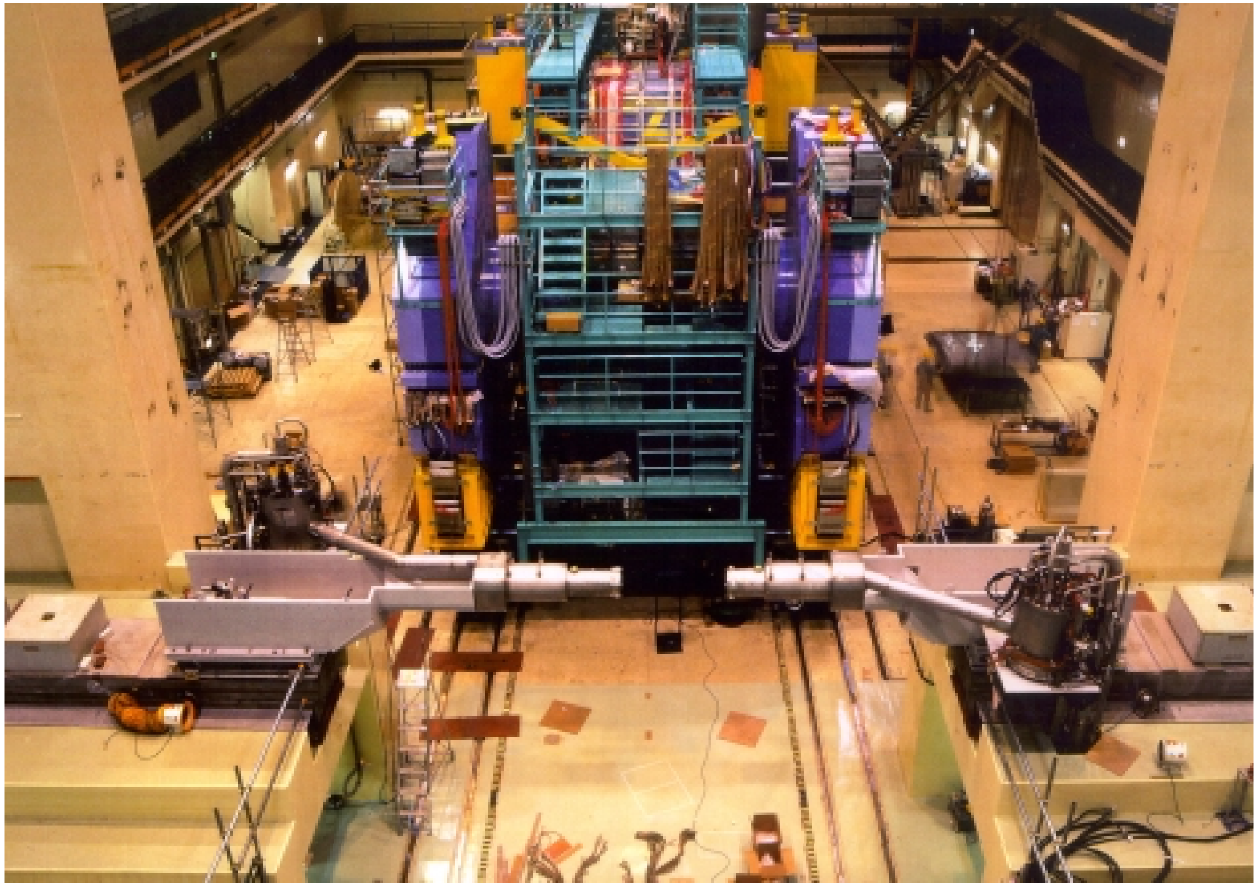


Proposed Magnet Lattice For the Right-Hand Side of #2 Interaction Point of LHC, showing from left to right:

- 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, ...).

$\Longrightarrow$ They can be used as a test bench for more innovative designs.

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.

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.

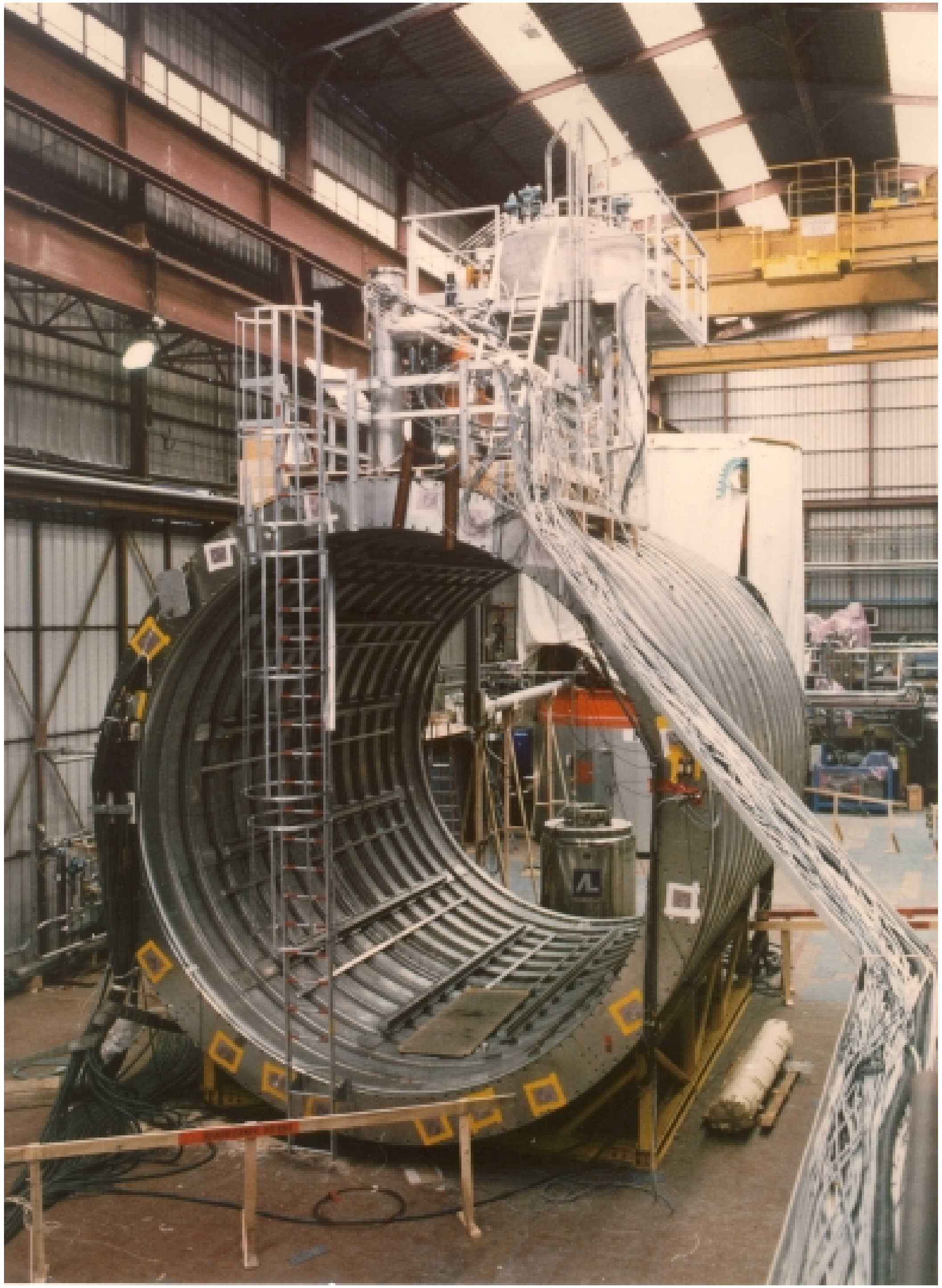
Detector Magnets (2/2)

- 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.

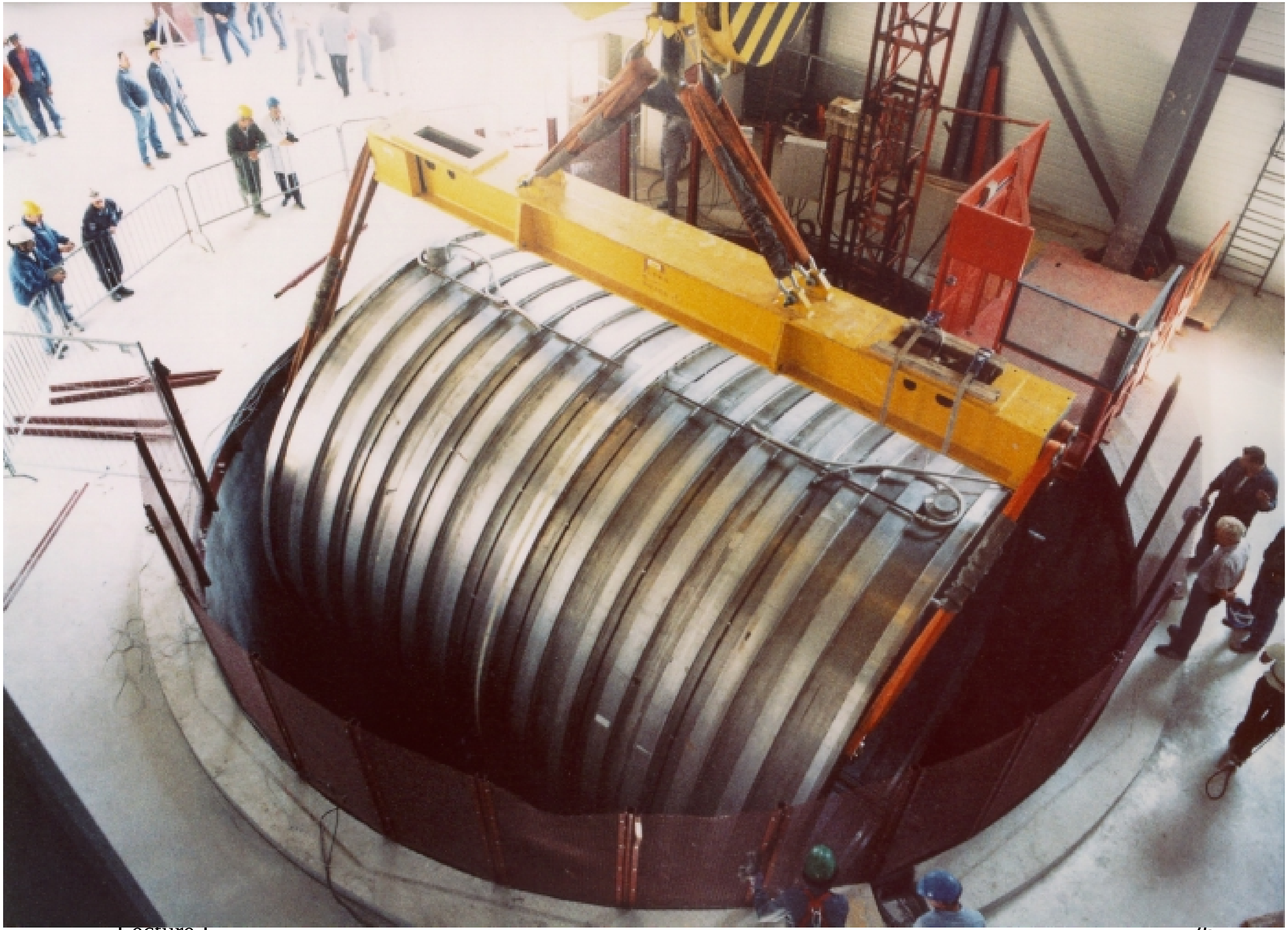
Winding of ALEPH Solenoid at CEA/Saclay.



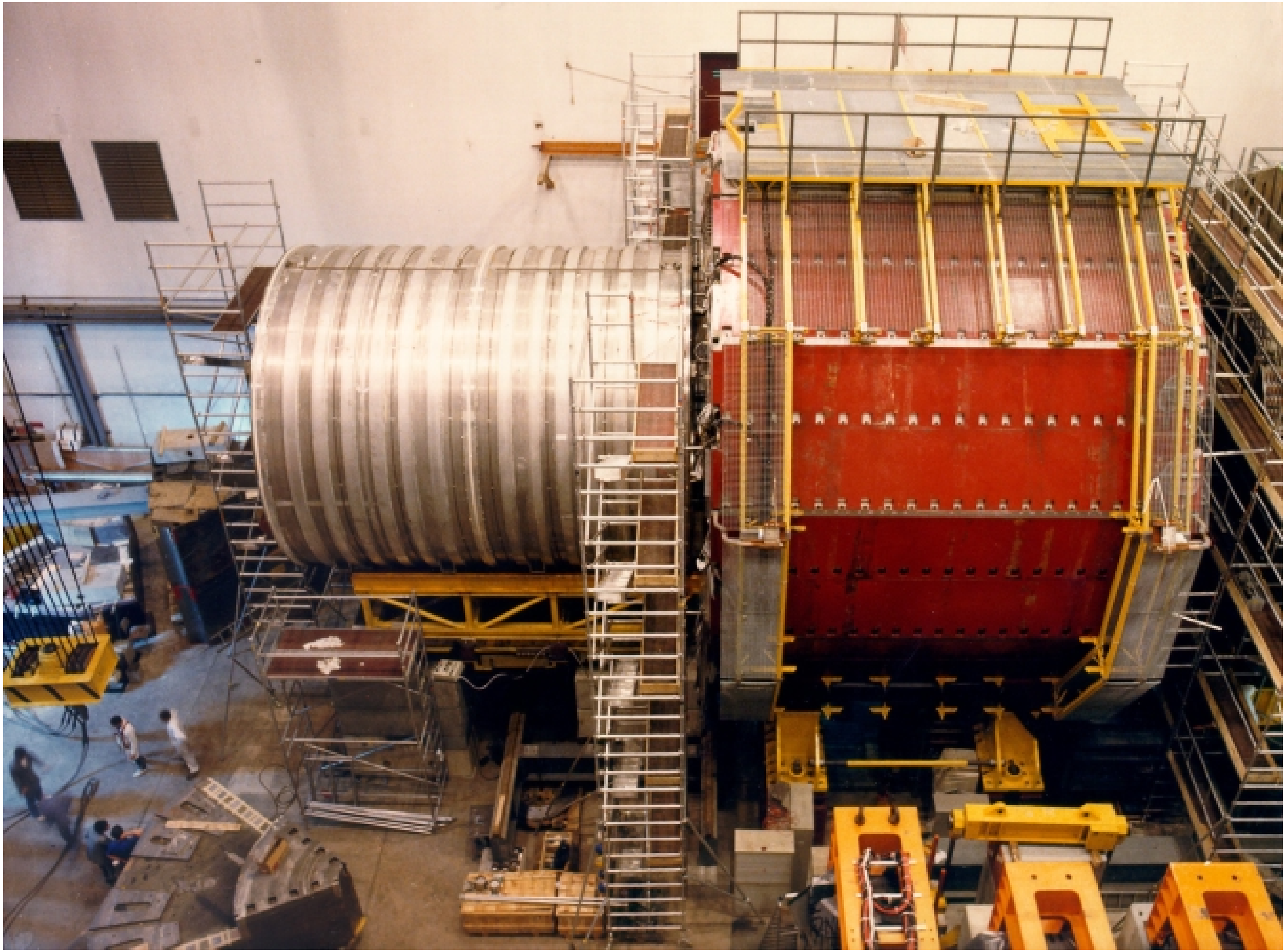
ALEPH Solenoid Undergoing Cold Tests at CEA/Saclay.

ALEPH Solenoid Upon its Departure From CEA/Saclay.

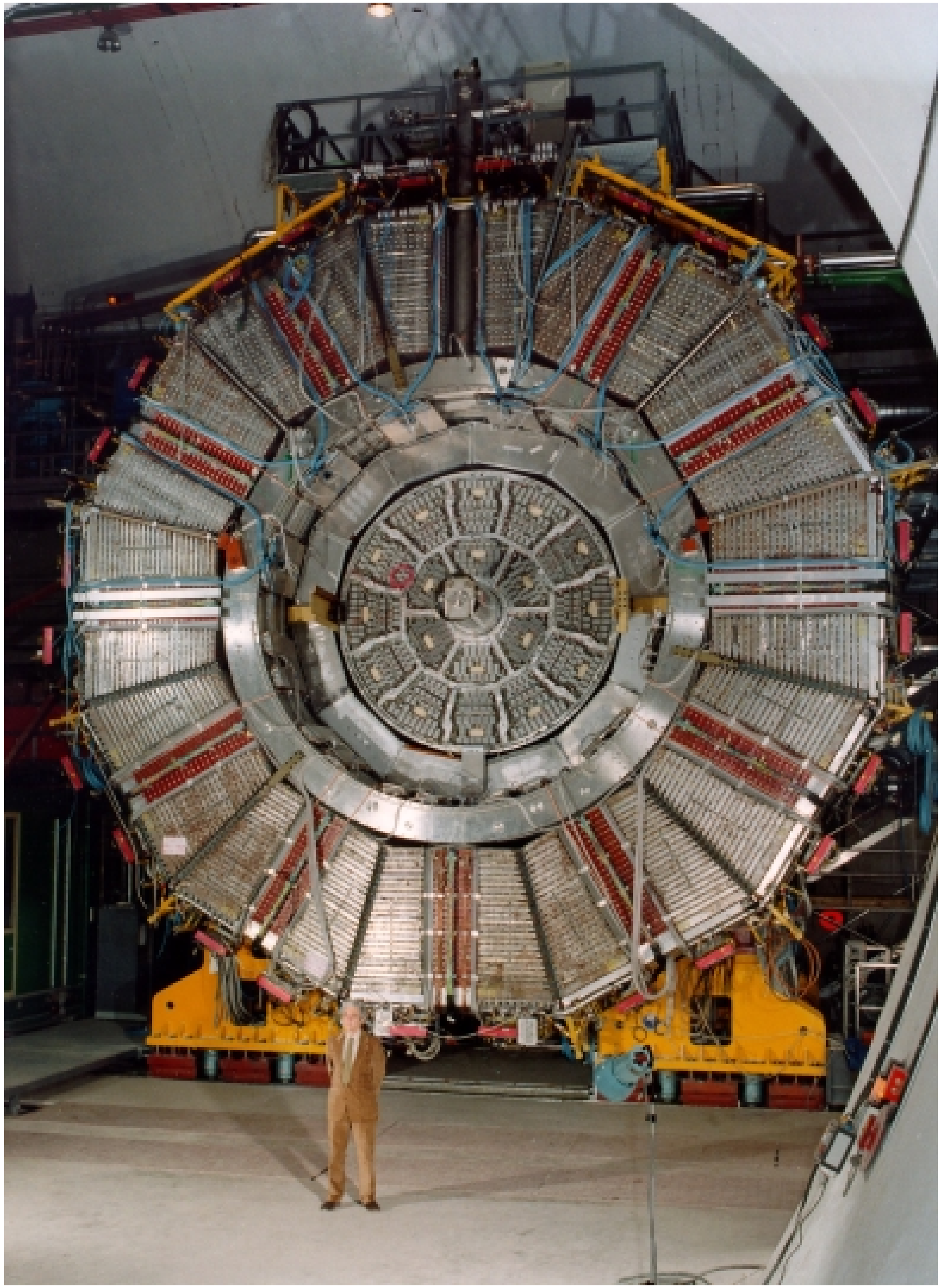
ALEPH Solenoid En Route to CERN.



Lowering of ALEPH Solenoid Into Experimental Pit at CERN.



Insertion of ALEPH Solenoid Into Experiment.



ALEPH Experiment at CERN
With its Embedded Solenoid.

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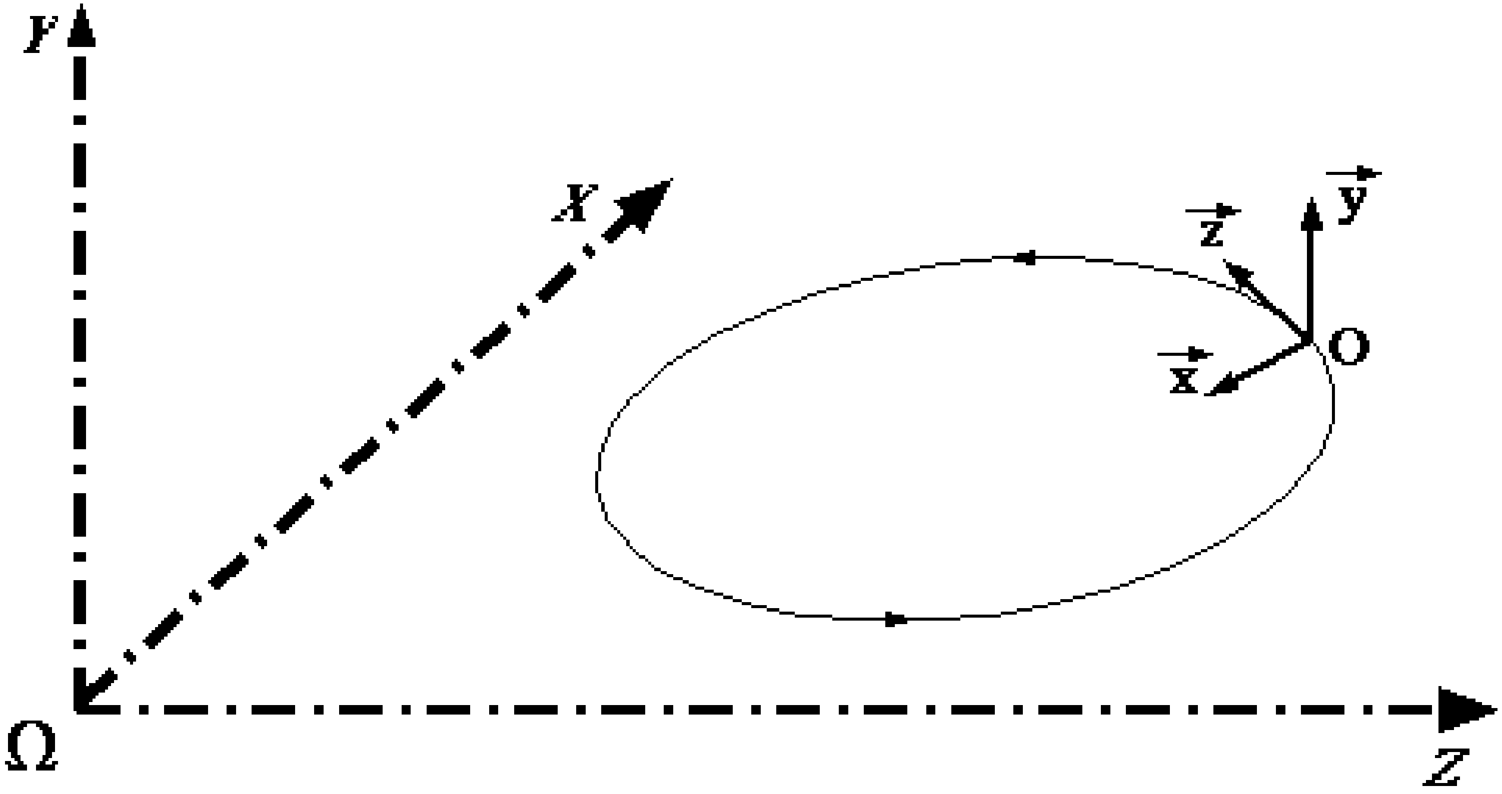
Coordinate Systems



- 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.

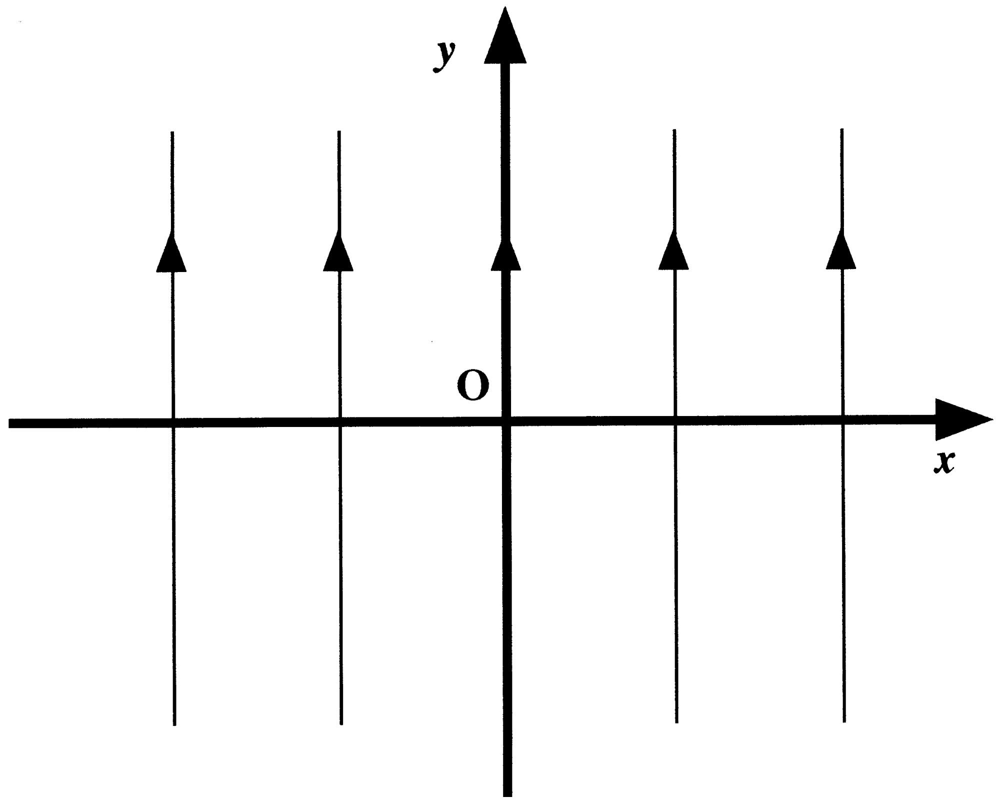
Dipole Magnets (1/4)

- 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 *z*-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.*

Dipole Magnets (2/4)



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

Dipole Magnets (3/4)

- 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 $(\vec{x}, \vec{z})$ plane, and of radius of curvature, χ.
- The angular deflection, ϕ_{dip}, of the particle trajectory can be estimated as

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

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

Dipole Magnets (4/4)

- 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_{dip} = 14.2 m and χ = 2784.32 m
  (yellow book design).

  It follows that

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

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

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

  arc dipole magnets.

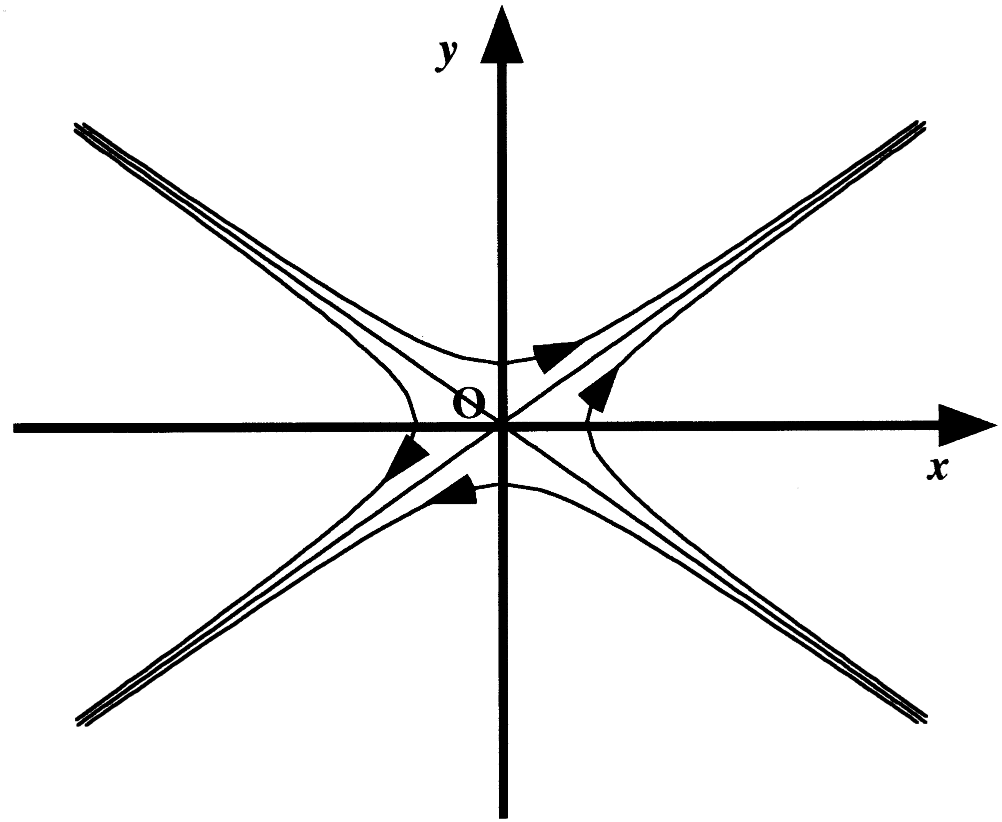
Quadrupole Magnets (1/6)

- 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

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

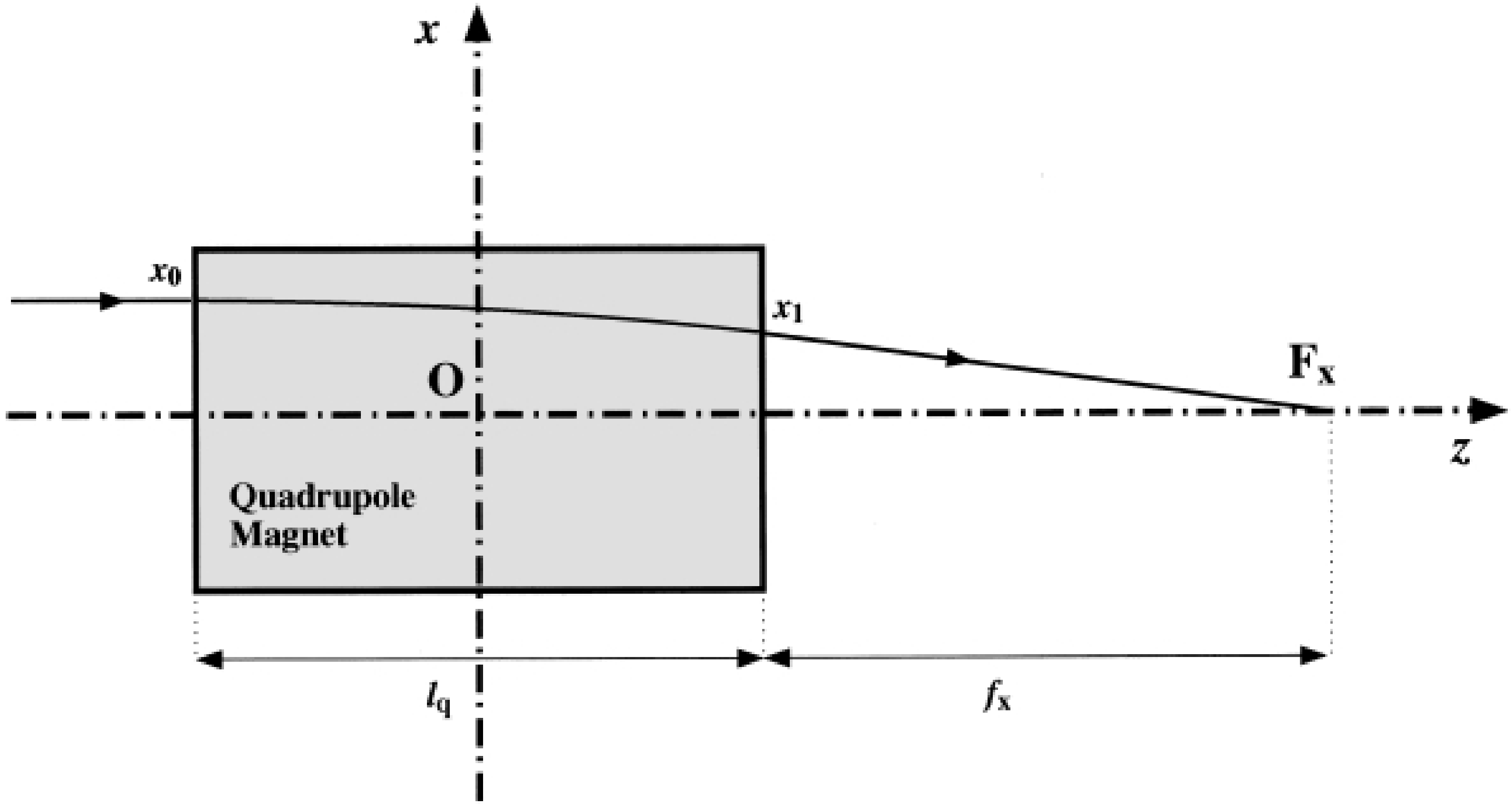
where B_x, B_y and B_z are the *x*-, *y*- and *z*-components of the magnetic flux density, and *g* is a constant referred to as the *quadrupole field gradient (T/m).*

Quadrupole Magnets (2/6)



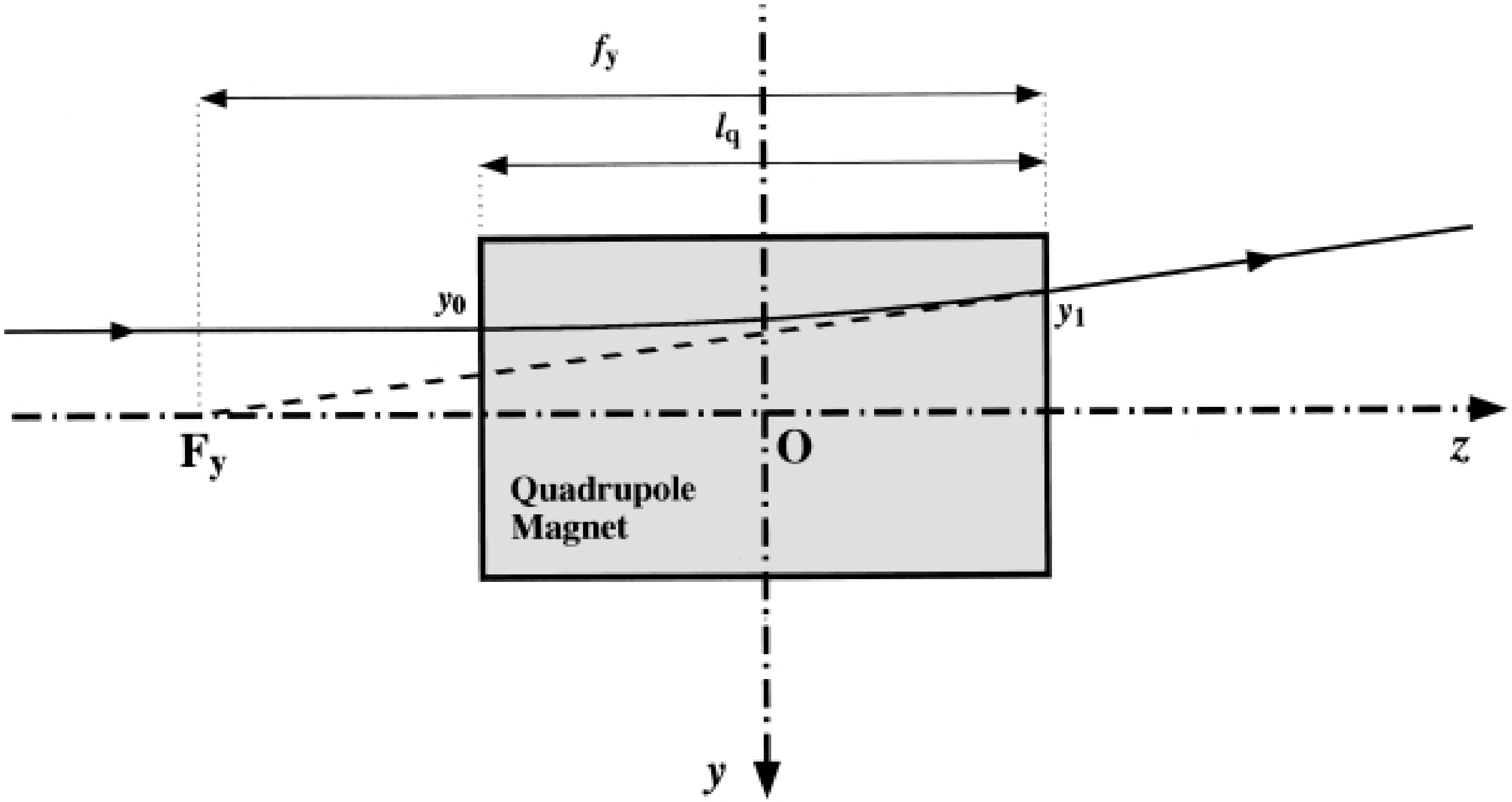
- The field lines of an ideal normal quadrupole magnet are hyperbolae of center O whose asymptotes are parallel to the first and second bisectors.

Quadrupole Magnets (3/6)



- 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.

Quadrupole Magnets (4/6)



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

Quadrupole Magnets (5/6)

- 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.

Quadrupole Magnets (6/6)

- 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.