Introduction to Accelerator Physics

Pedro Castro / Accelerator Physics Group (MPY)
Hamburg, 2 August 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Accelerator lectures framework in this Summer School

18th and 19th Aug.: Future accelerators:

- Future colliders for the energy frontier, K. Buesser
- Plasma accelerators, J. Osterhoff

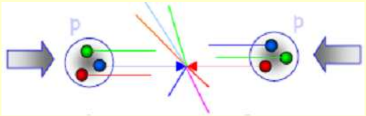
Today: focus on present day (and last 50 years) accelerator technology

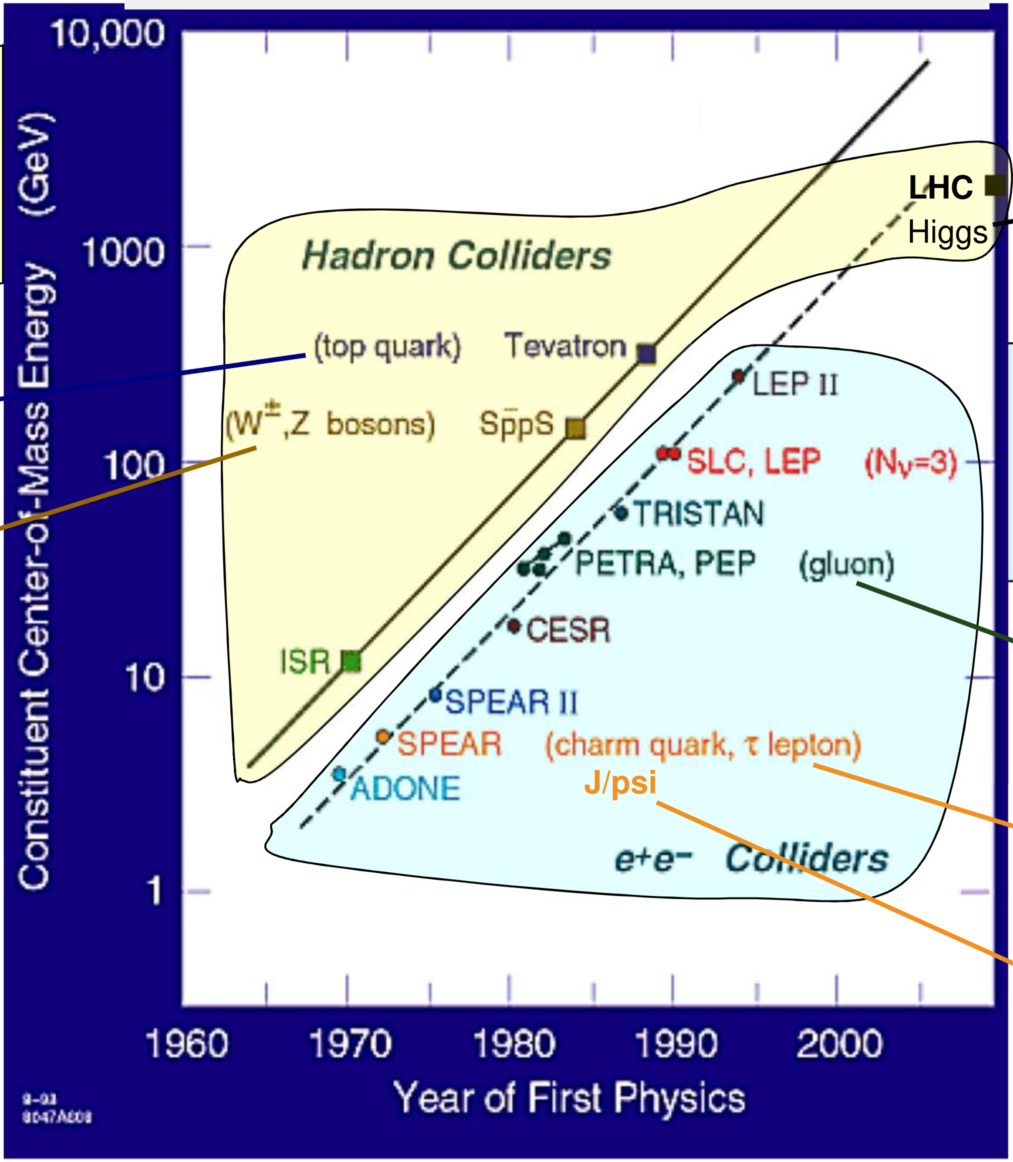
synchrotrons: machines for discoveries

Main HEP discoveries at synchrotrons in the last 50 years

Livingston plot (doubling E every 3.5 years)

hadron colliders:
$E_{cm} / 3$ quarks



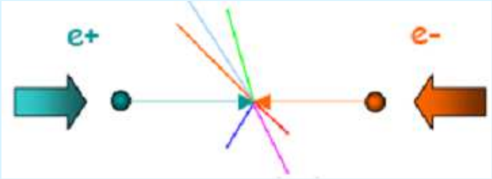


discovered 1995

discovered 1983
NP 1984

discovered 2012
NP 2013

e+e- colliders:



discovered 1979

discovered 1975
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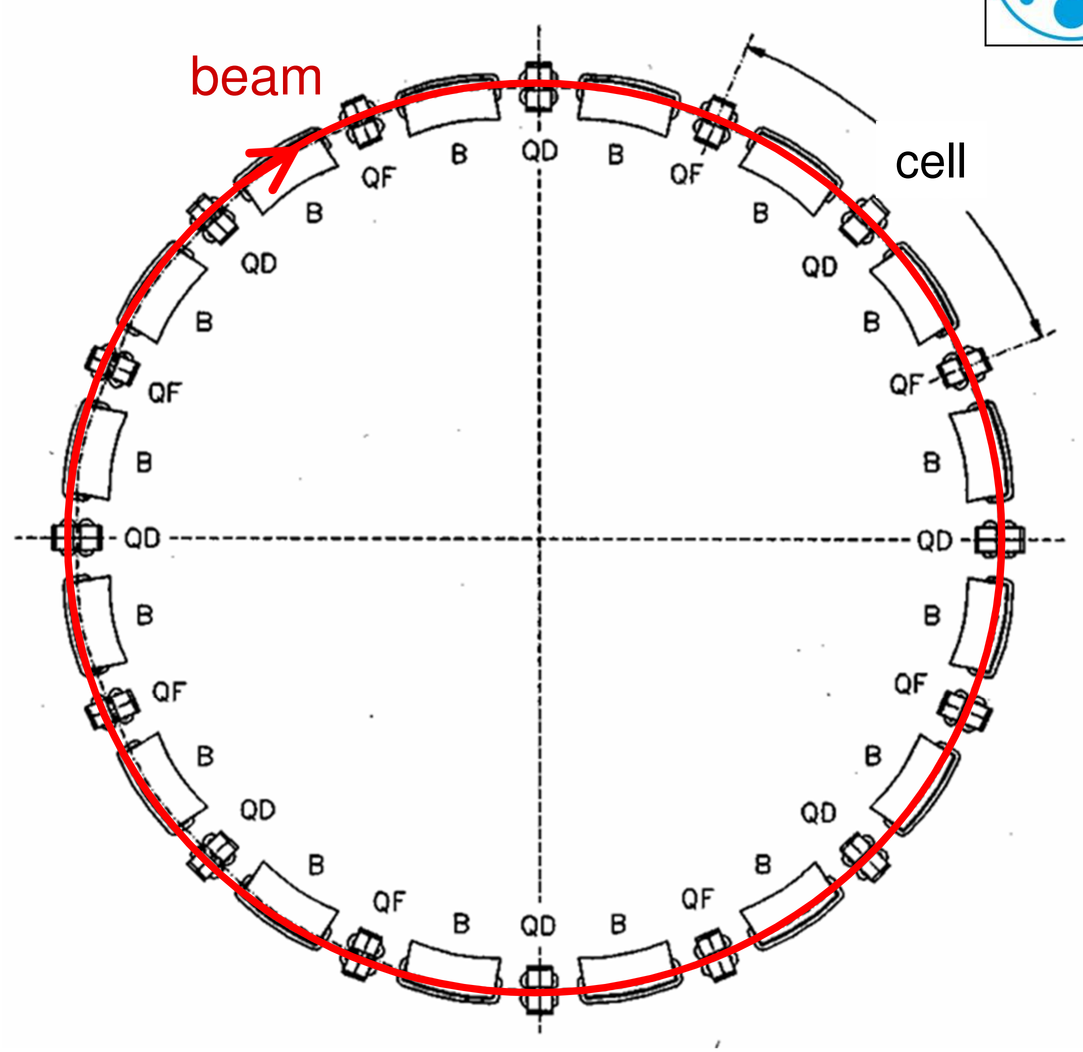
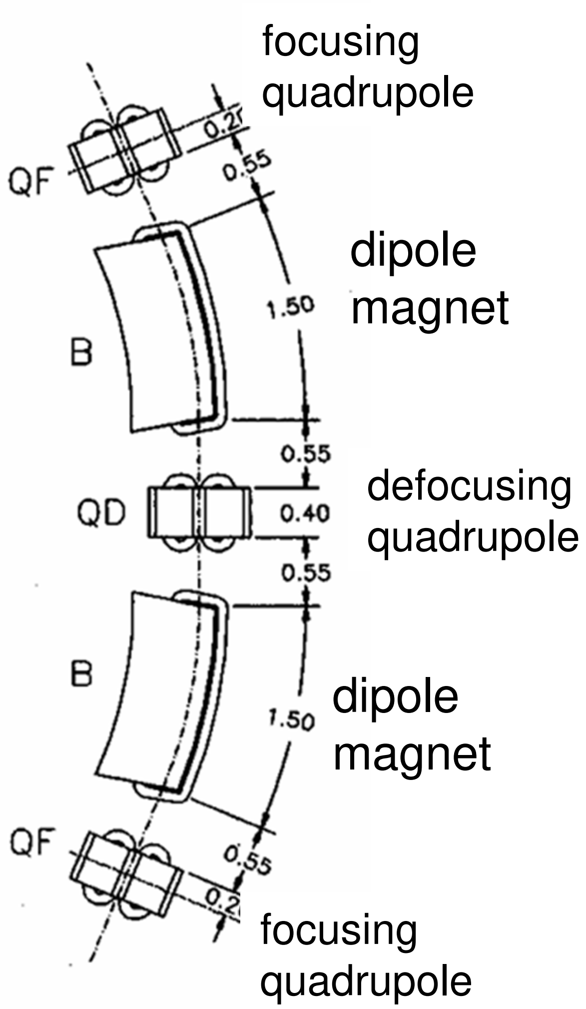
NP 1976

Scope of this lecture:

1. Why synchrotrons are called synchrotrons?



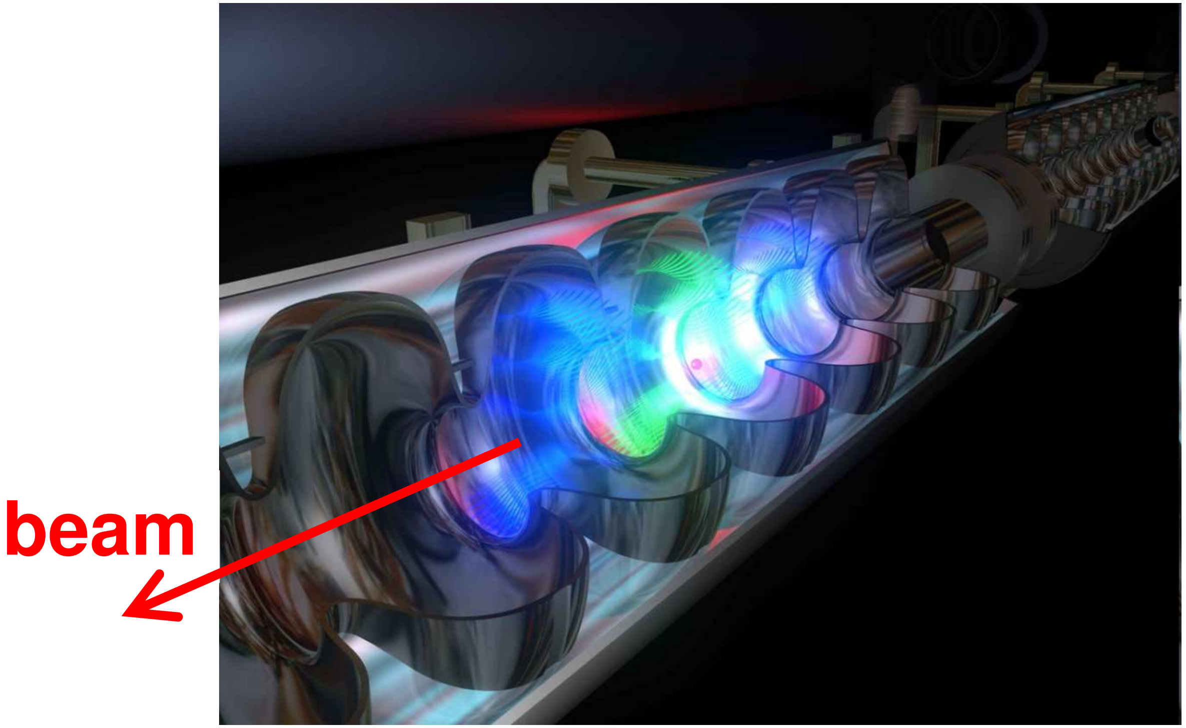


Scope of this lecture:

1. Why synchrotrons are called synchrotrons?

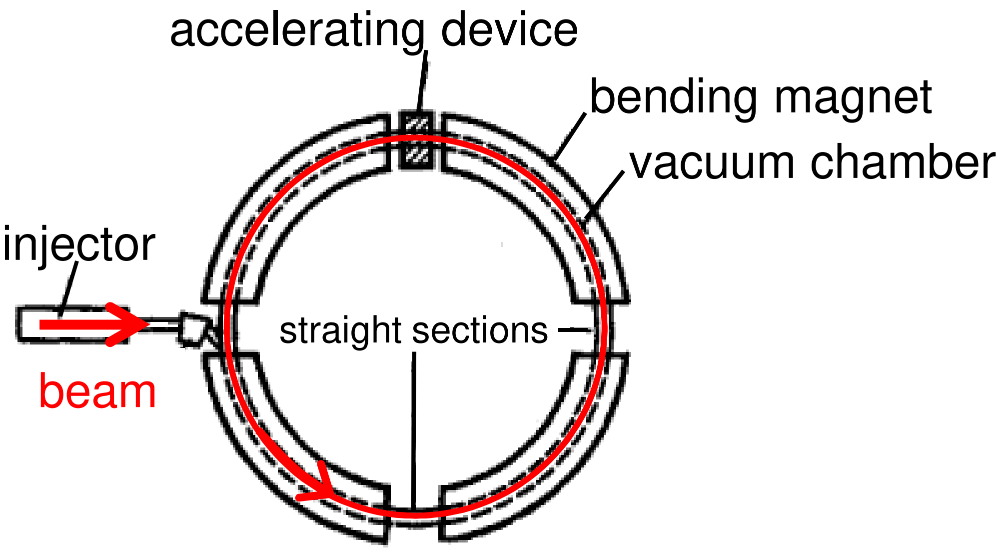
Key components and their challenges to reach high energies:

1. Dipole magnetic fields
2. Superconducting dipoles
3. (~~Focusing beams using quadrupole magnets~~)
4. Acceleration using radio-frequency electomagnetic fields



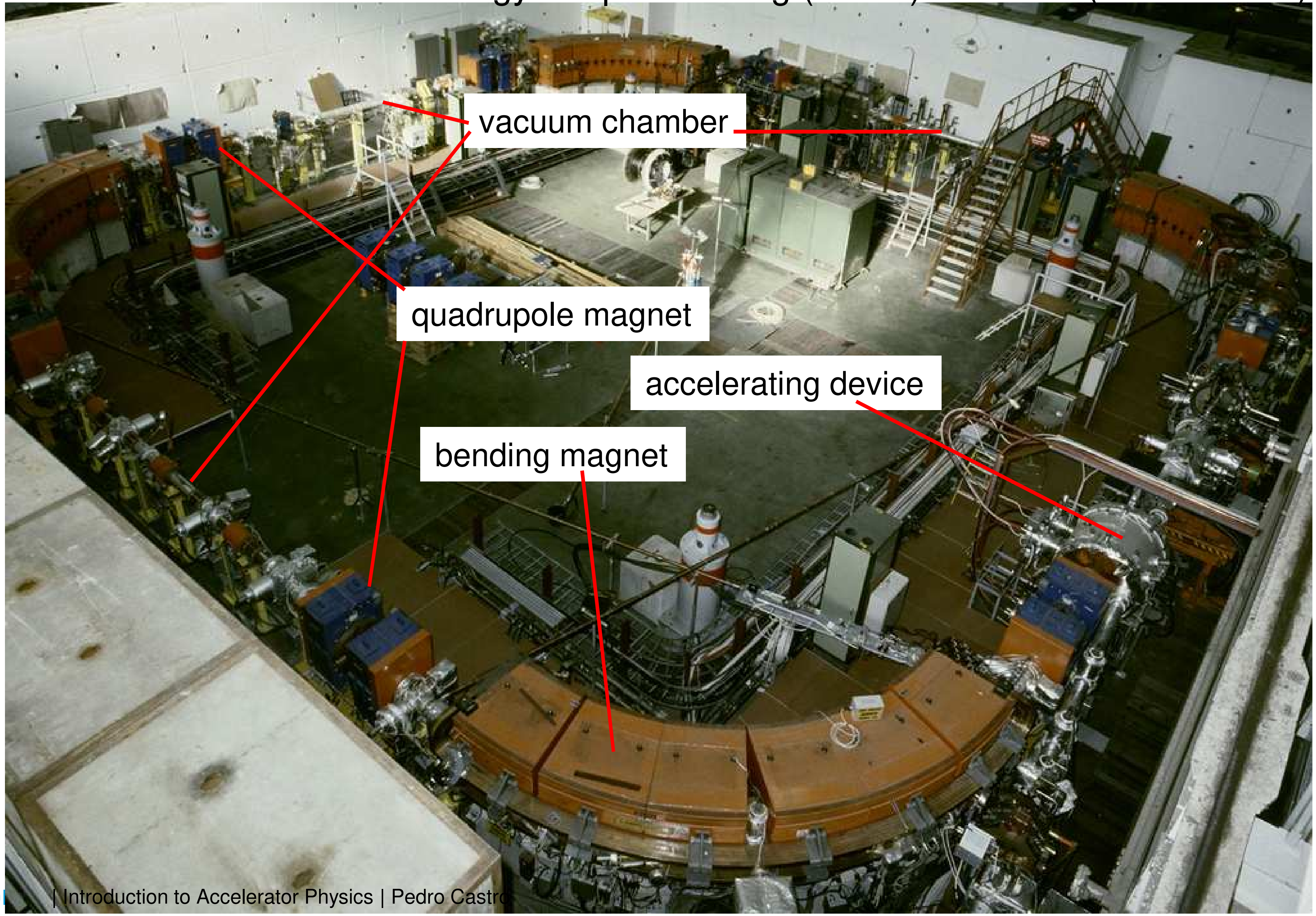
Circular accelerators: the synchrotron

1945: Veksler (UDSSR) and McMillan (USA) invent the synchrotron
1946: Goward and Barnes build the first synchrotron
1949: Wilson et al. at Cornell are first to store beam in a synchrotron
1949: McMillan builds a 320 MeV electron synchrotron

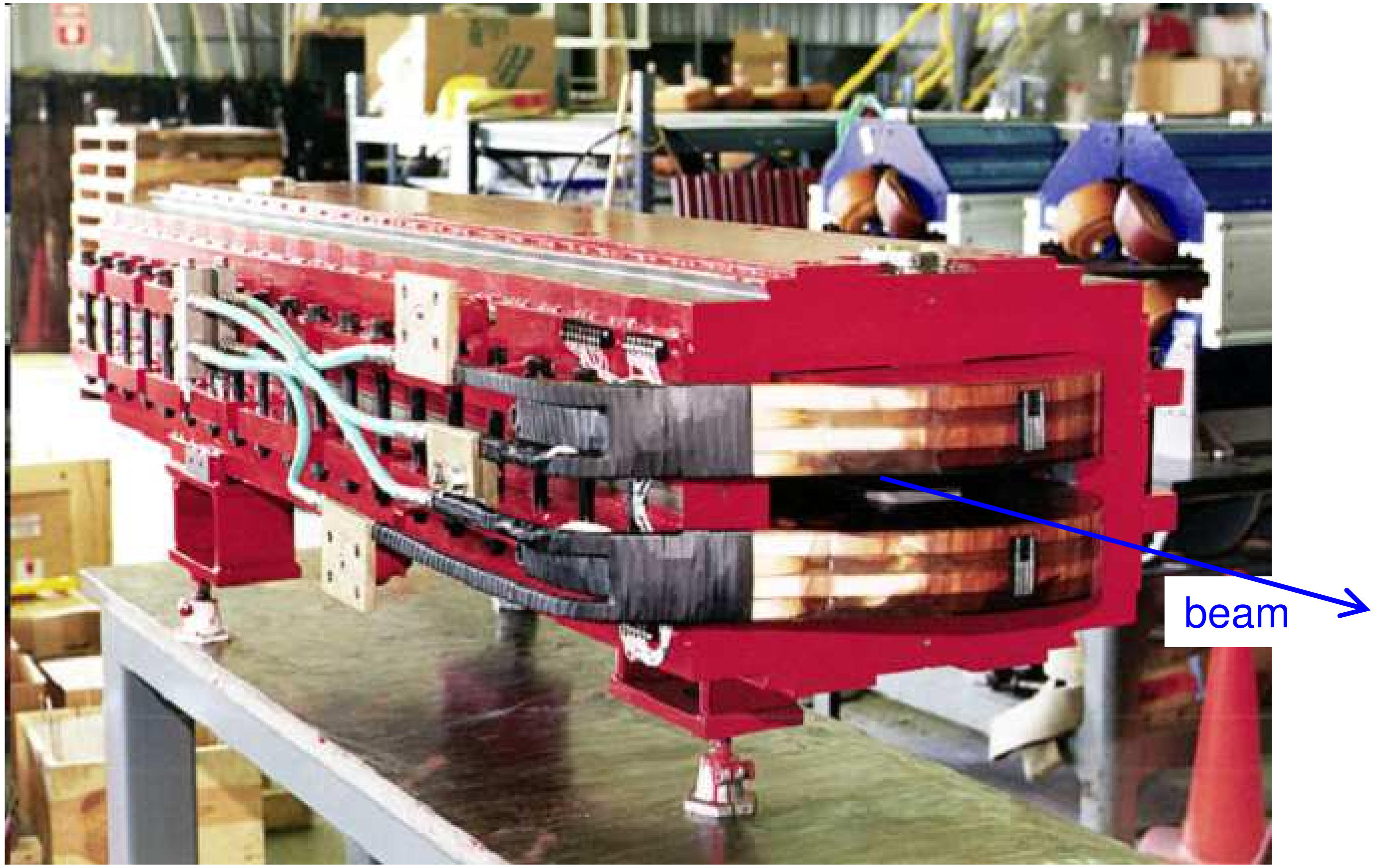


Circular accelerators: the synchrotron

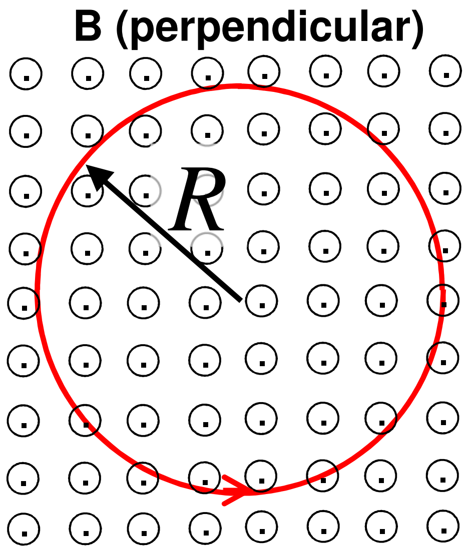
Low Energy Antiproton Ring (LEAR) at CERN (built in 1982)

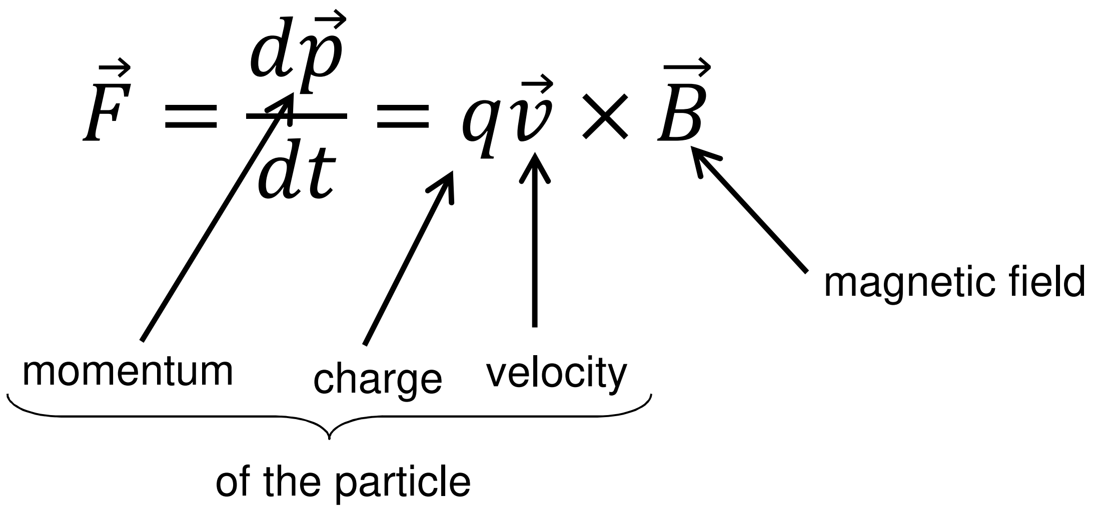


Dipole magnet



Circular accelerators: the synchrotron





$$\vec{F} = \frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B}$$

momentum charge velocity

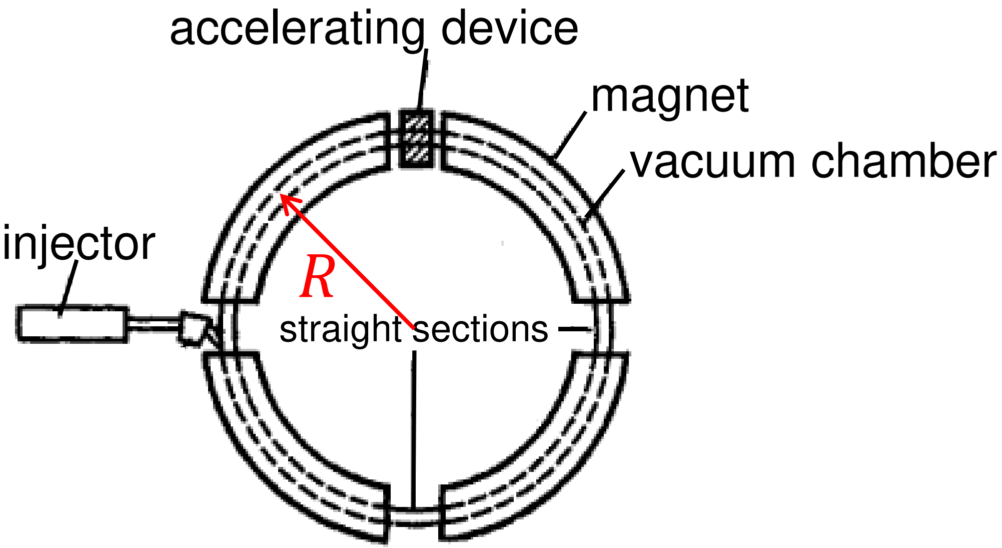
of the particle

magnetic field

$$\left.\begin{array}{lcl} \vec{B} \perp \vec{v} & \rightarrow & F = qvB \\[2ex] \vec{F} \perp \vec{v} & \rightarrow & F = m\dfrac{v^2}{R} \end{array}\right\} \; qB = \frac{mv}{R} \;\rightarrow\; R = \frac{mv}{qB}$$

(circular motion)

Circular accelerators: the synchrotron



$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = qvB$$

$$\vec{F} \perp \vec{v} \quad \rightarrow \quad F = m\frac{v^2}{R}$$

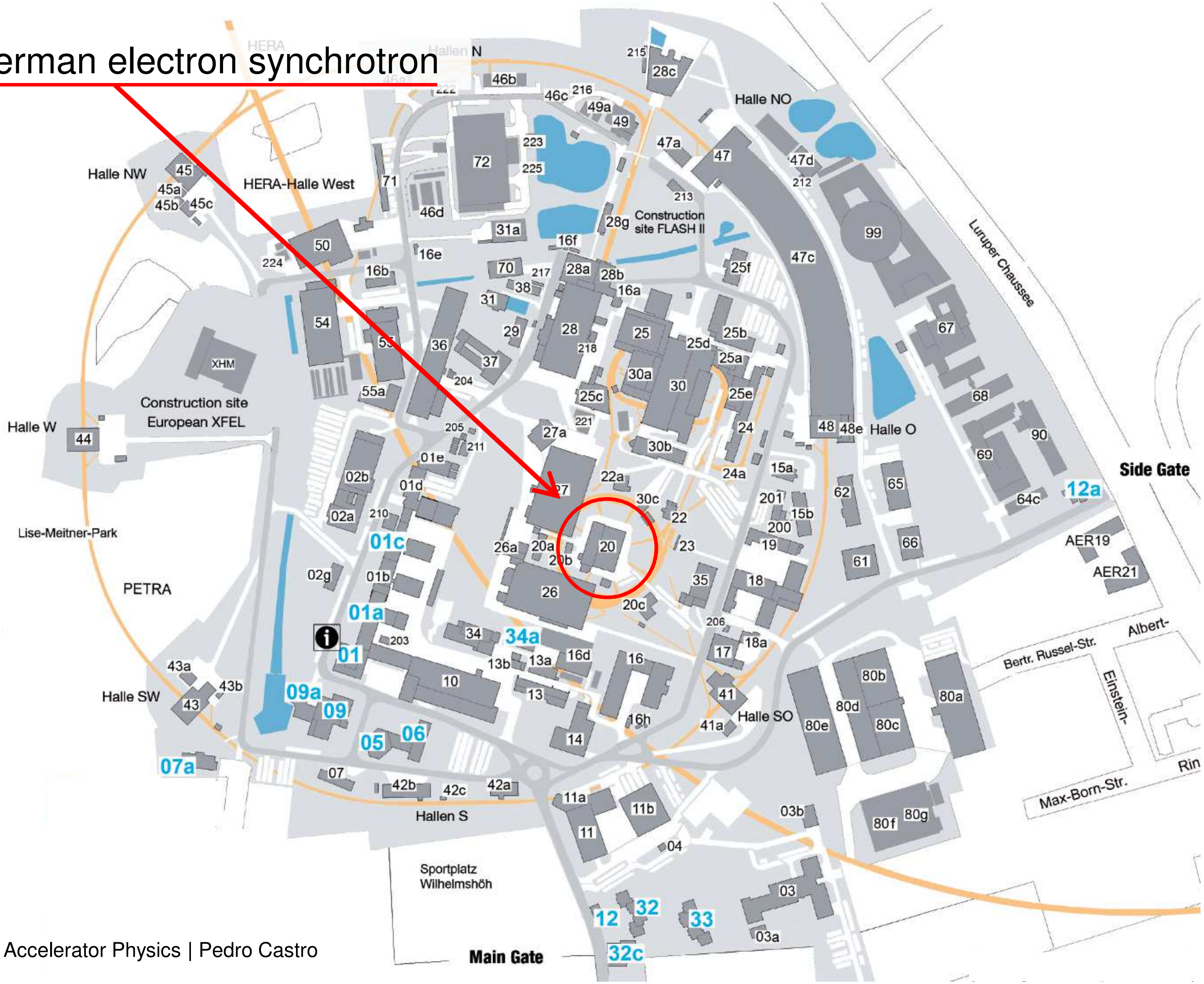
(circular motion)

$$\left.\right\} \; qB = \frac{mv}{R} \quad \rightarrow \quad R = \frac{mv}{qB} = constant$$

→ increase B synchronously with $p = mv$ of particle

DESY (<u>D</u>eutsches <u>E</u>lektronen <u>Sy</u>nchrotron)

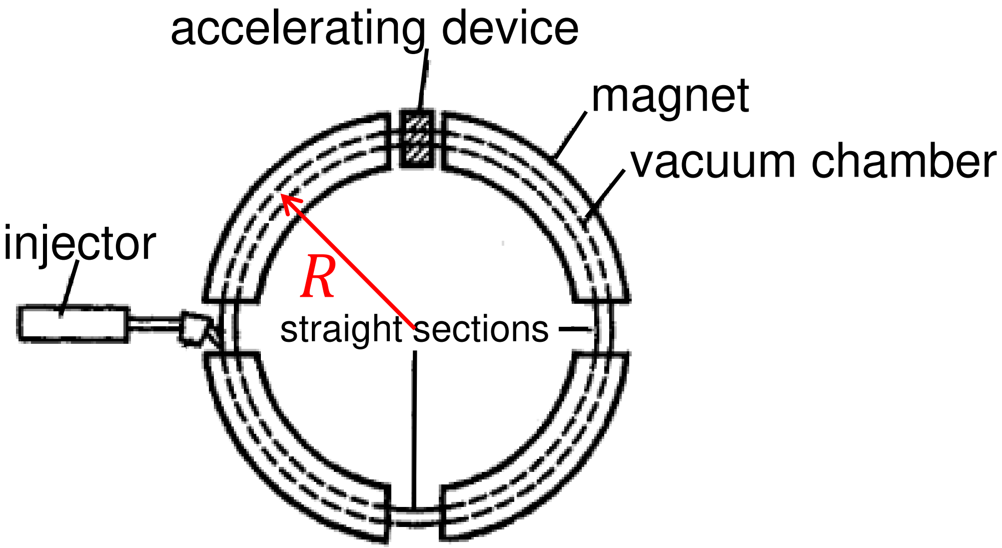
DESY: German electron synchrotron



DESY (Deutsches Elektronen Synchrotron)

DESY: German electron synchrotron, 1964, 7.4 GeV

Key components and their challenges to reach high energies:
Dipole magnetic fields



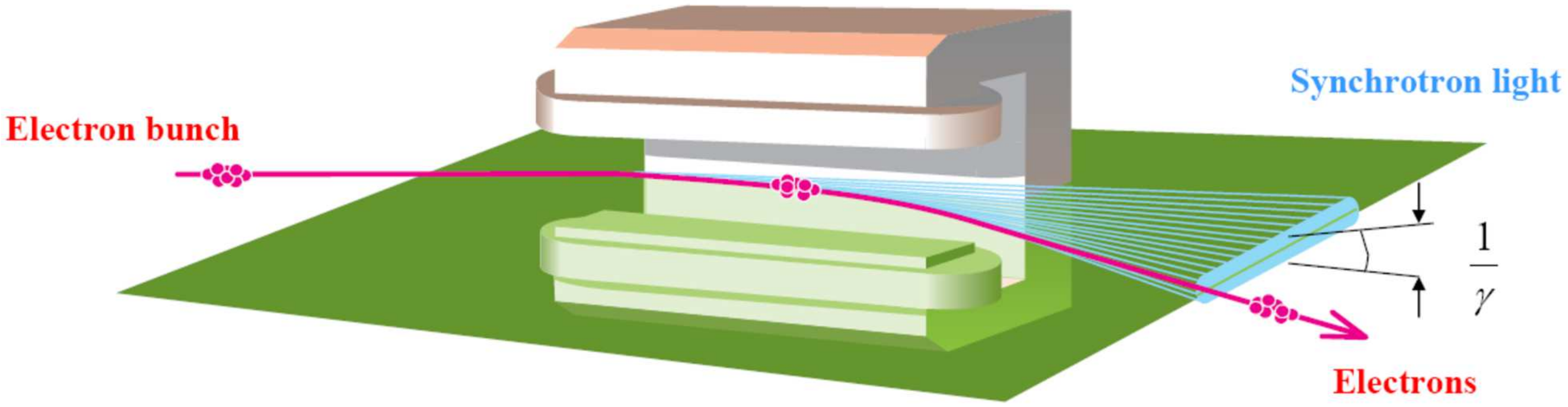
$$\left.\begin{array}{l} \vec{B} \perp \vec{v} \quad \rightarrow \quad F = qvB \\ \vec{F} \perp \vec{v} \quad \rightarrow \quad F = m\dfrac{v^2}{R} \\ \text{(circular motion)} \end{array}\right\} \; qB = \frac{mv}{R} \rightarrow R = \frac{(mv)_{max}}{qB_{max}} = constant$$

only for protons (or ions):

- goal: as higher magnetic field as possible

Synchrotron radiation

Dipole magnet



Power radiated by one electron in a dipole field *B*:

$$P = \frac{c\,q^2}{6\pi\,\varepsilon_0}\,\frac{\gamma^4}{r^2}$$

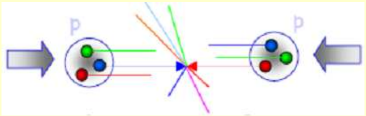
$$\gamma = \frac{E}{m_0 c^2}$$

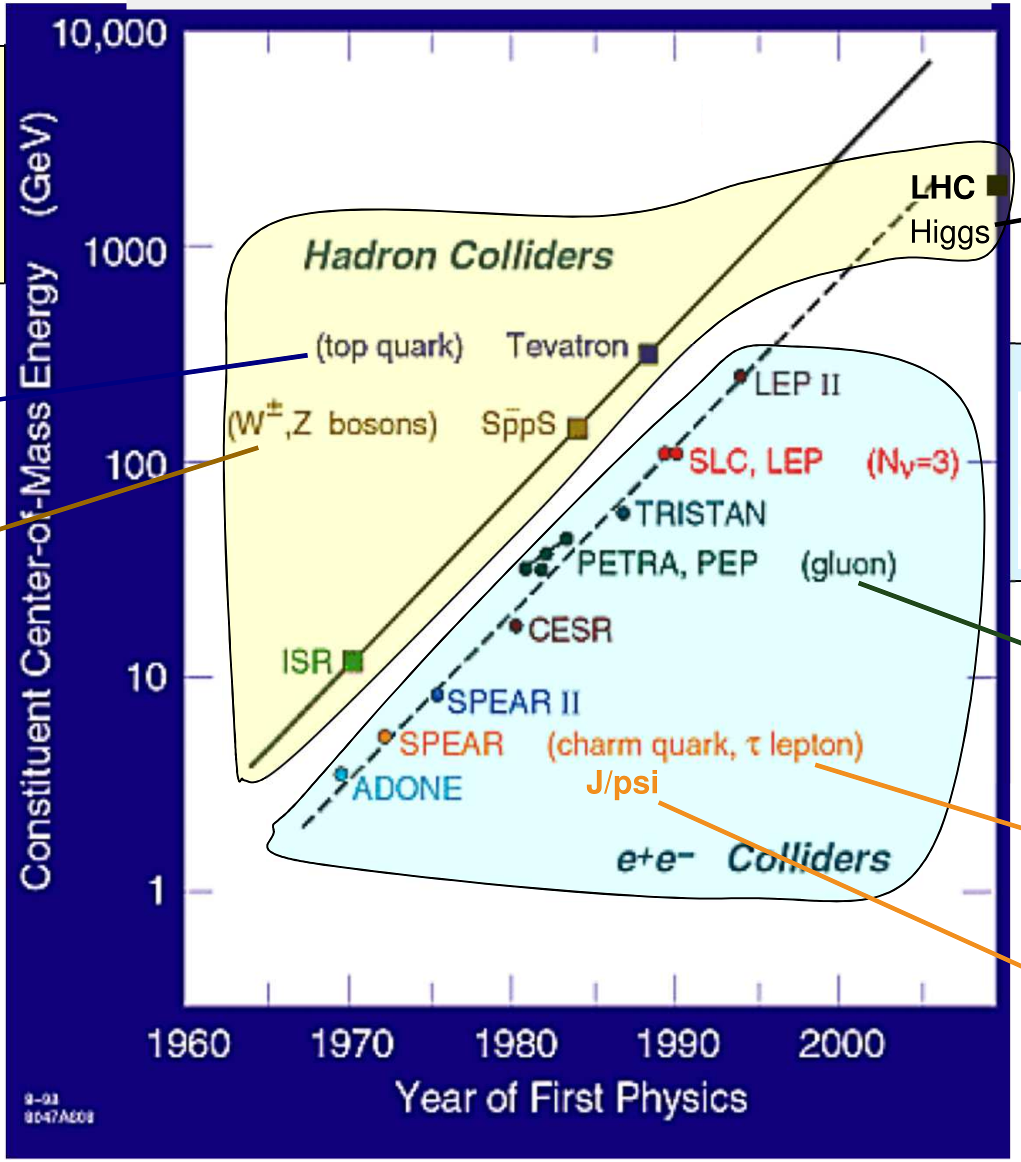
$$\frac{1}{r} = \frac{q\,B}{p}$$

vacuum permitivity

Livingston plot (doubling E every 3.5 years)

hadron colliders:
$E_{cm} / 3$ quarks





discovered 2012
NP 2013

discovered 1995

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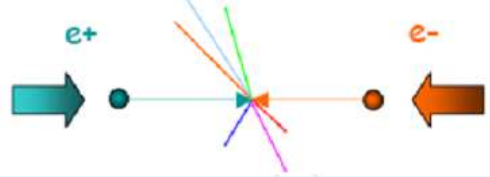
e+e- colliders:



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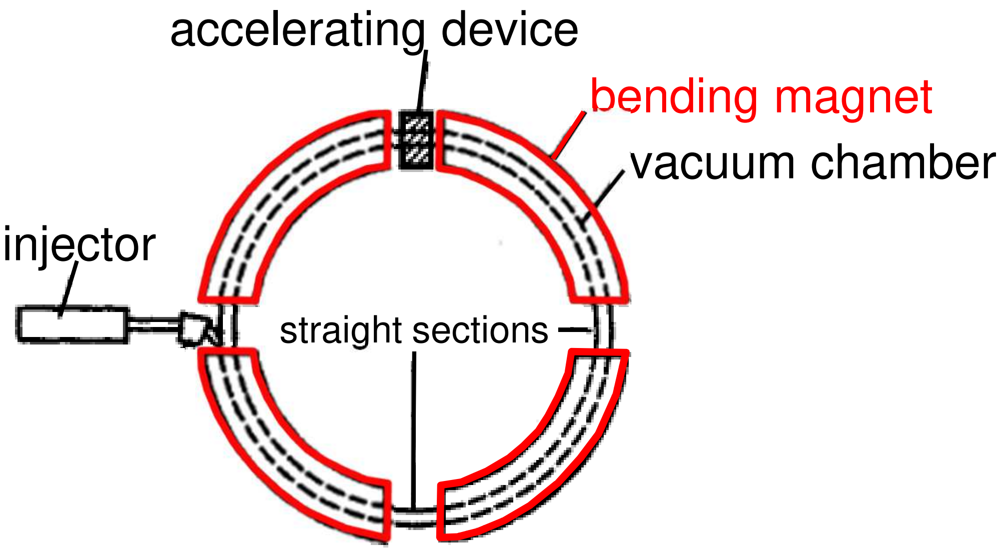
Key components and their challenges to reach high energies: Dipole magnetic fields



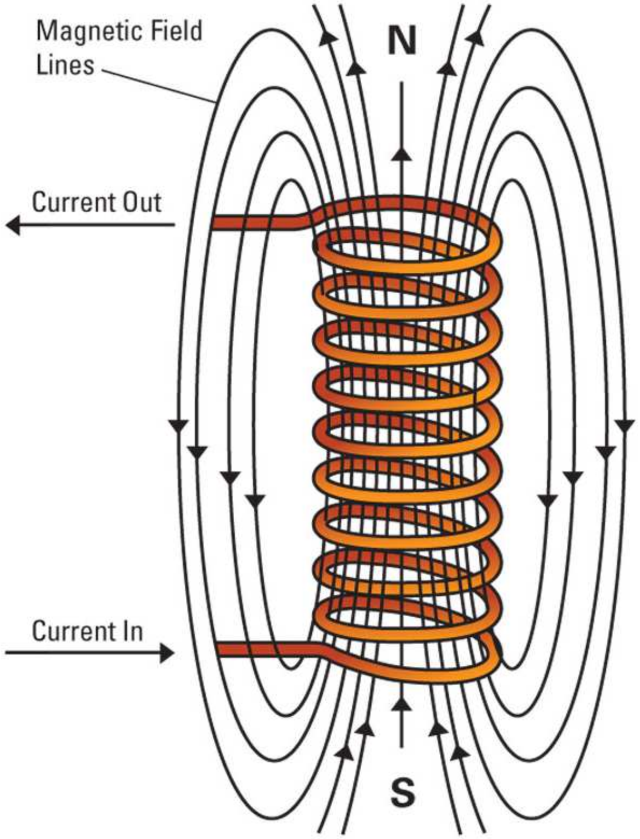
Requirements / challenges for bending magnets (dipoles):

- scalable field B with particle momentum/energy
- very homogeneous field (field quality)

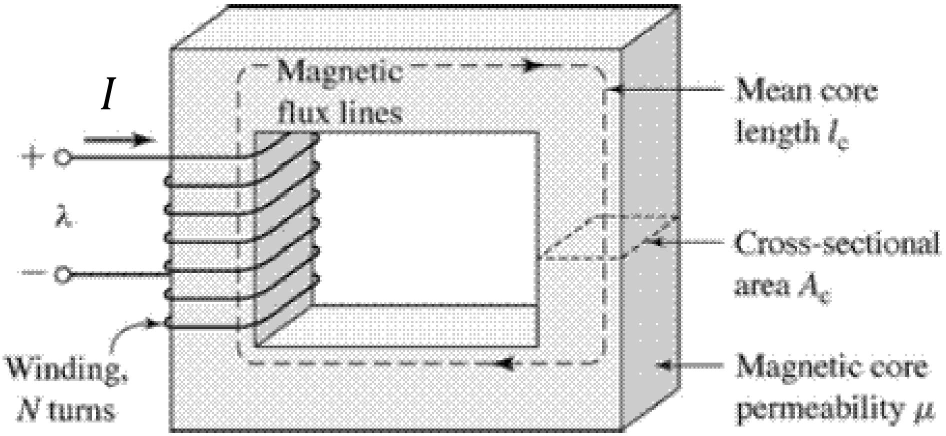
only for protons (or ions):

- as higher magnetic field as possible

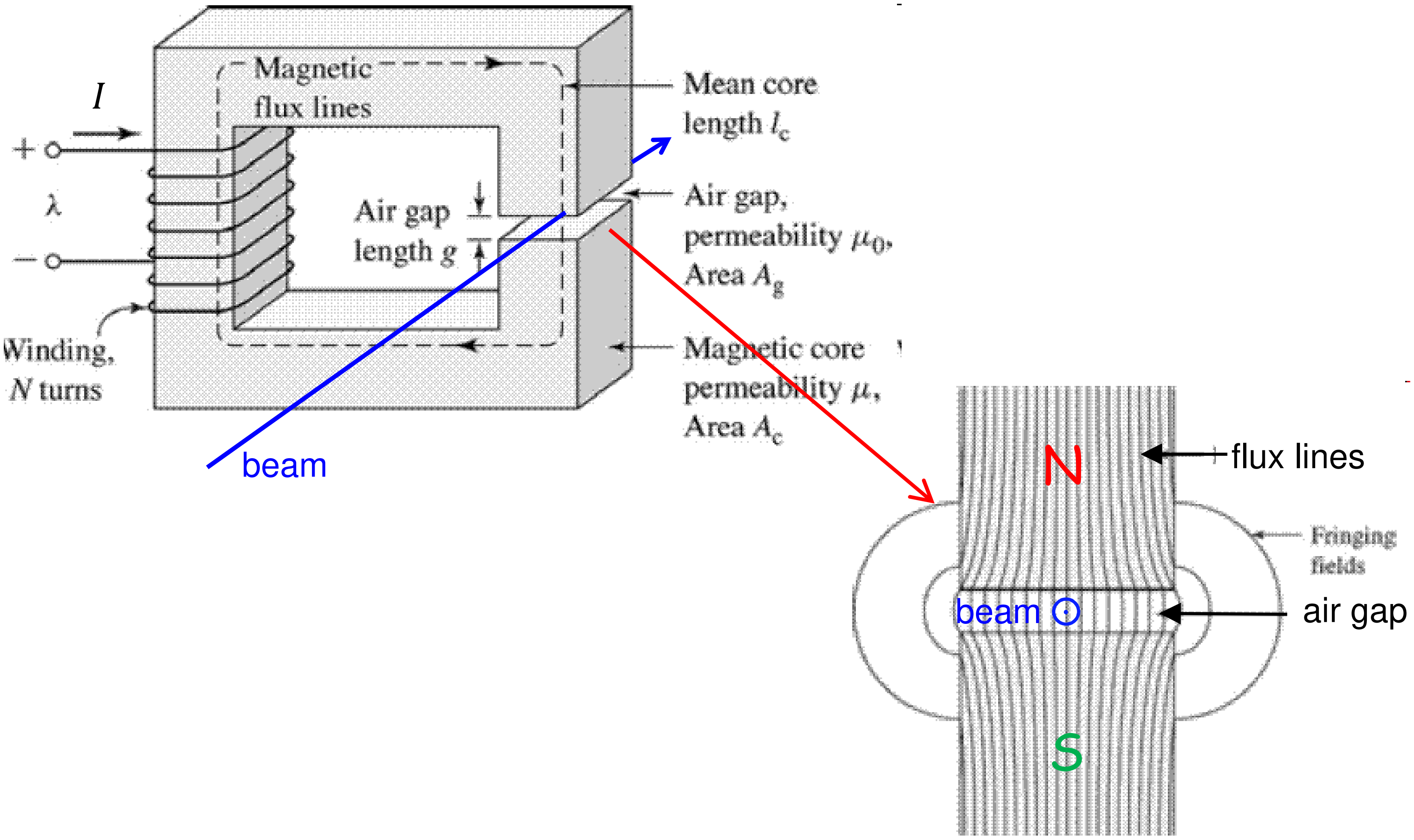
Electromagnet



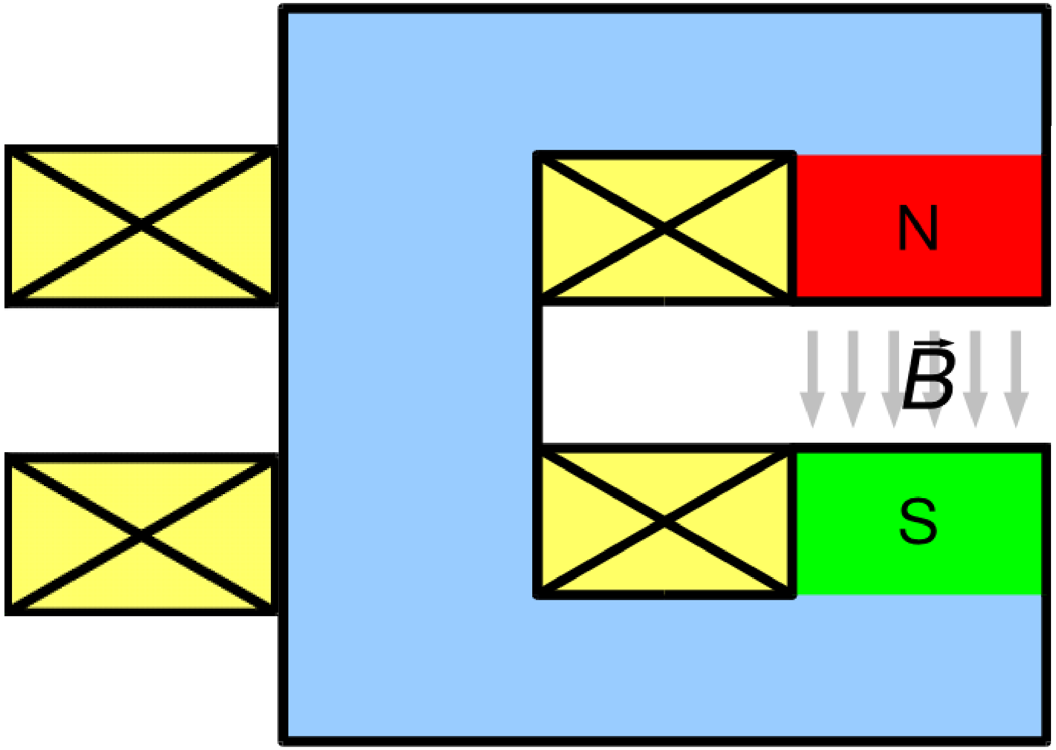
permeability of iron = 300…10000 larger than air



Dipole magnet



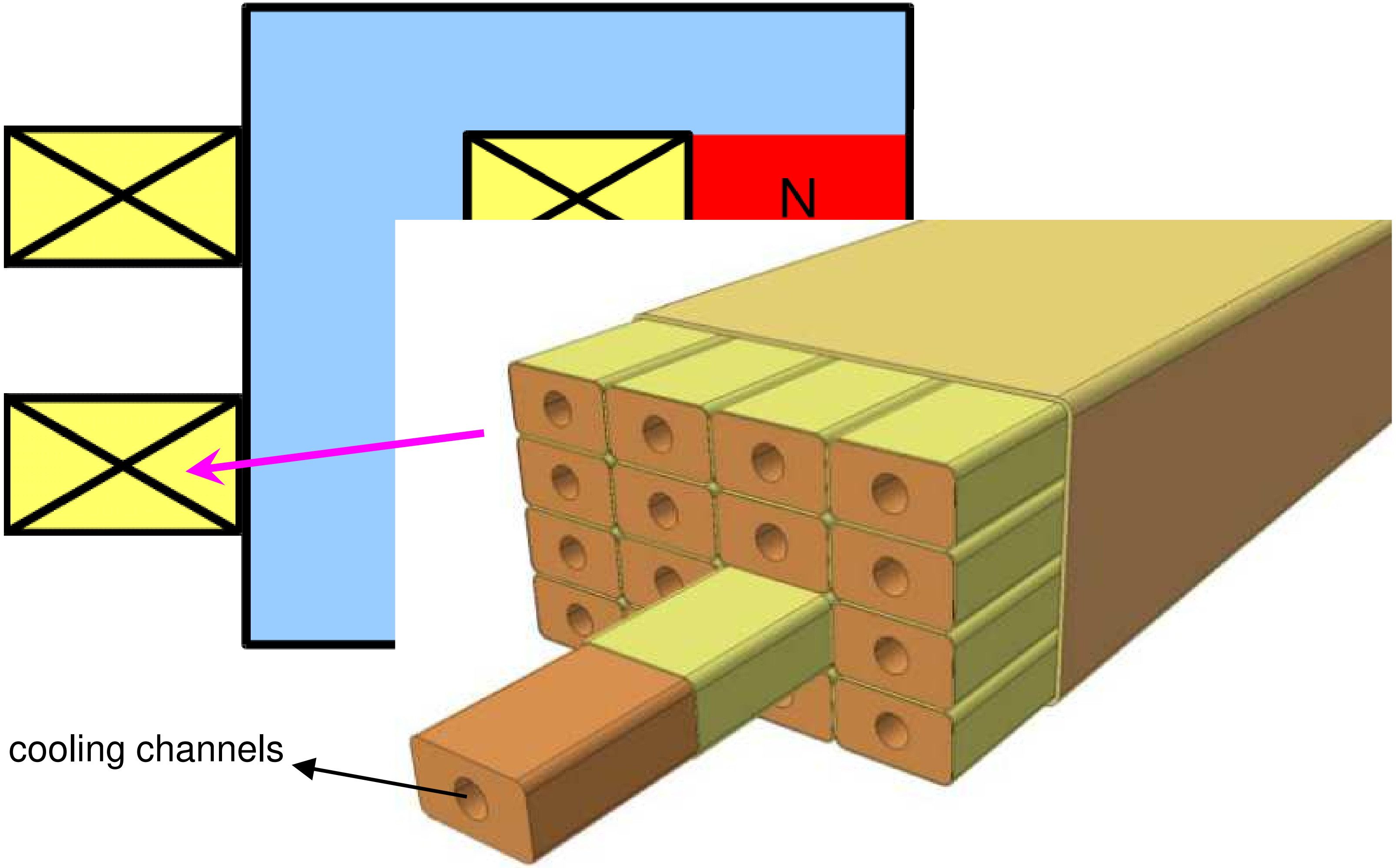
Dipole magnet cross section



increase B ➔ increase current, but power dissipated $\mathrm{P} = R \cdot I^2$

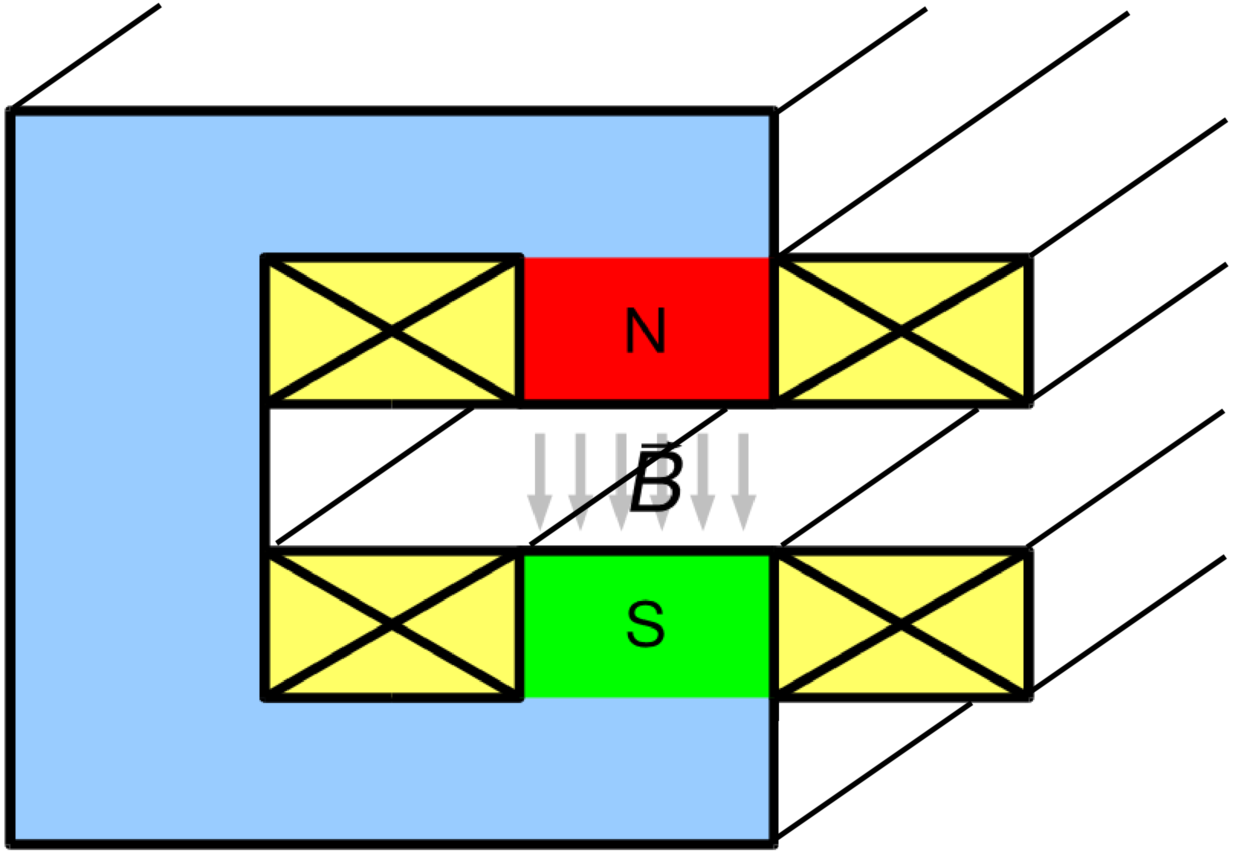
➔ large conductor cables

Dipole magnet cross section

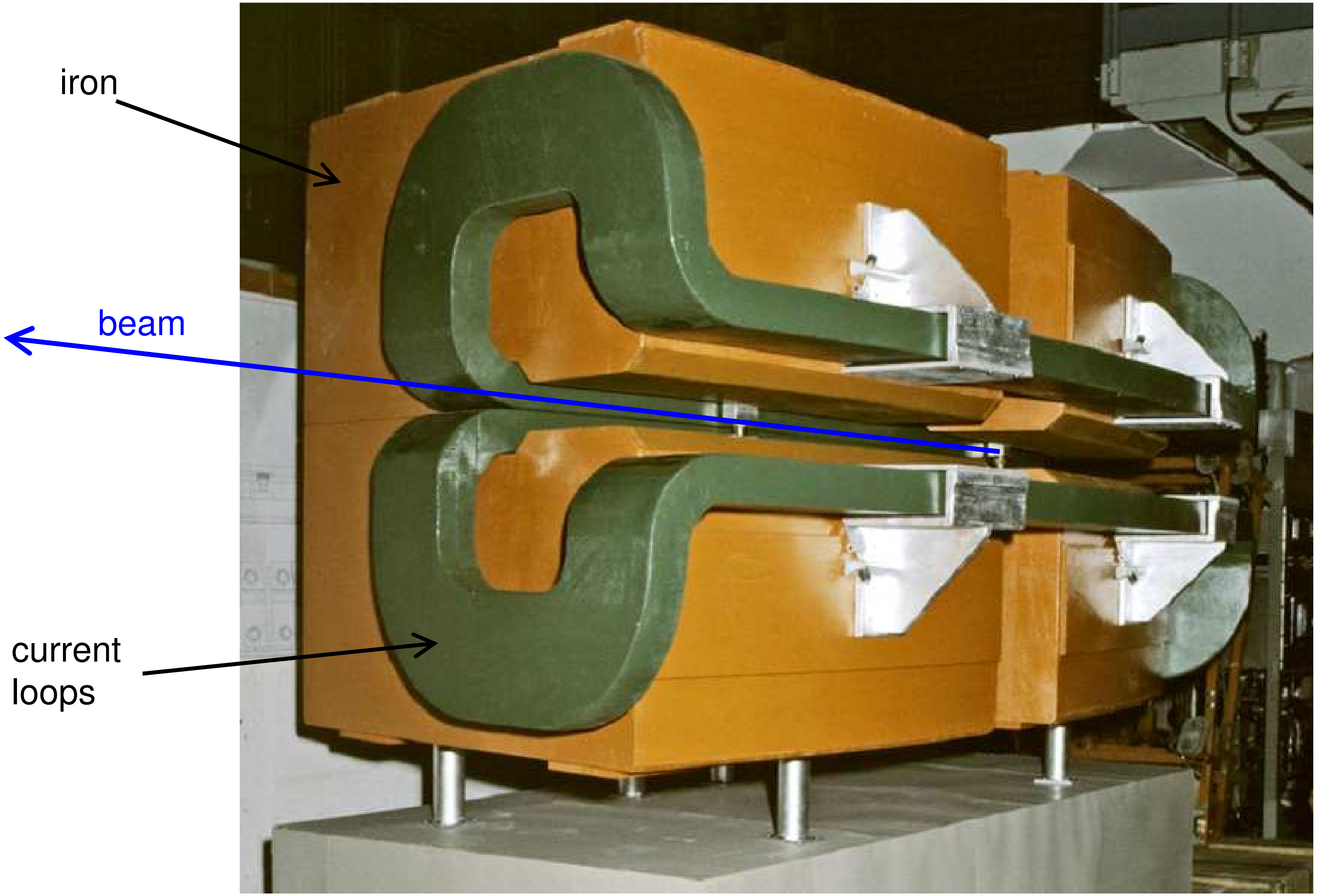


water cooling channels

Dipole magnet cross section

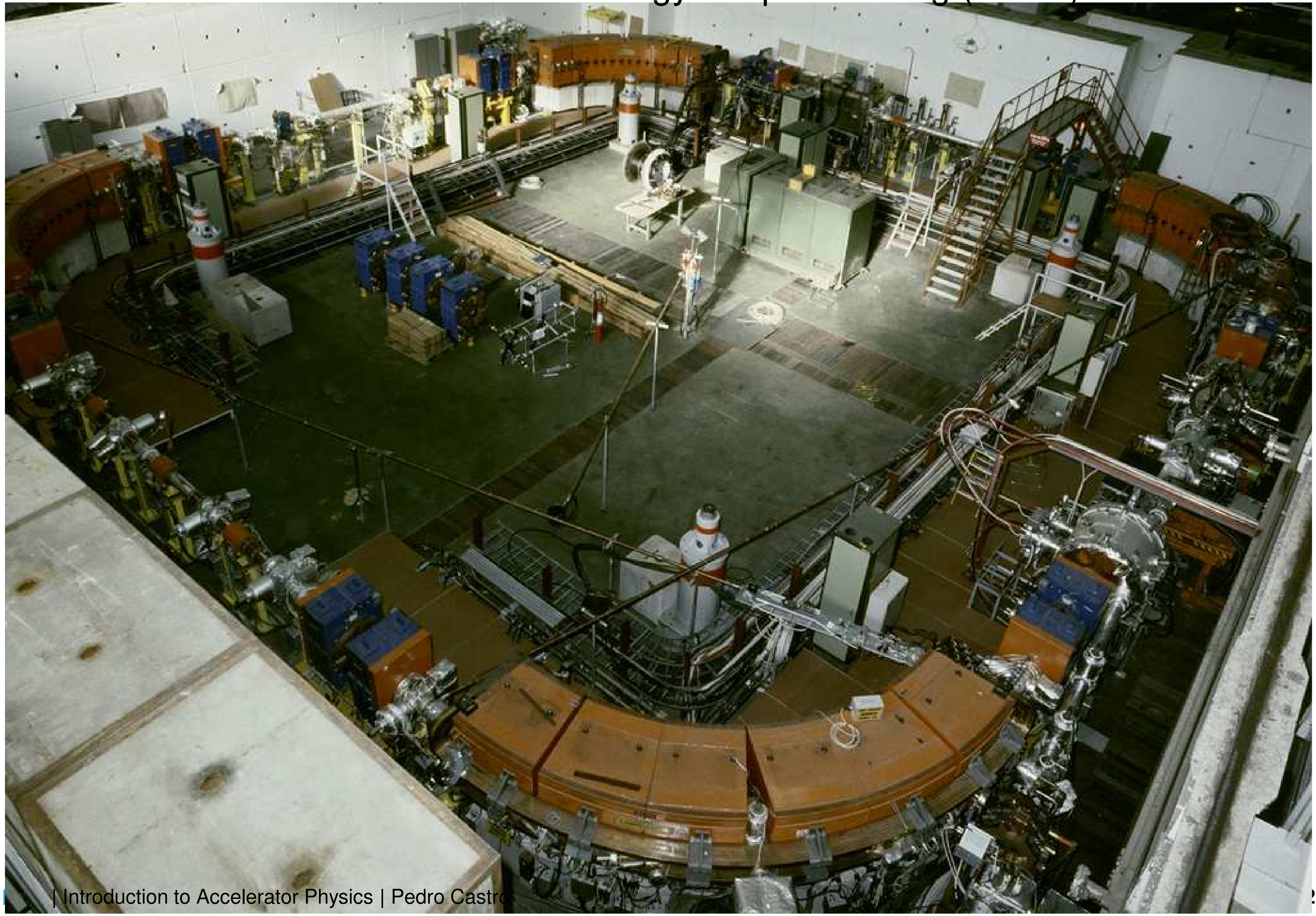


Dipole magnet

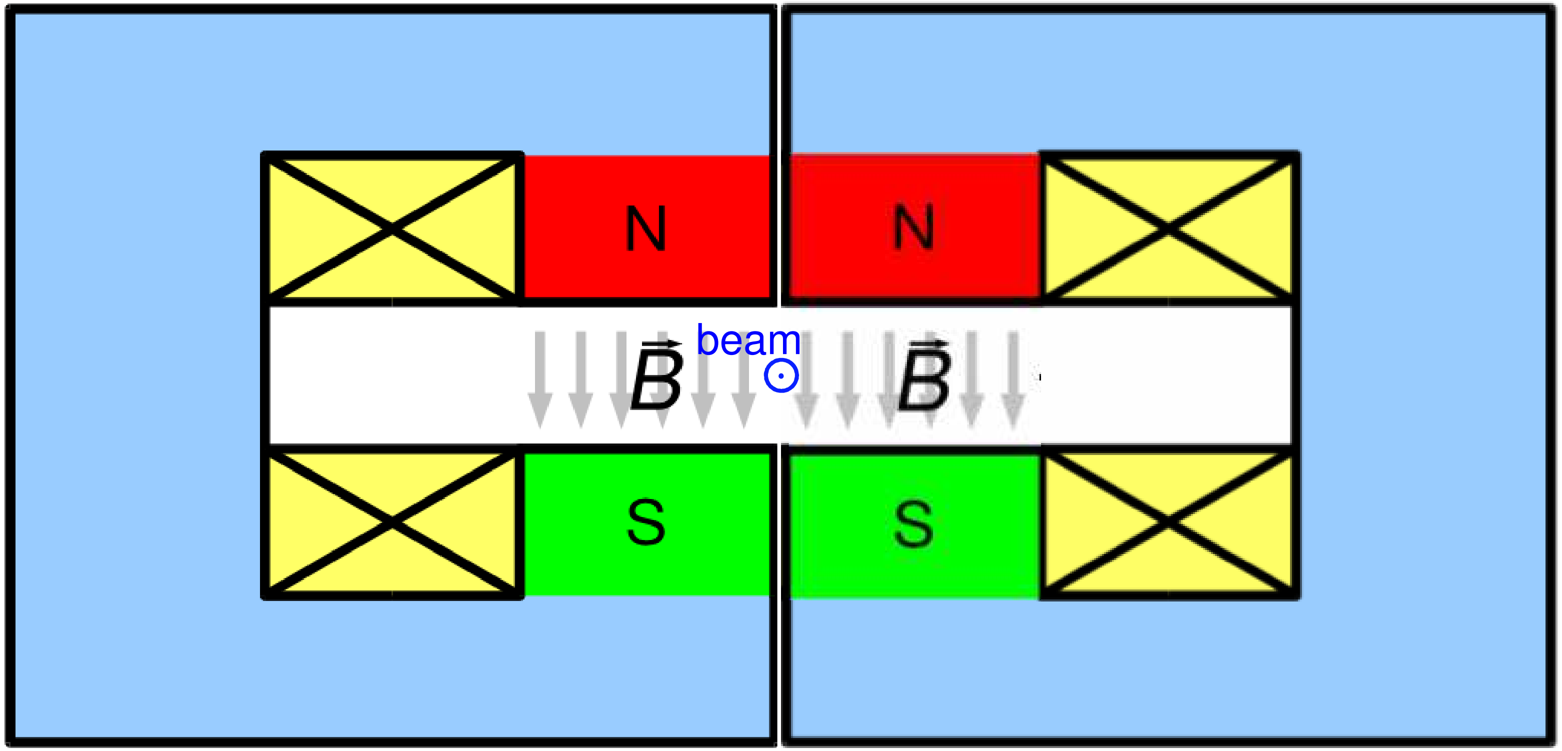


Dipole magnet

Low Energy Antiproton Ring (LEAR) at CERN

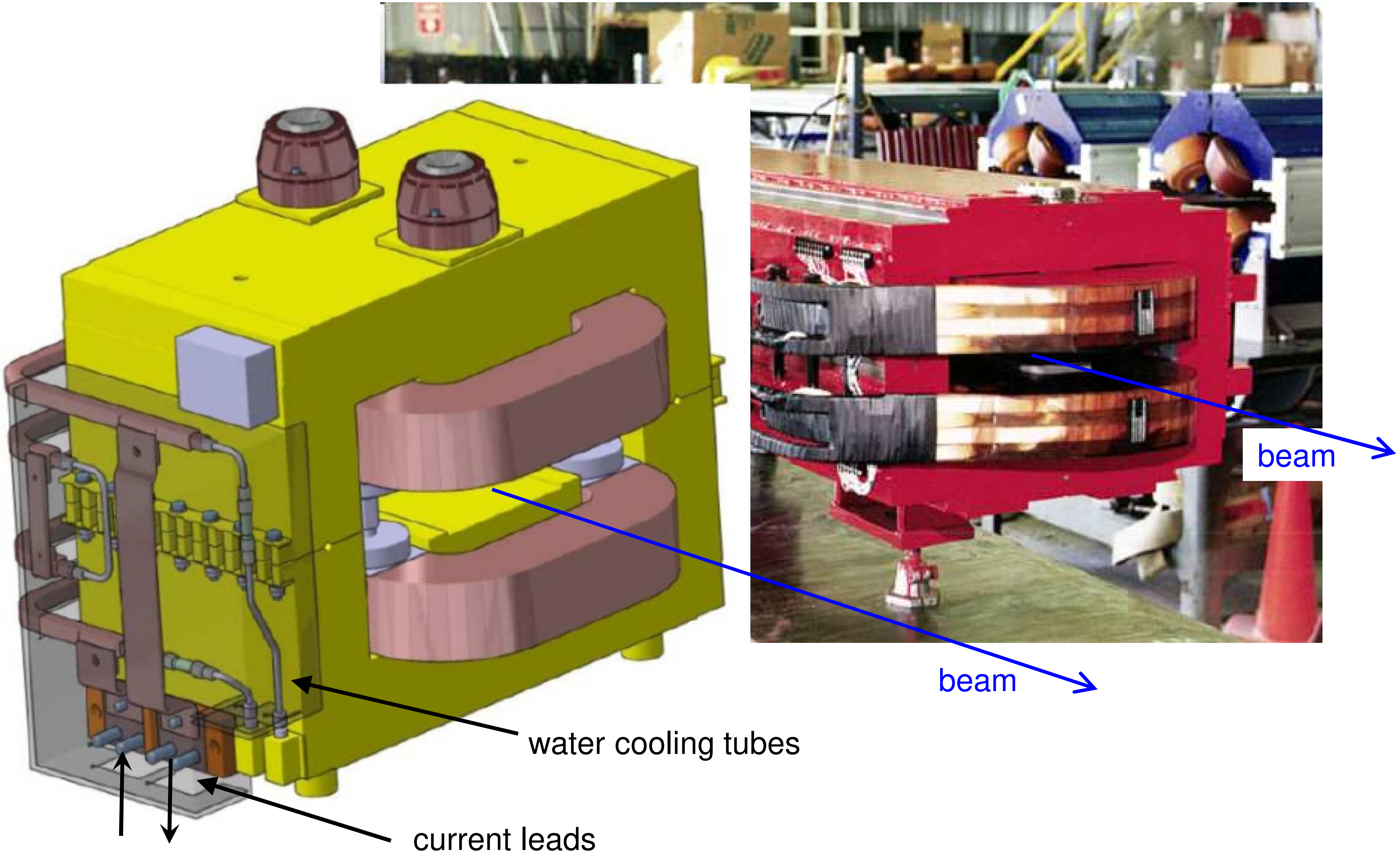


Dipole magnet cross section



C magnet + C magnet = H magnet

Dipole magnet cross section (another design)



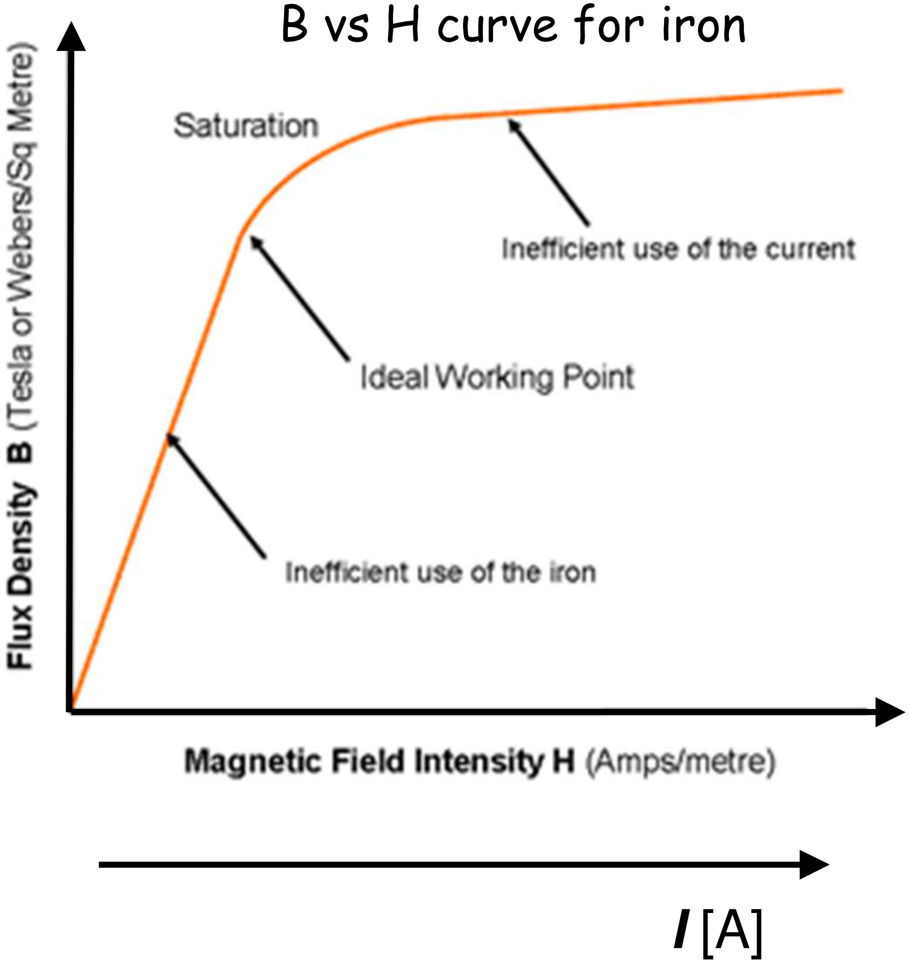
Key components and their challenges to reach high energies: Dipole magnetic fields

- ✓ field quality
- ✓ energy scalable: with current
- – very high magnetic fields (max. 2 T)

Saturation of iron: 1.6 – 2 T

Power dissipated: $P = R \cdot I^2$

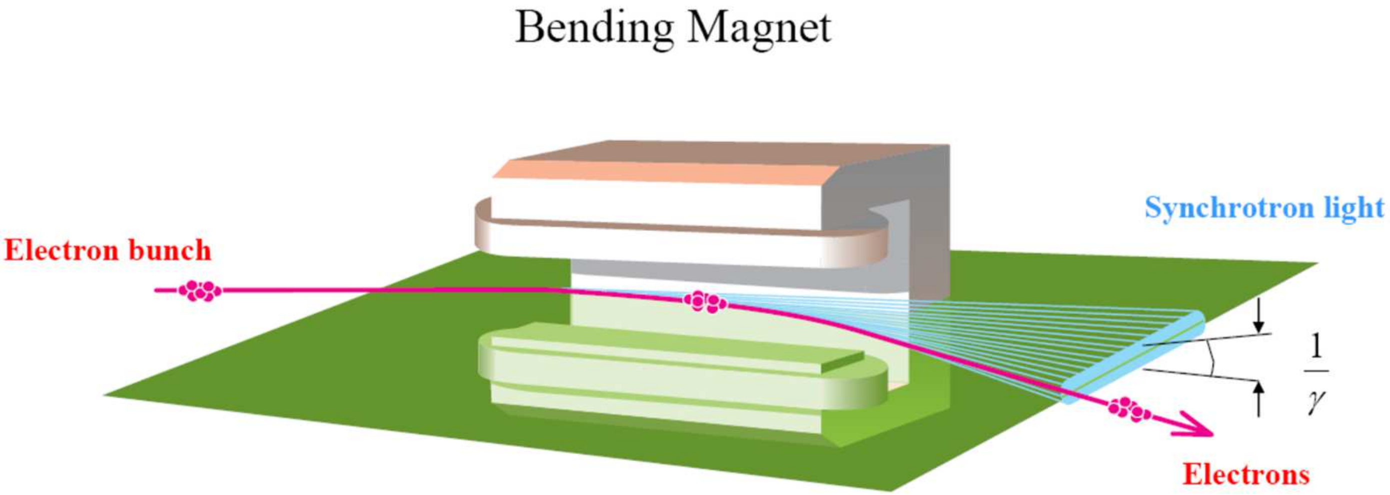
B vs H curve for iron



Key components and their challenges to reach high energies: Dipole magnetic fields

- ✓ field quality
- ✓ energy scalable: with current
- – very high magnetic fields (max. 2 T)

normal conducting magnets OK for electron synchrotrons



energy limitation for e- synchrotrons: energy loss due to synchrotron radiation

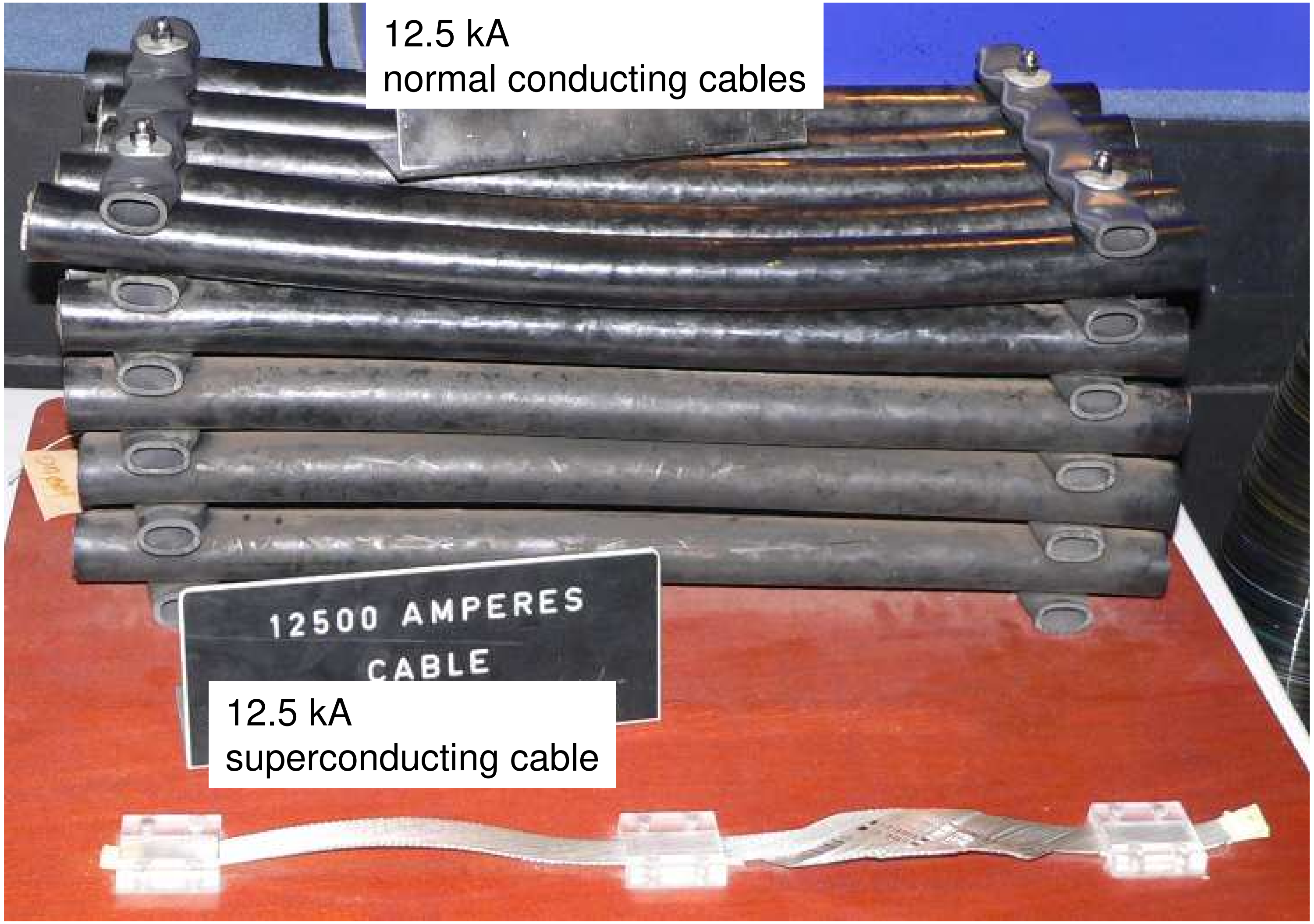
→ Future colliders for the energy frontier, K. Buesser

Key components and their challenges to reach high energies: Dipole magnetic fields

- ✓ field quality
- ✓ energy scalable: with current
- – very high magnetic fields (max. 2 T)

for proton (or heavy ion) synchrotrons ?

Superconductivity



12.5 kA
normal conducting cables

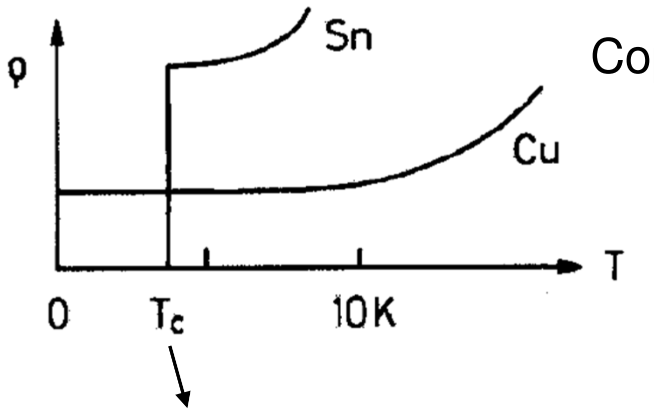
12.5 kA
superconducting cable

Superconductivity

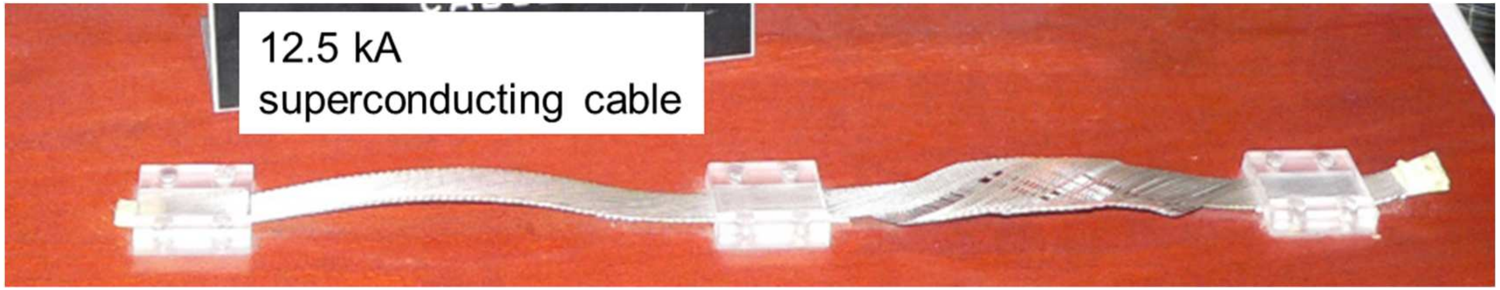
Tin

resistance

Copper



critical temperature (Tc):

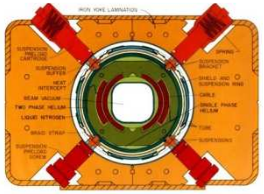
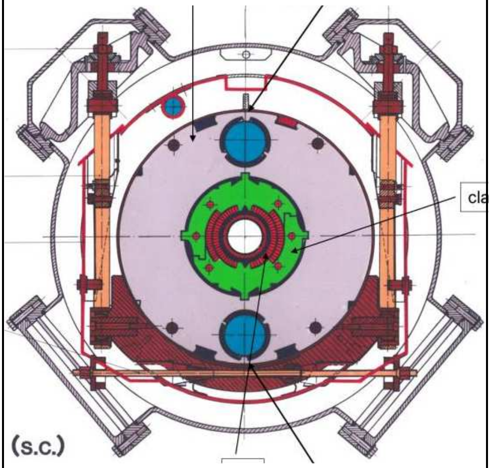
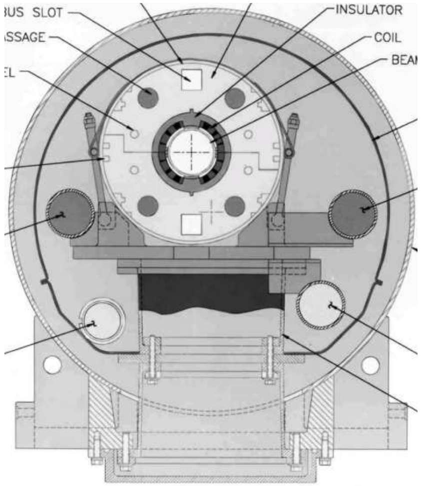
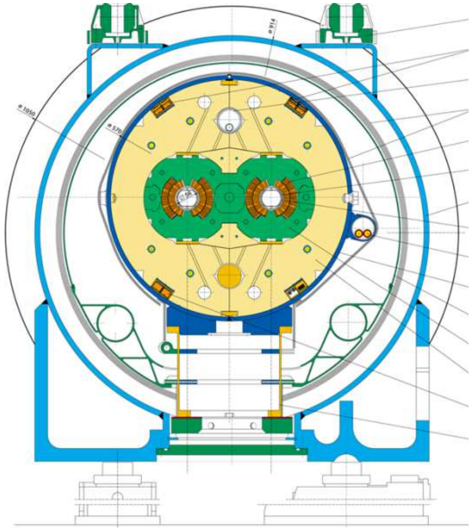


12.5 kA
superconducting cable

+

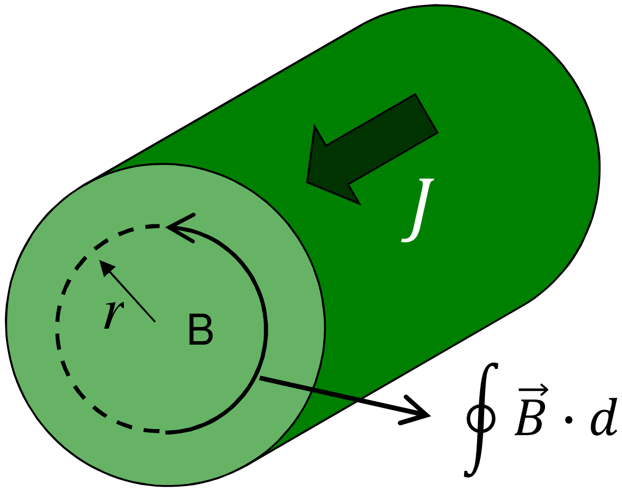
forget about iron

Superconducting dipole magnets: cross section

Tevatron	HERA	RHIC	LHC
Fermilab Chicago (USA)	DESY Hamburg (Germany)	Brookhaven Long Island (USA)	CERN Geneva (Switzerland)
4.5 T	5.3 T	3.5 T	8.3T
			

Dipole field inside 1 conductor

J: uniform current density

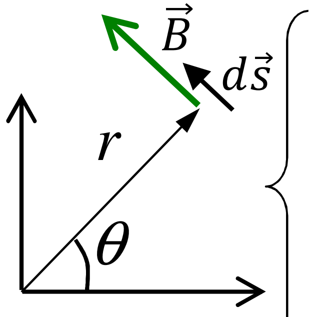


Ampere's law:

$$\oint \vec{B}\cdot d\vec{s} = \mu_0 I_{enclosed}$$

$$\oint \vec{B}\cdot d\vec{s} = \oint B\,ds = 2\pi r B = \mu_0 \pi r^2 J$$

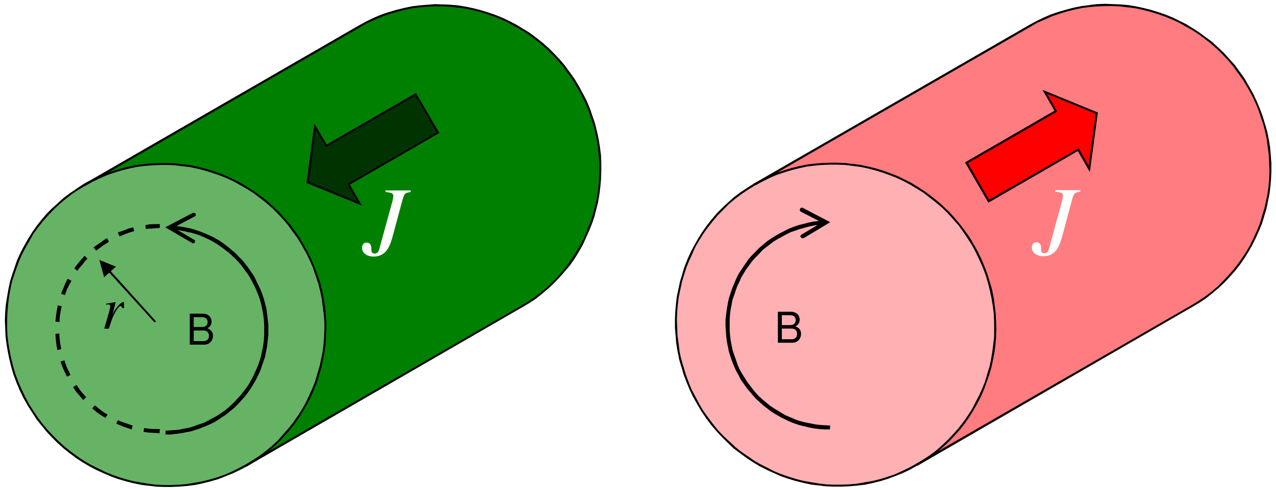
$$B = \frac{\mu_0 J}{2} r$$



$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\ B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$

Dipole field inside 2 conductors

$J =$ uniform current density



Dipole field inside 2 conductors

$$J = \text{uniform current density}$$

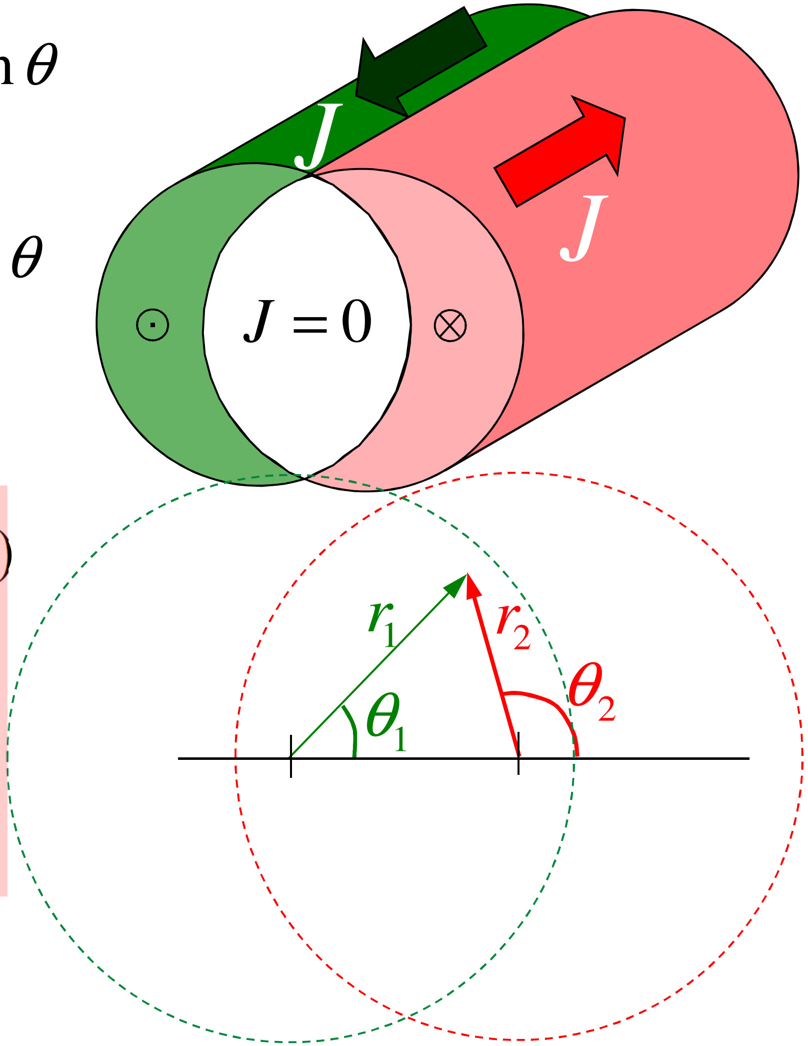
one conductor:

$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\[2ex] B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$

superposition:

$$B_x = \frac{\mu_0 J}{2}\left(-r_1 \sin\theta_1 + r_2 \sin\theta_2\right)$$

$$B_y = \frac{\mu_0 J}{2}\left(r_1 \cos\theta_1 - r_2 \cos\theta_2\right)$$

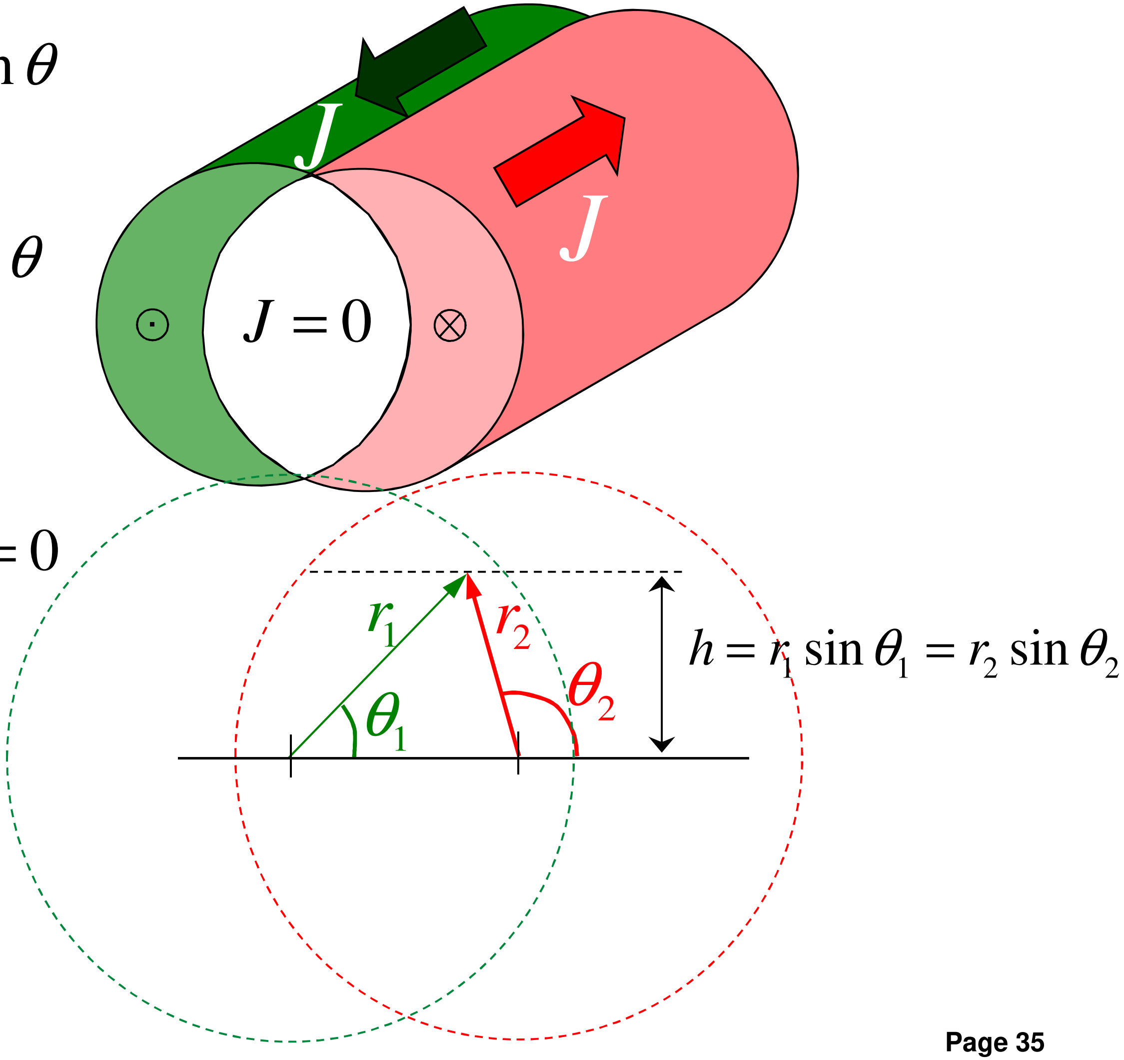


Dipole field inside 2 conductors

$$J = \text{uniform current density}$$

one conductor:

$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\[2ex] B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$



$$B_x = \frac{\mu_0 J}{2}(-r_1 \sin\theta_1 + r_2 \sin\theta_2) = 0$$

$$B_y = \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2)$$

Dipole field inside 2 conductors

$$J = \text{uniform current density}$$

one conductor: $$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\[2ex] B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$

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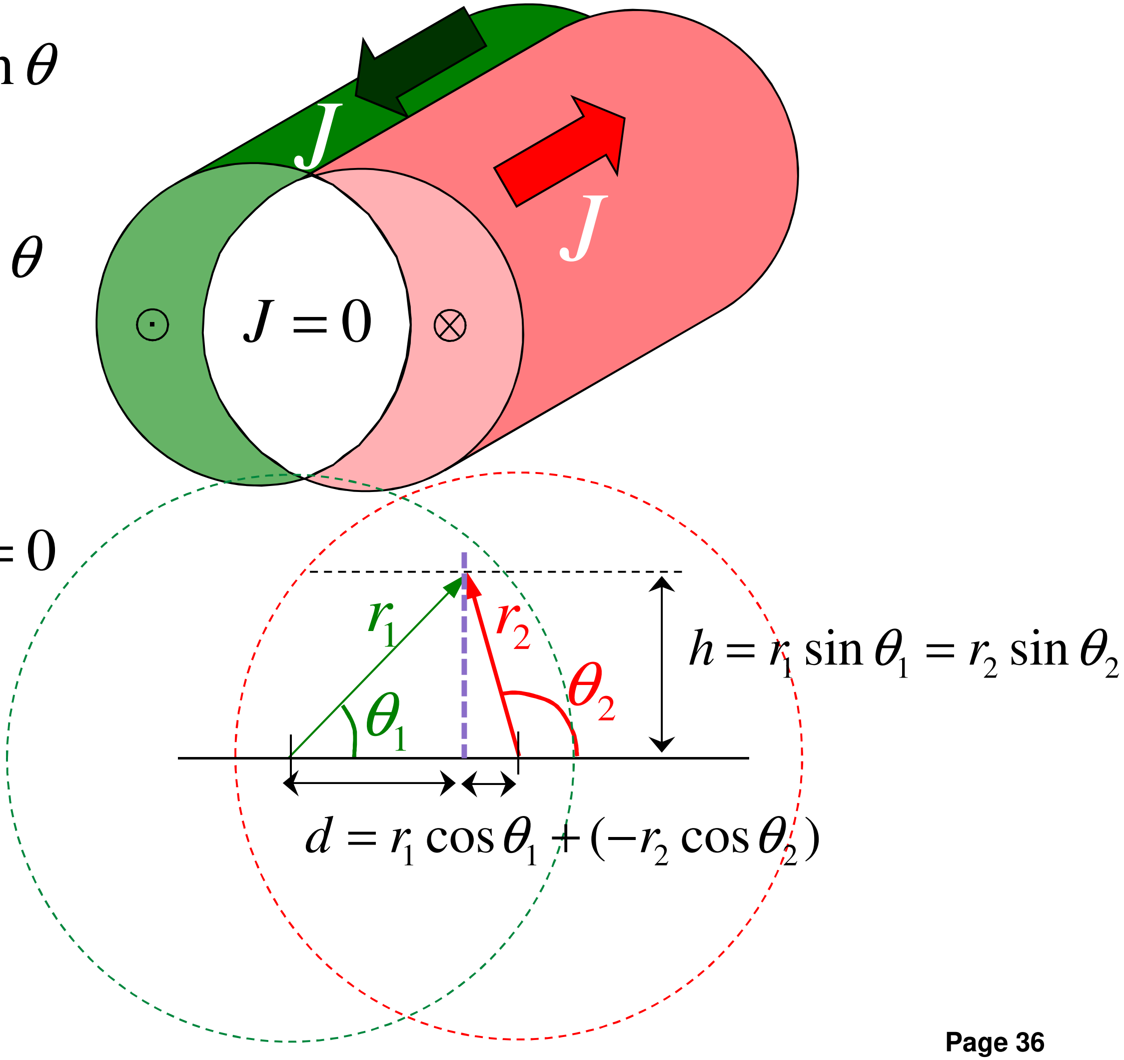


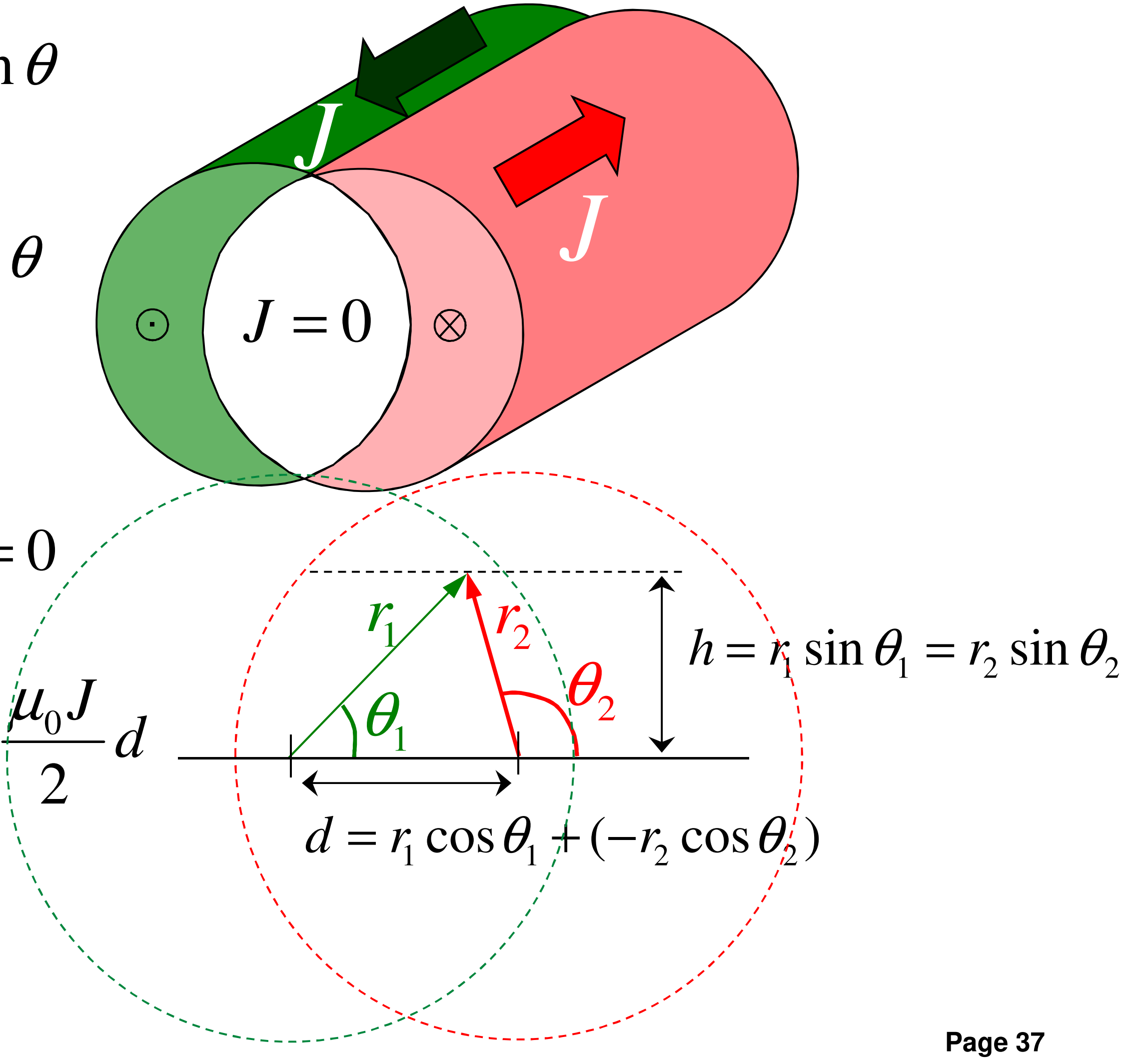
$$h = r_1 \sin\theta_1 = r_2 \sin\theta_2$$

$$d = r_1 \cos\theta_1 + (-r_2 \cos\theta_2)$$

Dipole field inside 2 conductors

$$J = \text{uniform current density}$$

one conductor:
$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\ B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$



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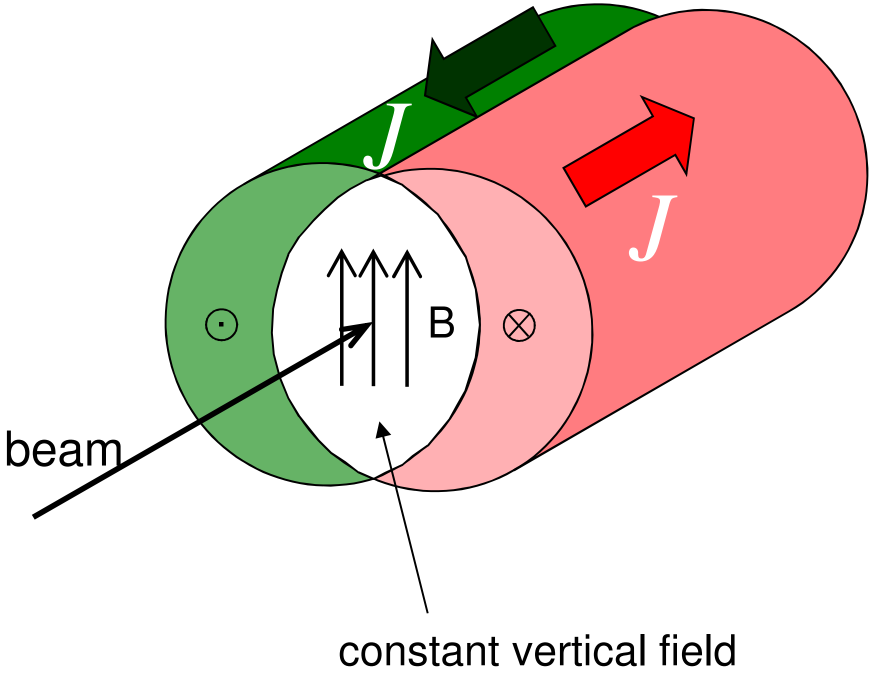
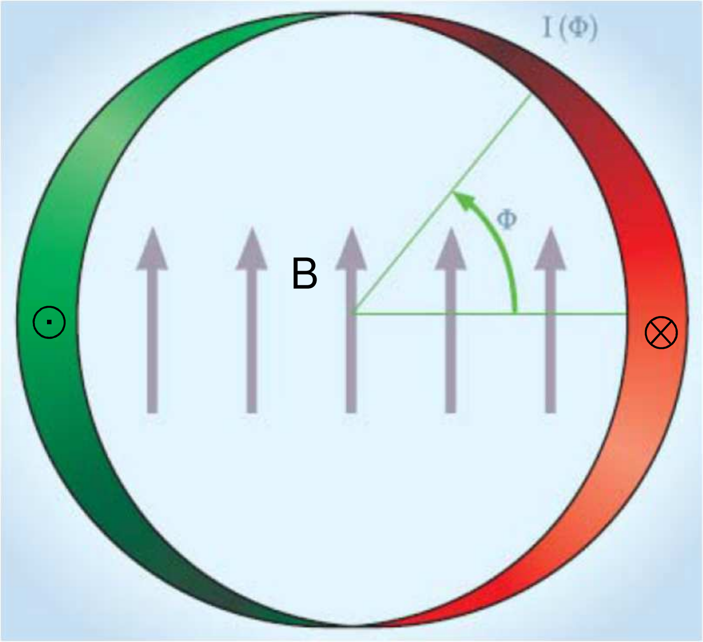
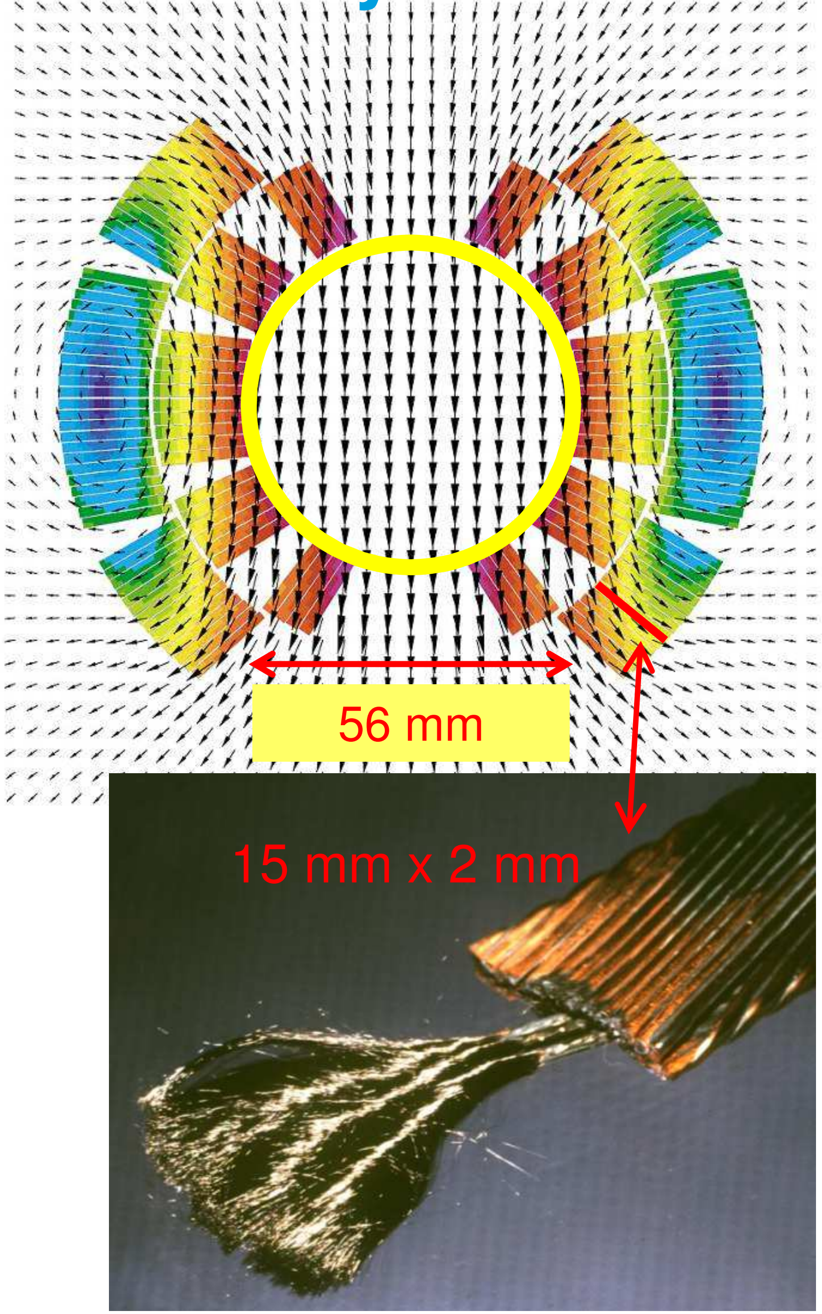
Dipole field inside 2 conductors



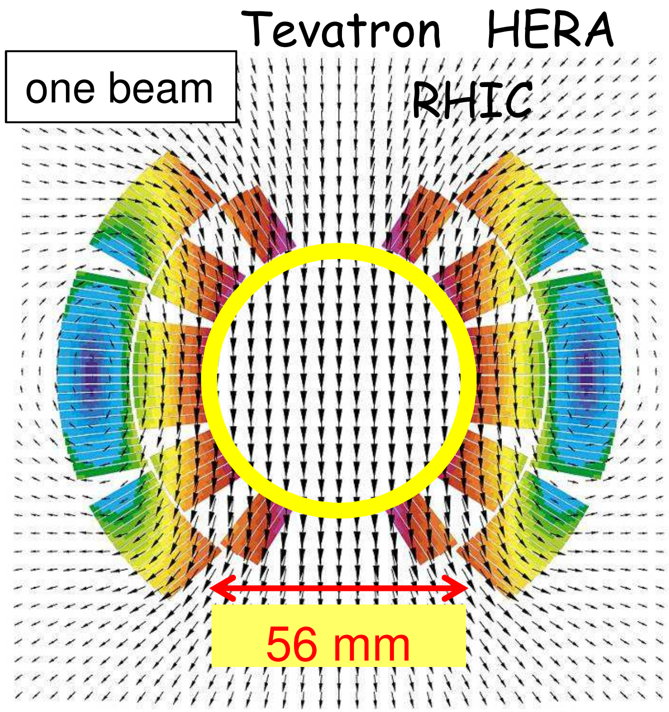
$$B_y = \frac{\mu_0 J}{2} d$$

From the principle … to the reality…





Computed magnetic field

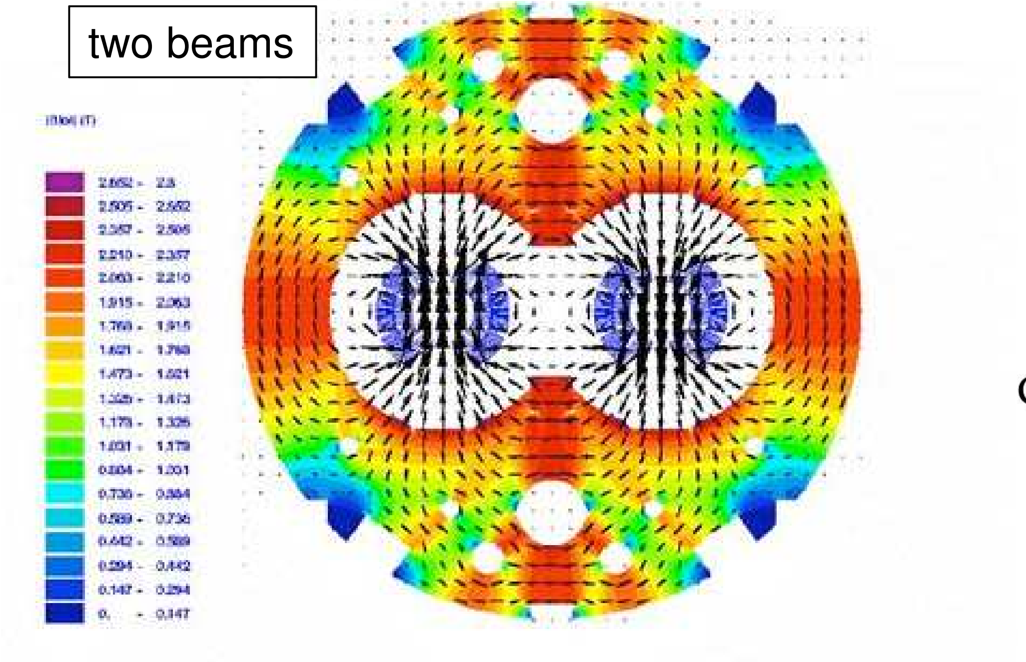


one beam

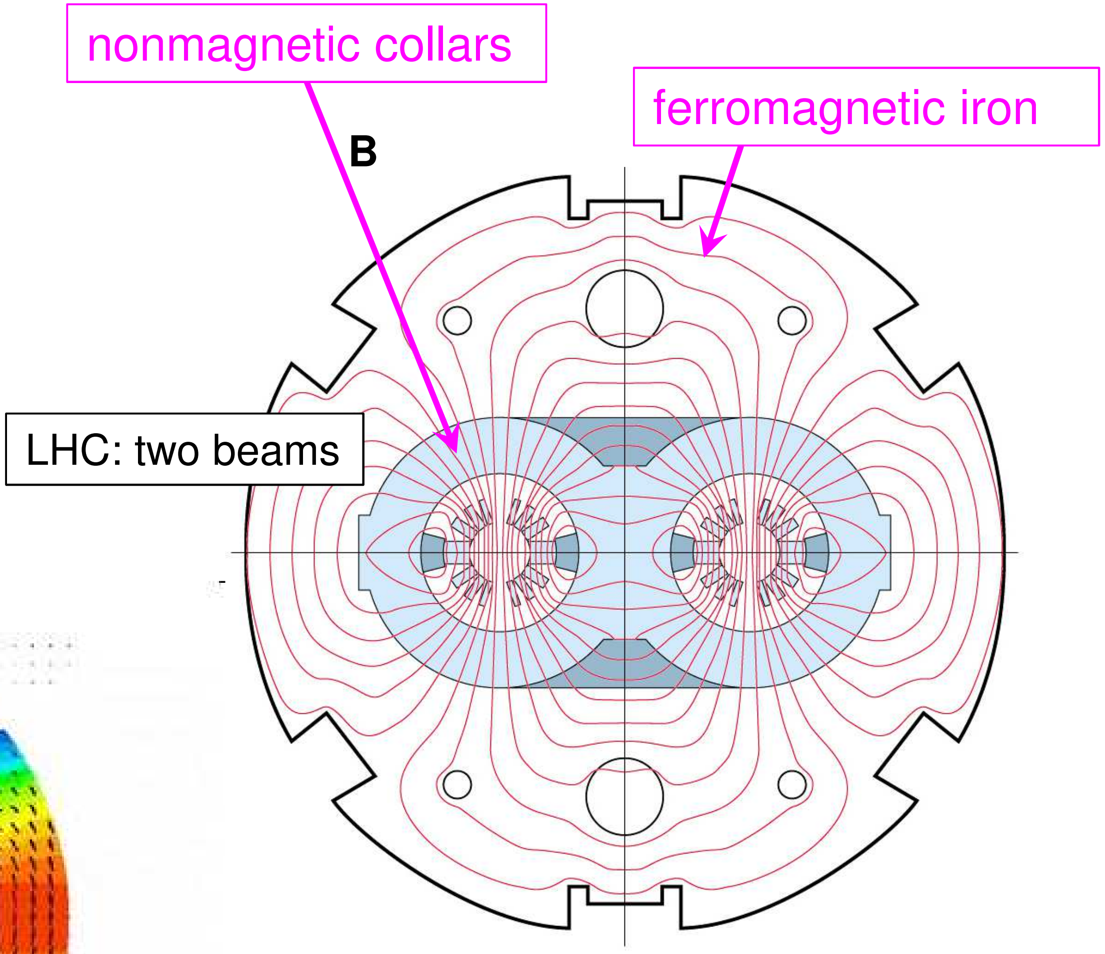
Tevatron HERA

RHIC

56 mm



two beams



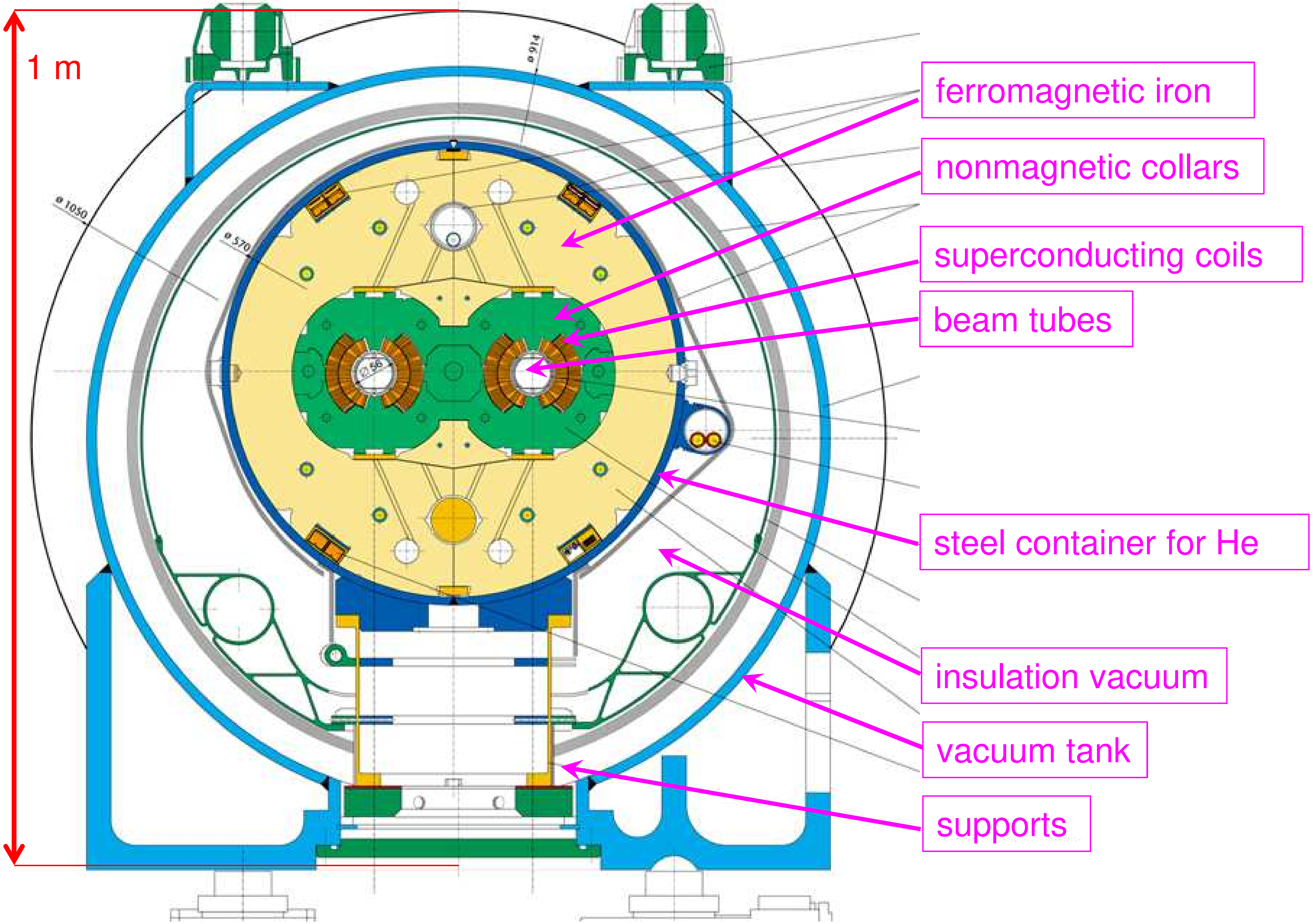
nonmagnetic collars

ferromagnetic iron

LHC: two beams

Computed magnetic flux map

LHC DIPOLE : STANDARD CROSS-SECTION



ferromagnetic iron

nonmagnetic collars

superconducting coils

beam tubes

steel container for He

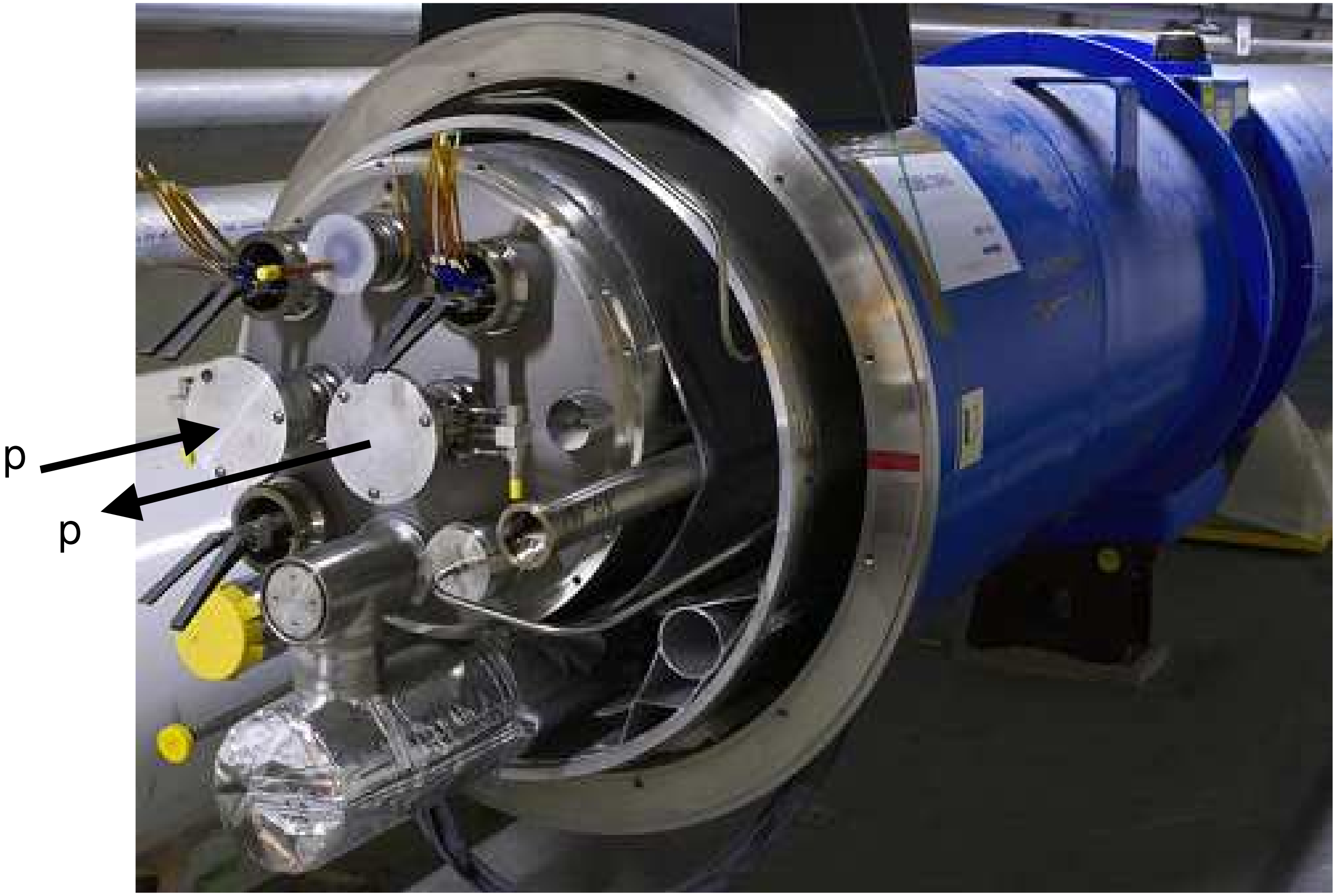
insulation vacuum

vacuum tank

supports

Superconducting dipole magnets

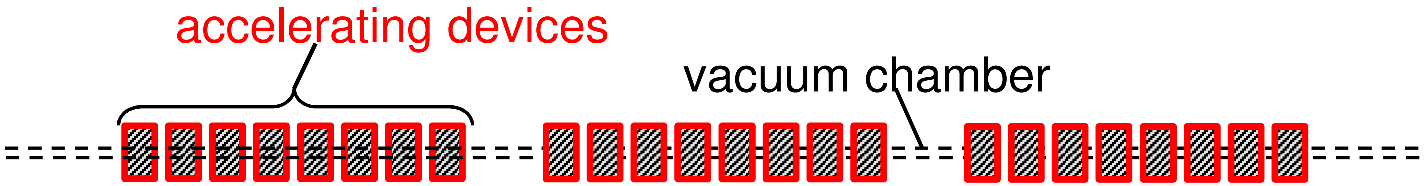
LHC dipole magnet interconnection:



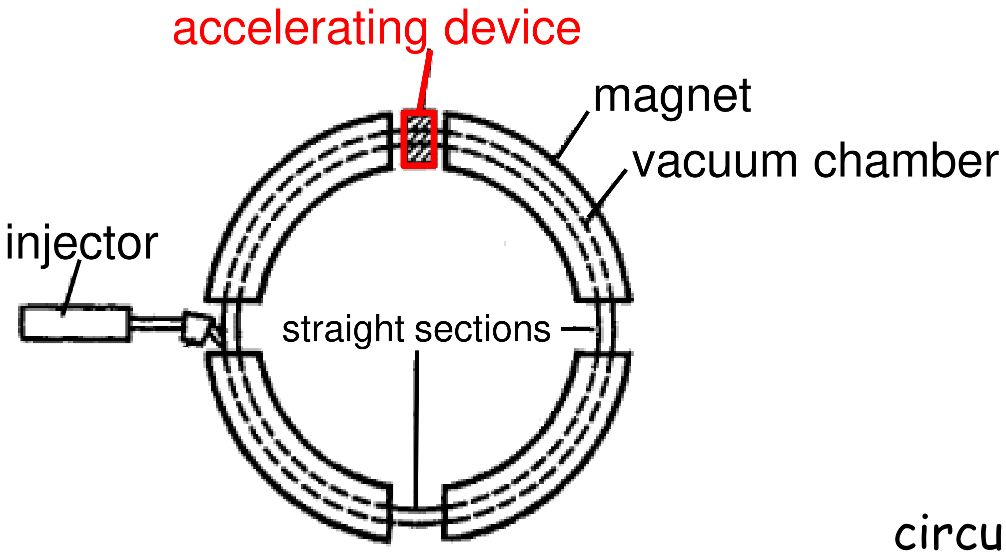
Key components and their challenges to reach high energies: Dipole magnetic fields

- ✓ field quality
- ✓ energy scalable: with current
- ✓ very high magnetic fields: using superconducting magnets (8.3 T at LHC)

Key components and their challenges to reach high energies: Acceleration of beams using radio-frequency electromagnetic fields



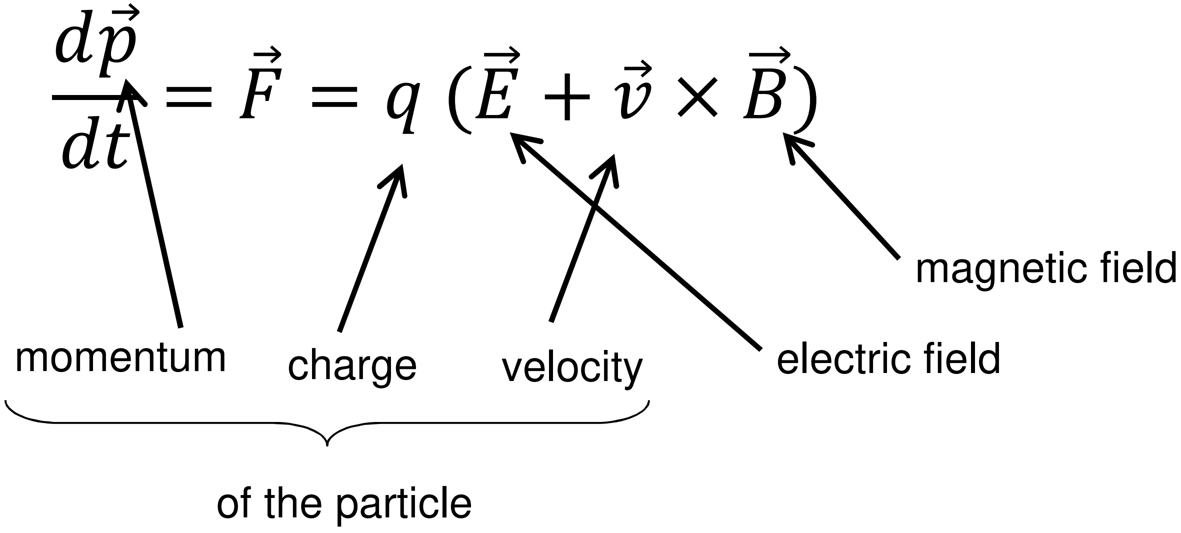
linear accelerator (linac)



circular accelerator: synchrotron

Motion in electric and magnetic fields

Equation of motion under Lorentz Force



$$\frac{d\vec{p}}{dt} = \vec{F} = q\,(\vec{E} + \vec{v} \times \vec{B})$$

magnetic field

momentum

charge

velocity

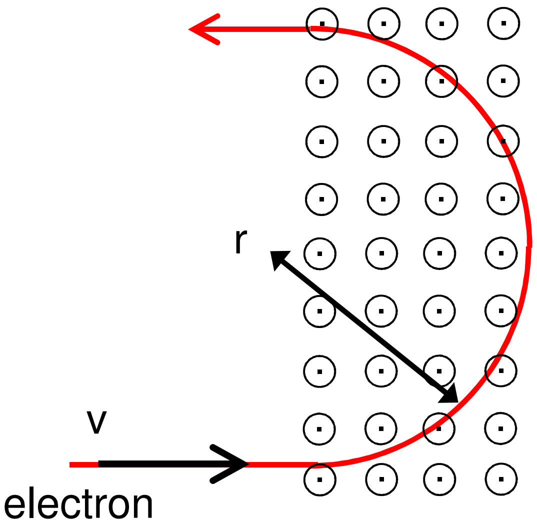
electric field

of the particle

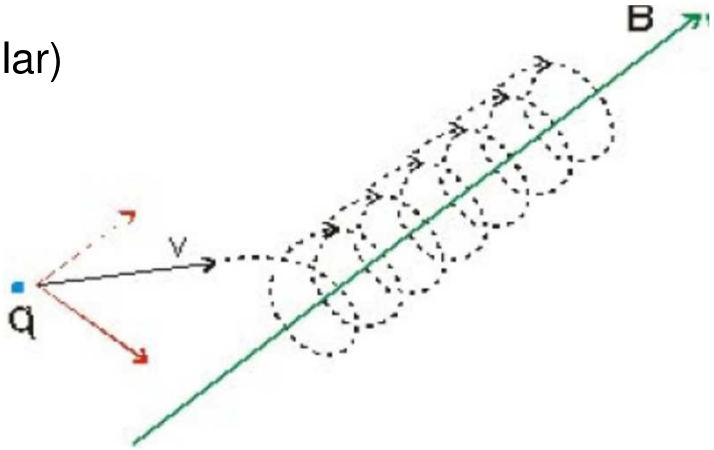
Motion in magnetic fields

if the electric field is zero ($\vec{E} = 0$), then

$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{v} \times \vec{B} \quad \rightarrow \quad \vec{F} \perp \vec{v}$$



B (perpendicular)



Magnetic fields <u>do not change</u> the particles energy

Motion in magnetic fields

if the electric field is zero (E=0), then

$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{v} \times \vec{B}$$

$$E^2 = \vec{p}^{\,2} c^2 + E_0^2$$

energy-momentum relation in special relativity

total energy

momentum

energy at rest

Motion in magnetic fields

if the electric field is zero (E=0), then

$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{v} \times \vec{B}$$

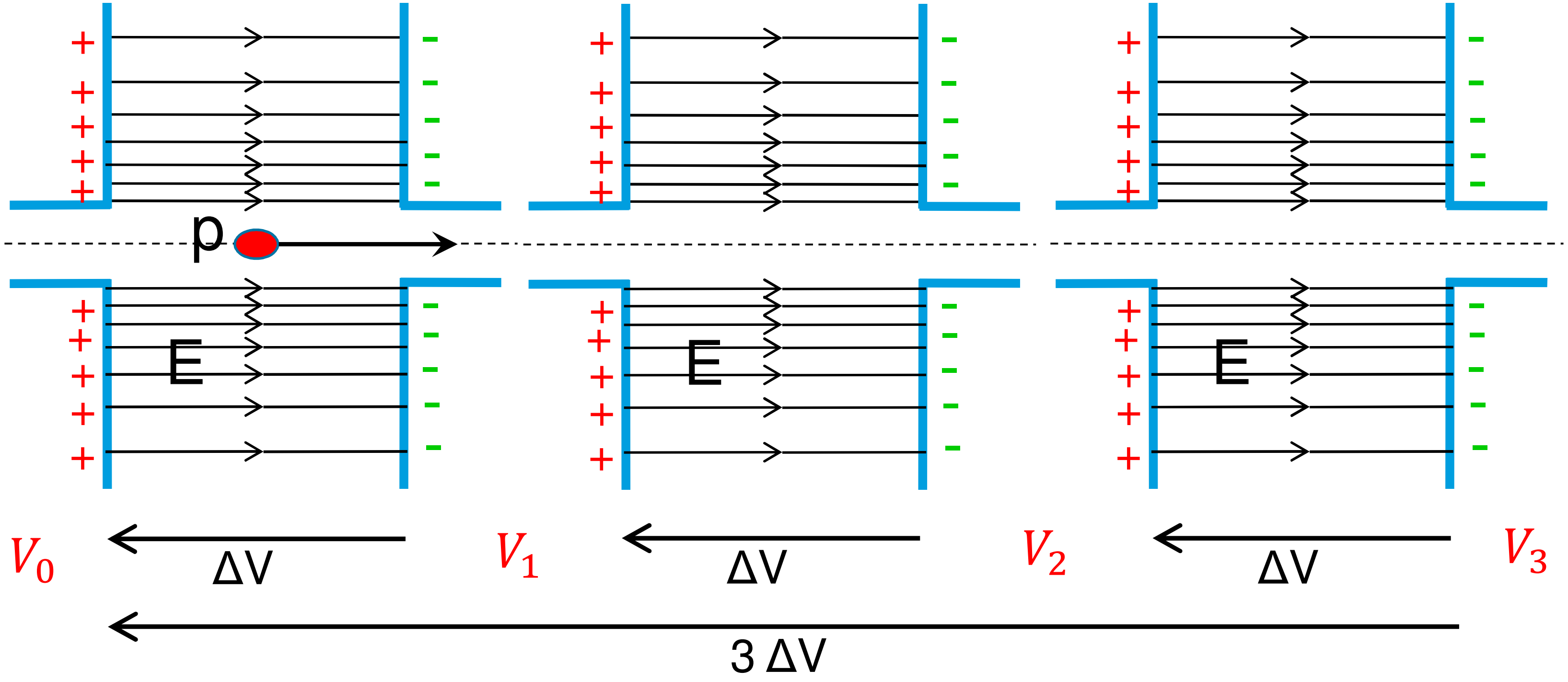
$$E^2 = \vec{p}^2 c^2 + E_0^2$$

$$E\frac{dE}{dt} = c^2 \vec{p}\frac{d\vec{p}}{dt} = c^2 q \vec{p}\left(\vec{v} \times \vec{B}\right) = c^2 q |\vec{p}| \left|\vec{v} \times \vec{B}\right| \cos\emptyset = 0$$

since $\vec{v} \times \vec{B} \perp \vec{v}$ ➔ $\emptyset = 90°$

Magnetic fields <u>do not change</u> the particles energy, only electric fields do !

acceleration with DC electric fields

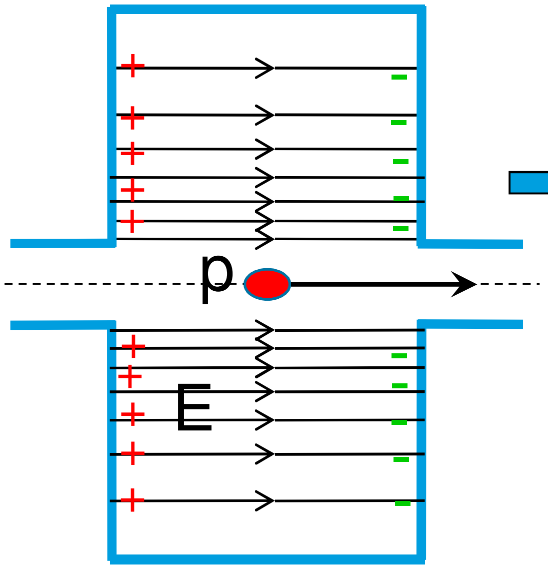


In general:

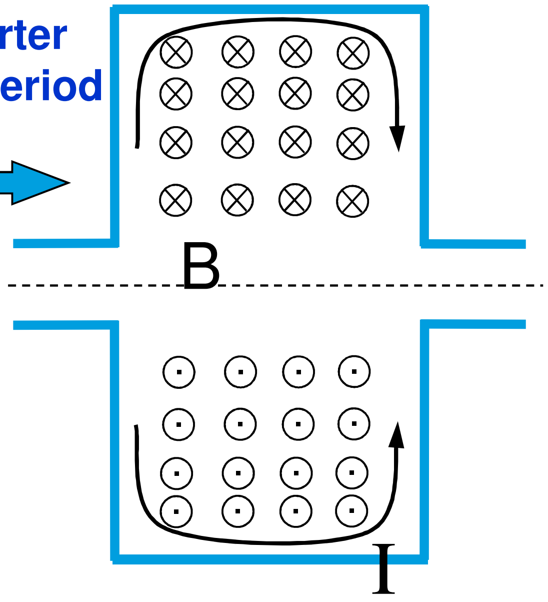
- Static magnetic fields → to guide (bend + focus) particle beams

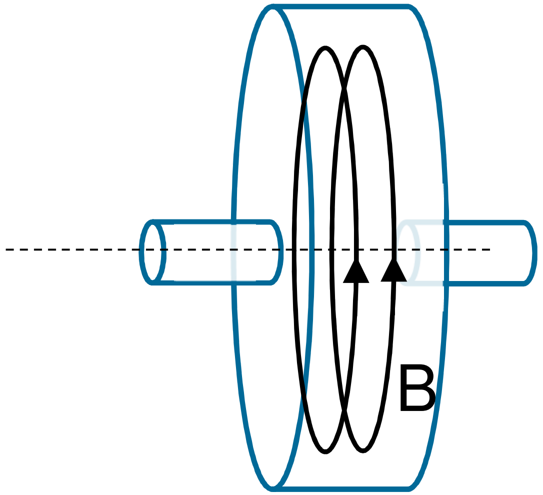
- Static electric fields → accelerate particle beams (low energy)
- Radio-frequency EM fields → accelerate particle beams (high E)

RF cavity basics: the pill box cavity

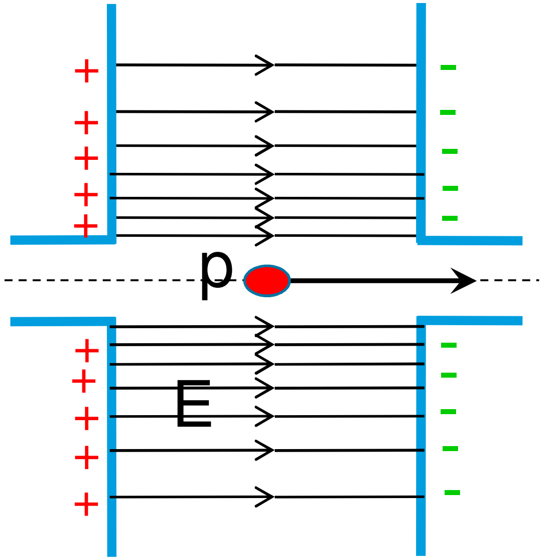


a quarter of a period later:

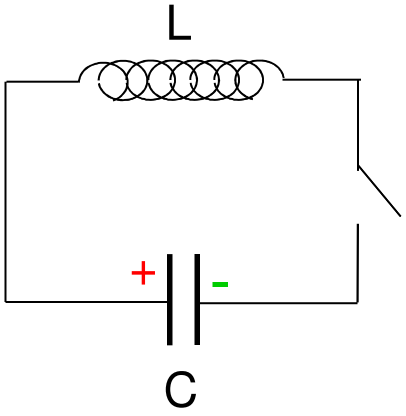




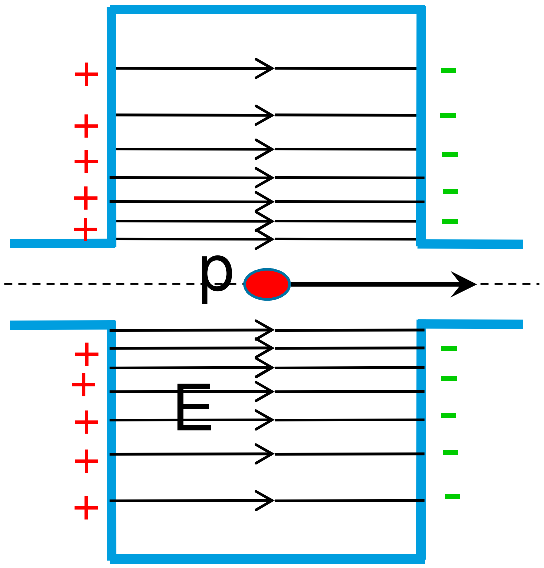
RF cavity basics: the pill box cavity



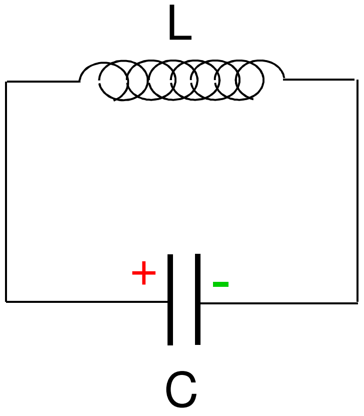
LC circuit (or resonant circuit) analogy:



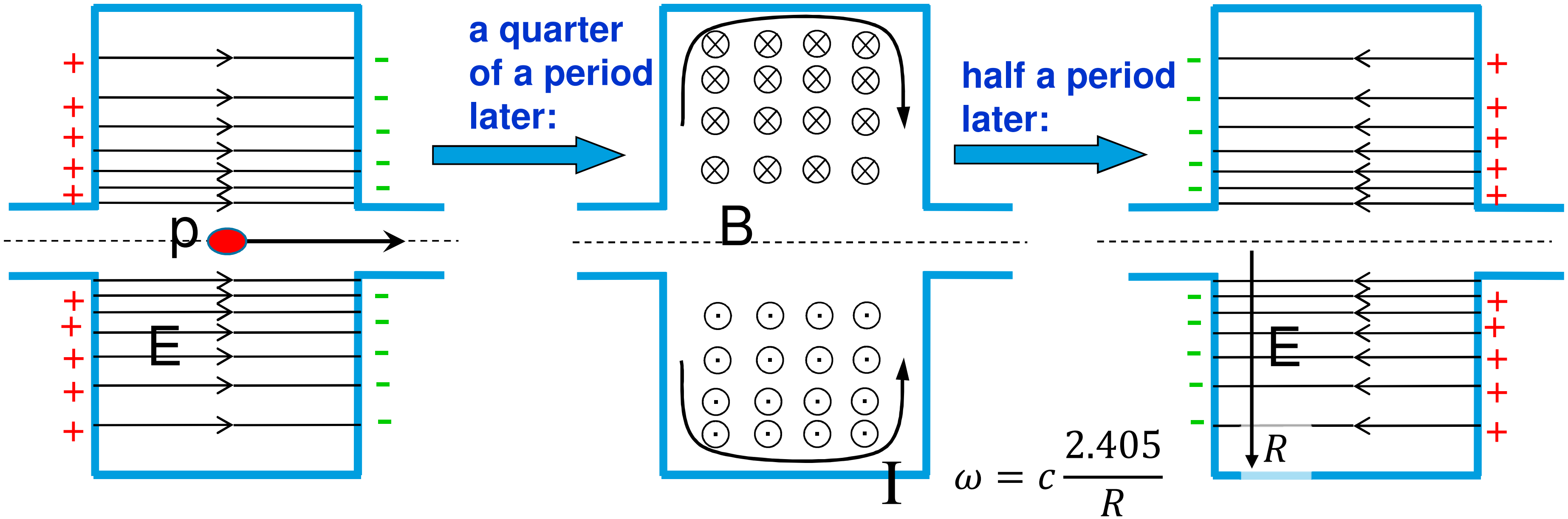
RF cavity basics: the pill box cavity



LC circuit (or resonant circuit) analogy:



RF cavity basics: the pill box cavity

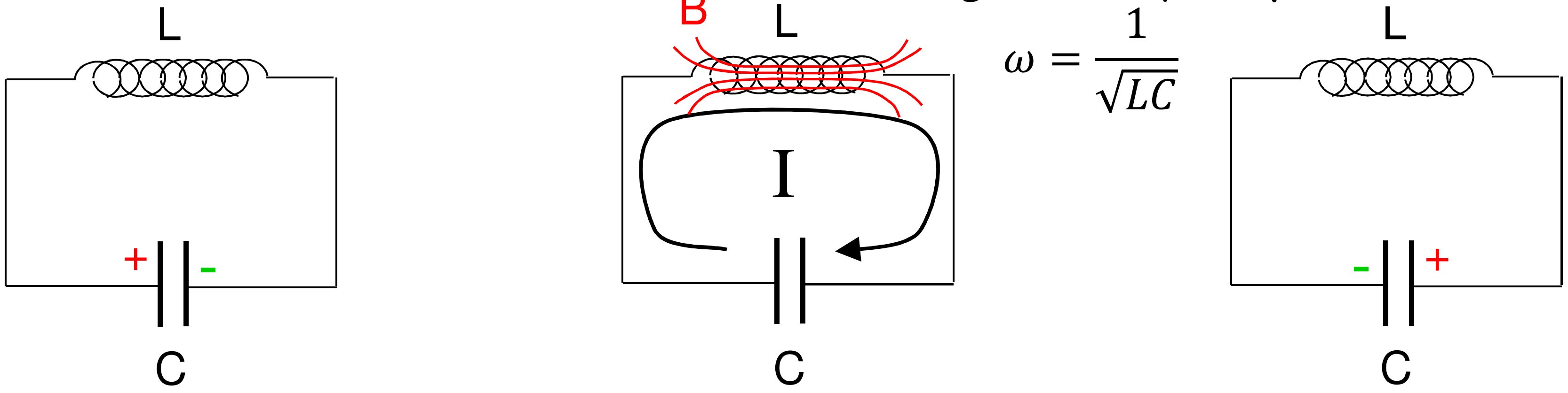


a quarter of a period later:

half a period later:

$$\omega = c\,\frac{2.405}{R}$$

LC circuit (or resonant circuit) analogy:

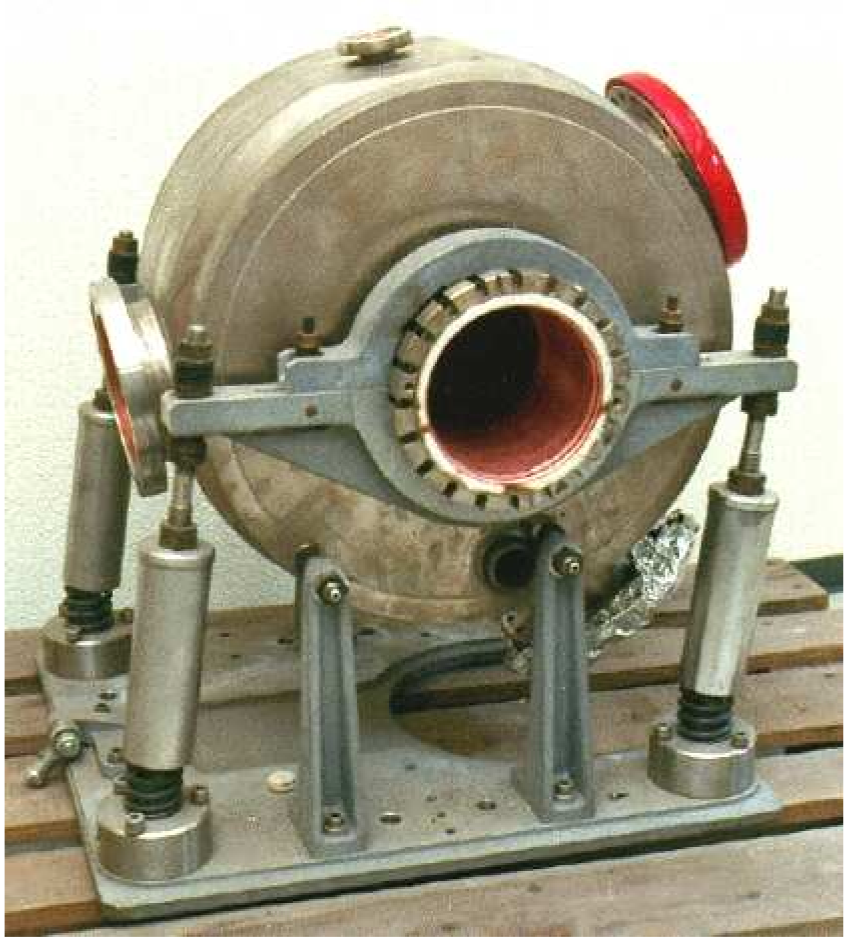


angular frequency:

$$\omega = \frac{1}{\sqrt{LC}}$$

Examples of pill box cavities

DESY cavity (pill box)

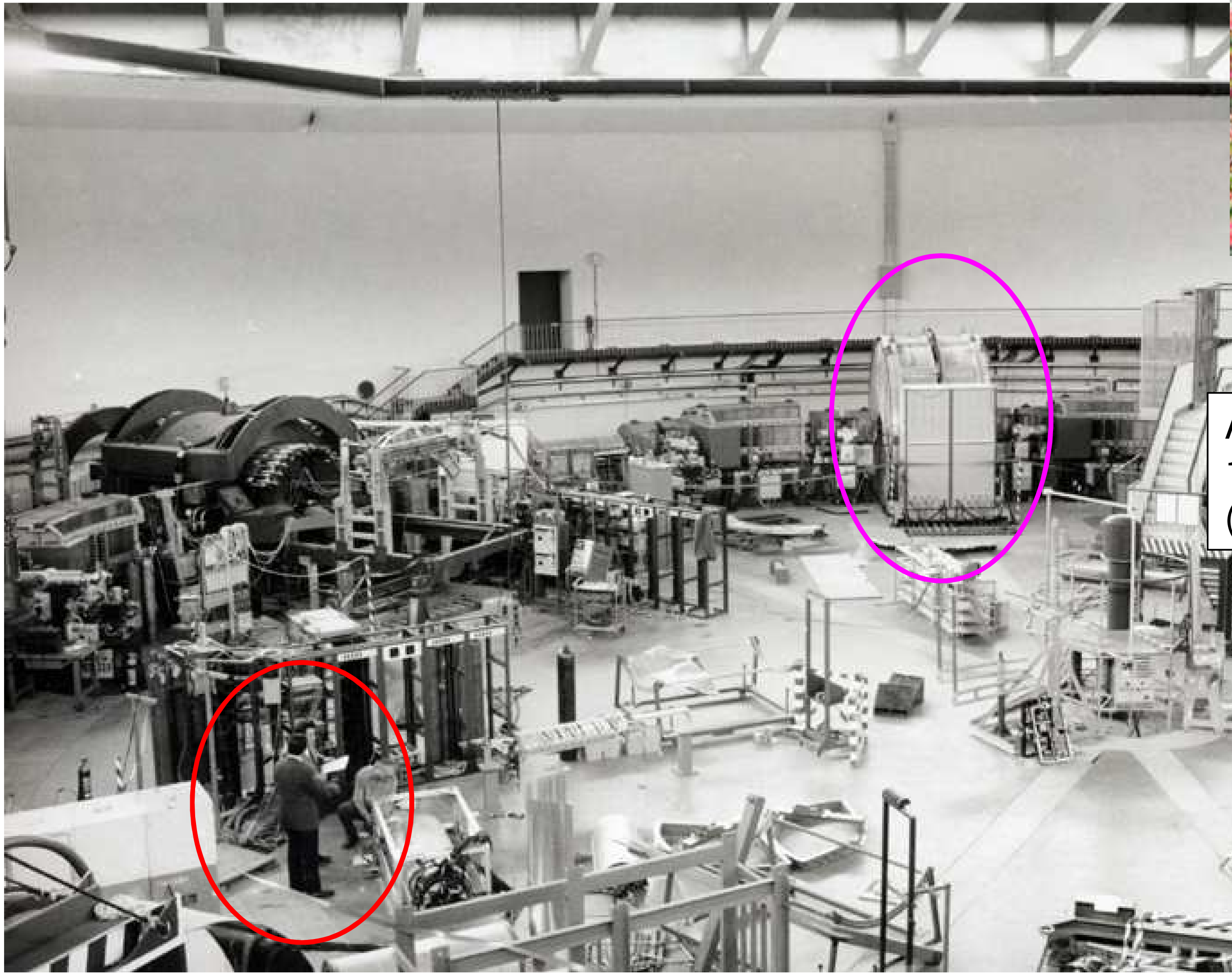


ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

Examples of pill box cavities

ADONE cavity 51 MHz (pill box)
Frascati lab, Italy

ADONE in 1963, Laboratori Nazionali di Frascati, Italy



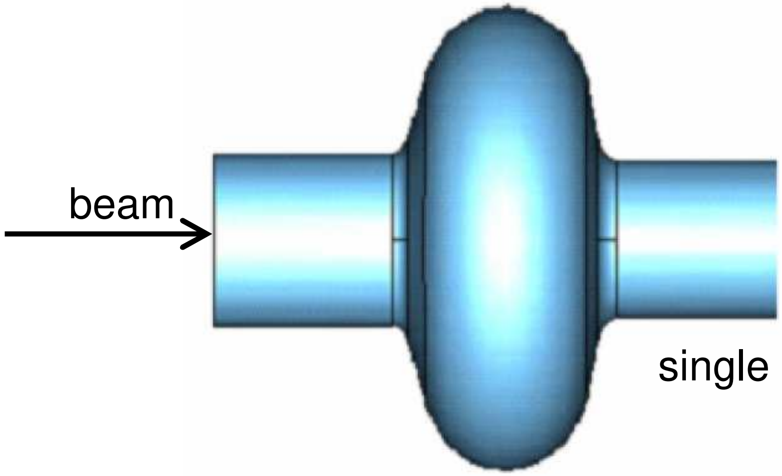
ADONE length = 105 m
18th harmonic
(exercise)

Key components and their challenges to reach high energies: Acceleration of beams using radio-frequency electromagnetic fields

- ✓ high acceleration electric fields: up to 50-60 MV/m (normal conducting)
- – low power efficiency: (wall-losses ∝ E^2)

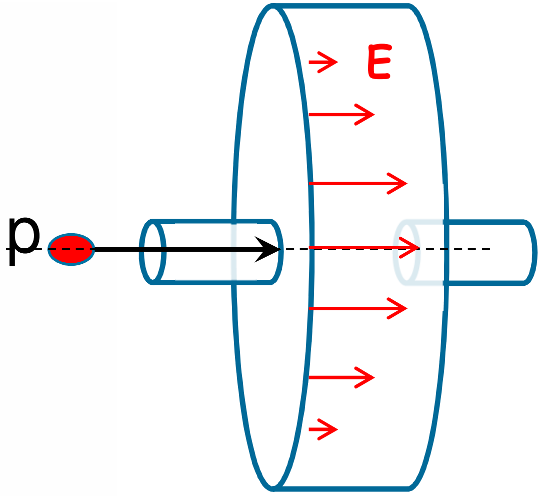
particle collider:	need high number of collisions, events
spallation neutron source:	need high number of protons
synchrotron light source:	need high number of photons

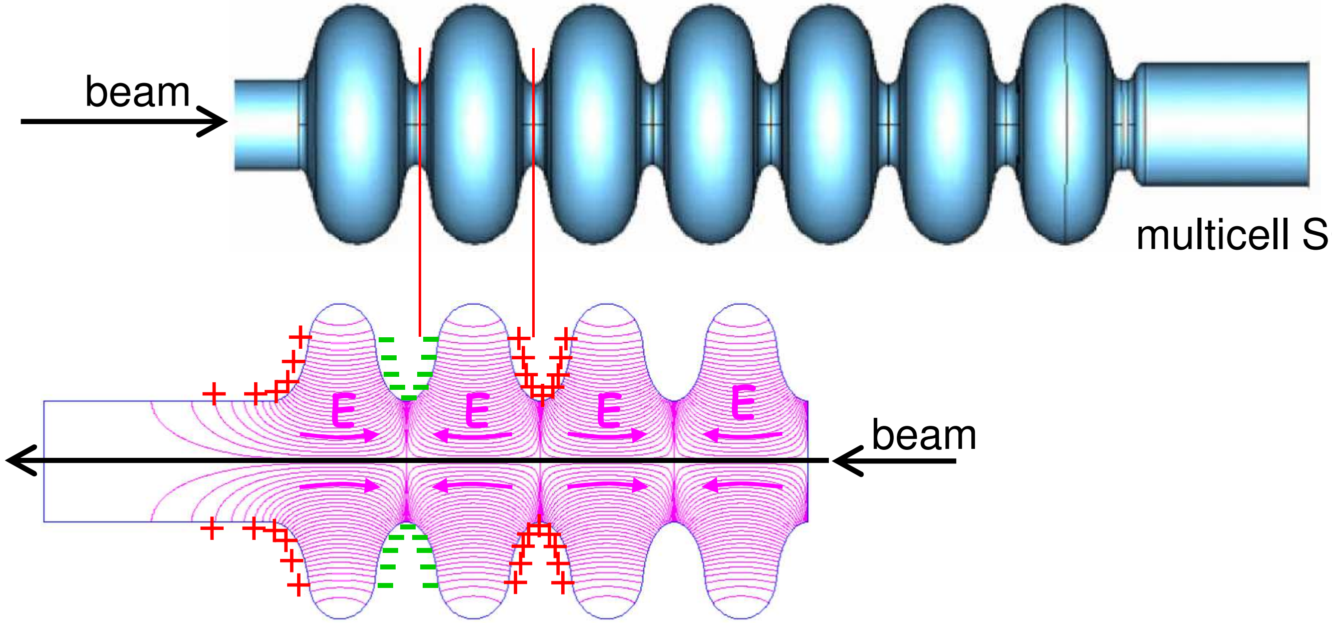
Superconducting cavities



single cell SC cavity

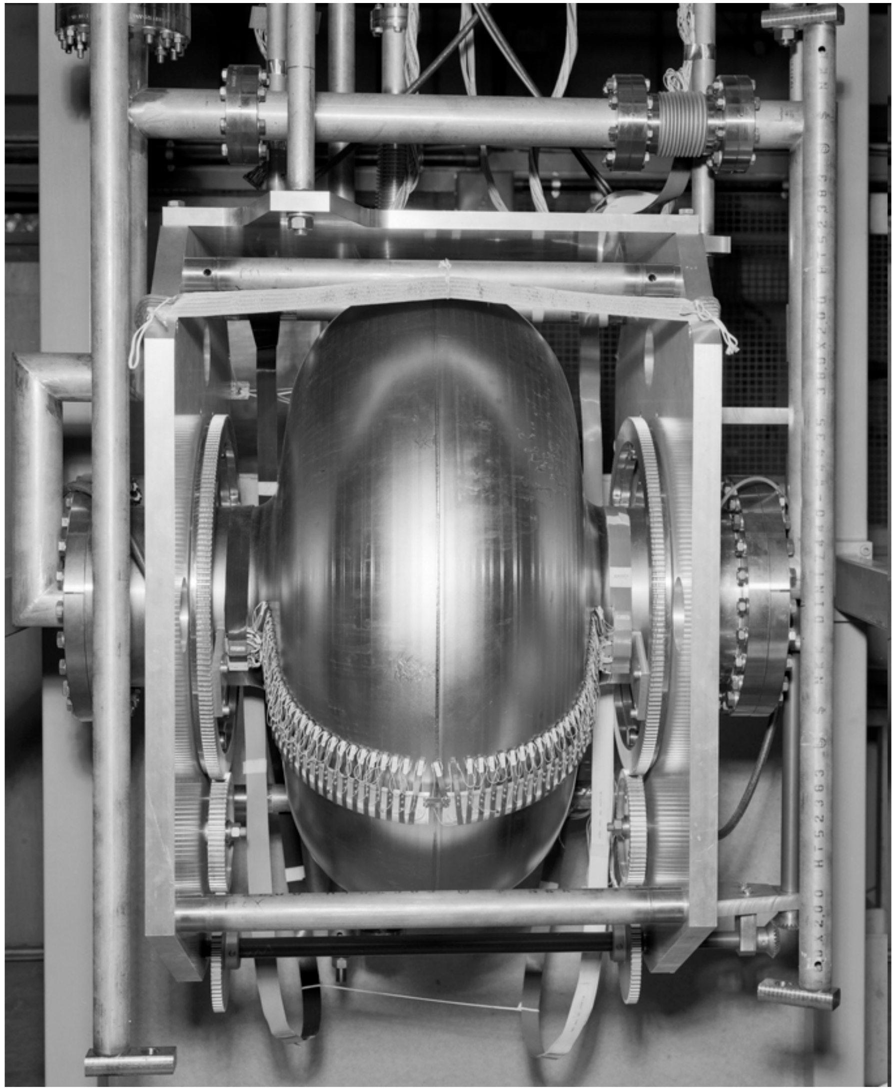
pill box cavity



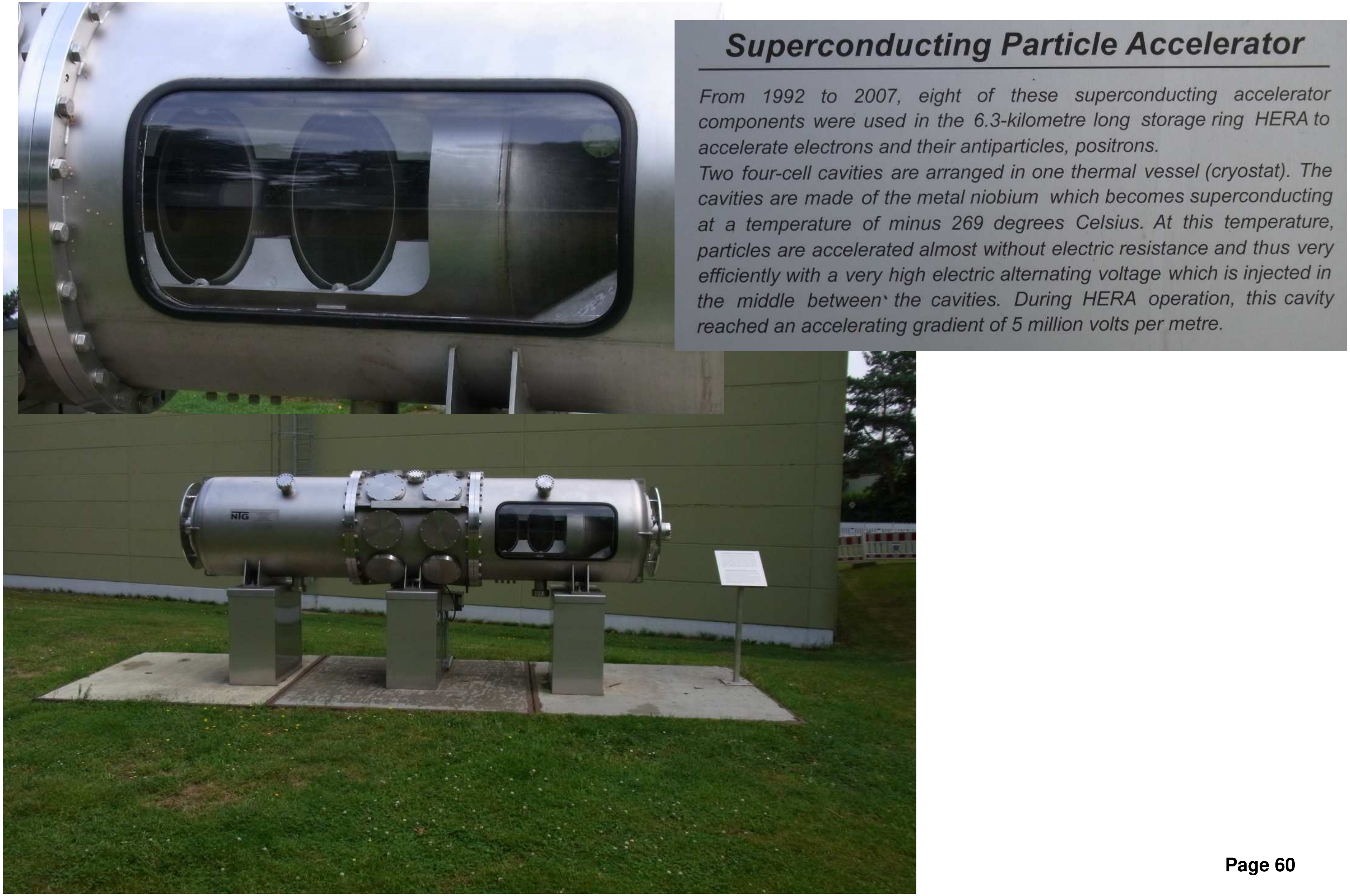


multicell SC cavity

Superconducting cavities at LEP



Superconducting cavities at HERA

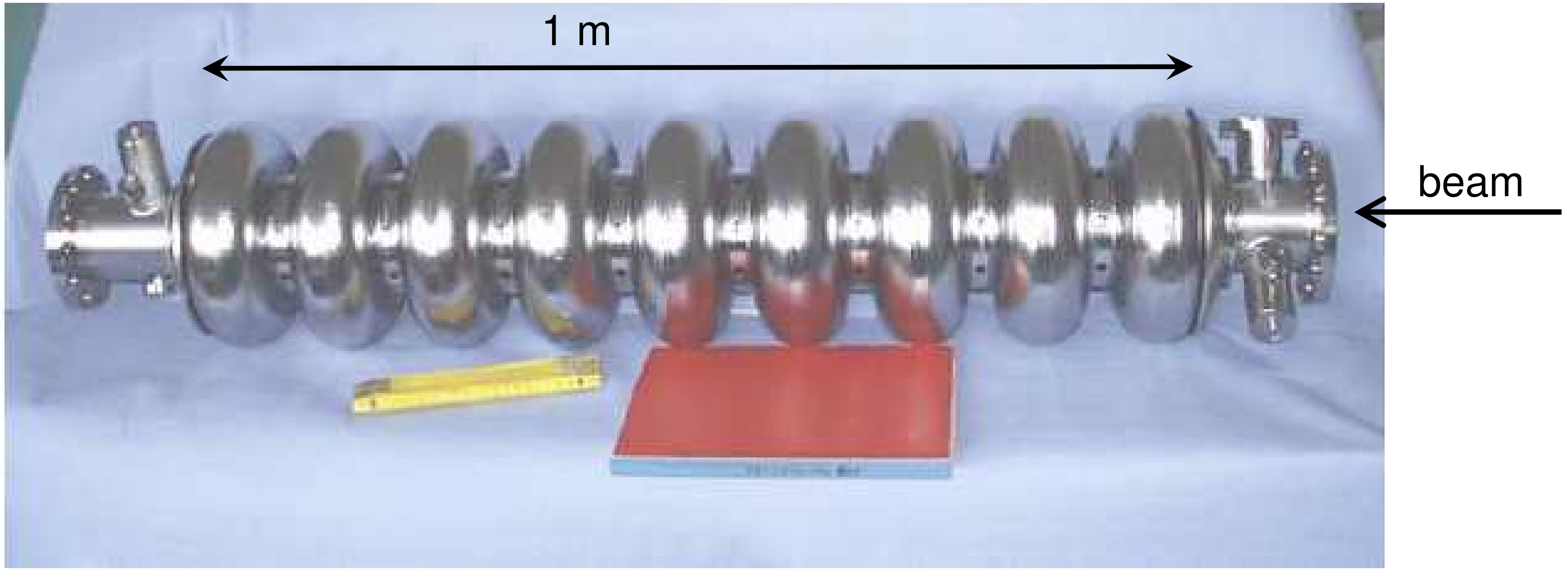


Superconducting Particle Accelerator

From 1992 to 2007, eight of these superconducting accelerator components were used in the 6.3-kilometre long storage ring HERA to accelerate electrons and their antiparticles, positrons.

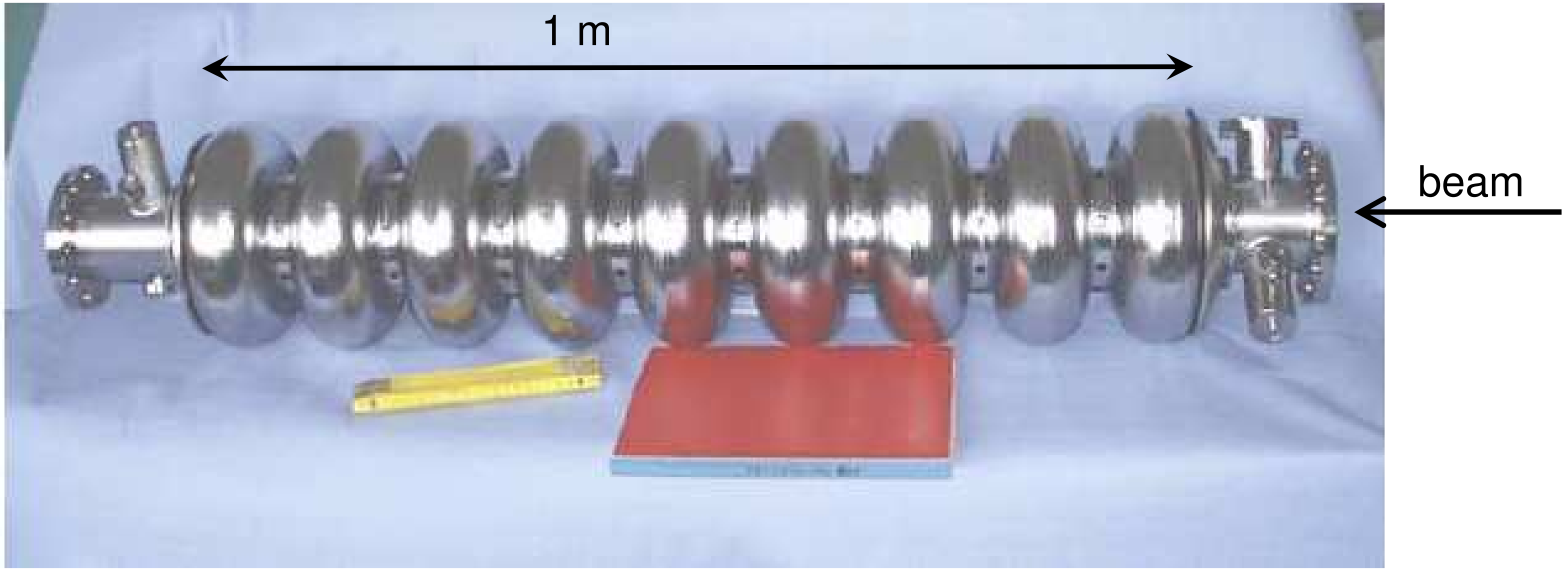
Two four-cell cavities are arranged in one thermal vessel (cryostat). The cavities are made of the metal niobium which becomes superconducting at a temperature of minus 269 degrees Celsius. At this temperature, particles are accelerated almost without electric resistance and thus very efficiently with a very high electric alternating voltage which is injected in the middle between the cavities. During HERA operation, this cavity reached an accelerating gradient of 5 million volts per metre.

Superconducting cavity used at DESY



European X-ray Free-Electron Laser	3 km	DESY	2016- ?	e-	17.5 GeV
International Linear Collider	30 km	?	?	e-/e+	2x250 GeV

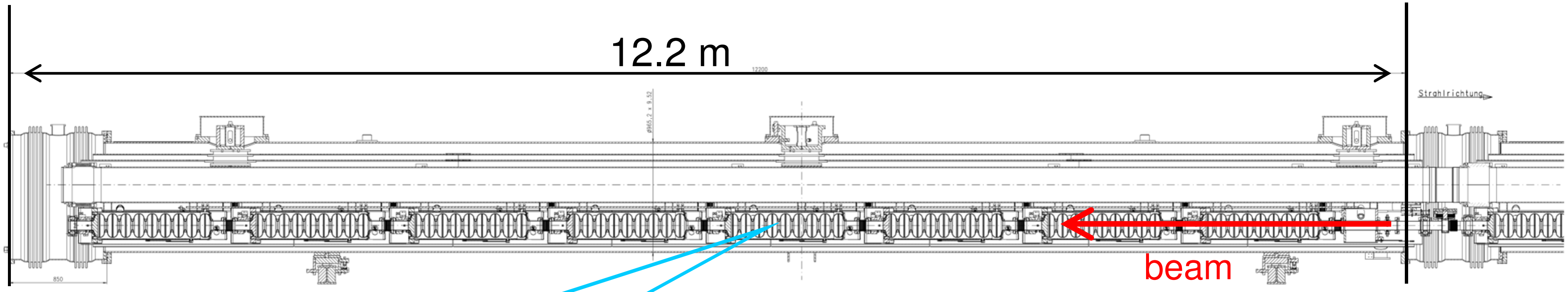
Superconducting cavity used at DESY

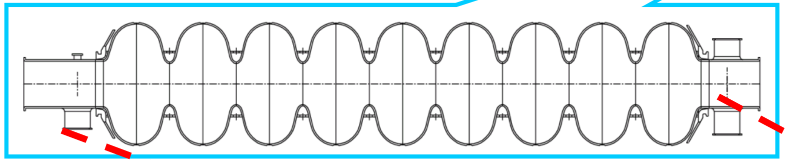


material: pure Niobium

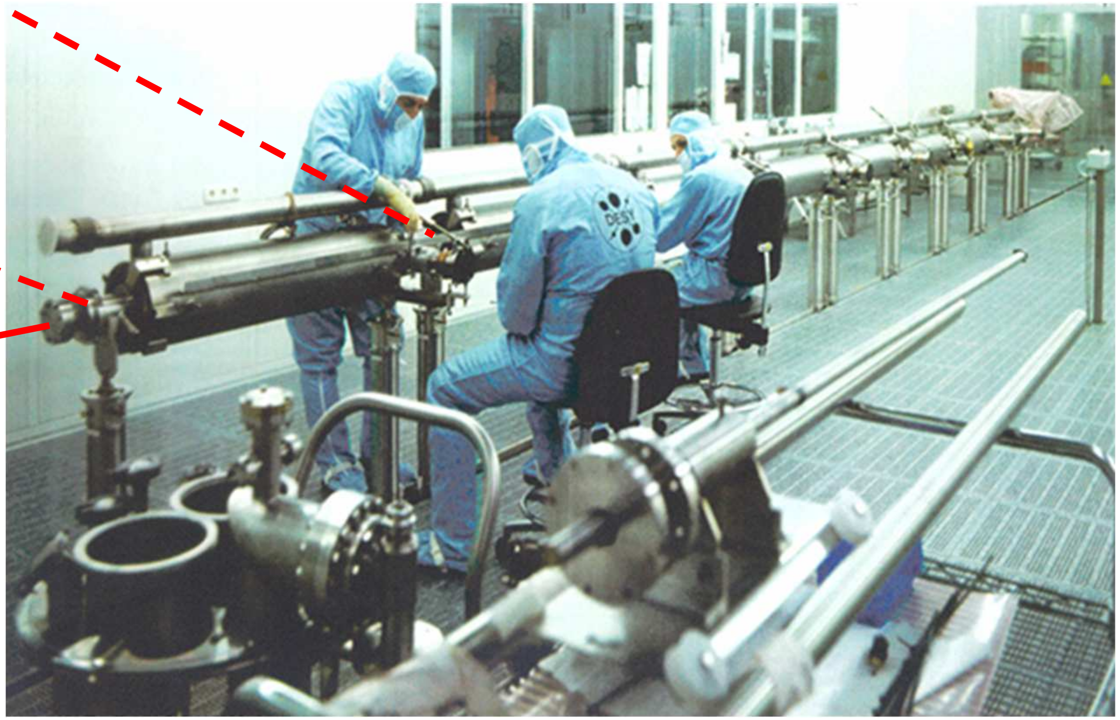
operating temperature: 2 K

accelerating field gradient: up to 35 MV/m



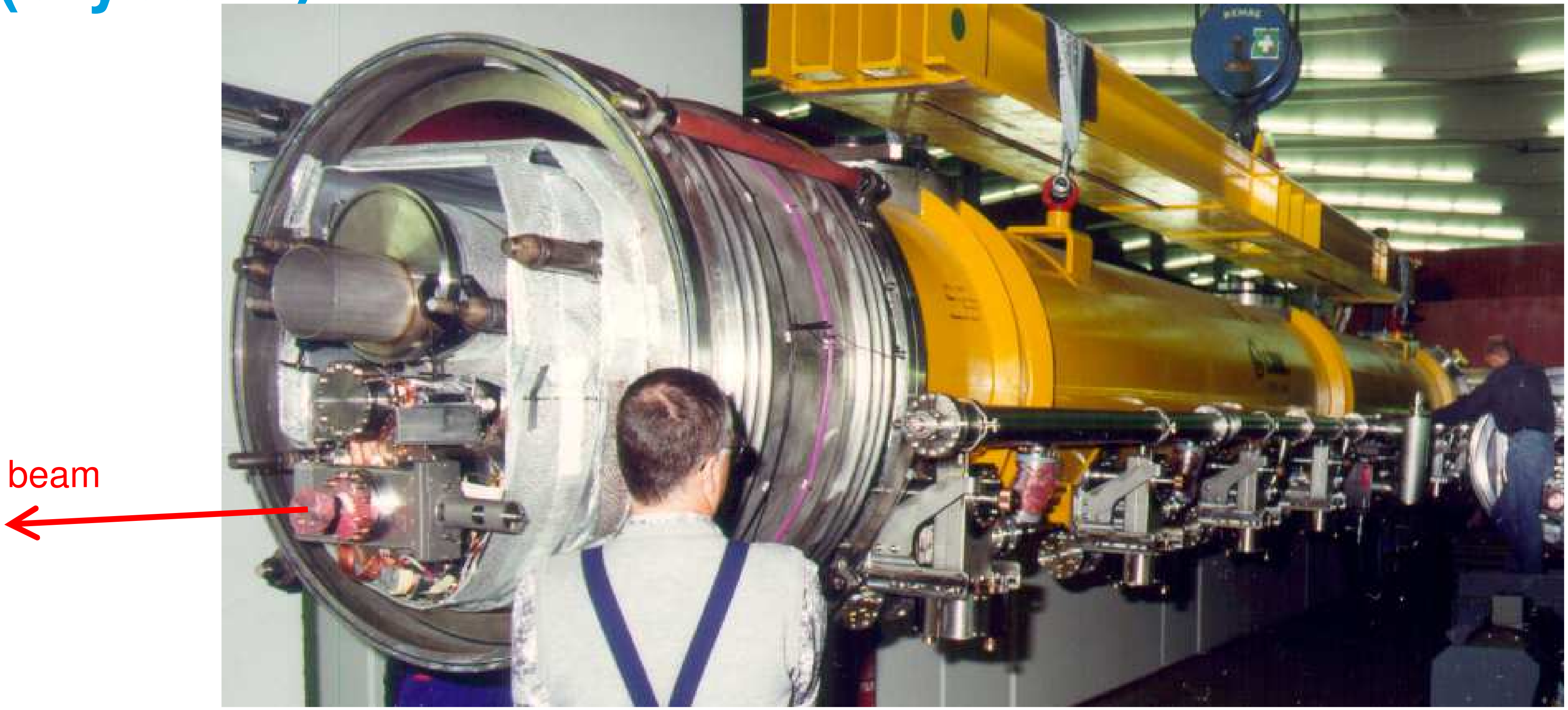


Number of cavities	8
Cavity length	1.038 m
Operating frequency	1.3 GHz
Operating temperature	2 K
Accelerating Gradient	23..35 MV/m



Cavities inside a cryostat

Cavities inside an accelerator module (cryostat)



module installation

Accelerators in Europe using superconducting cavities

- 5 de-commissioned
- 11 in operation
- 4 in construction
- 10 in design phase

Total = 30

sychrotrons (colliders): HERA, LEP, LHC, LHeC
sychrotrons (light sources): DIAMOND, ELETTRA, SLS, SOLEIL
FELs: LISA, ALICE, FLASH, LUNEX5, POLFEL
linear colliders: ILC
nuclear physics: ISOLDE, S-DALINAC, SPIRAL2, MYRRHA
spallation sources: ESS, EURISOL, TRASCO

full list: https://tesla.desy.de/srf_accelerators

Key components and their challenges to reach high energies:
Acceleration of beams using radio-frequency electromagnetic fields

- ✓ high acceleration electric fields: up to 35-40 MV/m (superconducting)
- ✓ up to 50-60 MV/m (normal conducting)
- ✓ very high power efficiency: using superconducting cavities

Thank you for your attention

Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

Pedro Castro
MPY
pedro.castro@desy.de