Introduction to Accelerators.

Scientific Tools for High Energy Physics and Synchrotron Radiation Research

Pedro Castro
Introduction to Particle Accelerators
DESY, July 2010

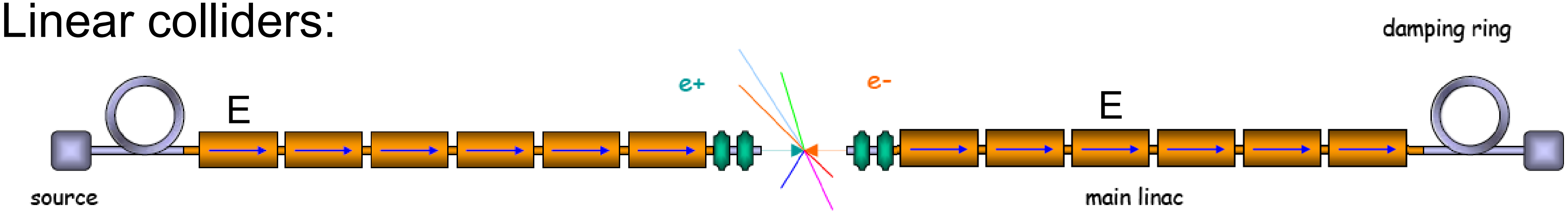
HELMHOLTZ | ASSOCIATION

DESY

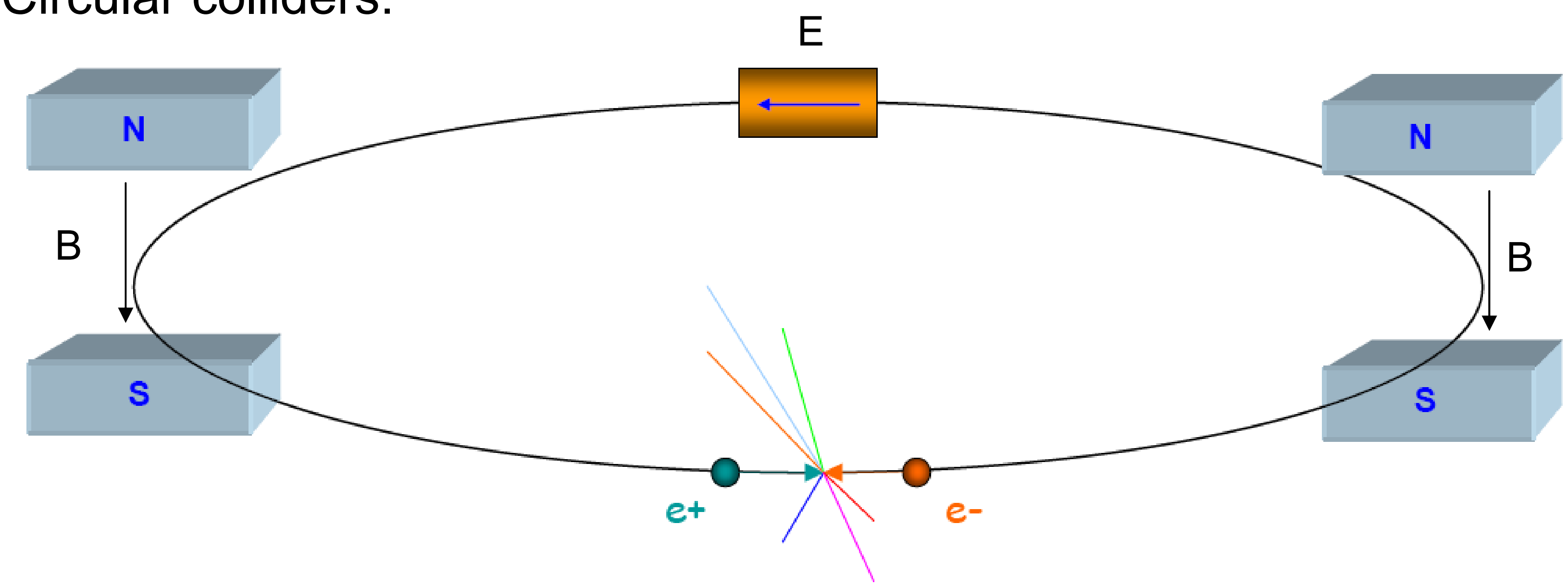
What you will see…

How to build colliders

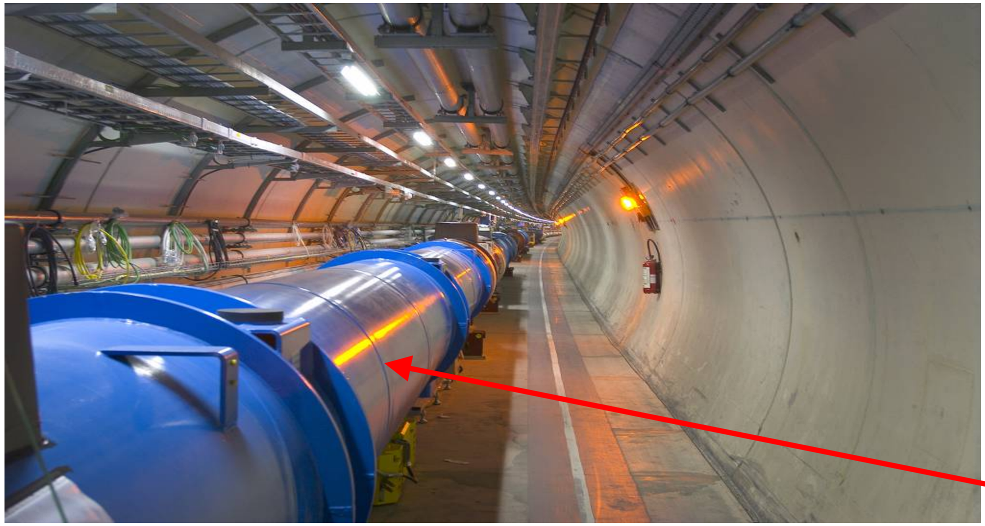
Linear colliders:



Circular colliders:

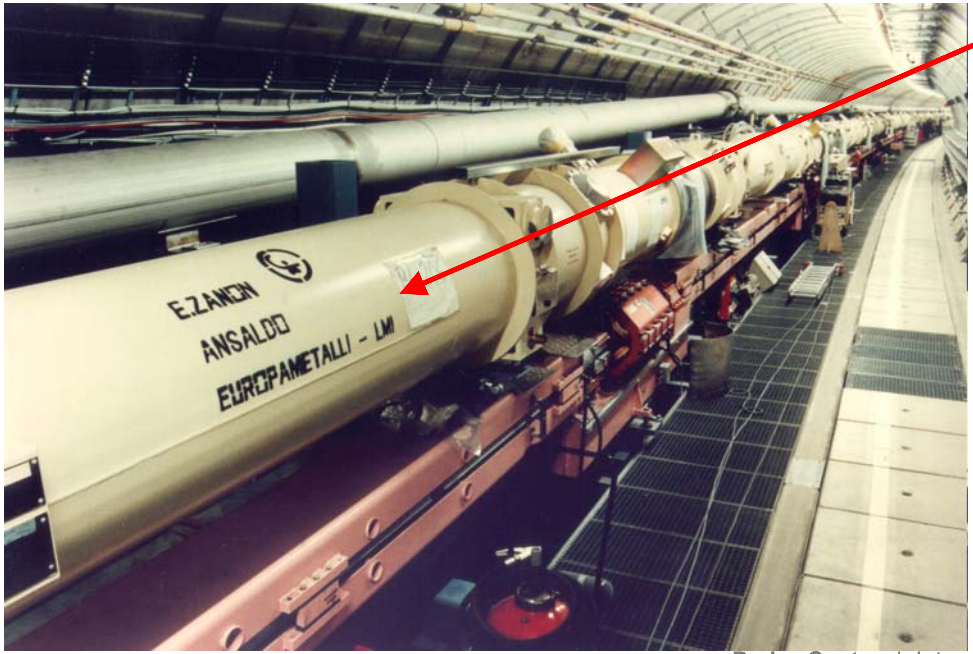


Superconducting magnets



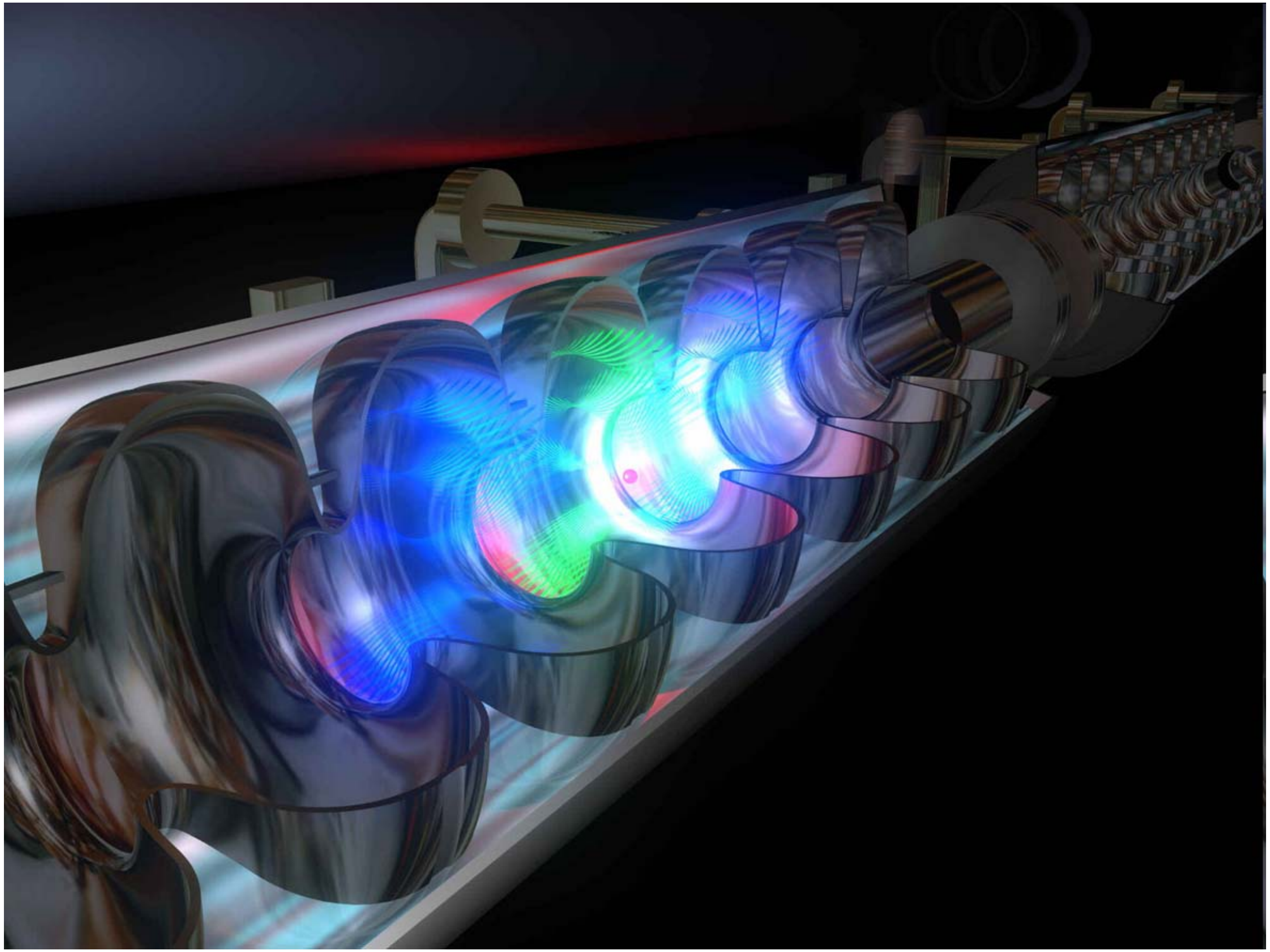
LHC

superconducting magnets



HERA

How electromagnetic fields accelerate particles



Differences between proton and electron accelerators

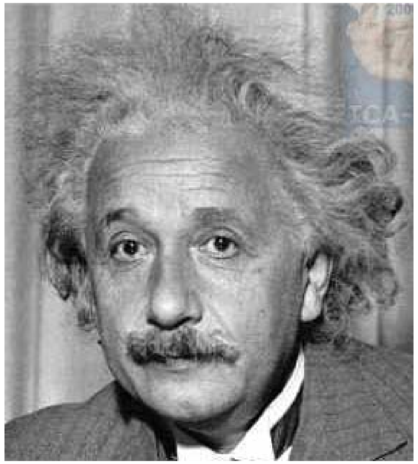
HERA (Hadron Electron Ring Accelerator) tunnel:

proton accelerator

electron accelerator

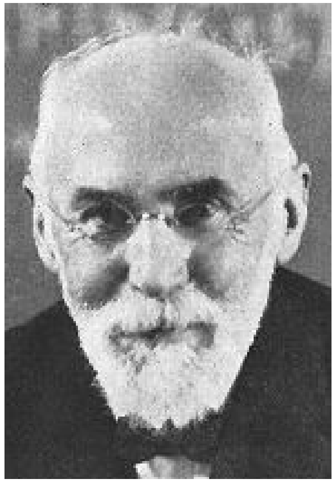
Fundamental principles at work

mass–energy equivalence $E = mc^2$



relativity

wave–particle duality $\lambda = \frac{h}{p}$ (de Broglie wavelength)

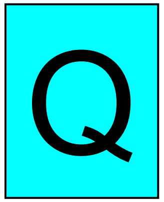


Lorenzt force

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Ampère's law $\nabla \times \mathbf{B} = \mu_0 \mathbf{J_f}$

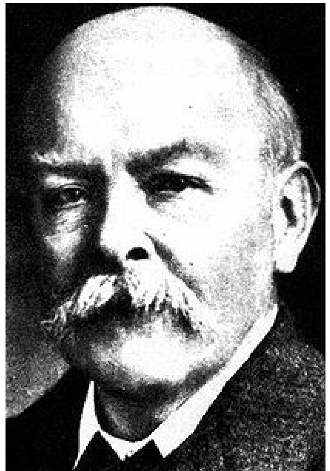
superconductivity



quantum effects

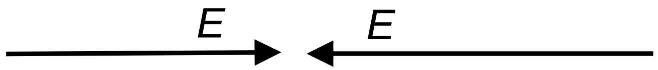
Poynting vector

$$\mathbf{S} = \frac{1}{\mu_0}\mathbf{E} \times \mathbf{B}$$

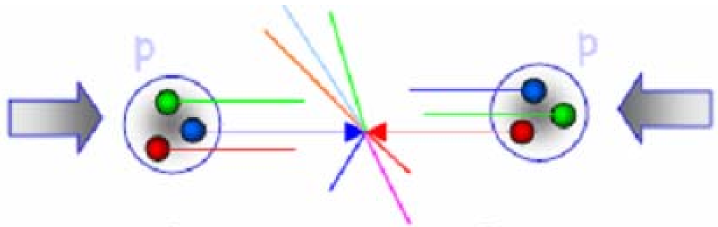


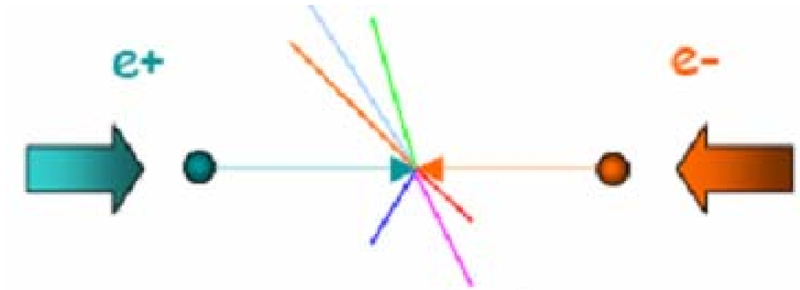
Accelerators as tools for researchers

> 1. Mass–energy equivalence: $$E = mc^2$$



➔ creation of much heavier particles

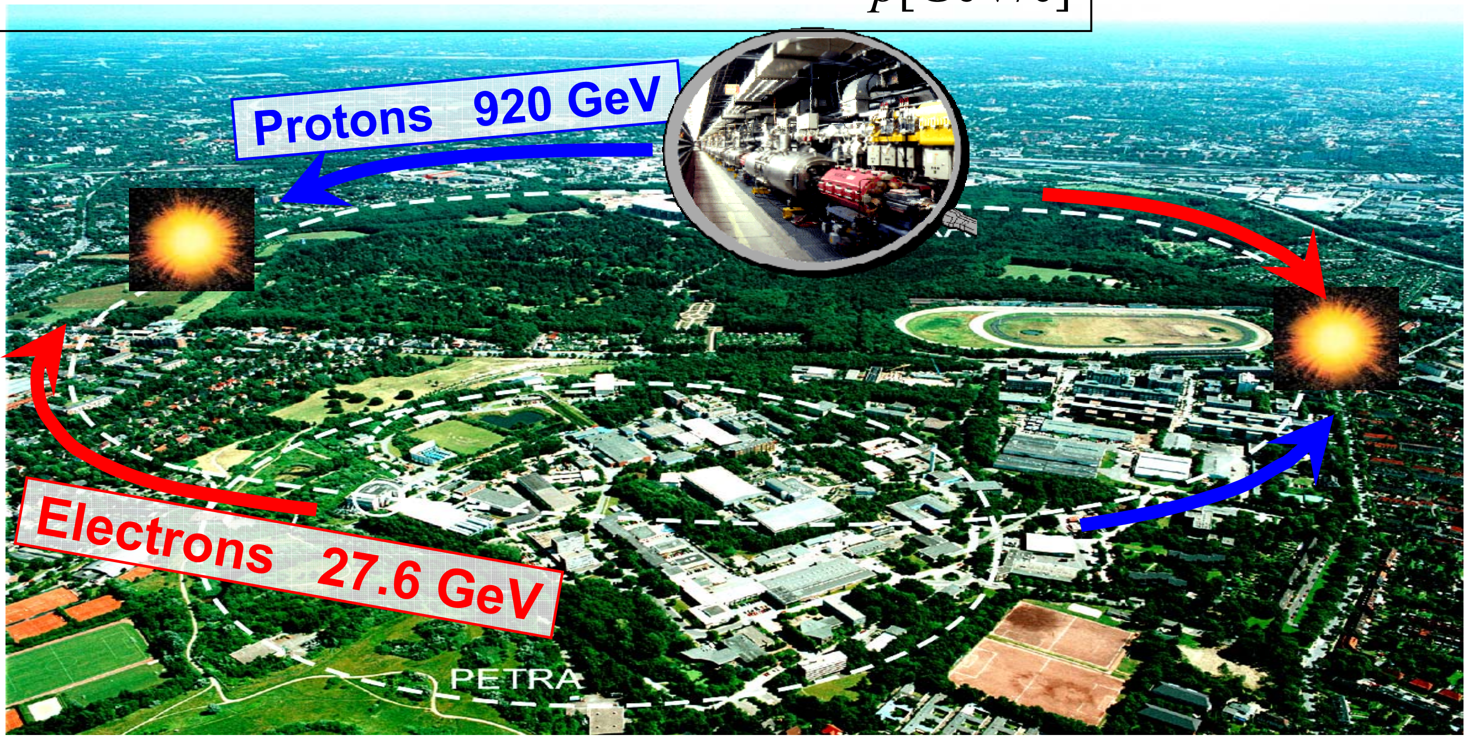




HERA: the super electron microscope

Resolution = de Broglie wavelength $\longrightarrow$ $\lambda[\text{fm}] = \dfrac{1.2}{p[\text{GeV/c}]}$

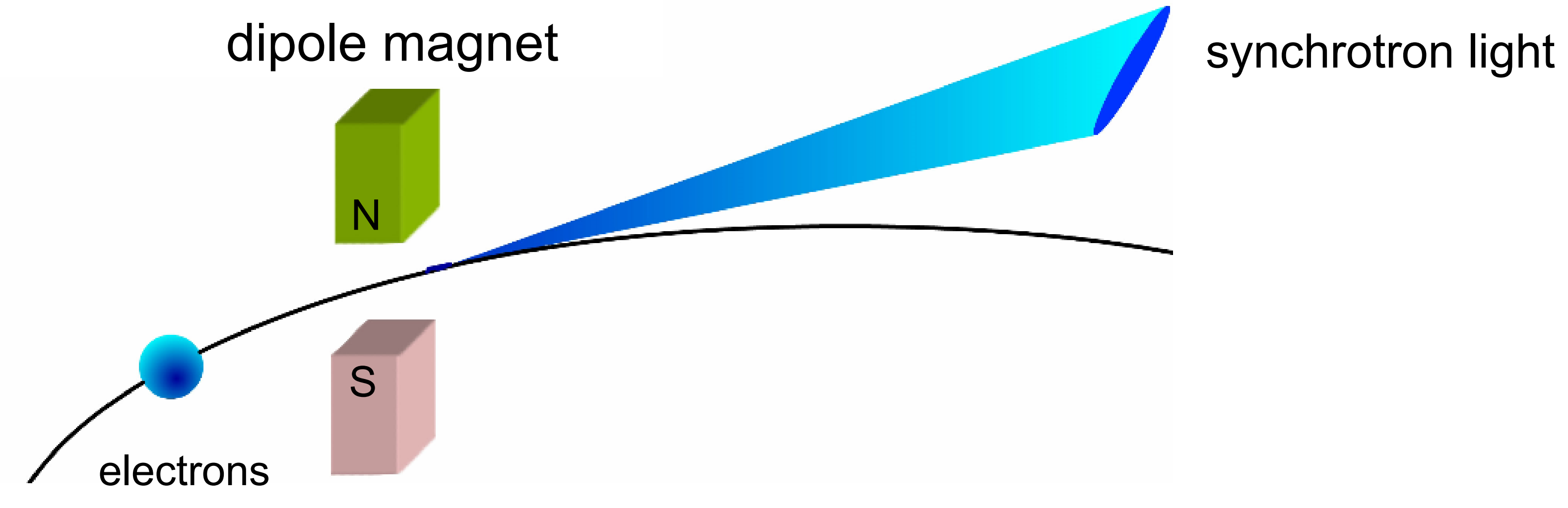
1.6 fm = diameter of proton



HERA: Hadron-Electron Ring Accelerator, 6.3 km ring, DESY
(physics: 1992-2007), max. E = 27.5 GeV for electrons, 920 GeV for protrons

collision energy at <u>center of mass</u> frame = 318 GeV $\lambda[\text{fm}] = \dfrac{1.2}{318\ \text{GeV/c}} = 0.0038\ \text{fm}$

Accelerators as light sources



spectroscopy, X-ray diffraction, X-ray microscopy, crystallography (of proteins), …

Other applications of accelerators?

- About 120 accelerators for research in “nuclear and particle physics”
- About 70 electron storage rings and electron linear accelerators used as light sources (so-called ‘synchrotron radiation sources’)

Other applications of accelerators

> About 120 accelerators for research in "nuclear and particle physics"

> About 70 electron storage rings and electron linear accelerators used as light sources (so-called 'synchrotron radiation sources')

$< 1\%$

Other applications:

> More than 7,000 accelerators for medicine

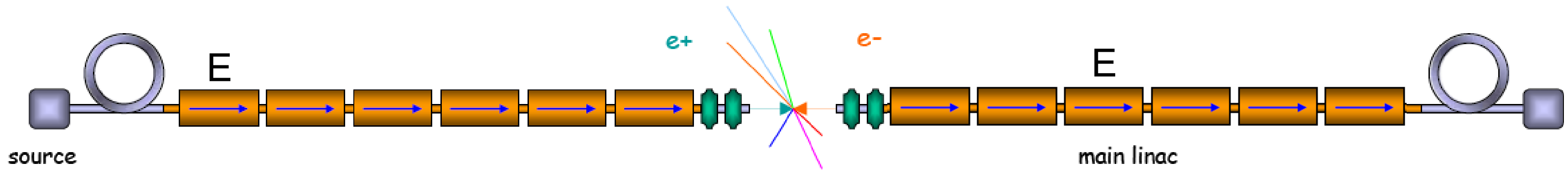
radiotherapy (>7,500), radioisotope production (200)

> More than 18,000 industrial accelerators

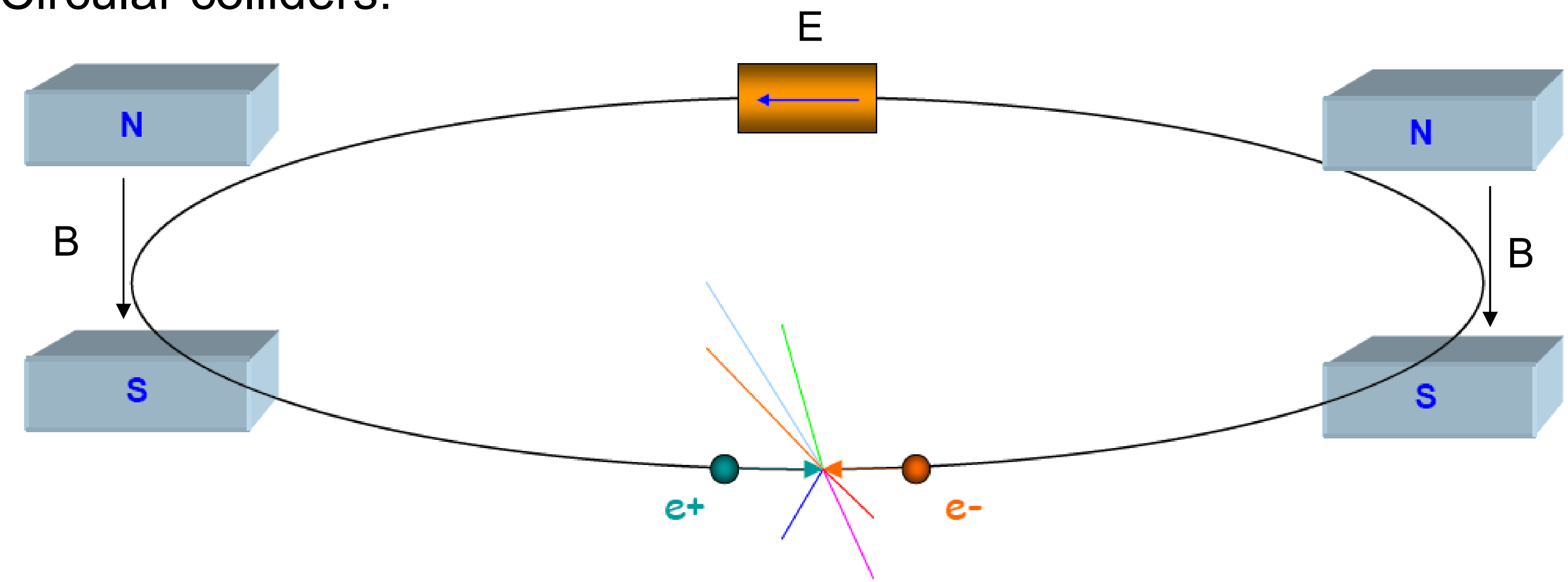
ion implantation (>9,000) , electron cutting and welding (>4,000) …

How to build colliders

Linear colliders:



Circular colliders:



Motion in electric and magnetic fields

Equation of motion under Lorentz Force

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

magnetic field

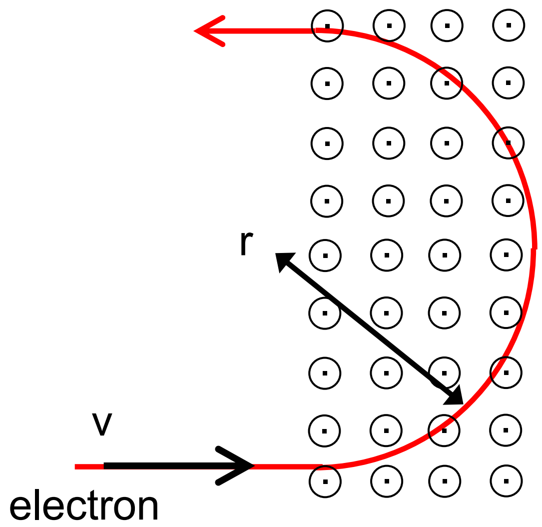
momentum charge velocity electric field

of the particle

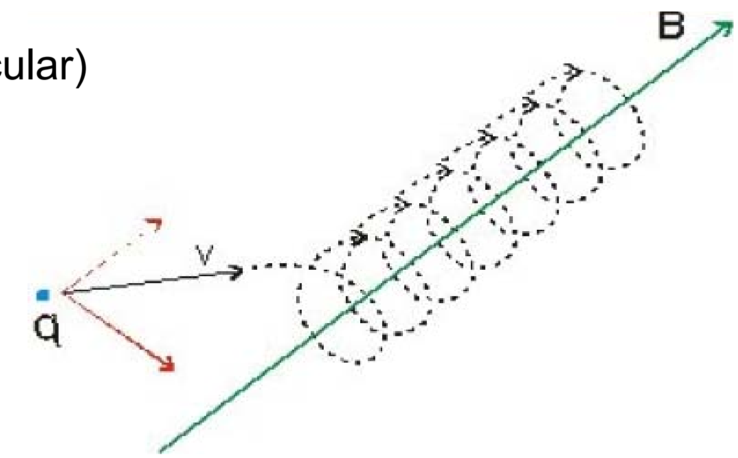
Motion in magnetic fields

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

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



B (perpendicular)

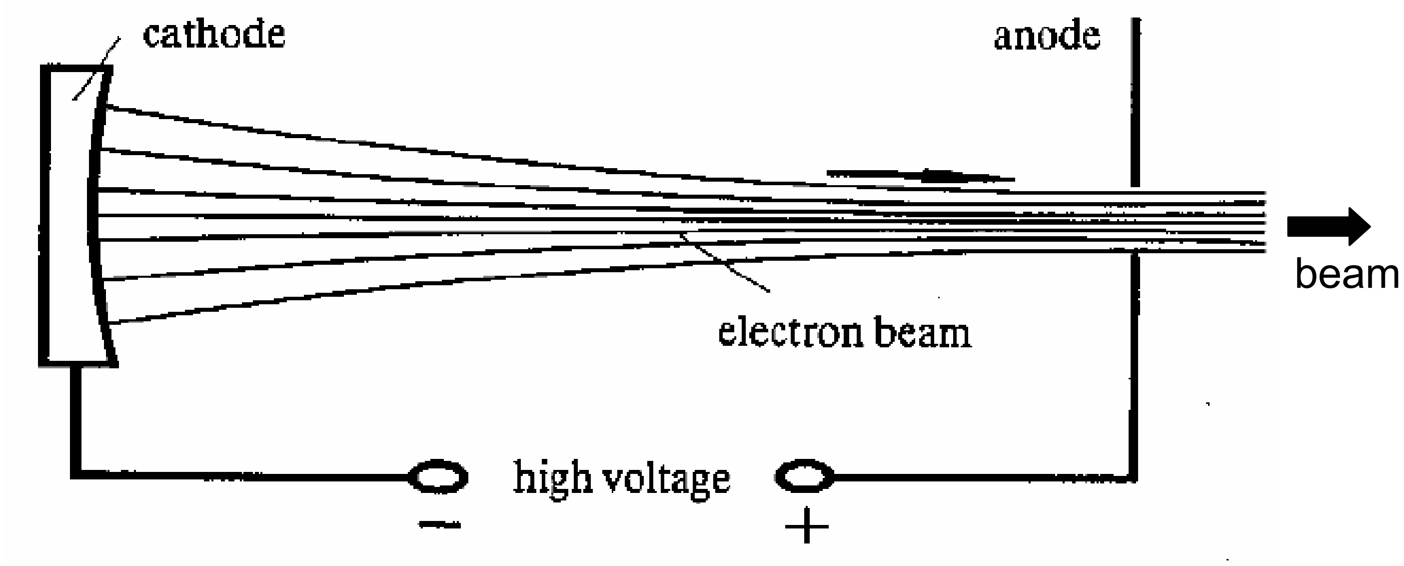


Magnetic fields <u>do not change</u> the particles energy, only electric fields do !

Acceleration with an electrostatic field

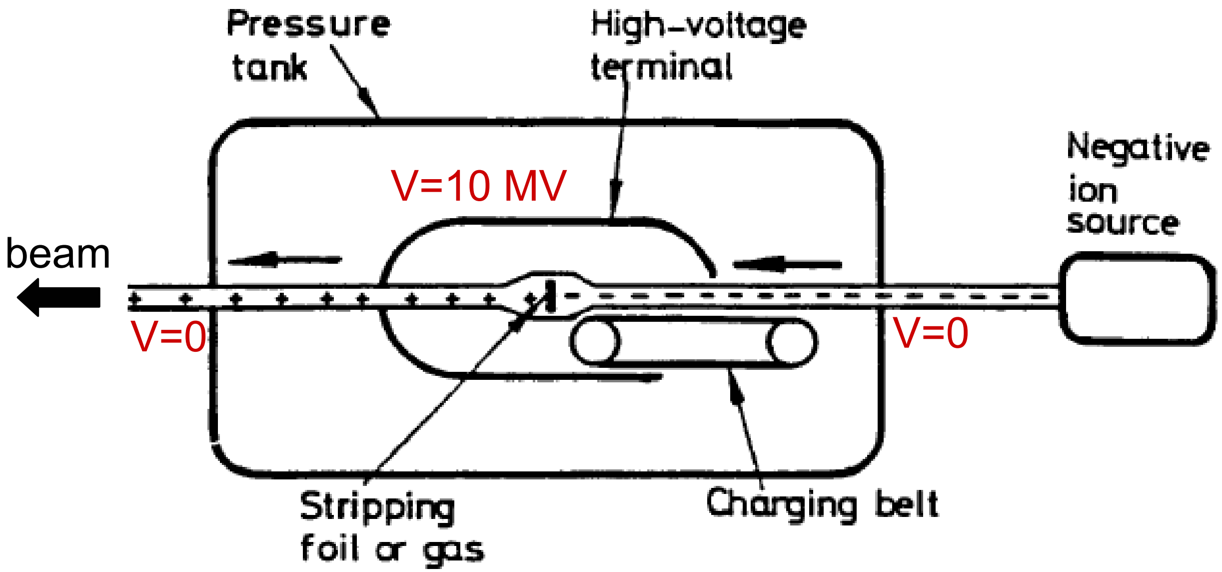
$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{E}$$

principle:



maximum voltage ~ 5-10 MV in Van der Graaff generators

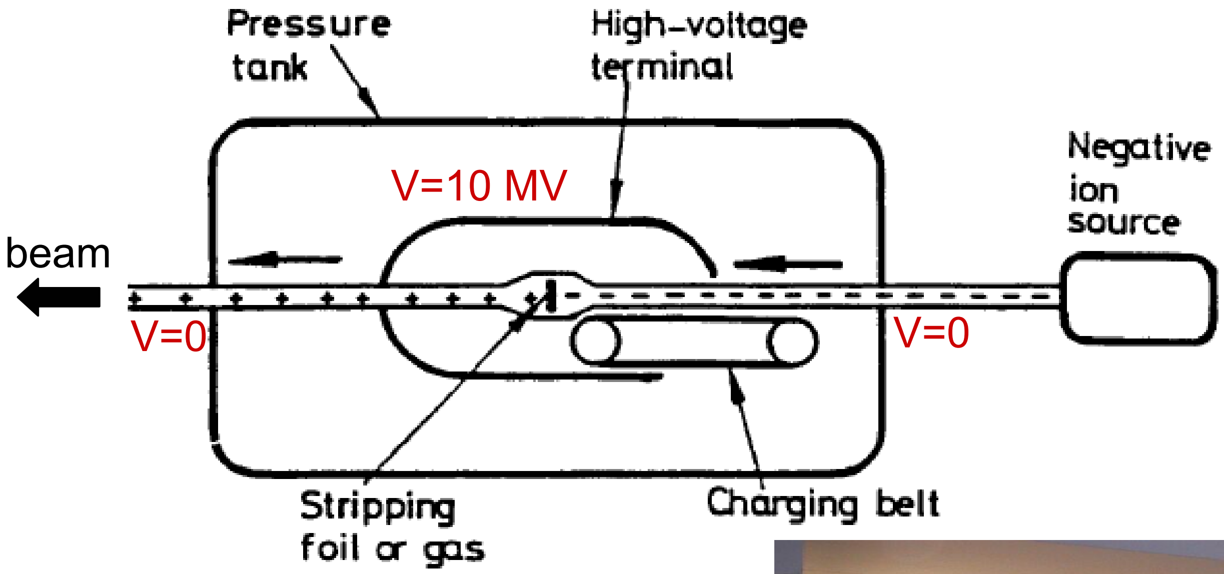
Acceleration with an electrostatic field



Tandem Van der Graff accelerator

tandem = “two things placed one behind the other”

Acceleration with an electrostatic field



12 MV-Tandem van de Graaff Accelerator
at MPI Heidelberg, GE

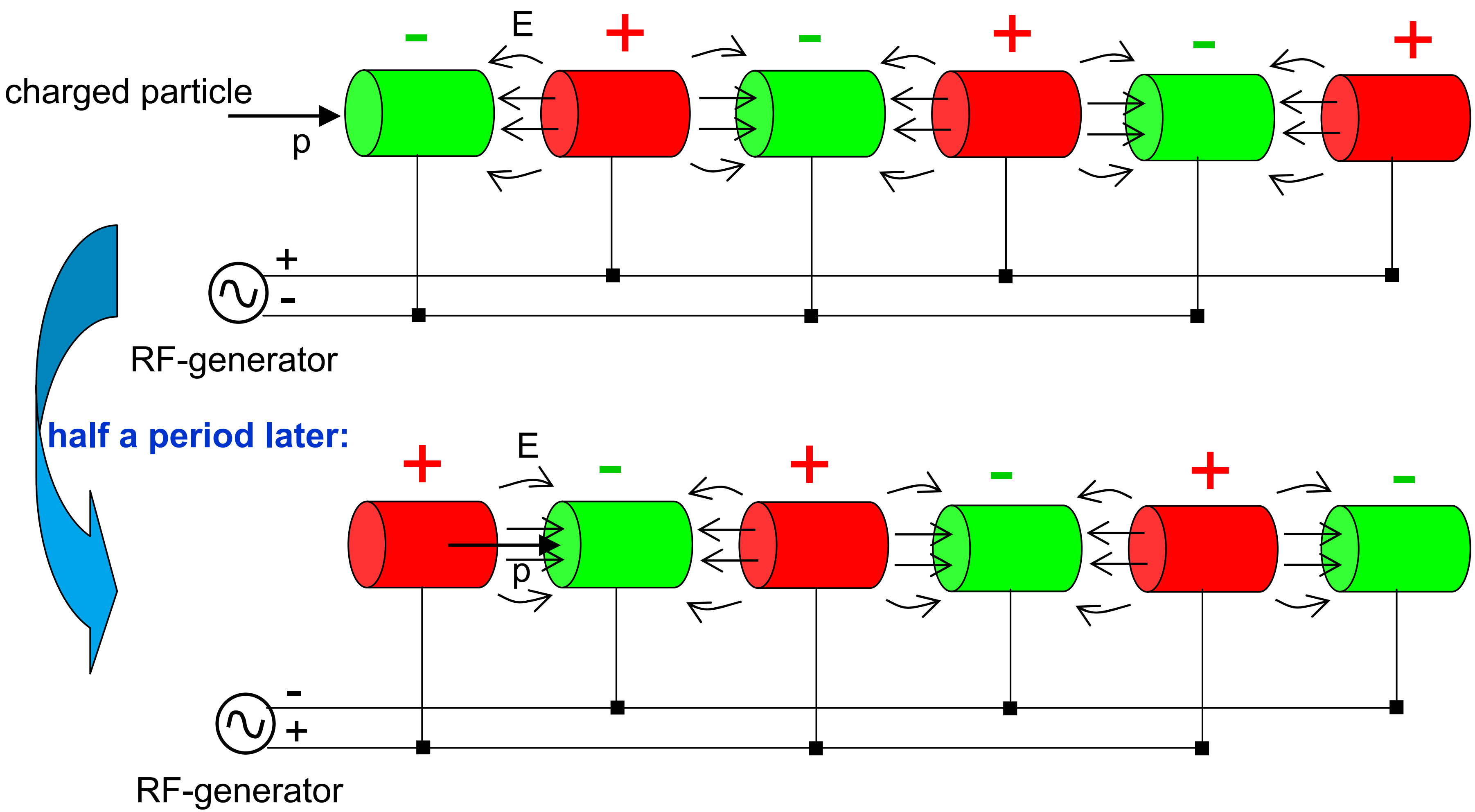
Acceleration with an electrostatic field

20 MV-Tandem
at Daresbury, UK

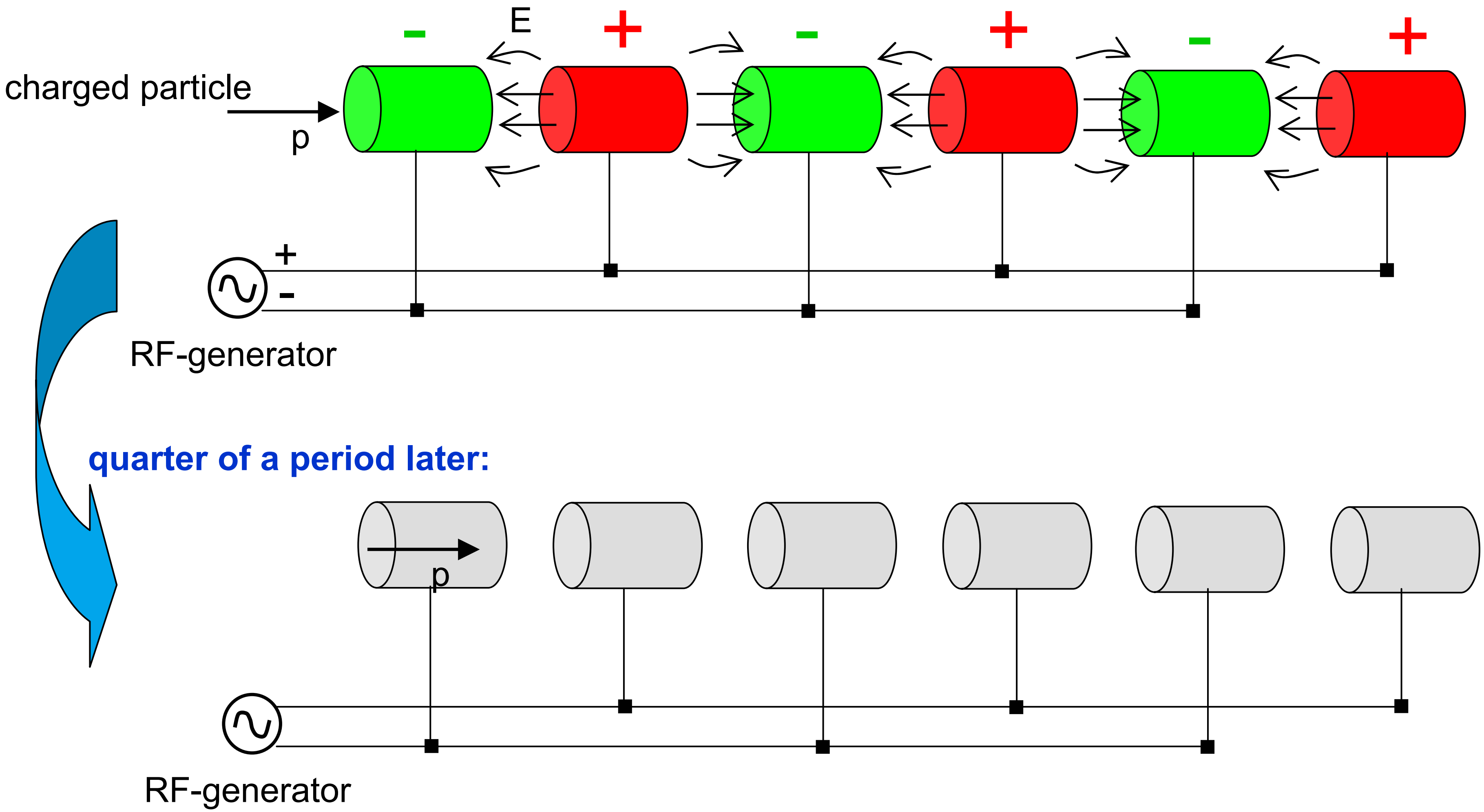
12 MV-Tandem van de Graaff Accelerator
at MPI Heidelberg, GE

Acceleration using Radio-Frequency (RF) generators

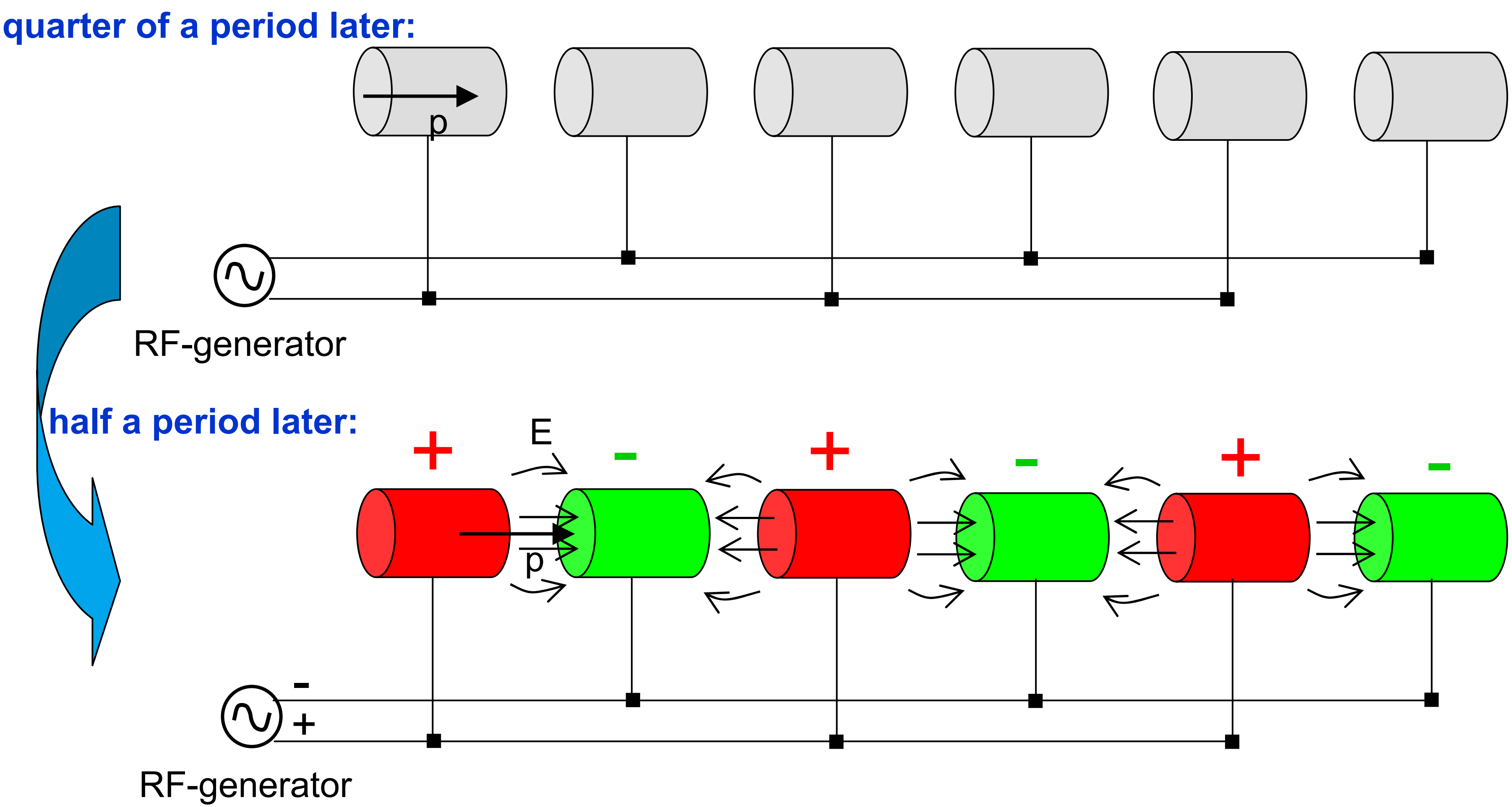
Wideroe (1928): apply acceleration voltage several times to particle beam



Acceleration using Radio-Frequency (RF) generators

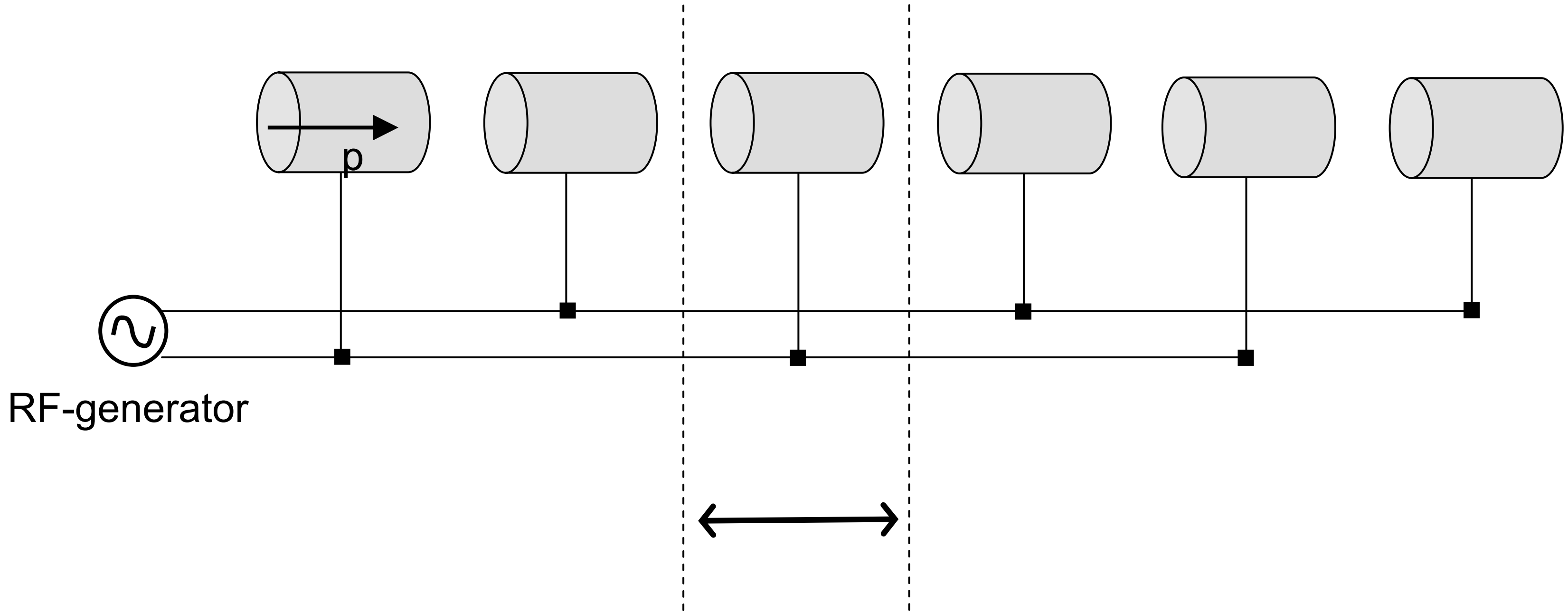


Acceleration using Radio-Frequency (RF) generators



Acceleration using Radio-Frequency (RF) generators

Drift-tube principle



jargon:

synchronous condition

Restrictions of RF

> particles travel in groups → called bunches

> bunches are travelling synchronous with RF cycles → synchronous condition

> $$\Delta E \quad \rightarrow \quad \Delta v$$

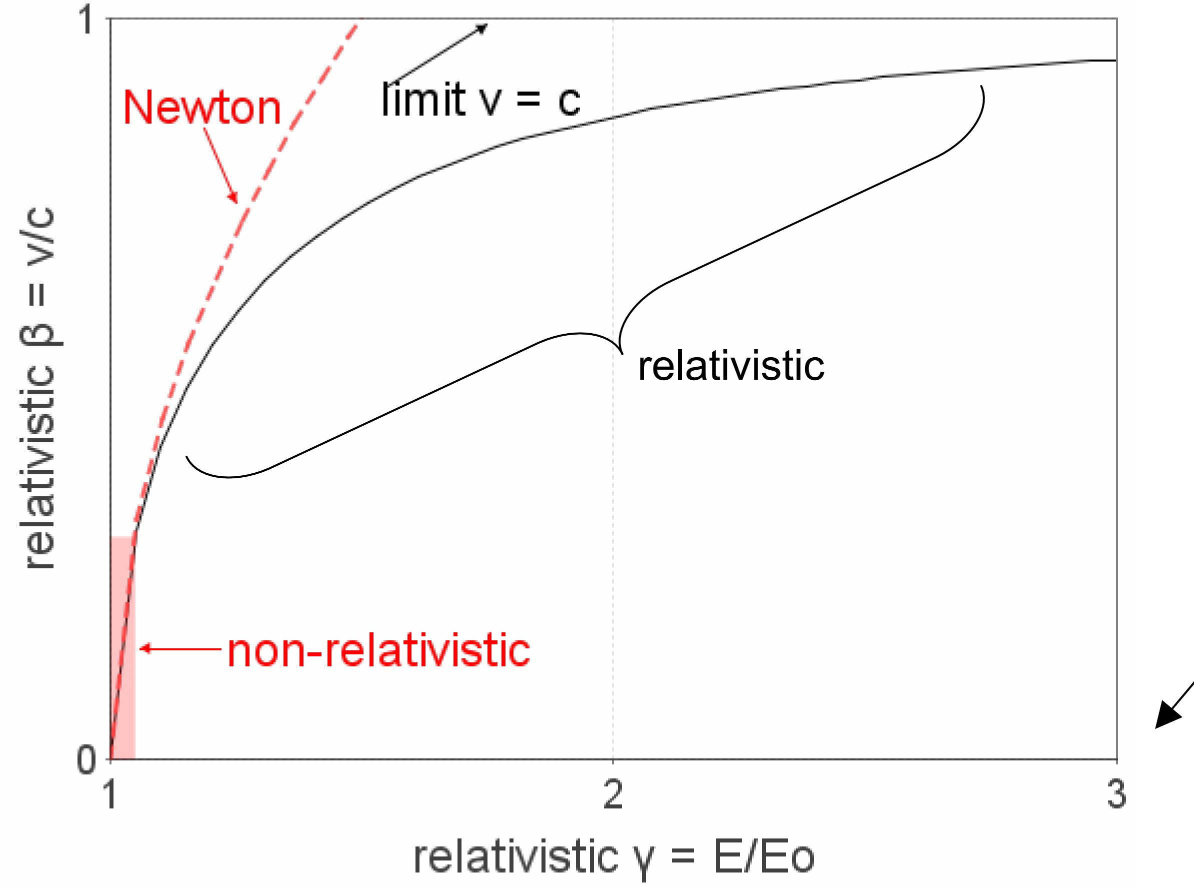
Velocity as function of energy → β as function of γ

Newton: $E_{kin} = \frac{1}{2} m v^2$

Einstein:

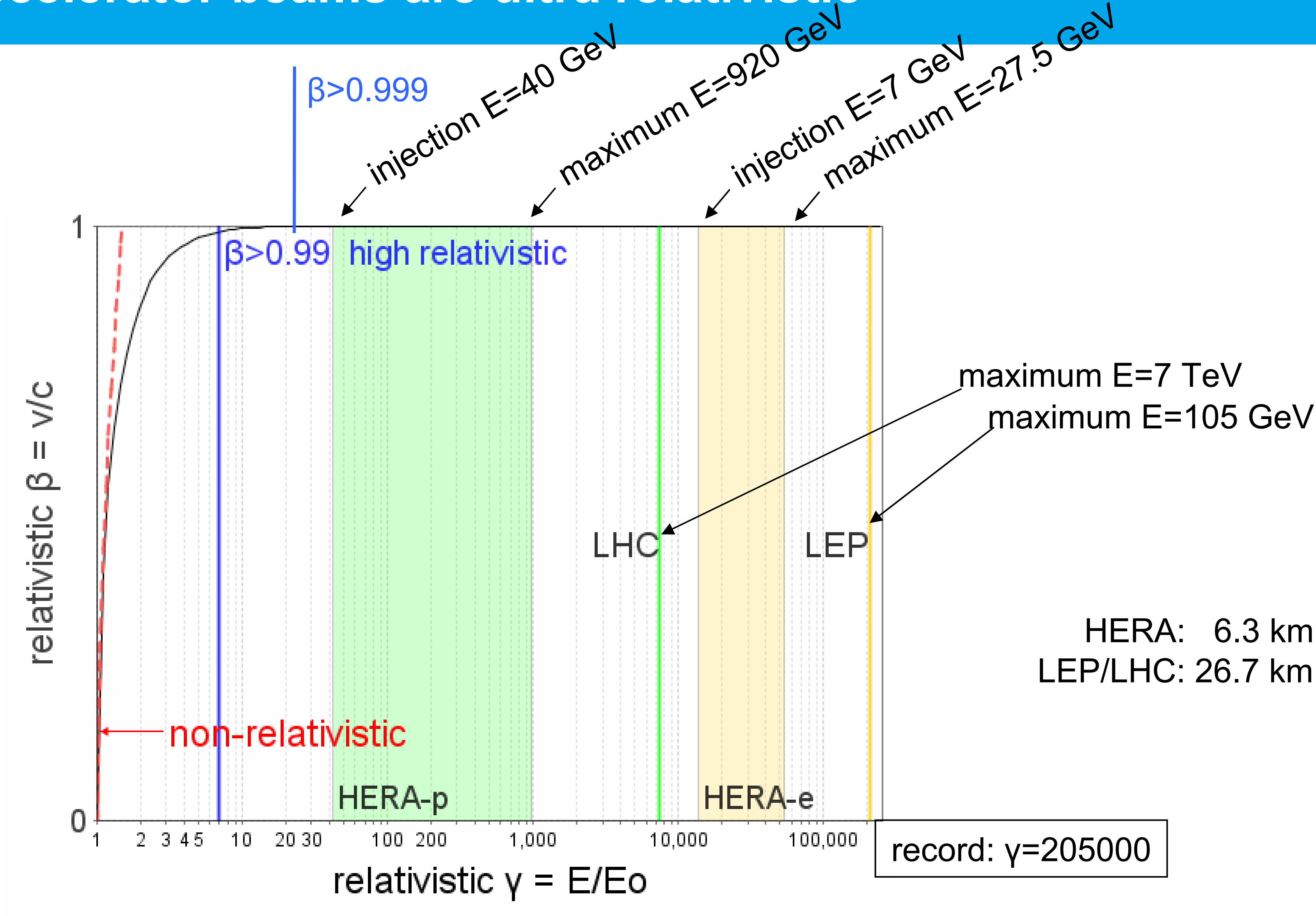
$$E = E_o + E_{kin} = \gamma m c^2 = \frac{mc^2}{\sqrt{1-\beta^2}}$$

$$\beta = \frac{v}{c}$$



relativistic γ = 3 :
2.8 GeV protron
1.5 MeV electron

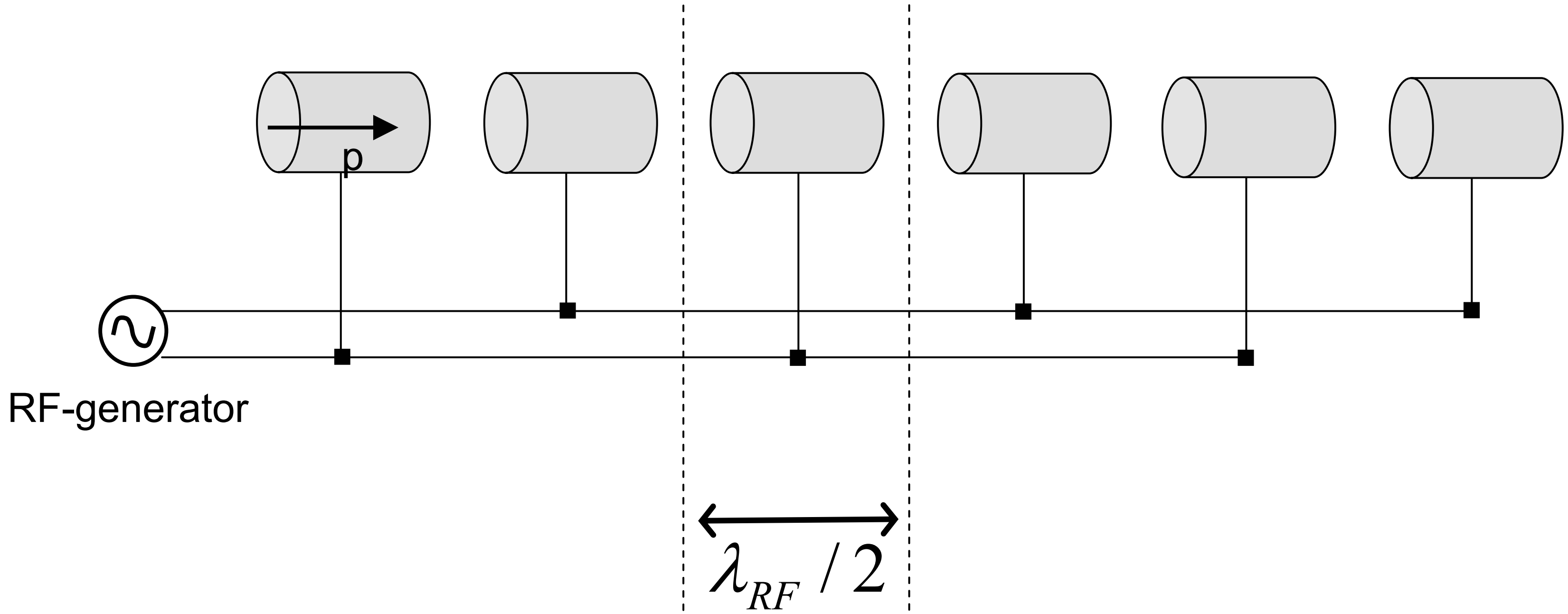
Accelerator beams are ultra relativistic



HERA: 6.3 km
LEP/LHC: 26.7 km

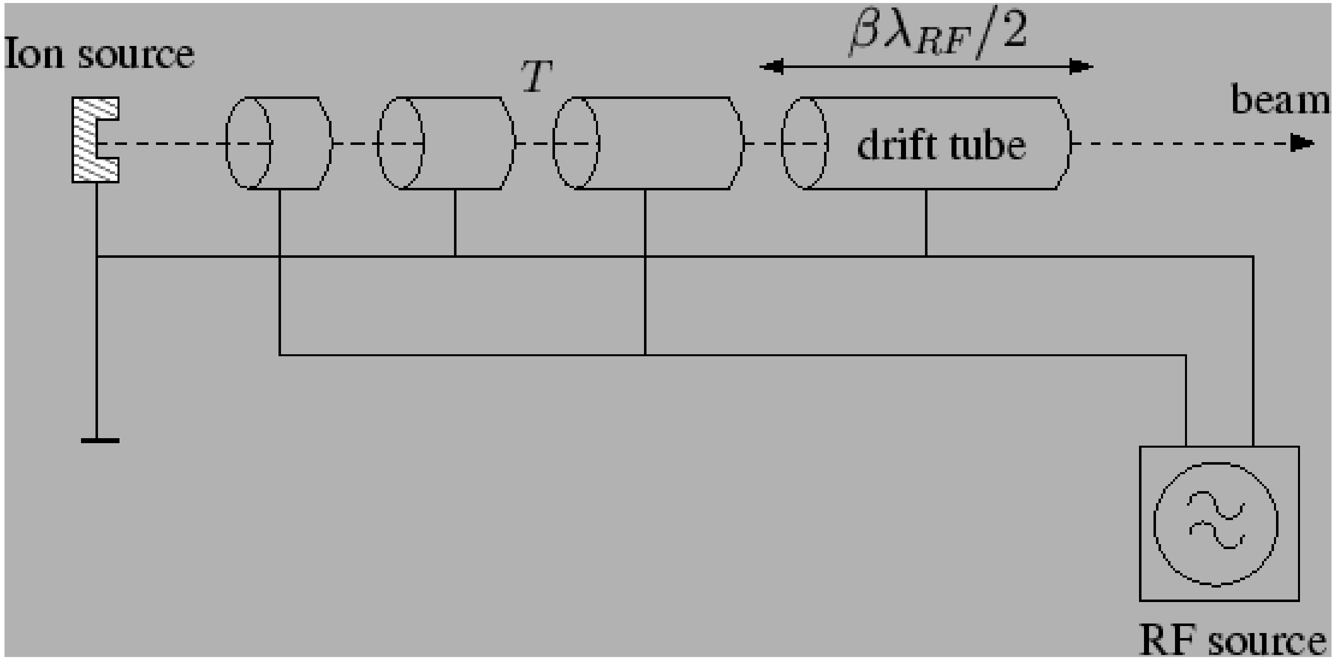
Acceleration using Radio-Frequency (RF) generators

$\beta = 1$ (ultra relativistic particles)



Acceleration using Radio-Frequency (RF) generators

$\beta < 1$



original Wideroe drift-tube principle

Drift tube accelerators

Limitations of drift tube accelerators:

> only low freq. (<10 MHz) can be used

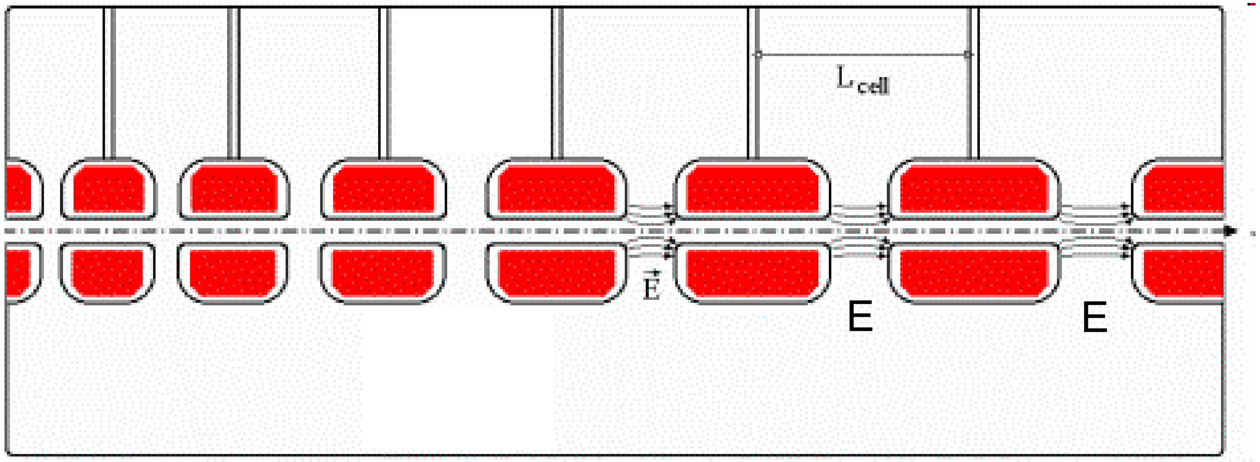
$$L_{tube} = \beta \frac{\lambda}{2} = \beta \frac{c}{2f}$$ → 30 m for β=1 and f=10 MHz

→ drift tubes are impracticable for ultra-relativistic particles (β=1)

→ only for very low β particles

Resonant cavities

Alvarez drift-tube structure:



RF resonator

Examples

DESY proton linac
(LINAC III)

$$E_{total} = 988\,MeV$$

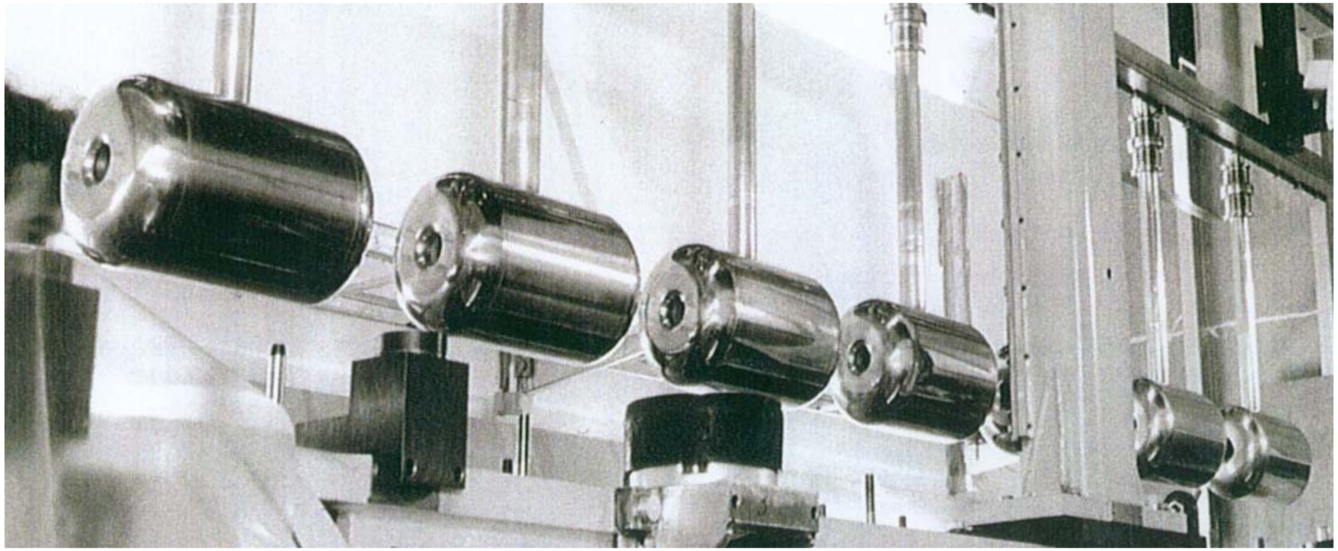
$$E_{kin} = E_{total} - m_0 c^2$$

$$E_{kin} = 50\,MeV$$

$$E^2 = c^2 p^2 + m_0^2 c^4$$

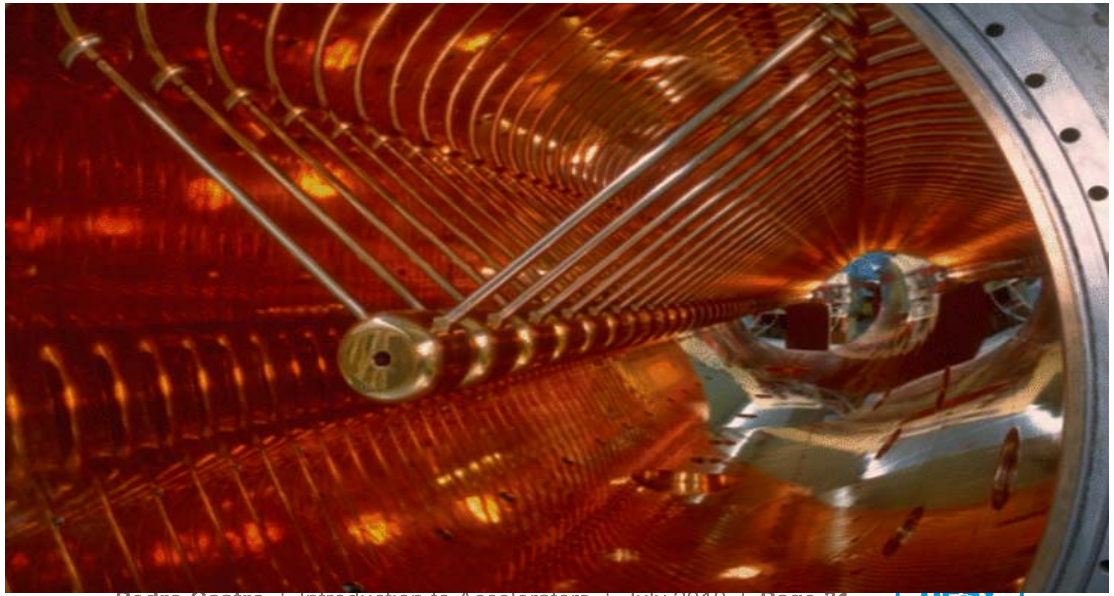
$$p = 310\,MeV / c$$

$\beta \approx 0.3$



GSI Unilac
(GSI: Heavy Ion Research Center)
Darmstadt, Germany

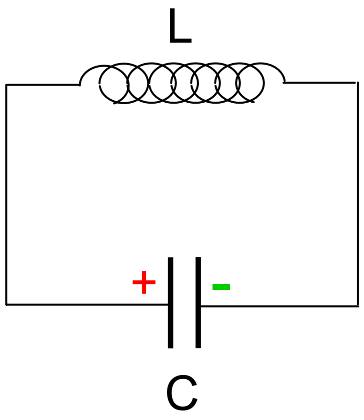
Protons/Ions
E ≈ 20 MeV per nucleon
$\beta \approx 0.04 \ldots 0.6$

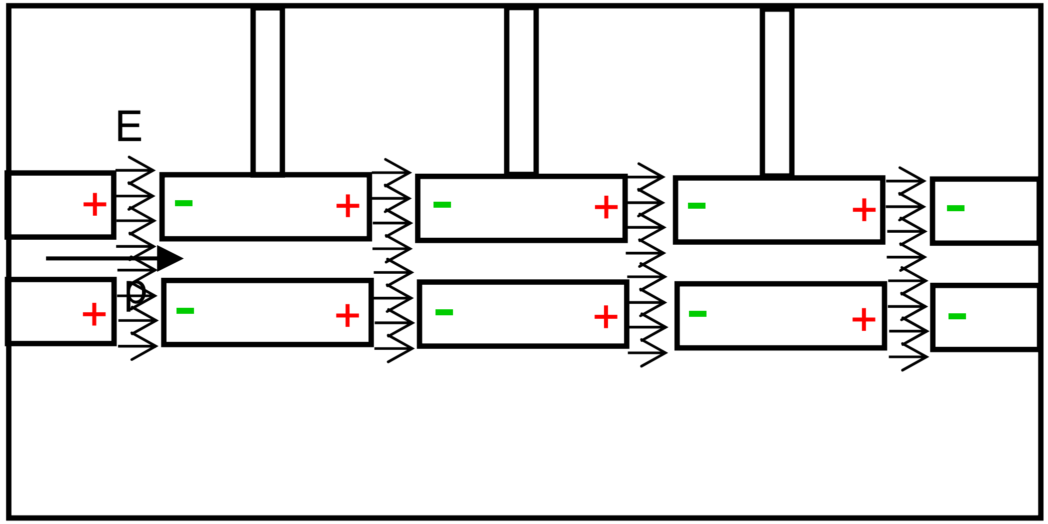


Charges, currents and electromagnetic fields

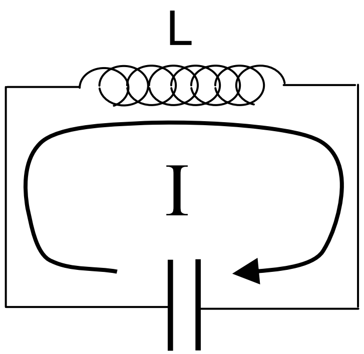
Alvarez drift-tube

LC circuit analogy:

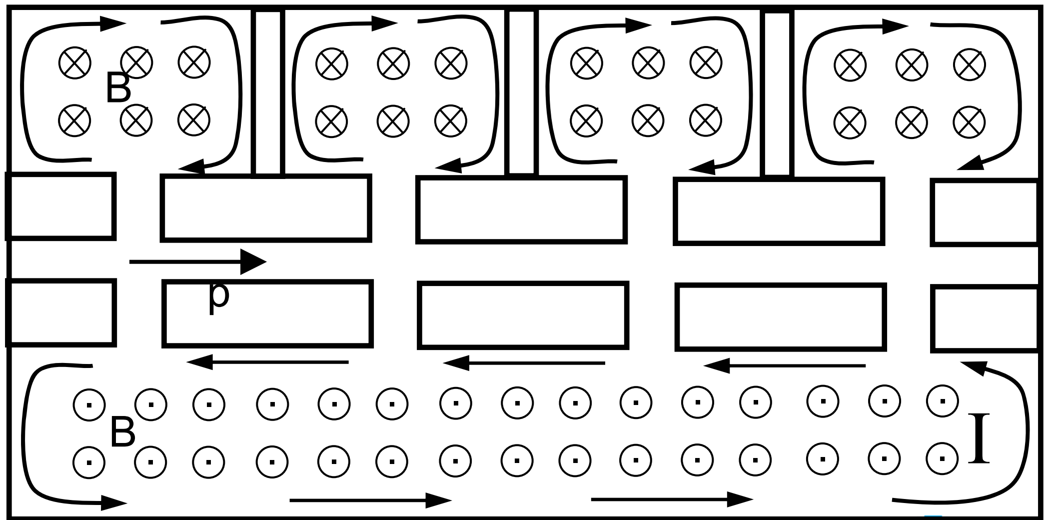




a quarter of a period later:

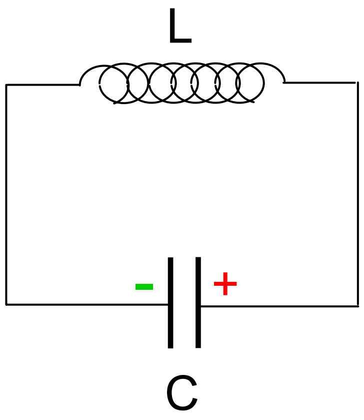


a quarter of a period later:

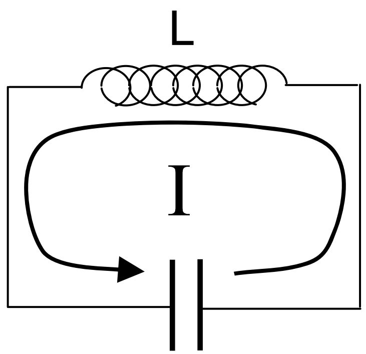


Charges, currents and electromagnetic fields

half a period later:

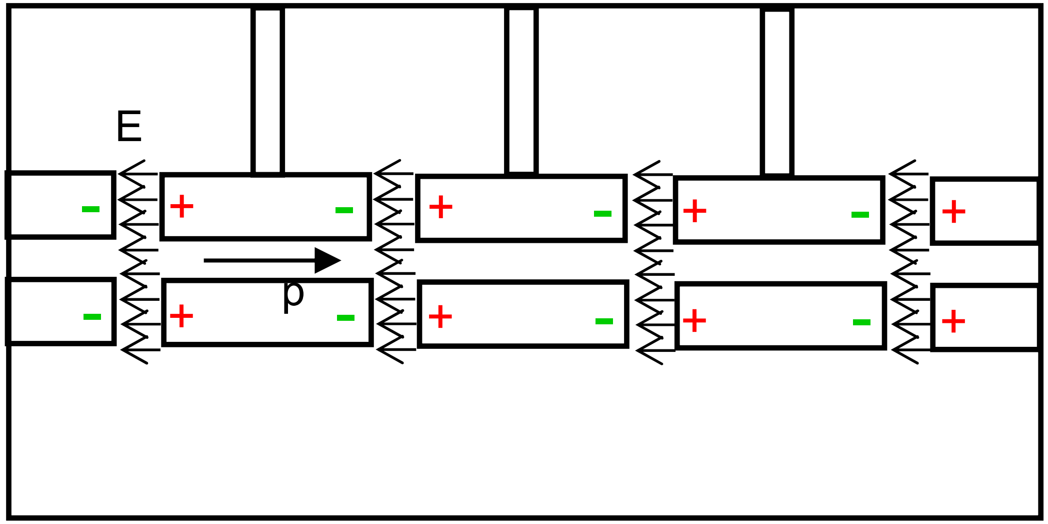


3 quarters of a period later:

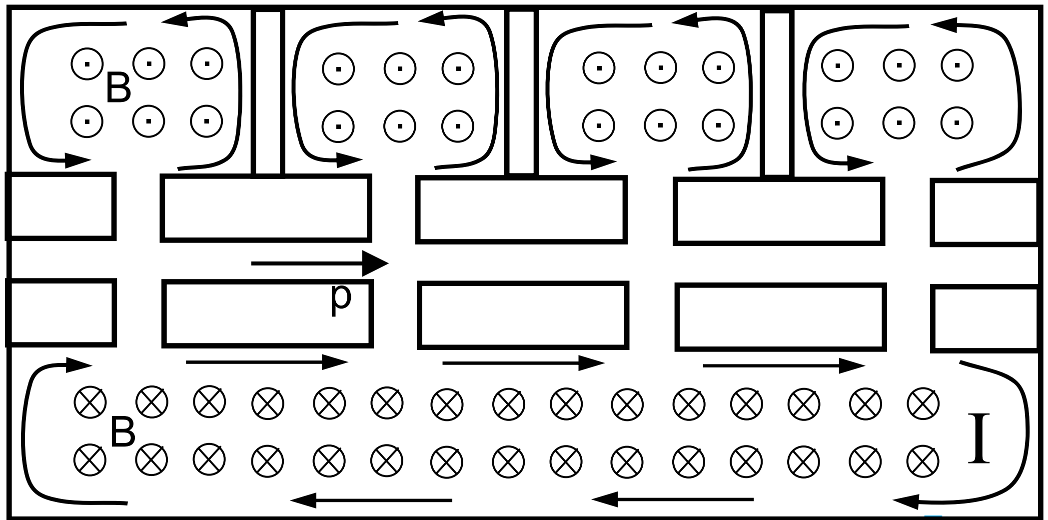


Alvarez drift-tube

half a period later:

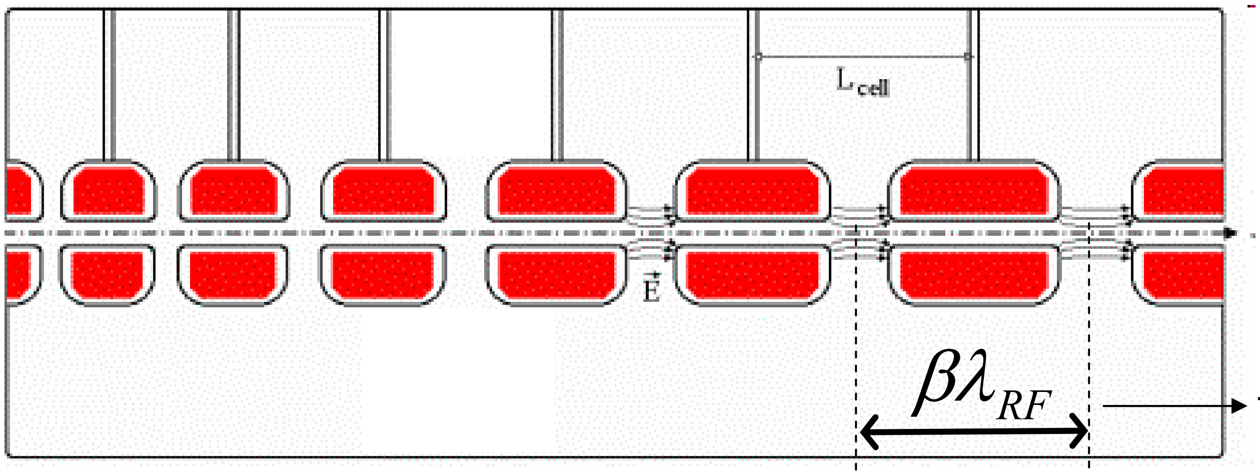


3 quarters of a period later:



Resonant cavities

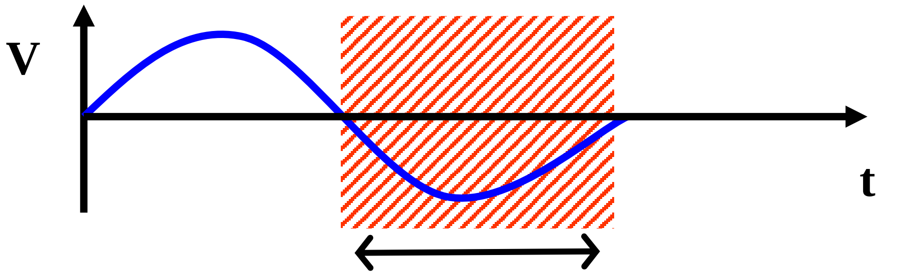
Alvarez drift-tube structure:



RF resonator

twice longer tubes

higher frequencies possible → shorter accelerator



length of the tube

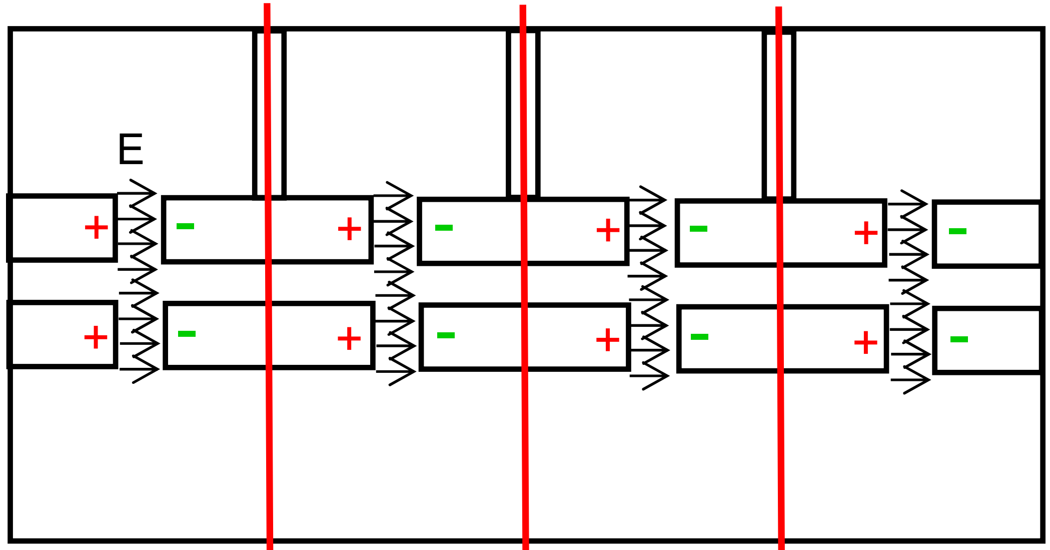
still preferred solution
for ions and protons
up to few hundred MeV

Examples

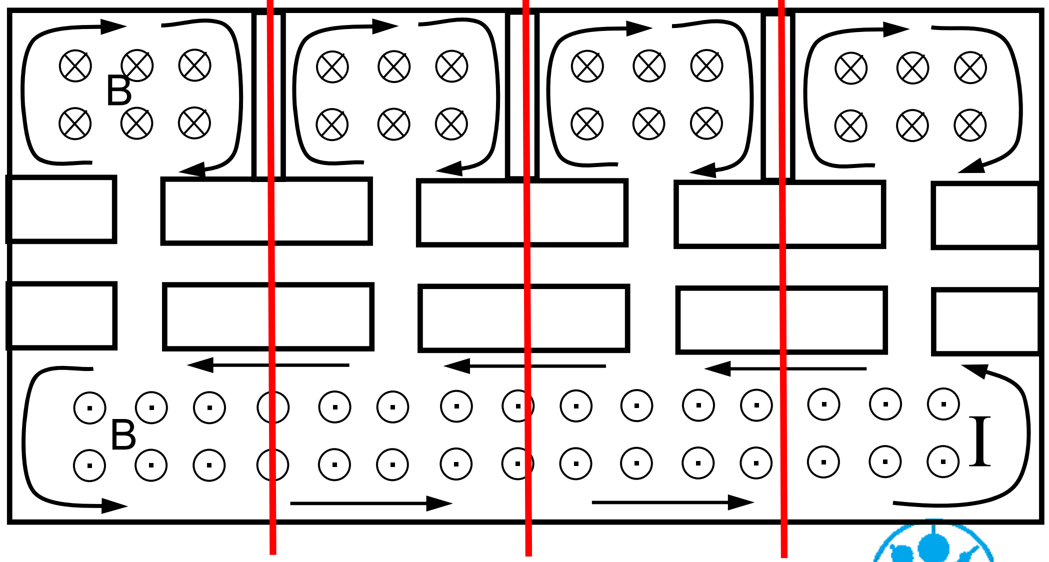
inside a drift tube linac

Linac2 at CERN, 50 MeV

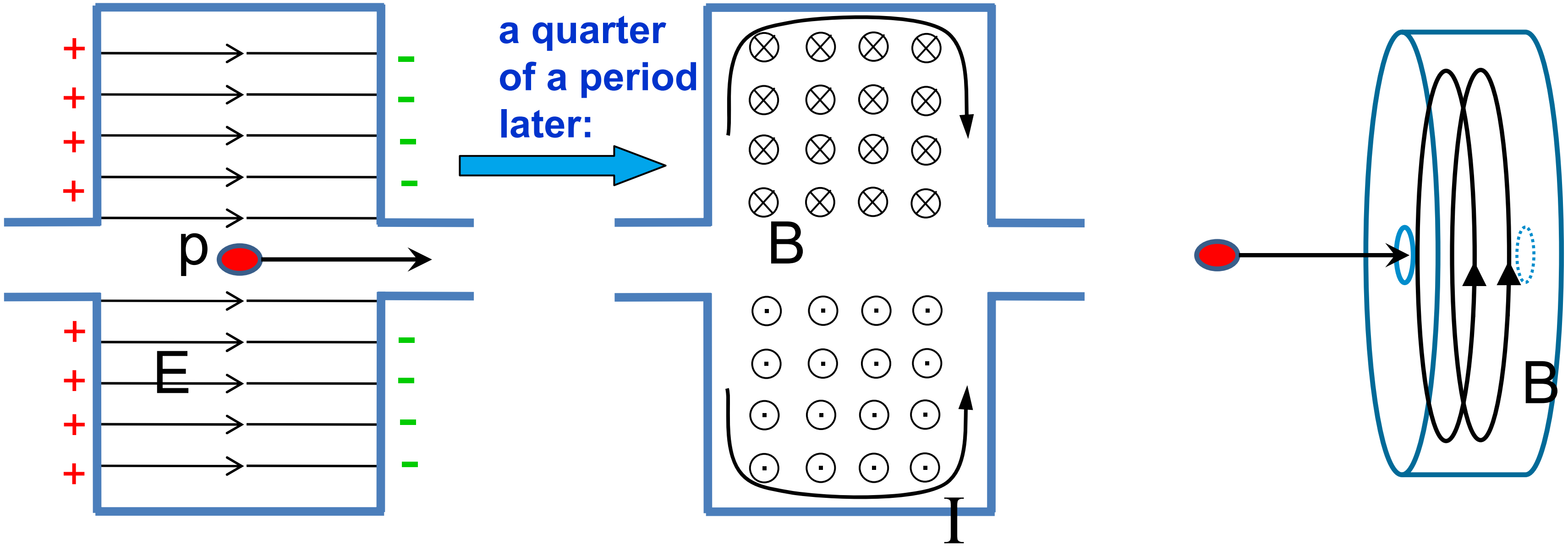
Alvarez drift-tube



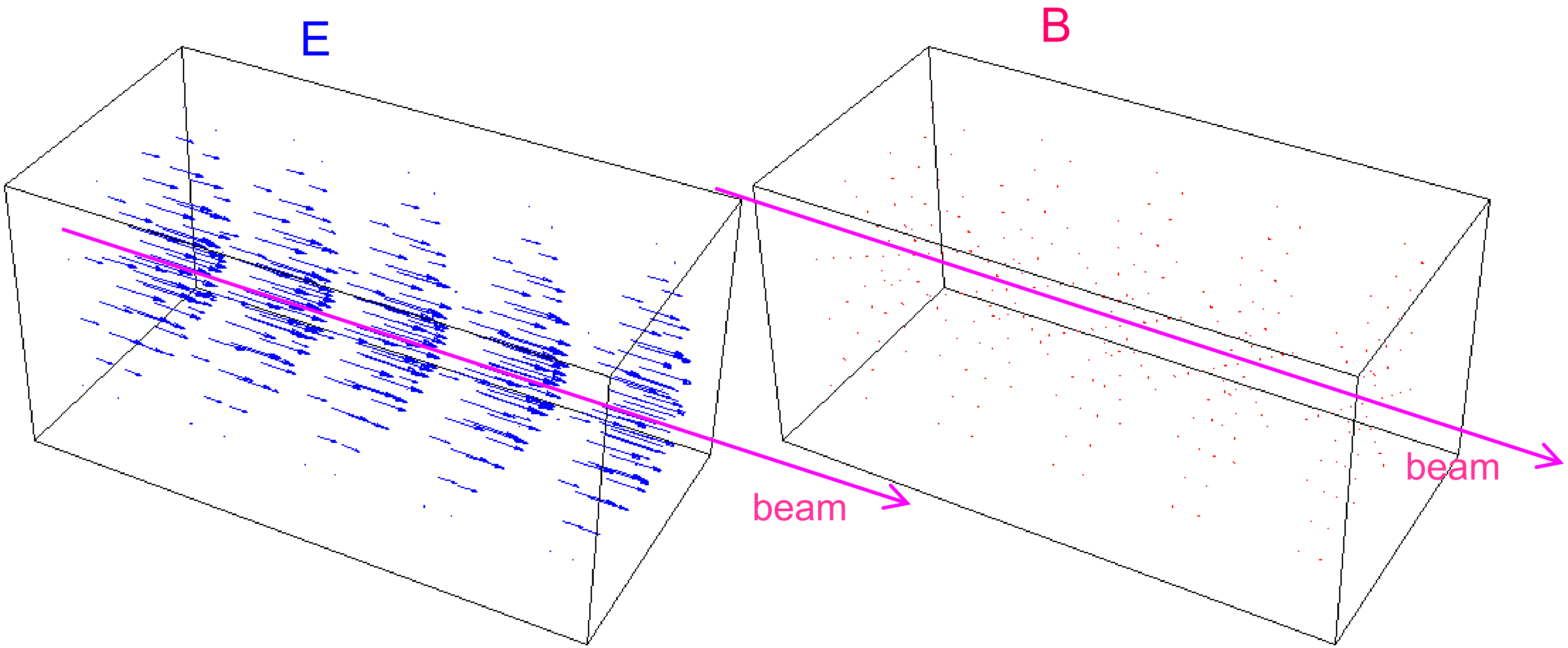
a quarter of a period later:



RF cavity basics: the pill box cavity

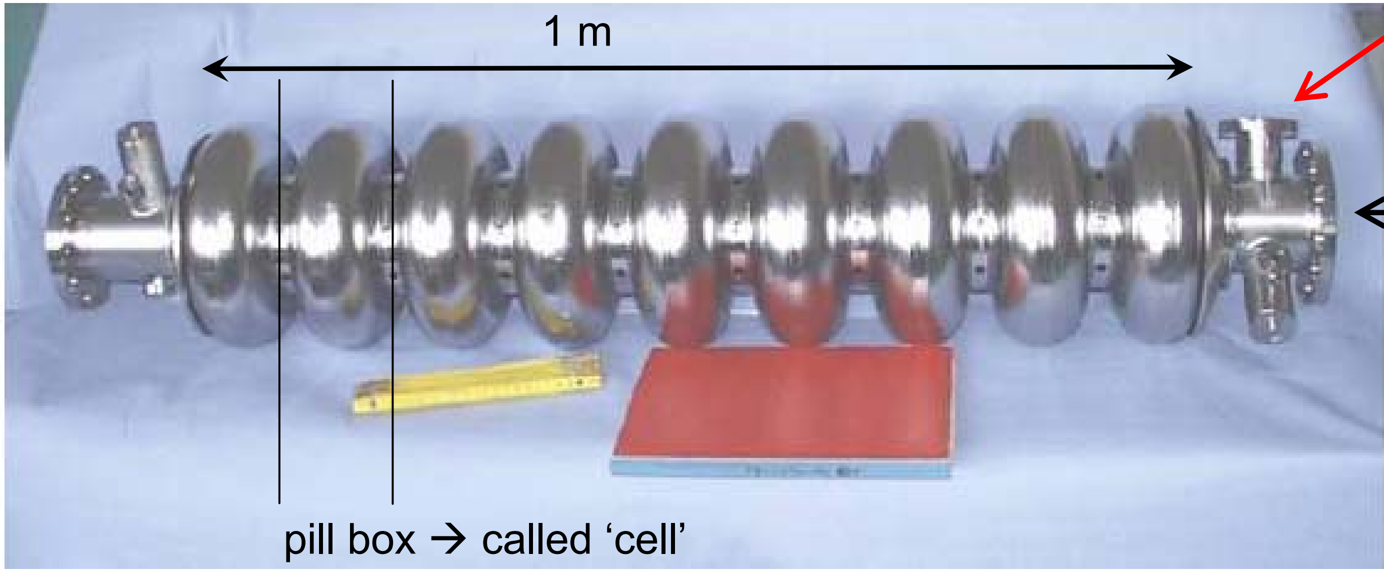


Pill box cavity: 3D visualisation of E and B



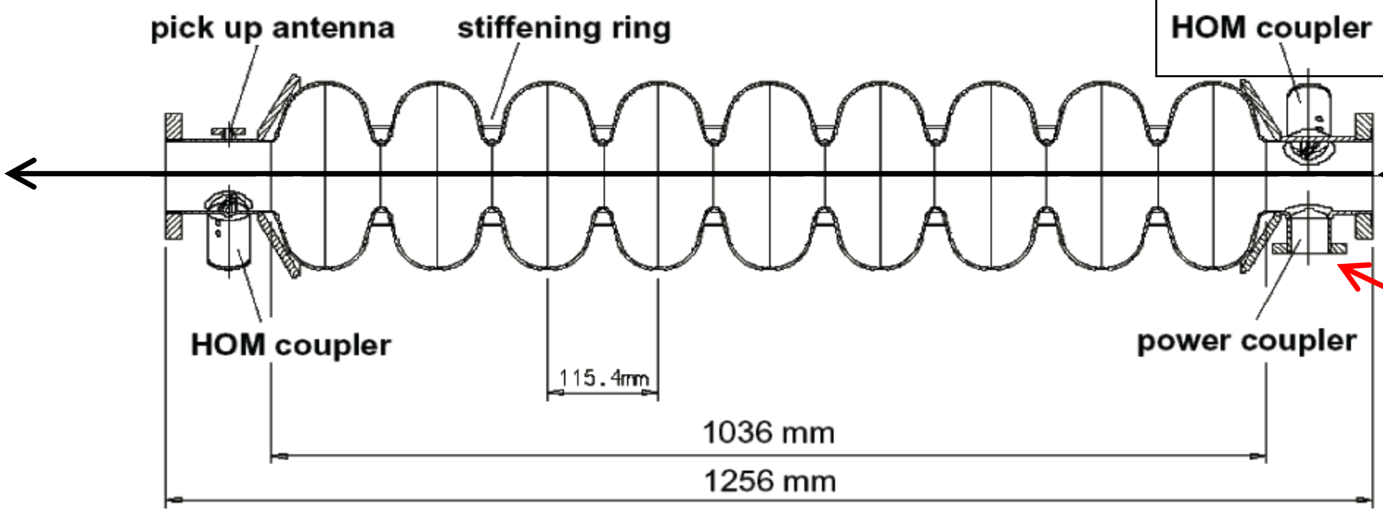
In reality…

Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)



RF input port
called ‘input coupler’
or ‘power coupler’

beam



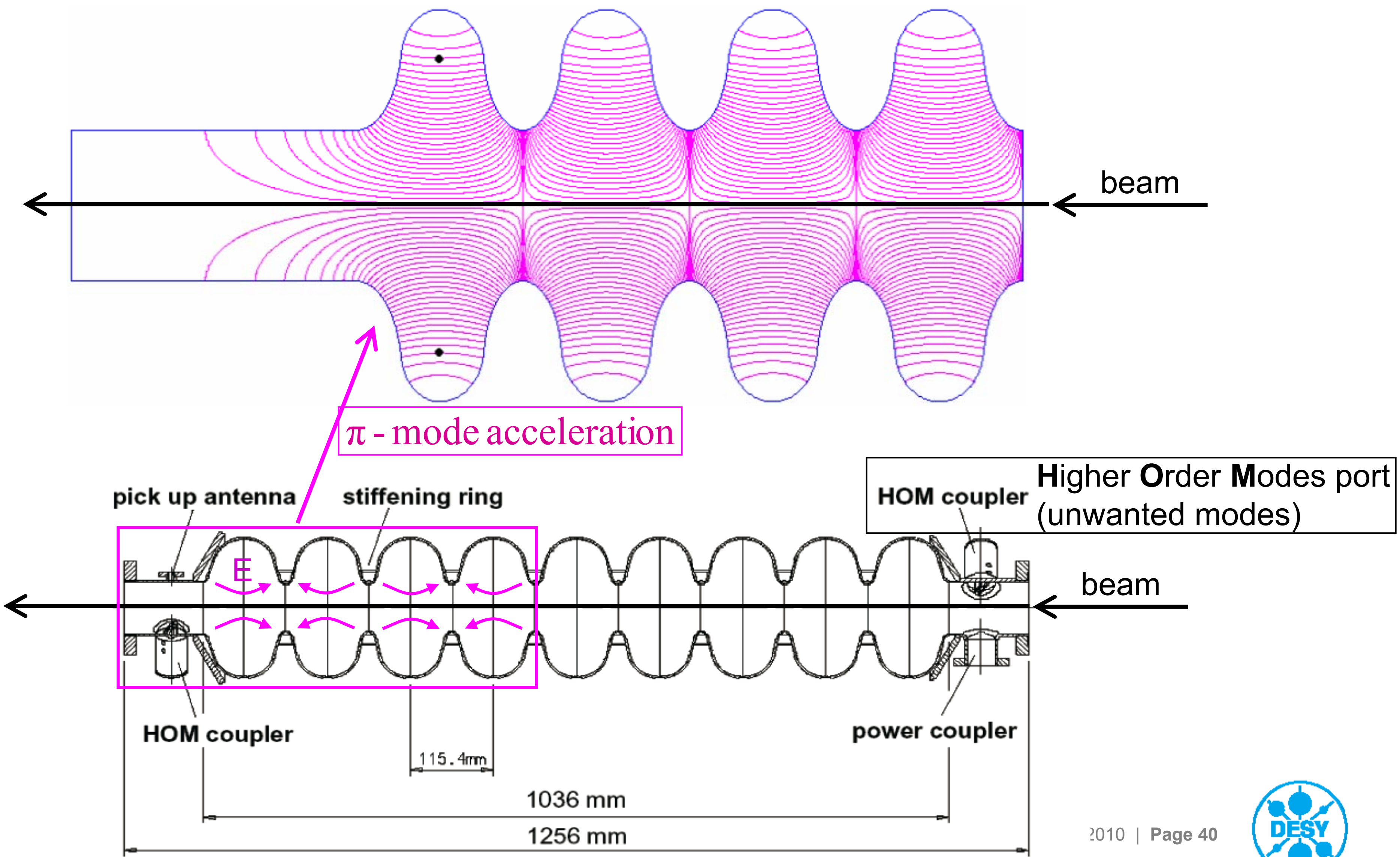
HOM coupler **H**igher **O**rder **M**odes port (unwanted modes)

beam

RF input port
called ‘input coupler’

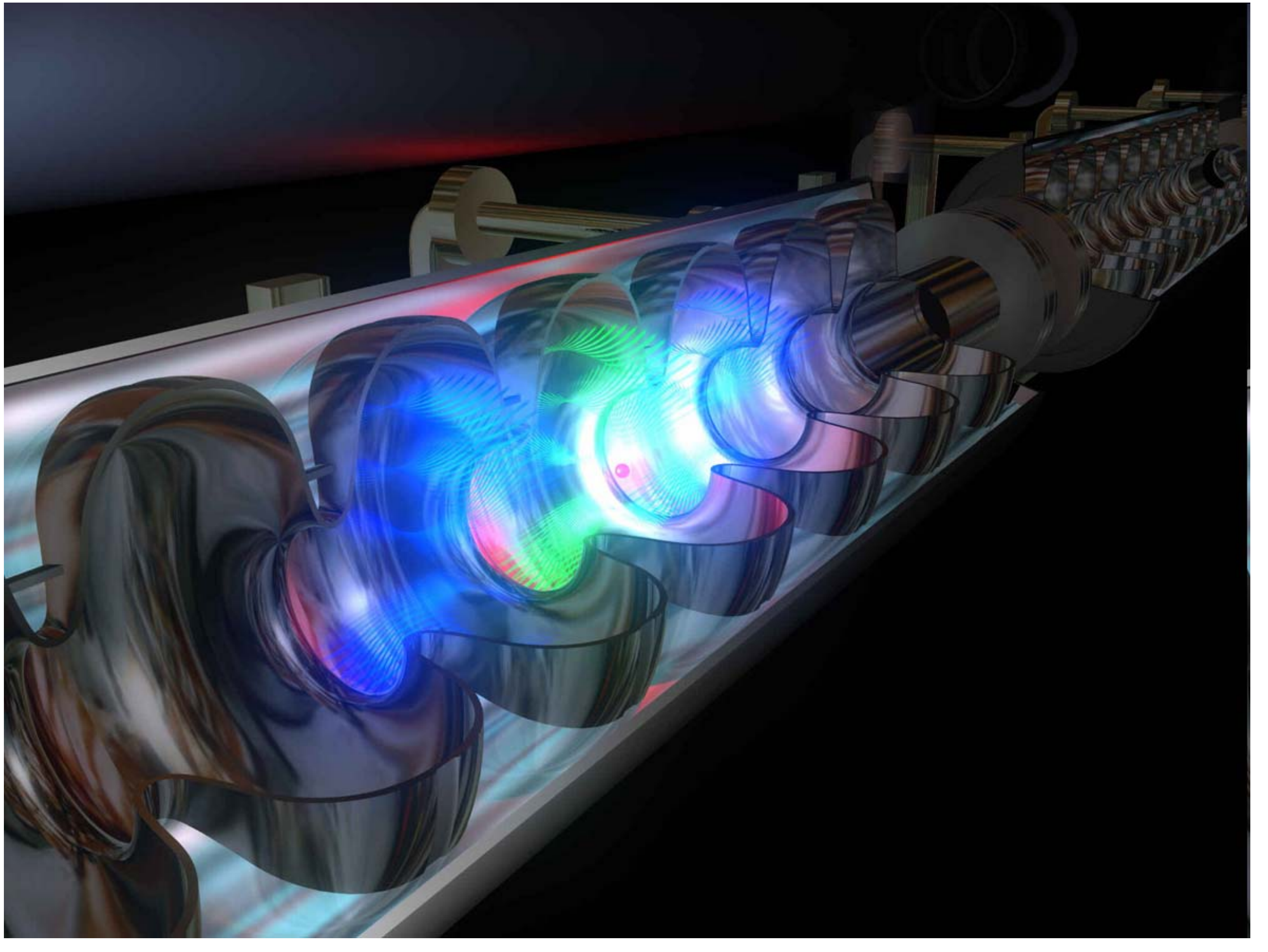
Superconducting cavity used in FLASH and in XFEL

Simulation of the fundamental mode: electric field lines



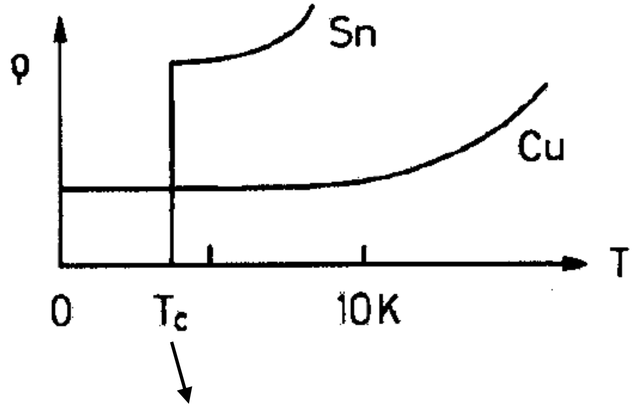
Artistic view?

"Electromagnetic fields accelerate the electrons in a superconducting resonator "



Advantages of RF superconductivity

resistance



critical temperature (Tc):

for DC currents !

at radio-frequencies, there is a “microwave surface resistance”

which typically is 5 orders of magnitude lower than R of copper

Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

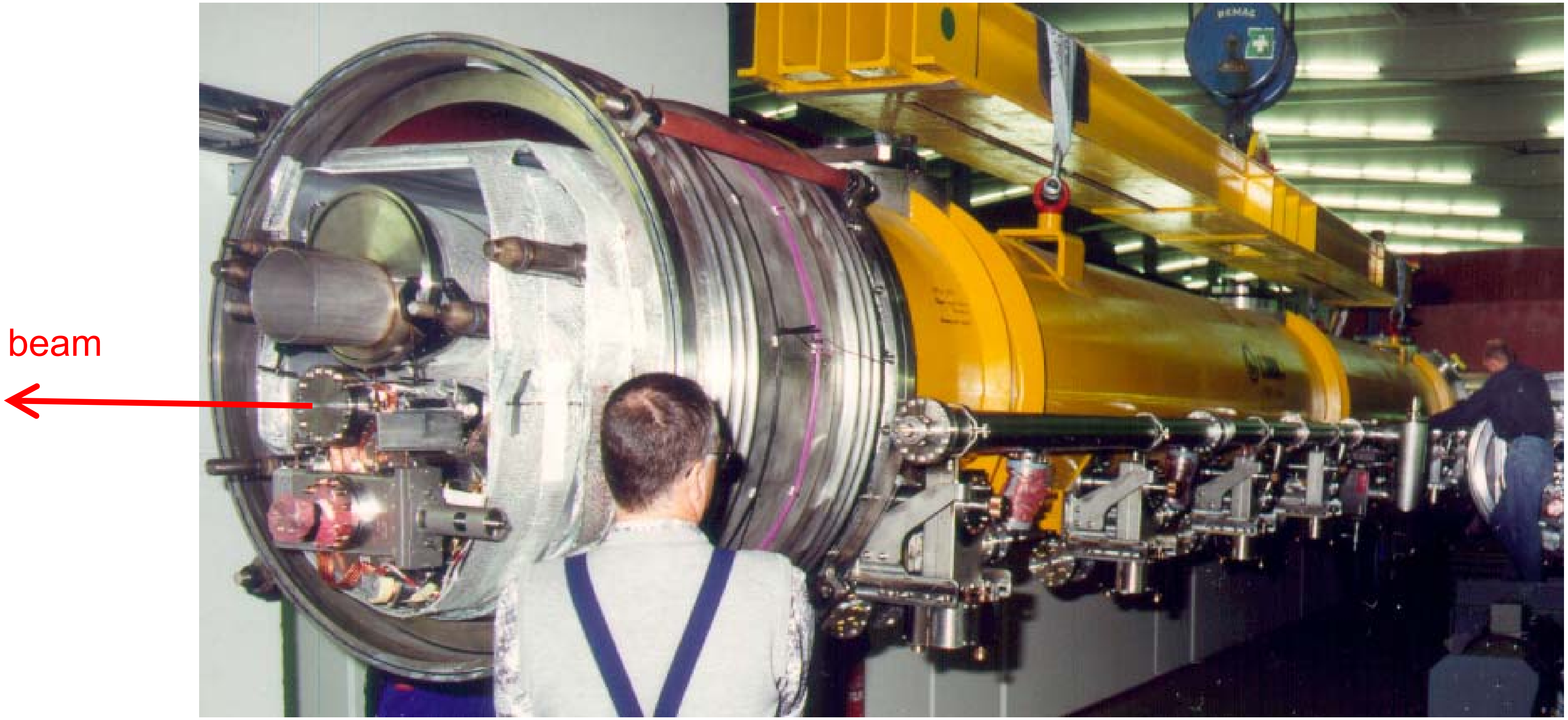
	superconducting cavity	normal conducting cavity	
for E = 1 MV/m	1.5 W / m at 2 K	56 kW / m	dissipated at the cavity walls

Carnot efficiency: $\eta_c = \dfrac{T}{300 - T} = 0.007$ x cryogenics efficiency 20-30%

for E = 1 MV/m	1 kW / m	56 kW / m	
for E = 1 MV/m	1 kW / m	112 kW / m	including RF generation efficiency (50%)

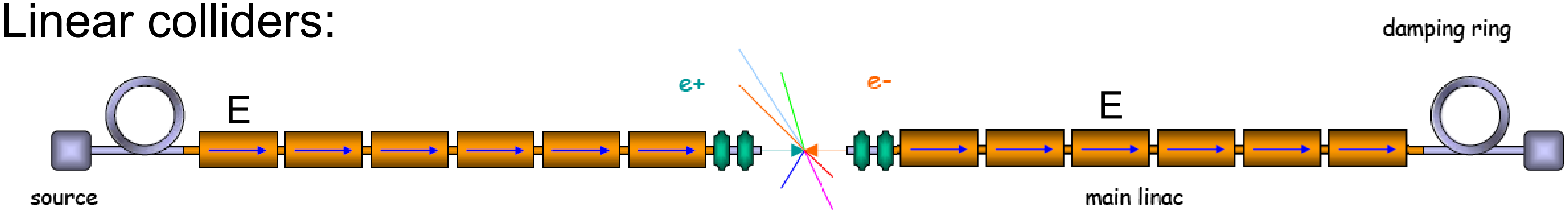
>100 power reduction factor

Cavities inside of a cryostat



How to build colliders

Linear colliders:



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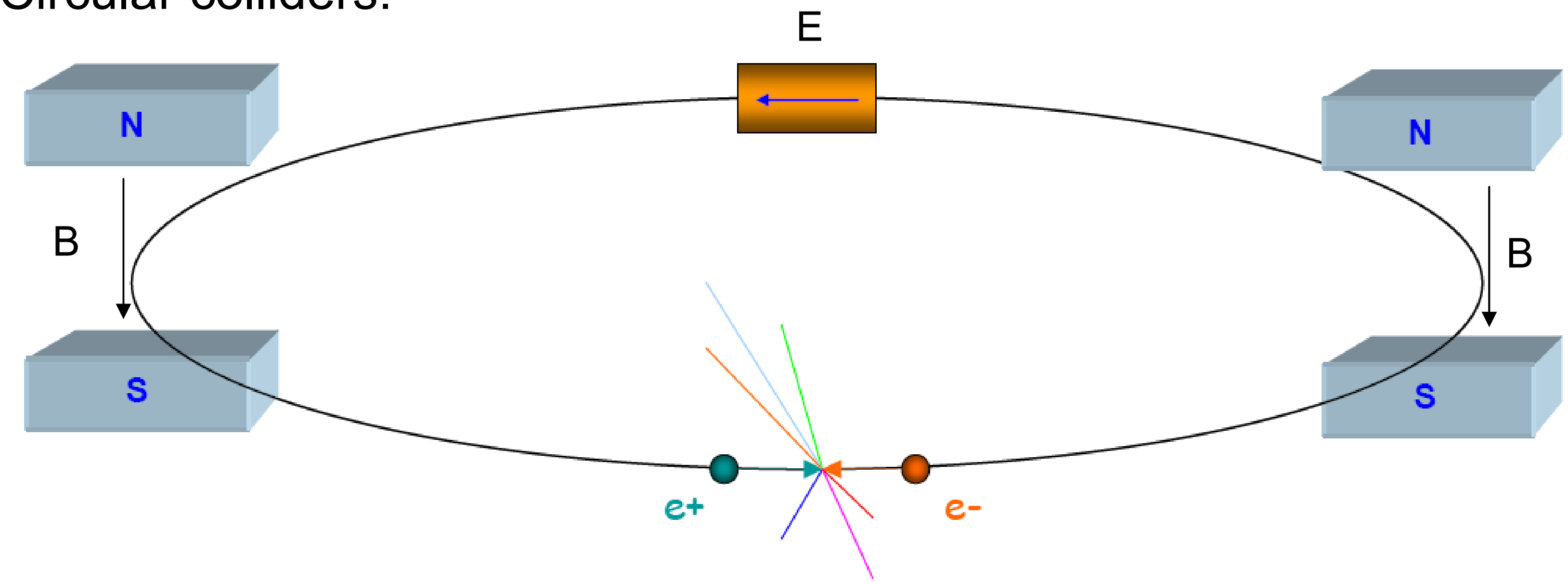


HERA: the super electron microscope

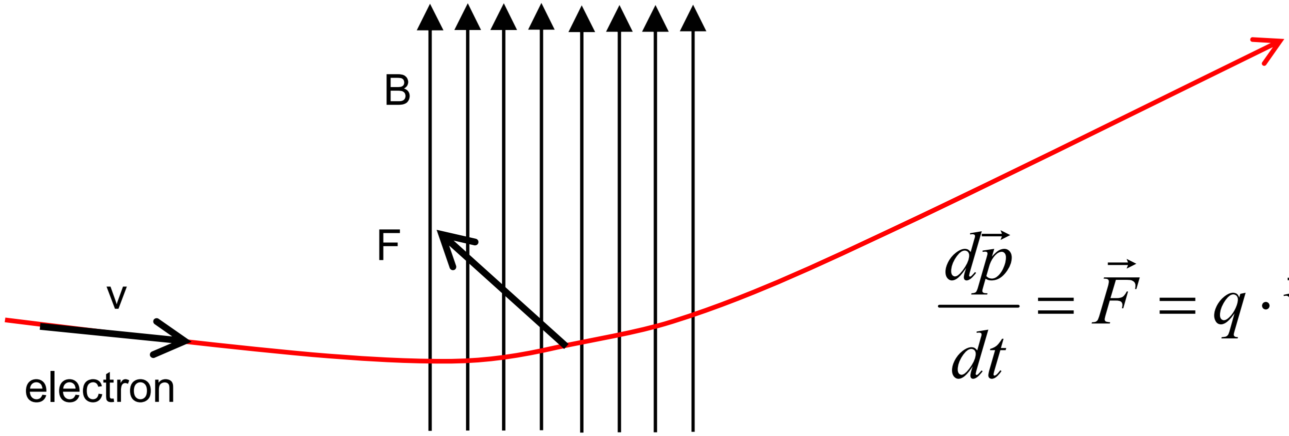
HERA (Hadron Electron Ring Accelerator) tunnel:

protons
("samples")
at 920 GeV

electrons at 27.5 GeV

Why do they look so different?

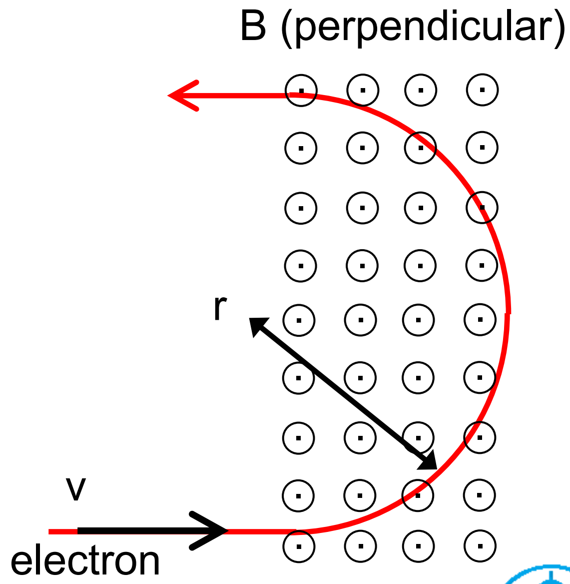
Implications of ultra relativistic approximations



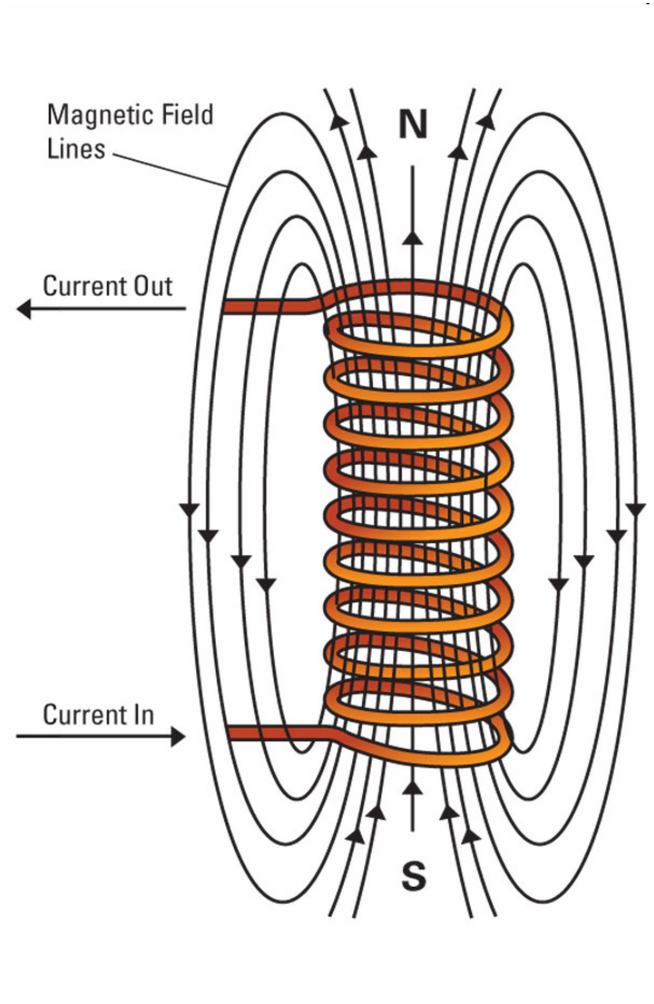
$$\frac{d\vec{p}}{dt} = \vec{F} = q \cdot \vec{v} \times \vec{B}$$

$$\gamma m \frac{v^2}{r} = qvB \quad \Rightarrow \quad \frac{1}{r} = \frac{qB}{\gamma m v} = \frac{qB}{p} \cong \frac{cqB}{E}$$

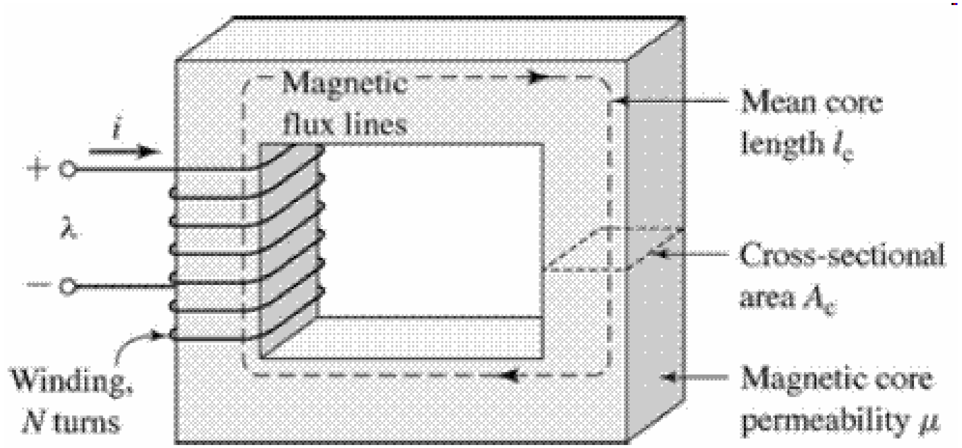
$$\beta \cong 1$$



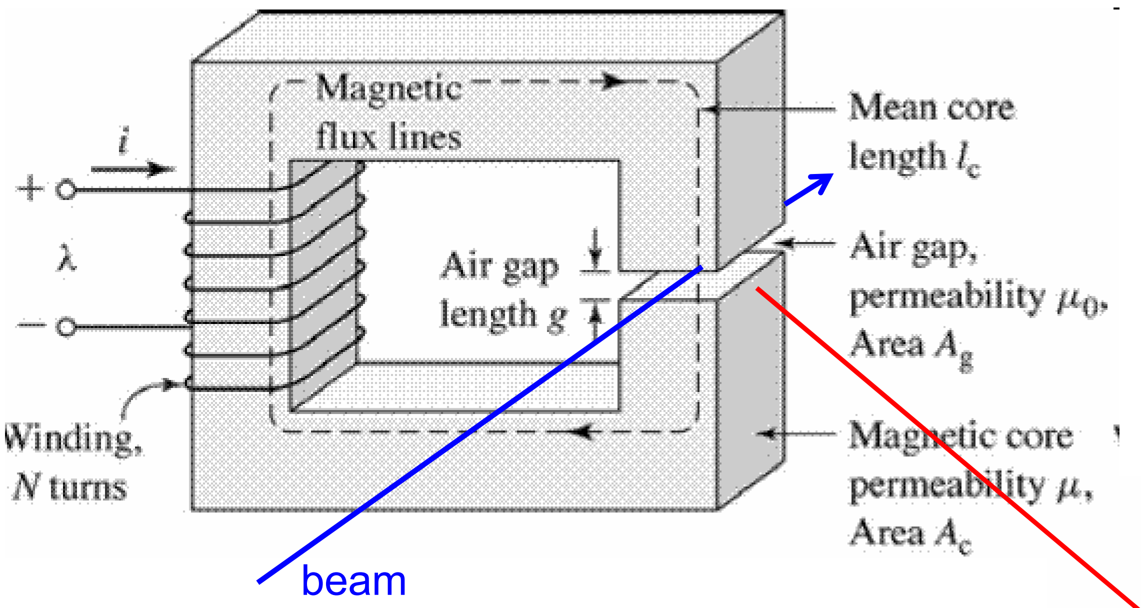
Dipole magnet

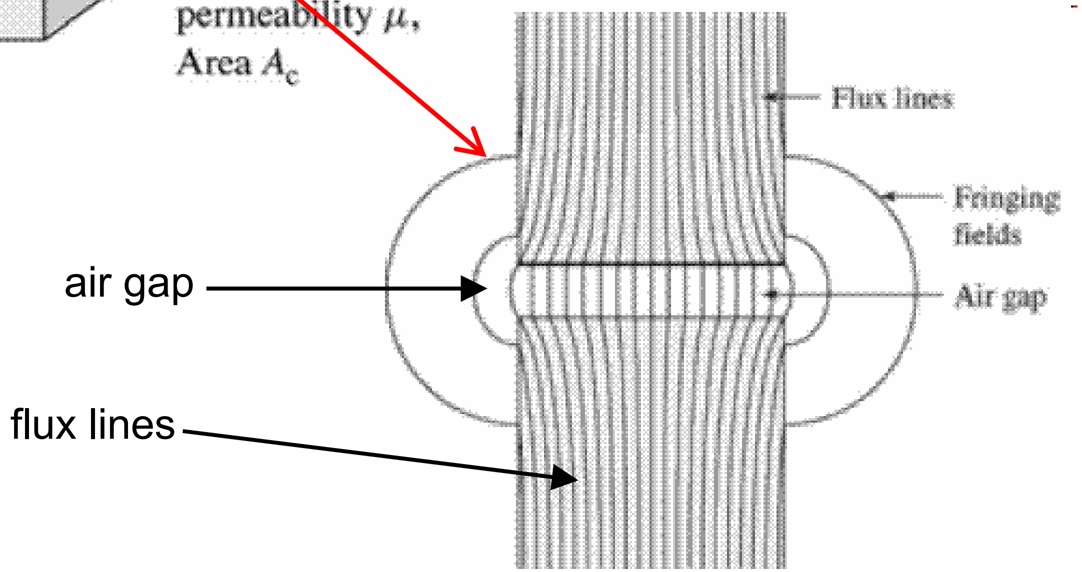


permeability of iron = 300…10000
larger than air

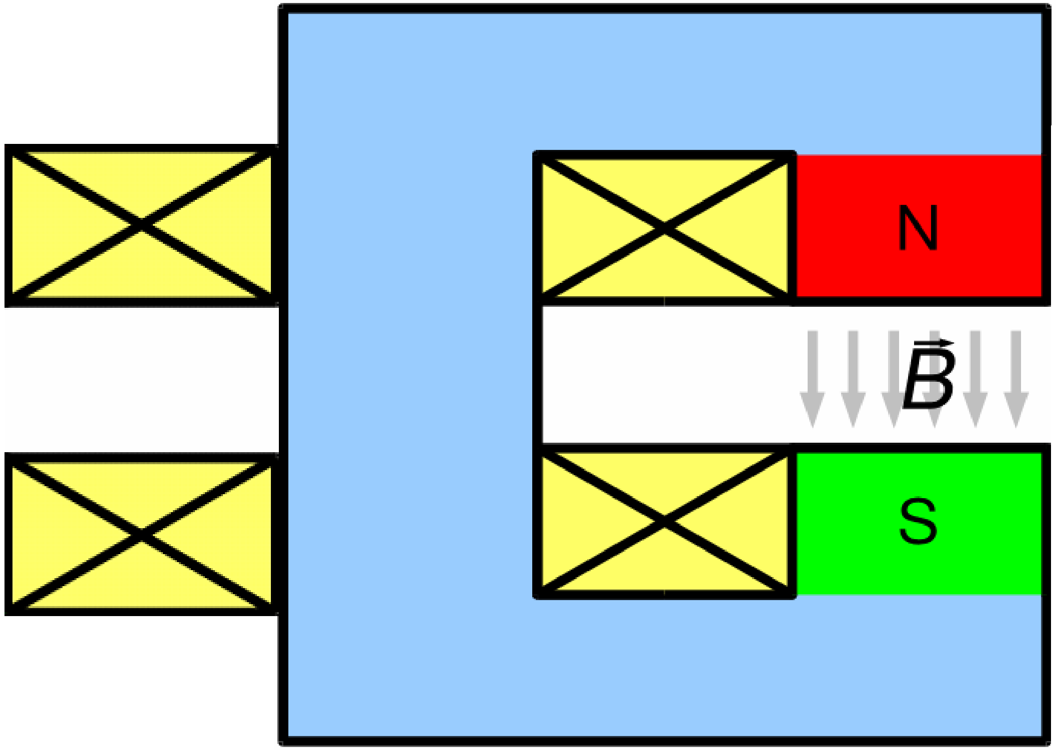


Dipole magnet





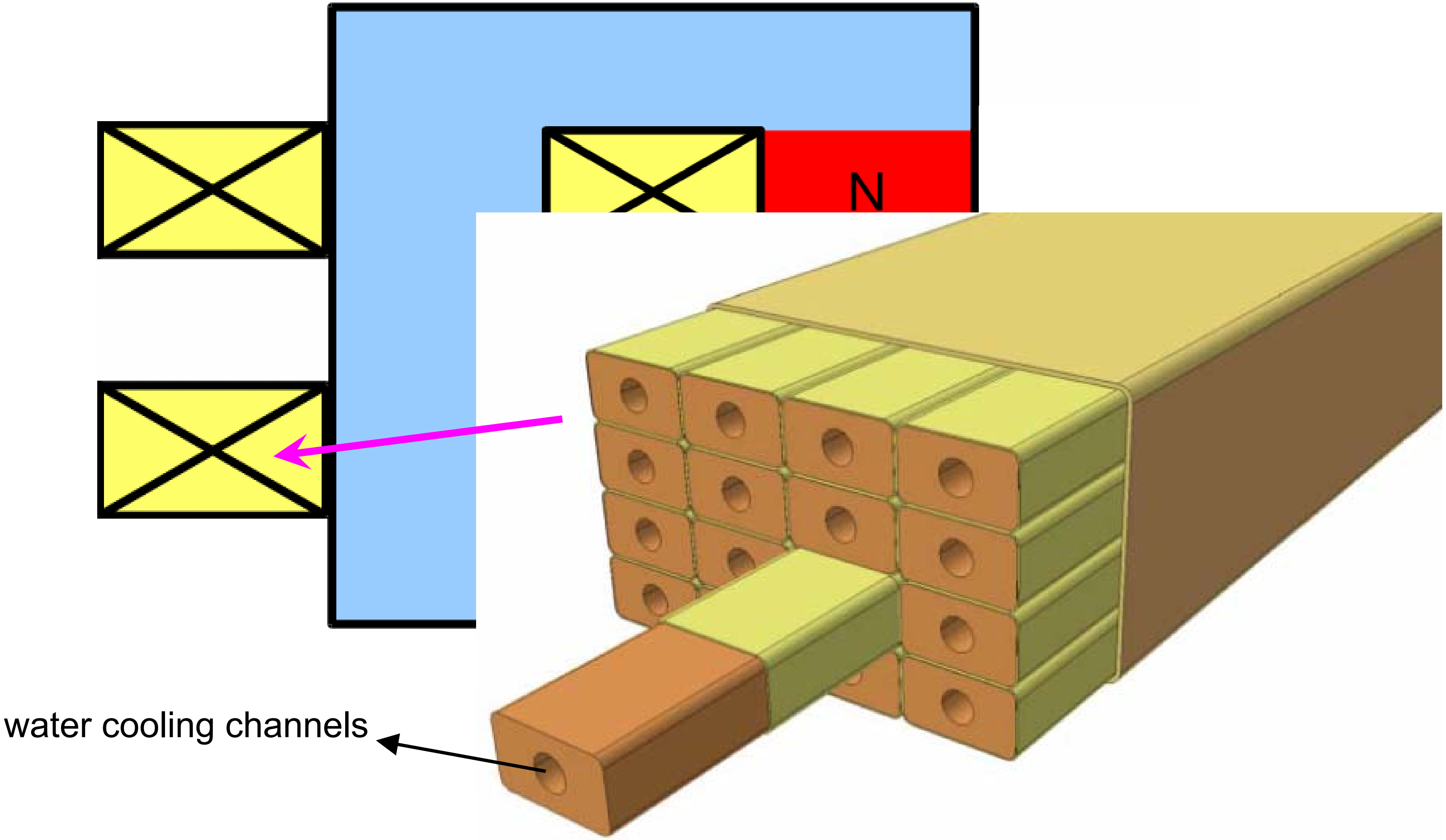
Dipole magnet cross section



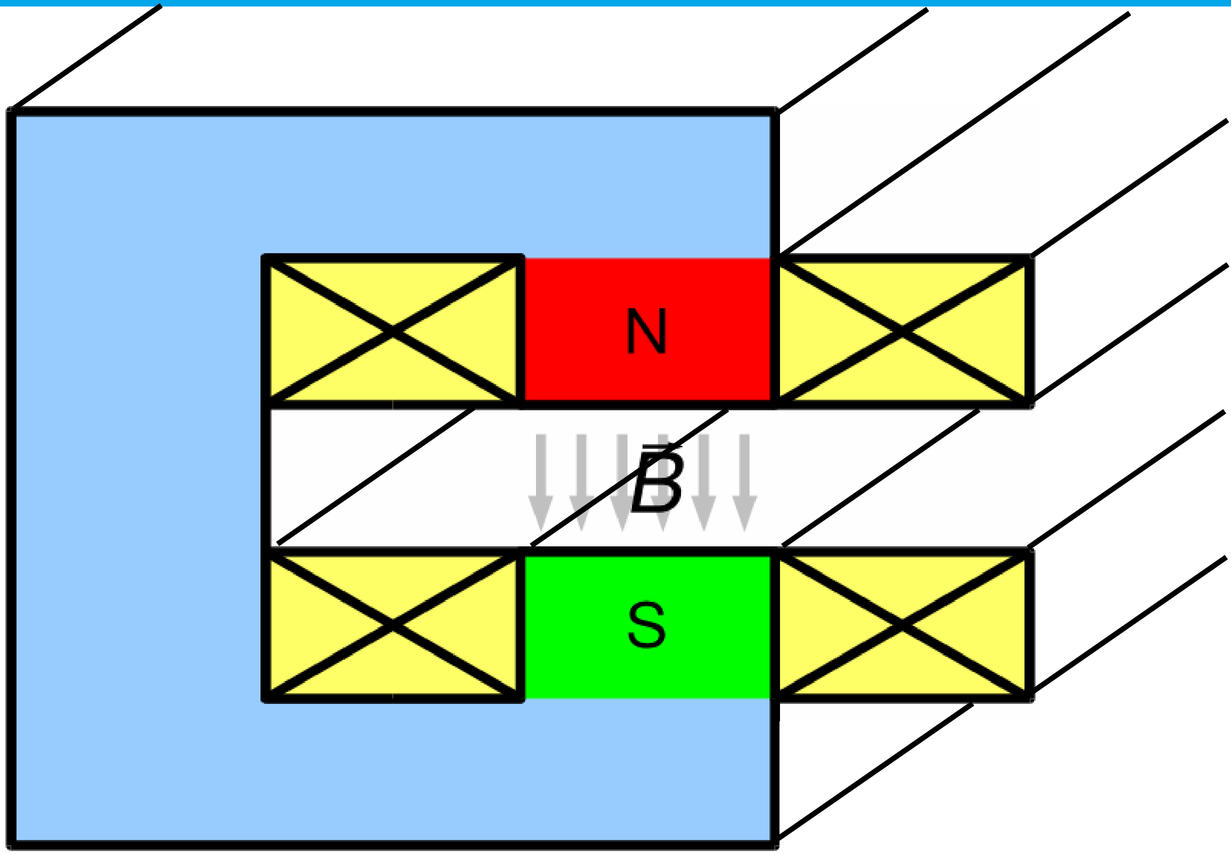
Max. B ➔ max. current ➔ large conductor cables

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

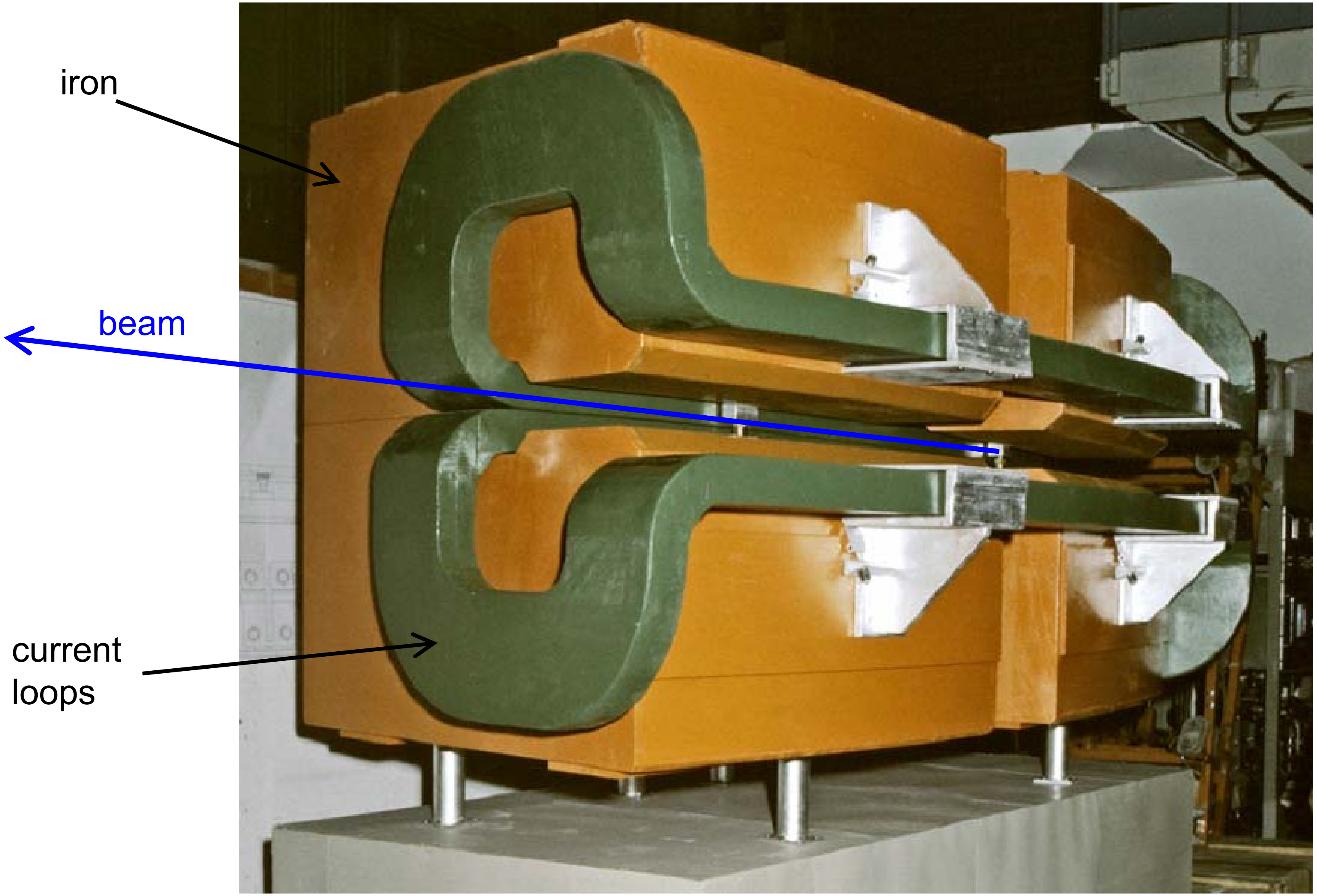
Dipole magnet cross section



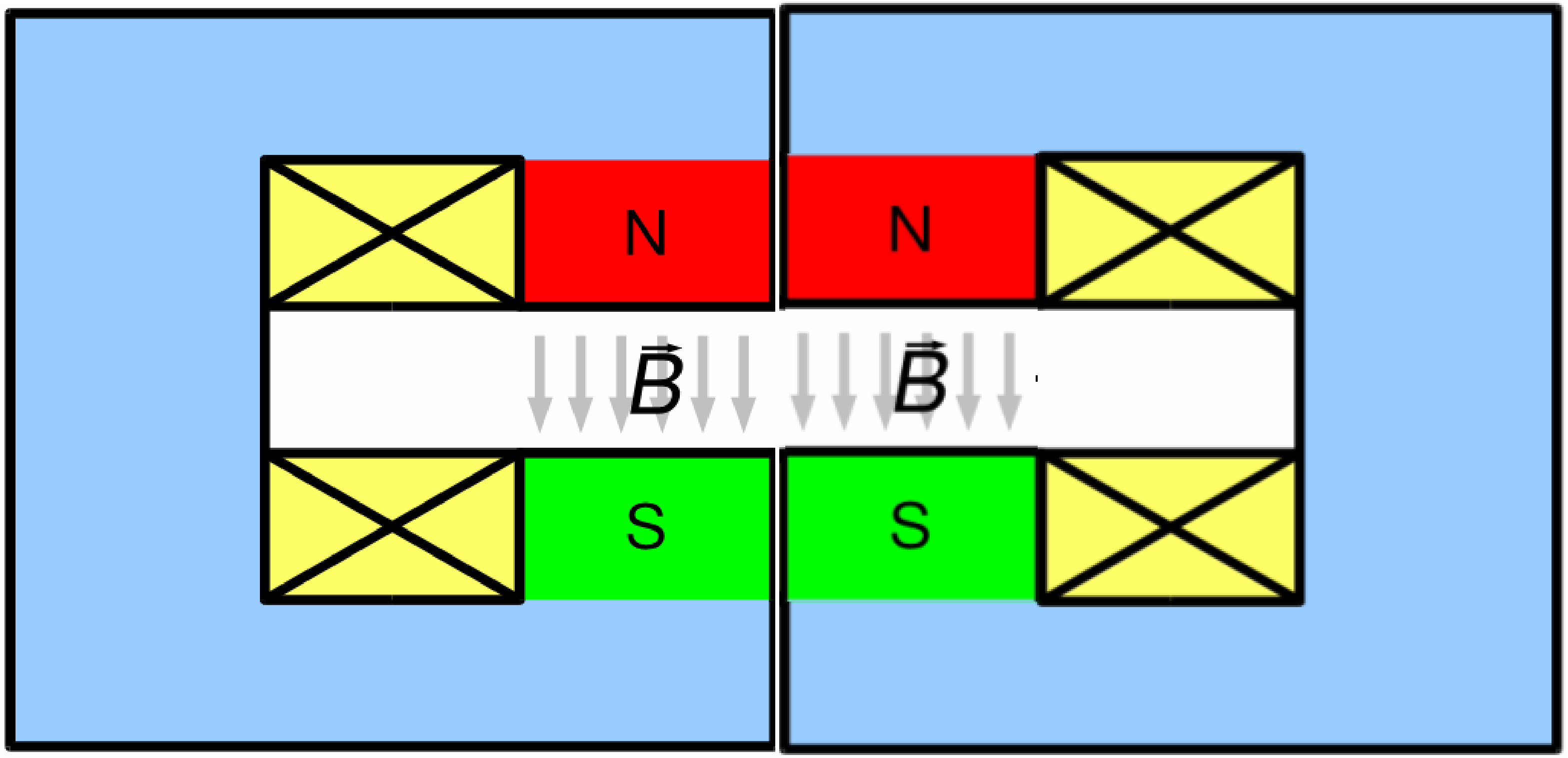
Dipole magnet cross section



Dipole magnet

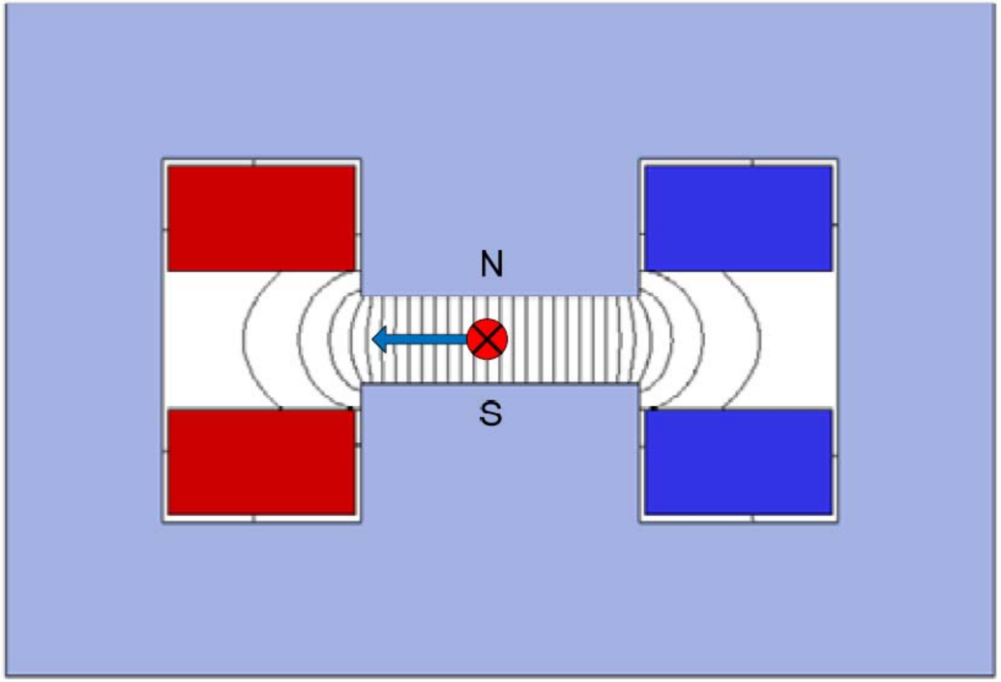


Dipole magnet cross section

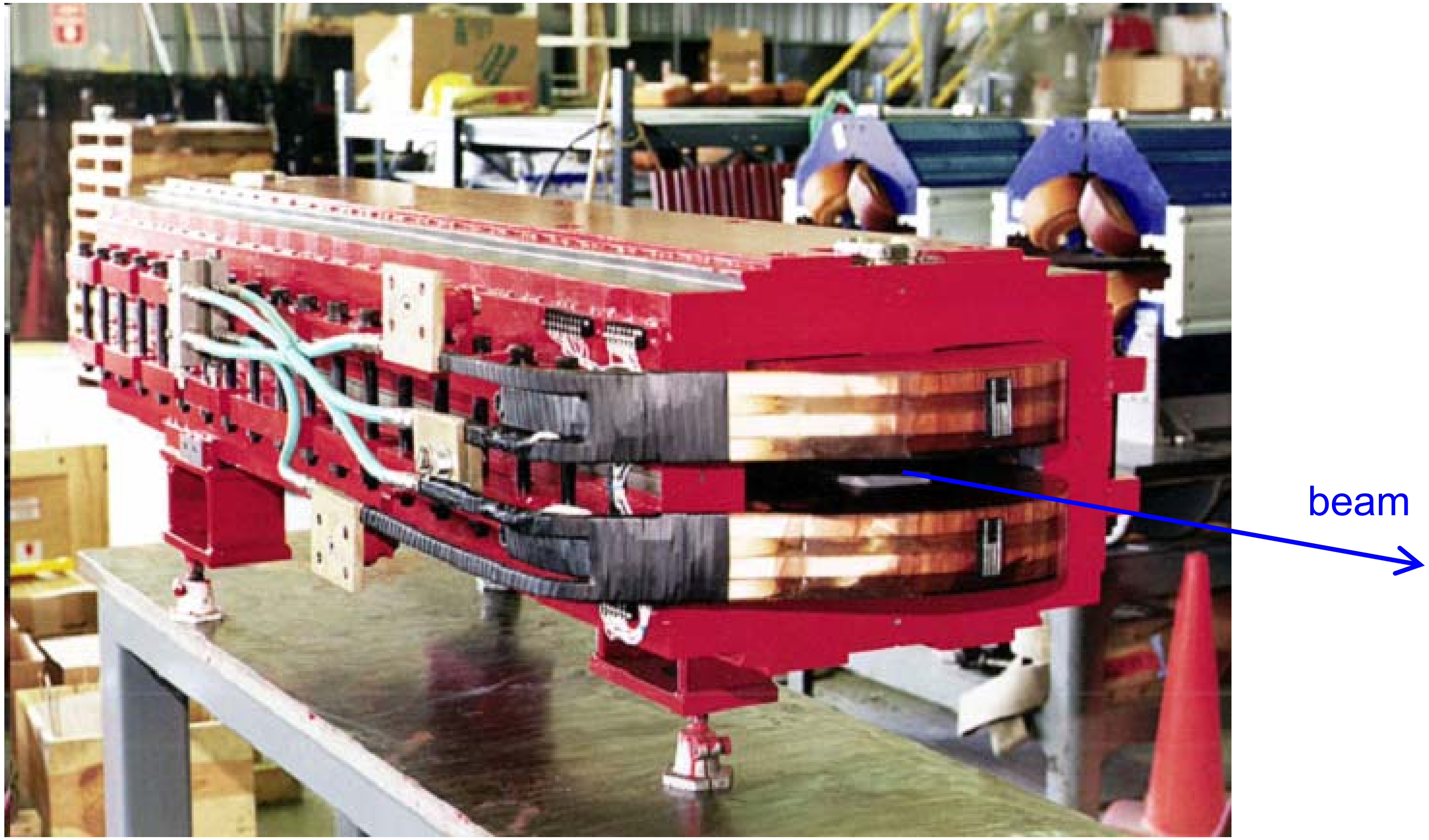


C magnet + C magnet = H magnet

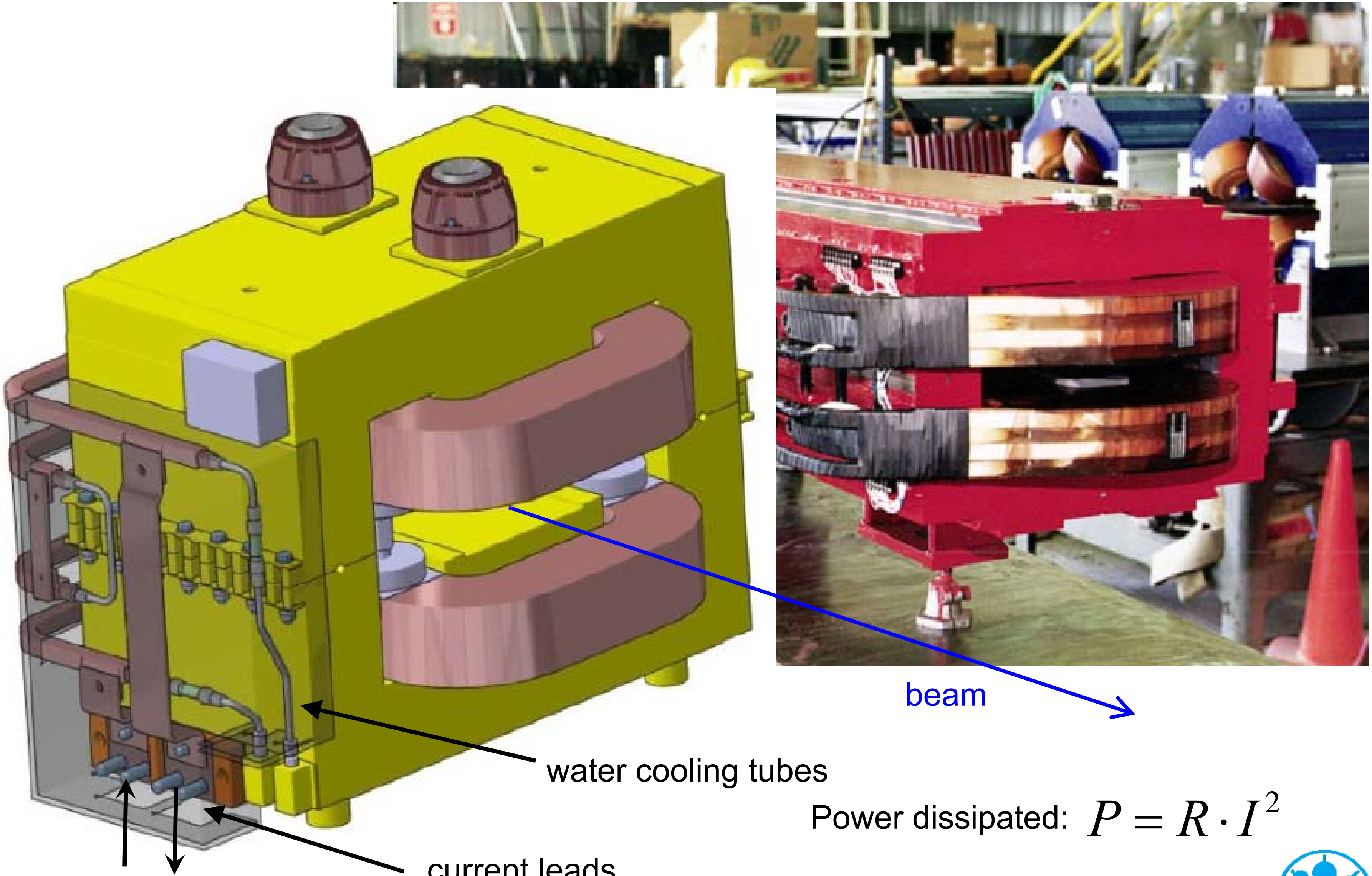
Dipole magnet cross section (another design)



Dipole magnet cross section (another design)

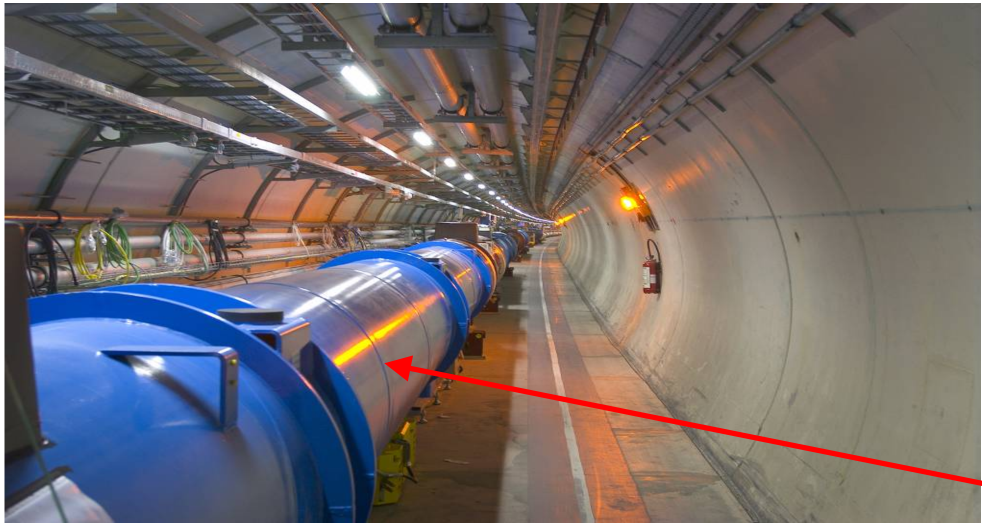


Dipole magnet cross section (another design)



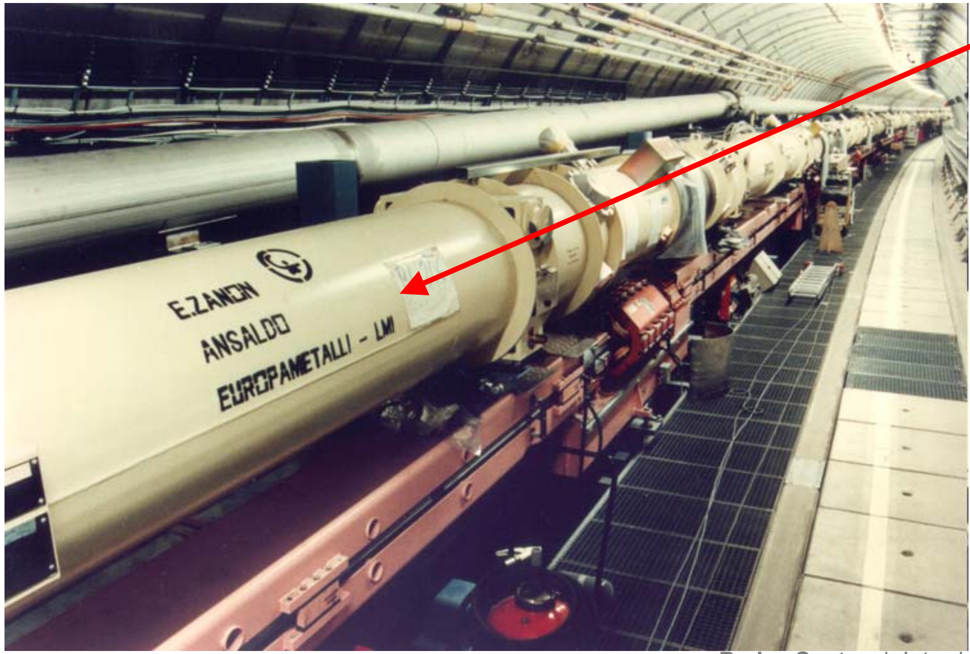
Power dissipated: $P = R \cdot I^2$

Superconducting dipole magnets



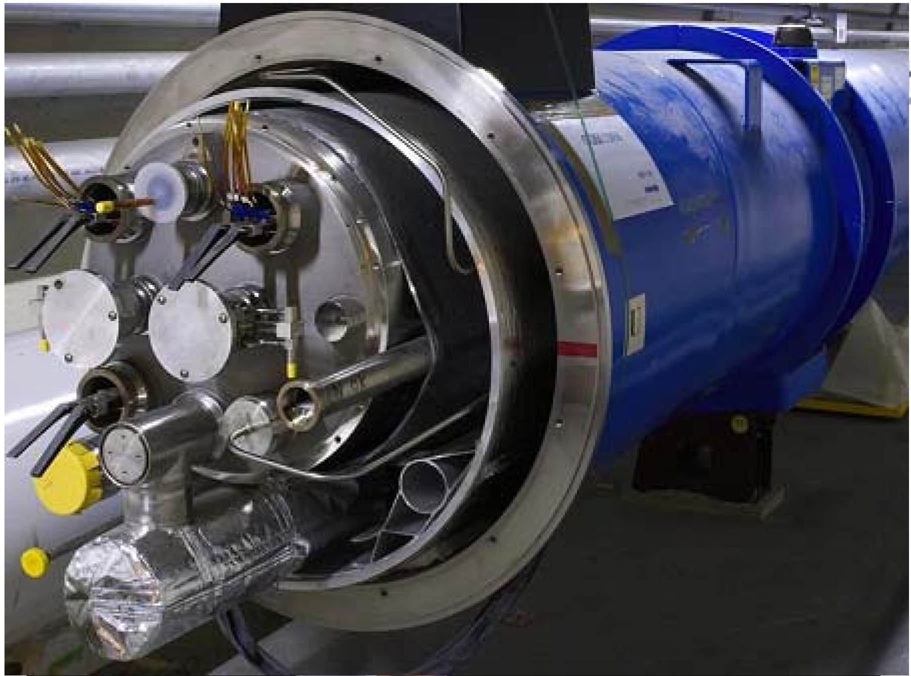
LHC

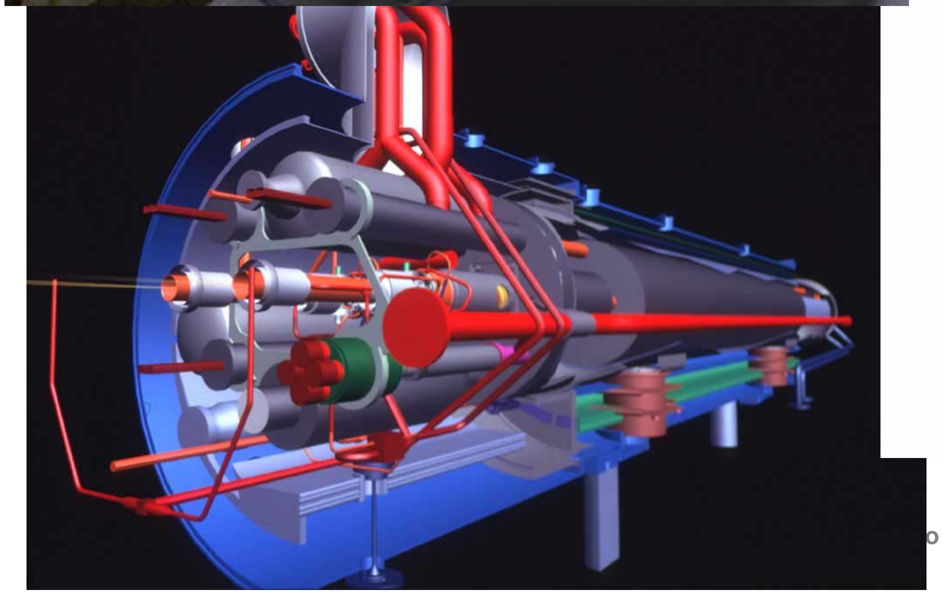
superconducting dipoles

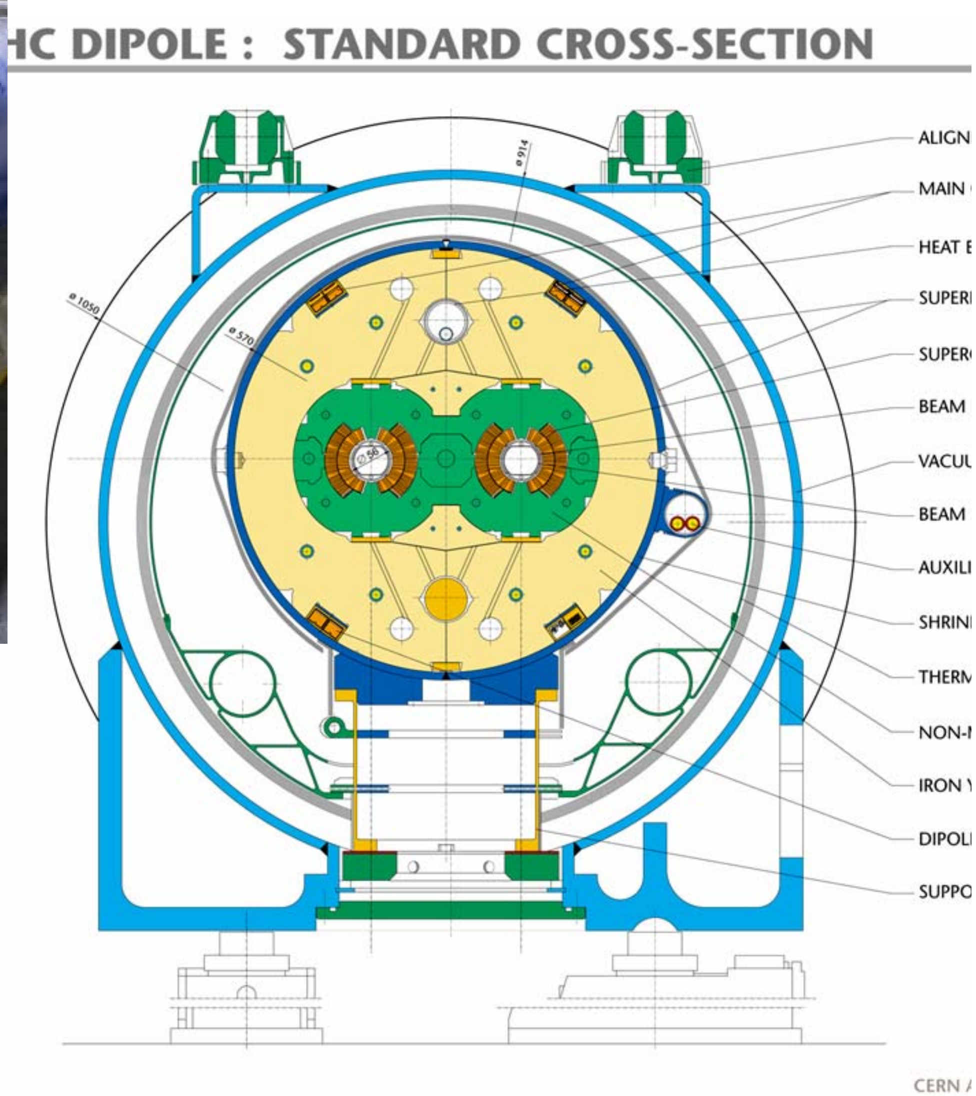


HERA

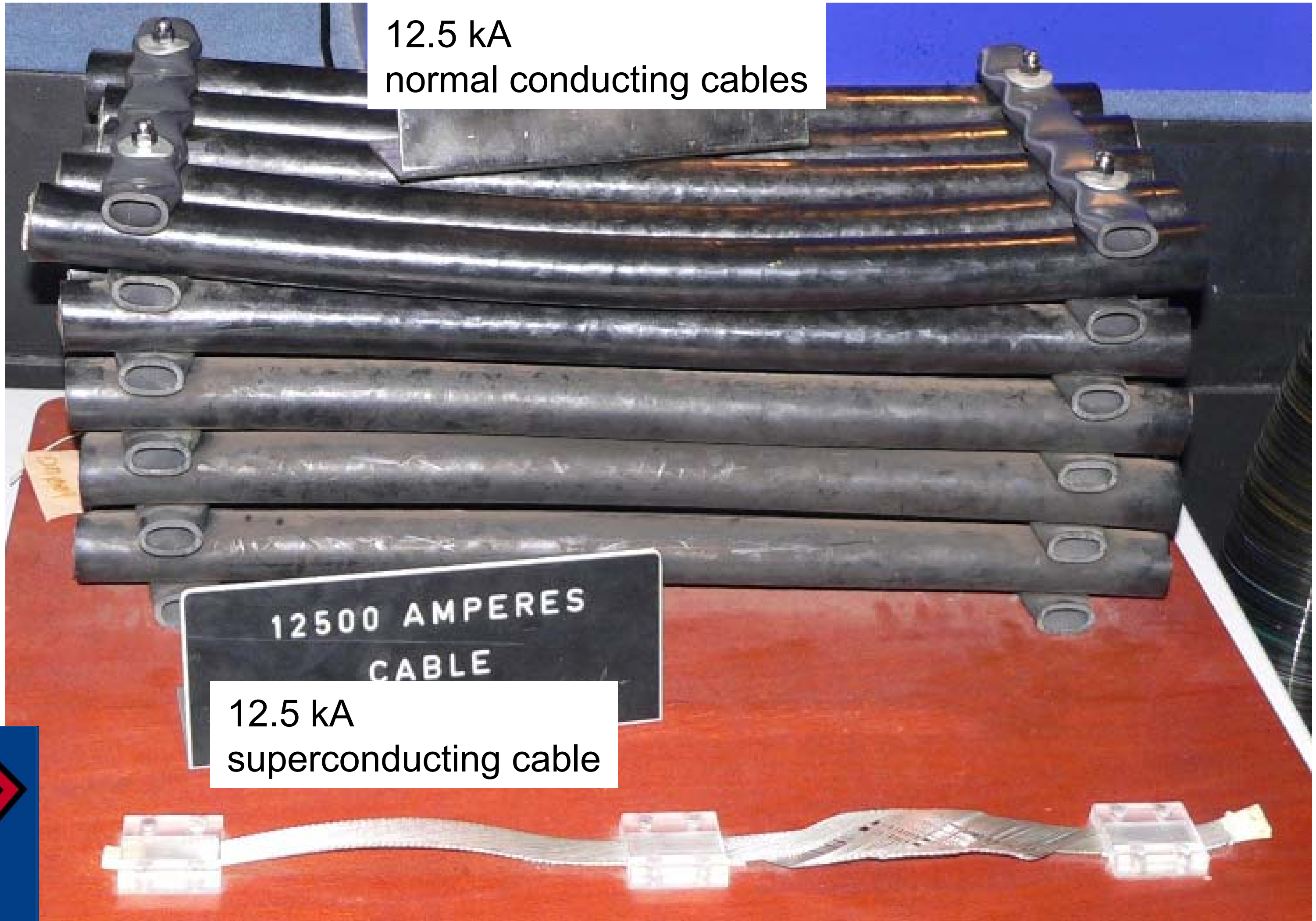
Superconducting dipole magnets





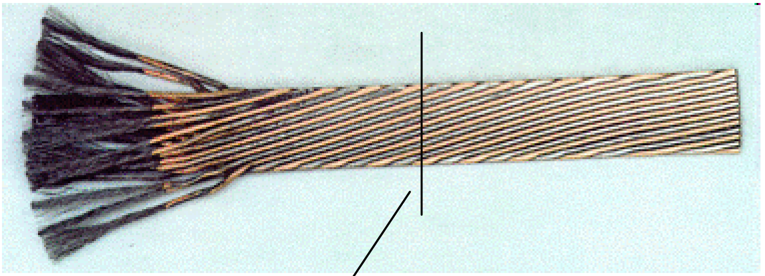


Superconductivity



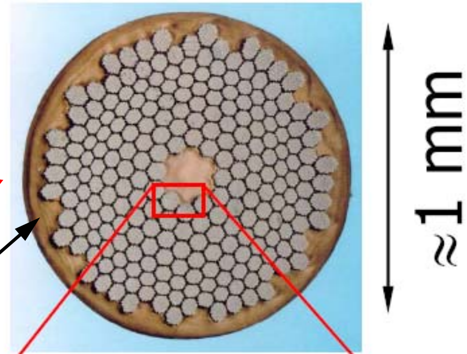
LHC cables

1 cable houses 36 strands



cross section

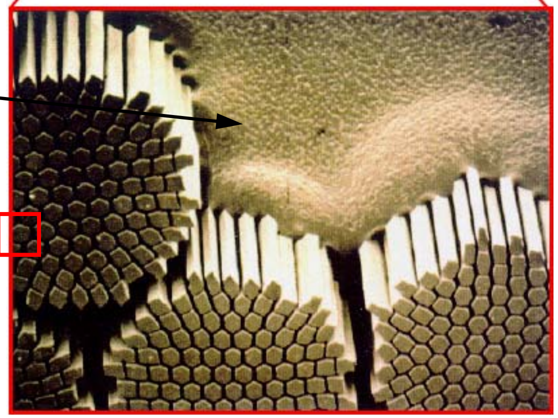
1 strand = 0.825 mm diameter
houses 6300 filaments



Copper is the insulation material
between two filaments

(around each filament: 0.5 μm Cu)

1 filament = 6 μm



cables from Rutherford company

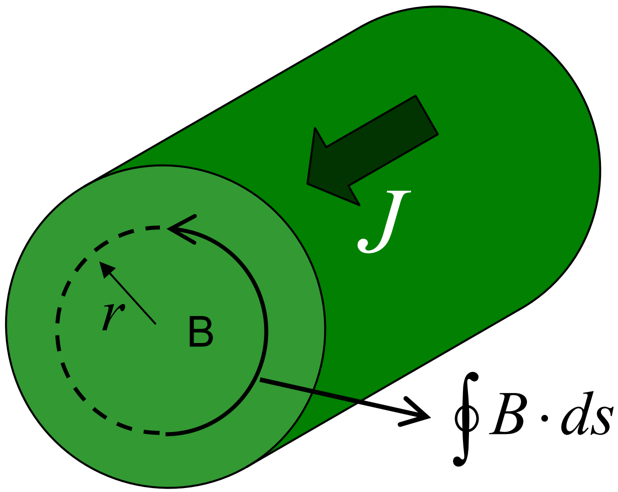
Dipole field from 2 coils

$J =$ uniform current density

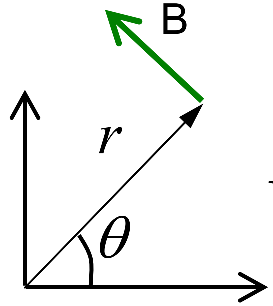
Ampere's law:

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

current through the circle



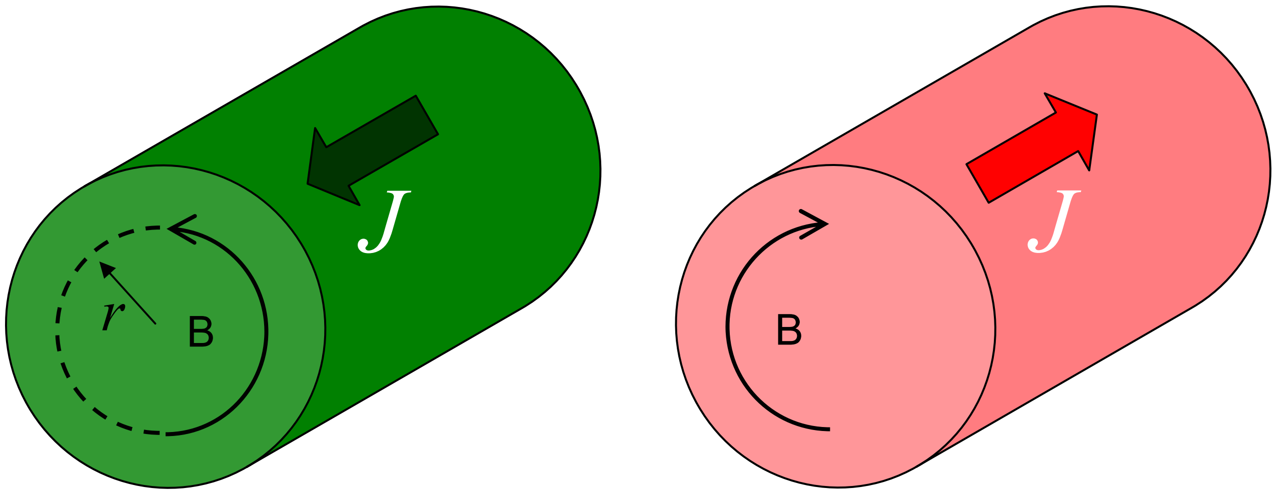
$$\oint B \cdot ds = 2\pi r B = \mu_0 \pi r^2 J \quad \rightarrow \quad B = \frac{\mu_0 J r}{2}$$



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

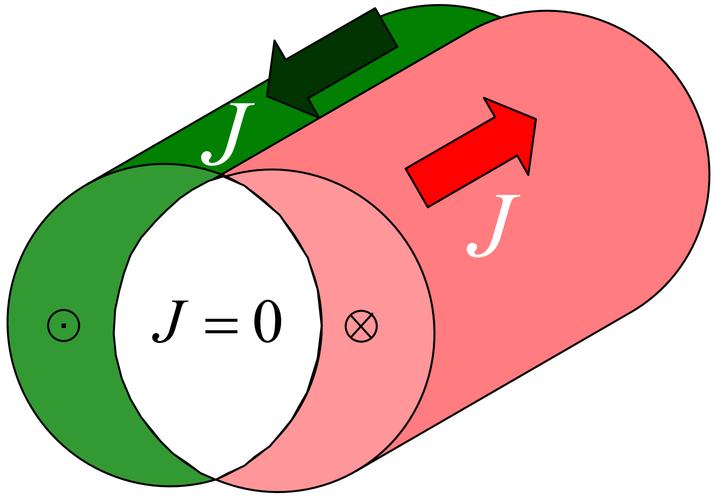
Dipole field from 2 coils

J = uniform current density



Dipole field from 2 coils

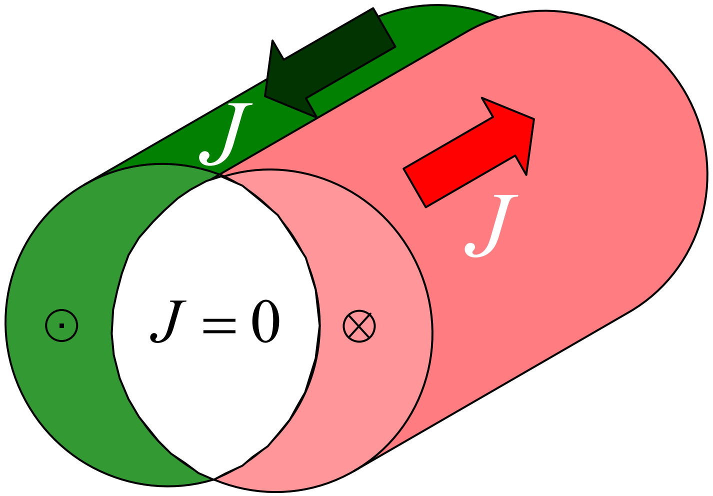
J = uniform current density



Dipole field from 2 coils

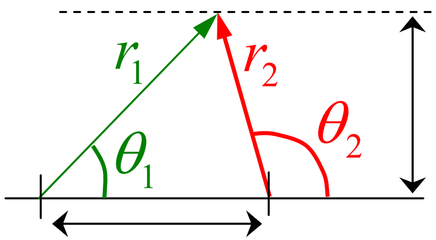
$$J = \text{uniform current density}$$

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



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

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

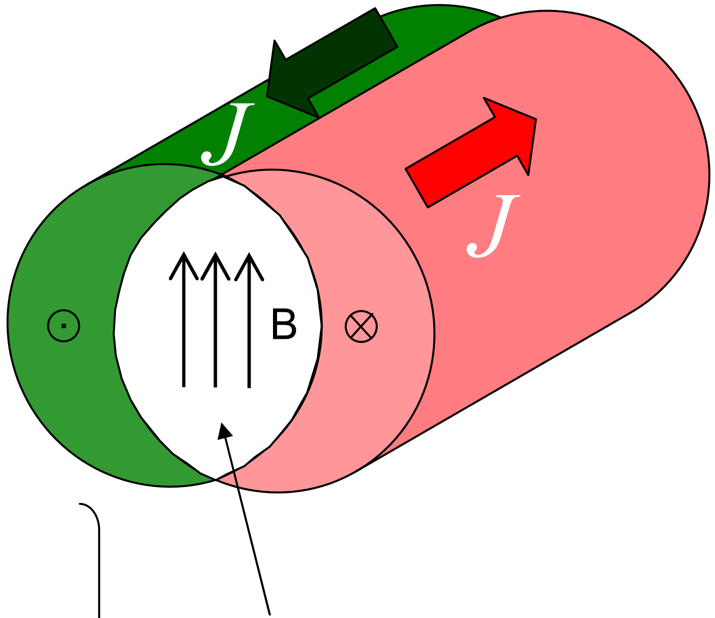


$$h = r_1 \sin\theta_1 = r_2 \sin\theta_2$$

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

Dipole field from 2 coils

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

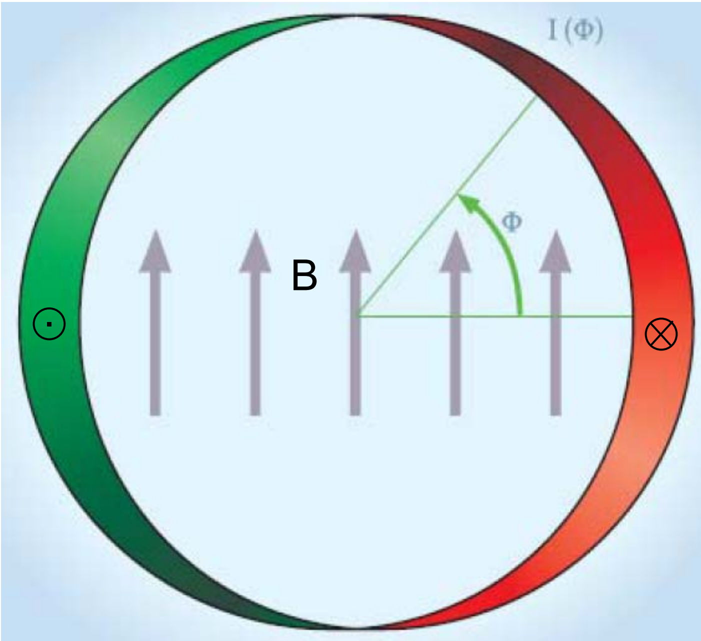


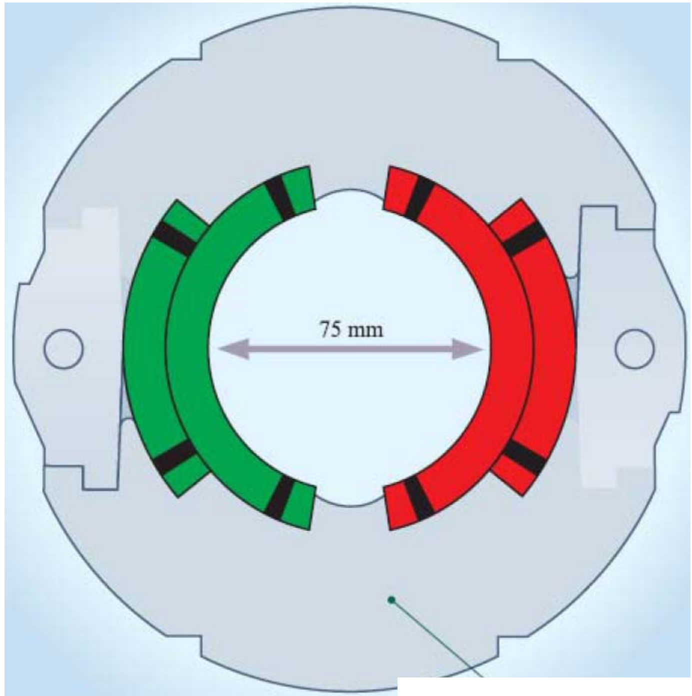
$$B_x = \frac{\mu_0 J}{2}(r_1 \sin\theta_1 - r_2 \sin\theta_2) = 0$$

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

constant vertical field

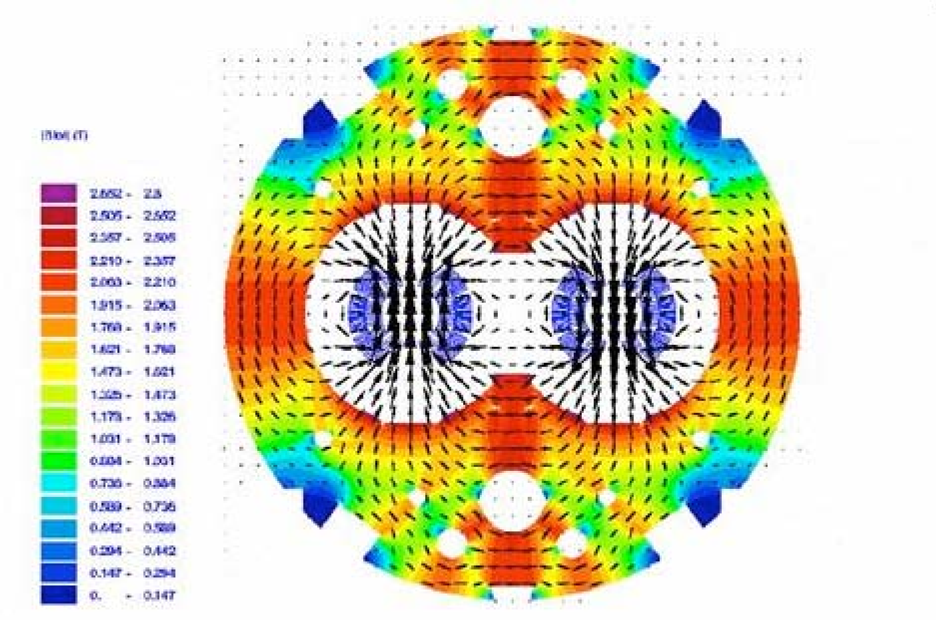
From the principle … to the reality…

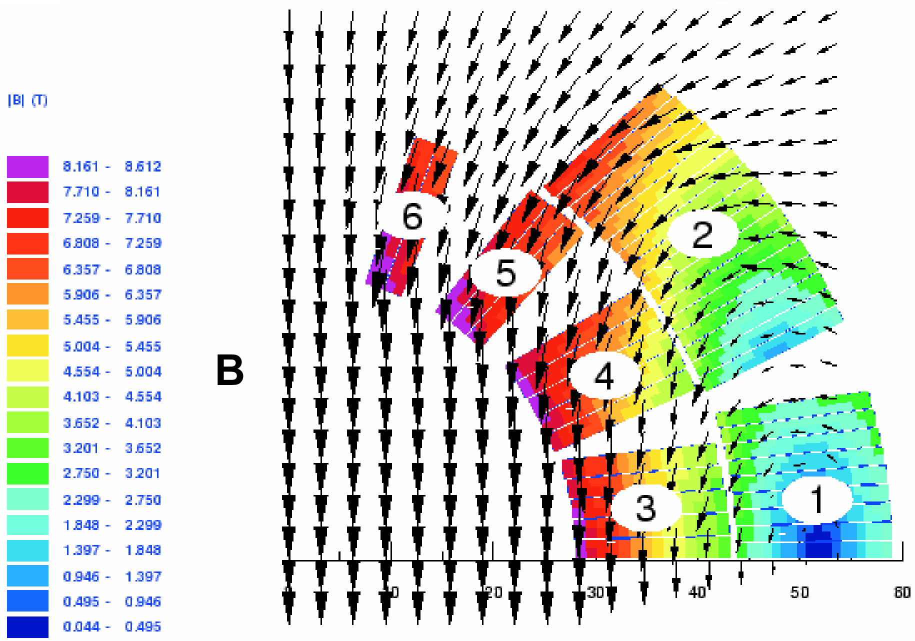


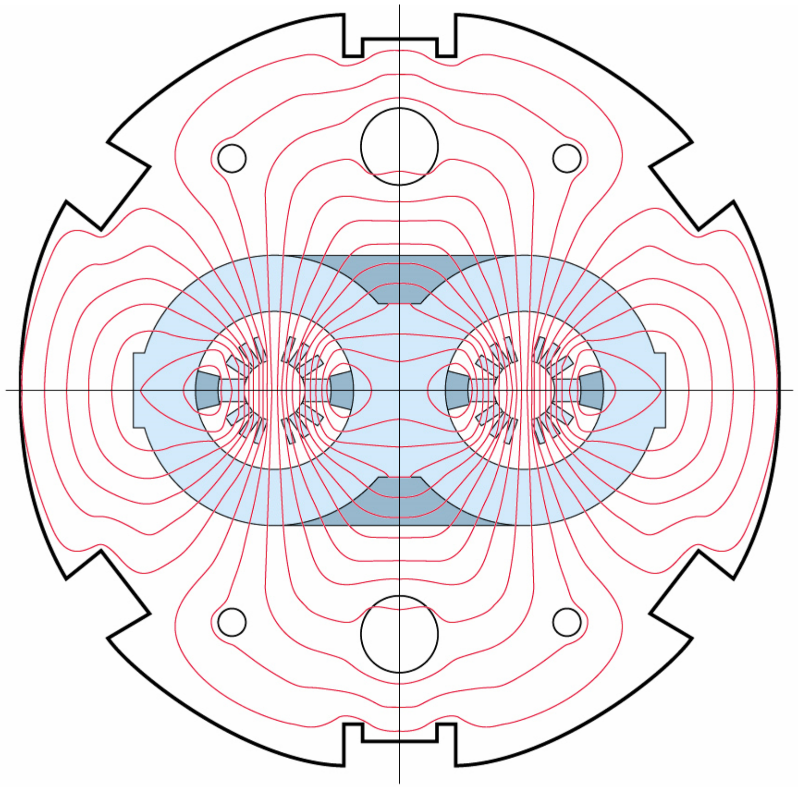


Aluminium collar

Simulation of the magnetic field

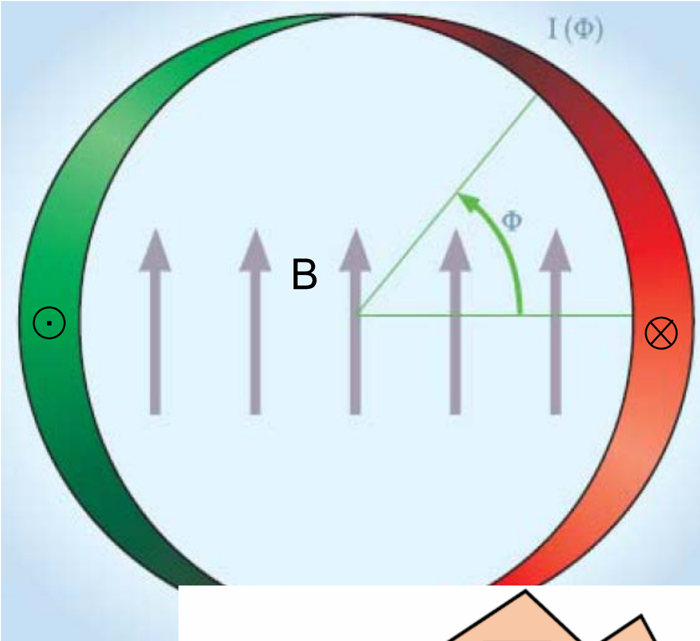


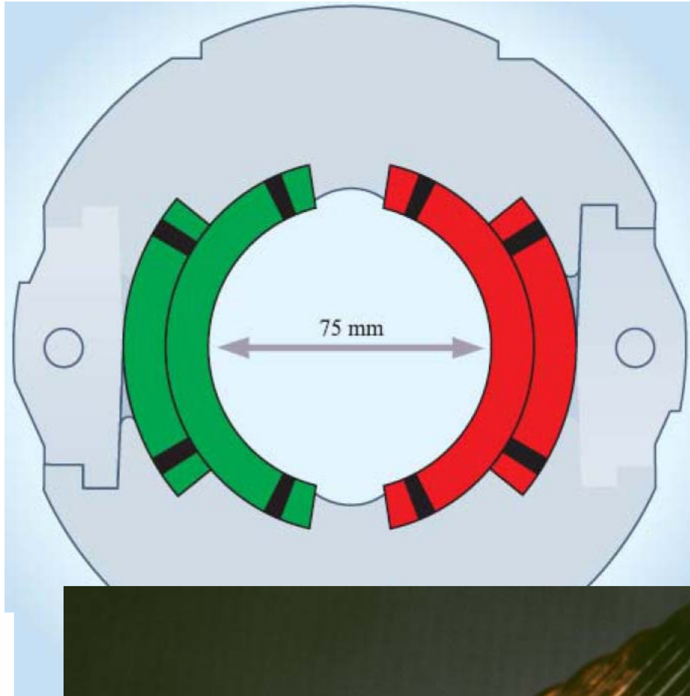


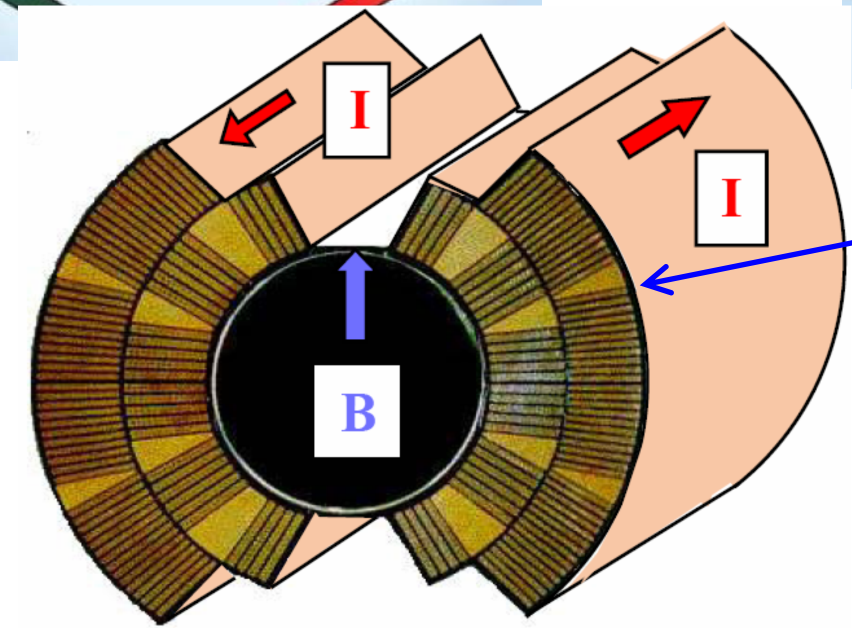


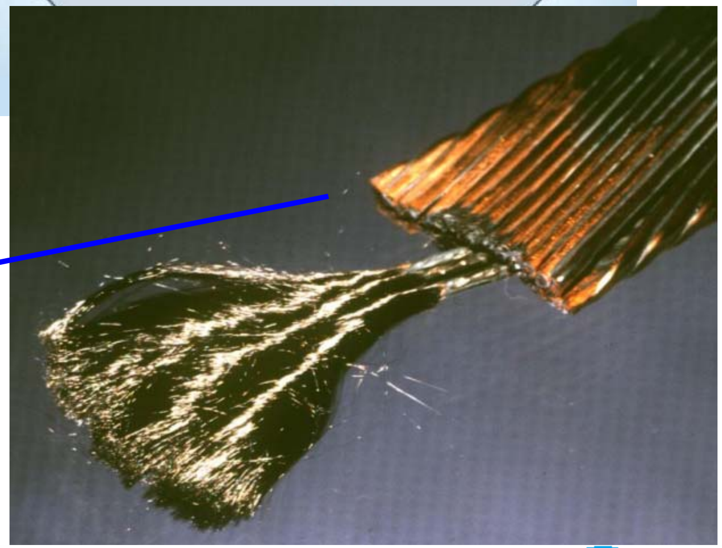
Computed magnetic flux map at B_0=10 Tesla

From the principle to the reality…

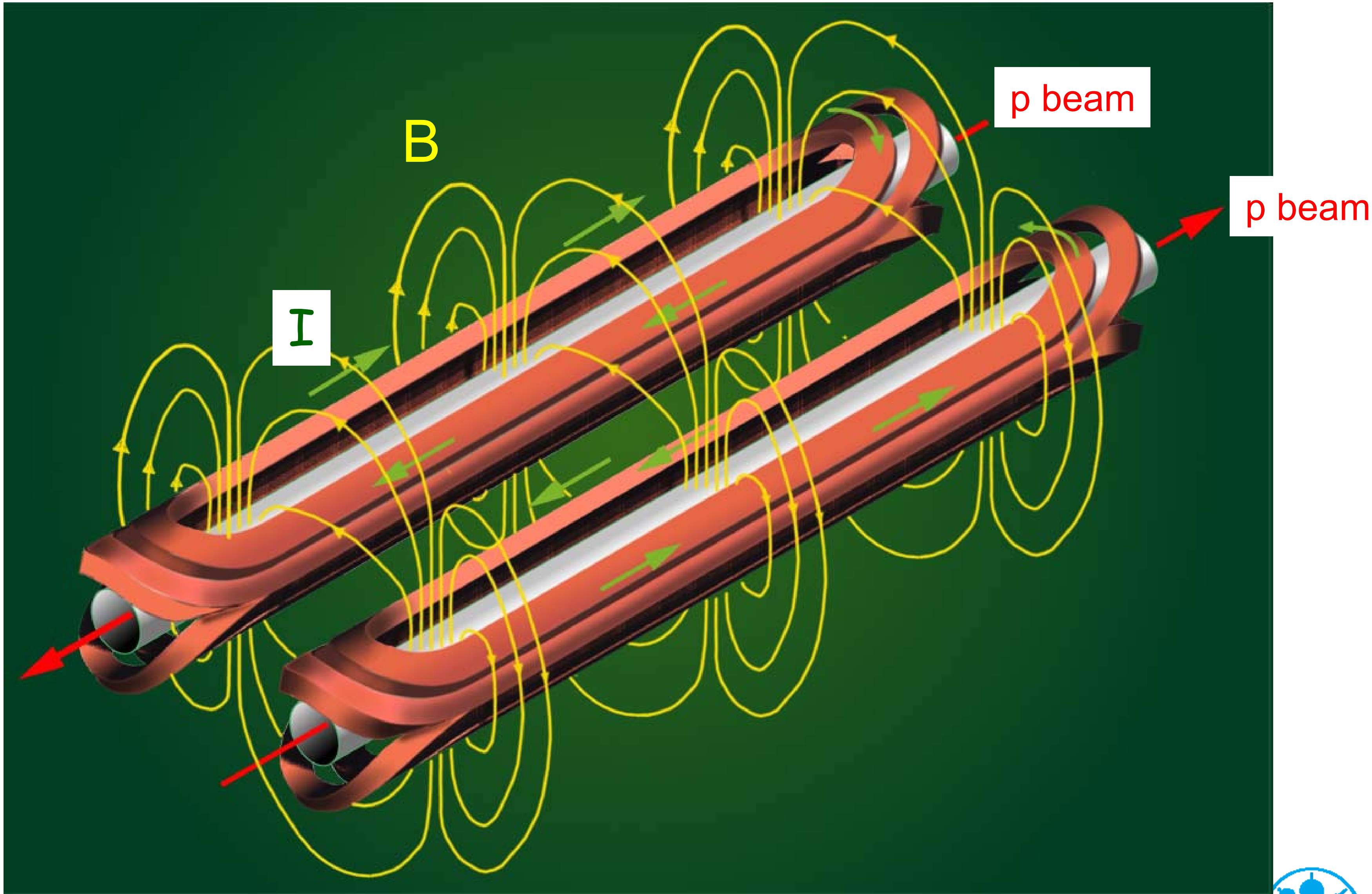




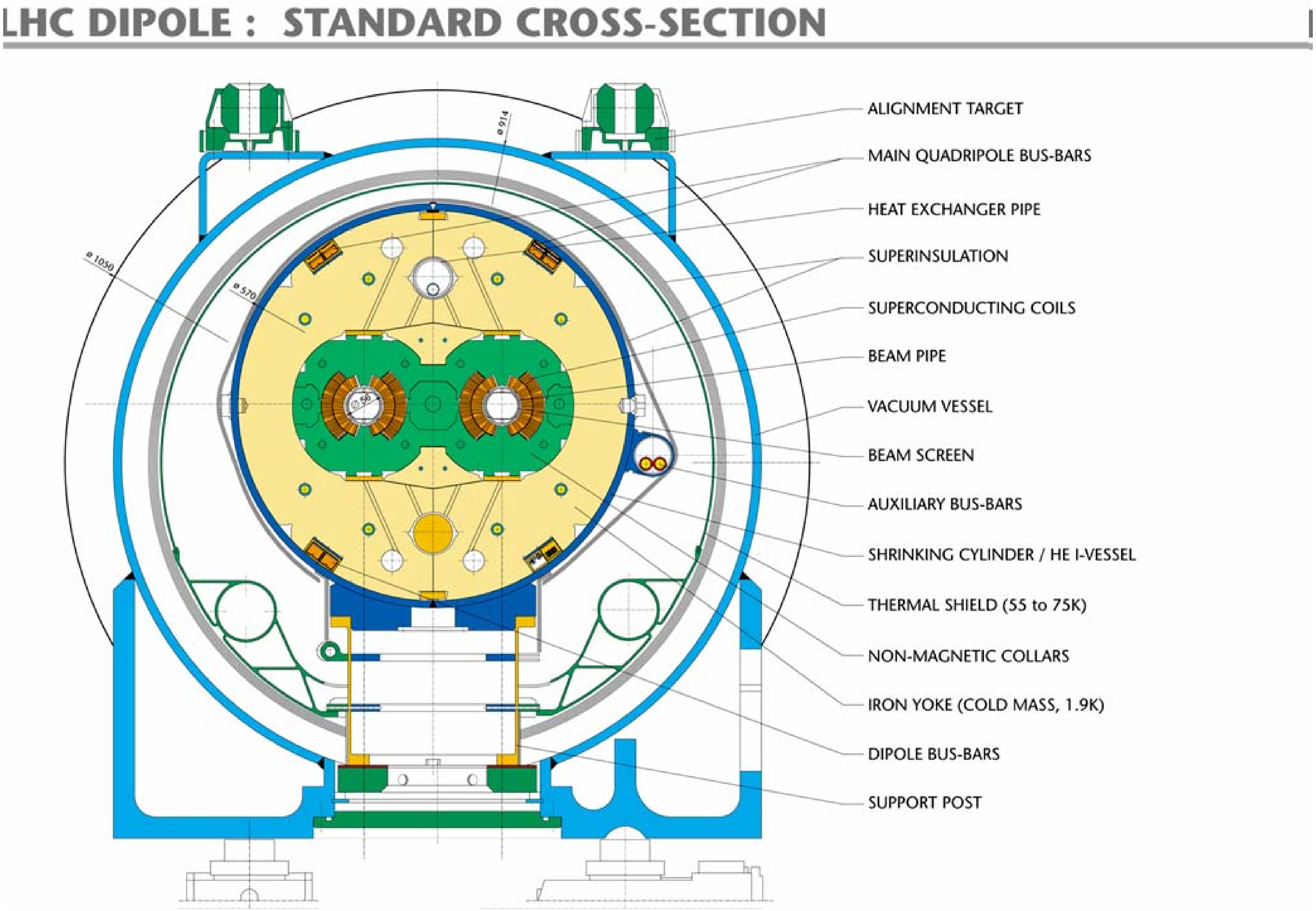




LHC dipole coils in 3D

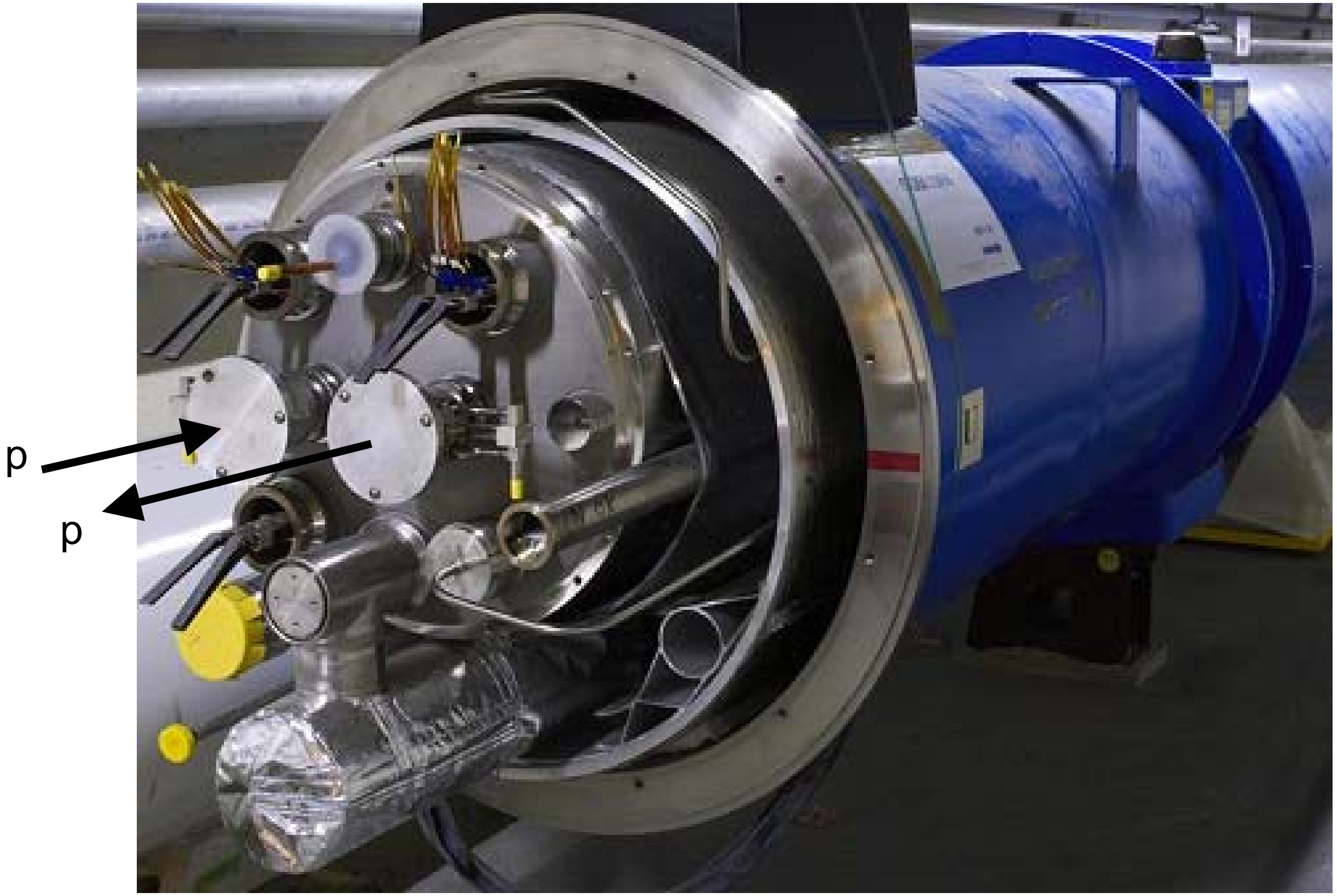


LHC dipole magnet (cross-section)



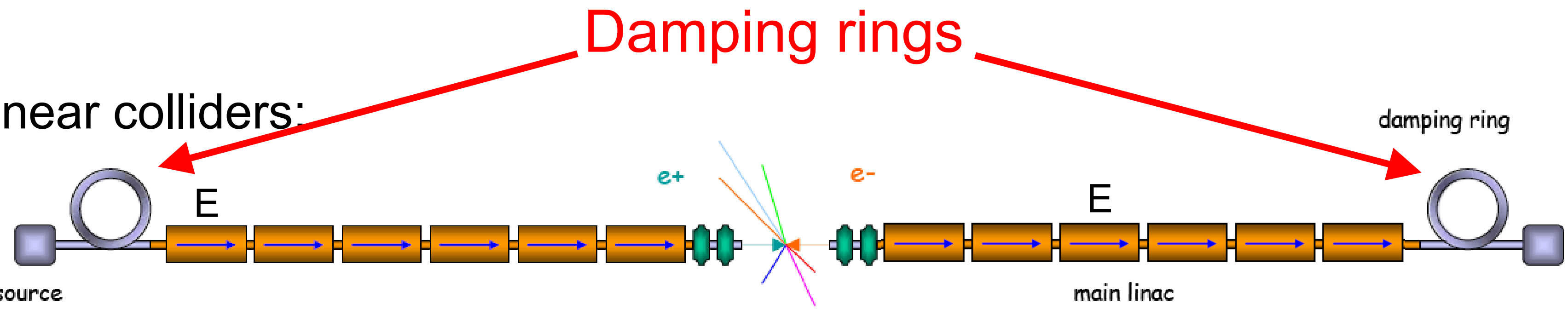
Superconducting dipole magnets

LHC dipole magnet interconnection:

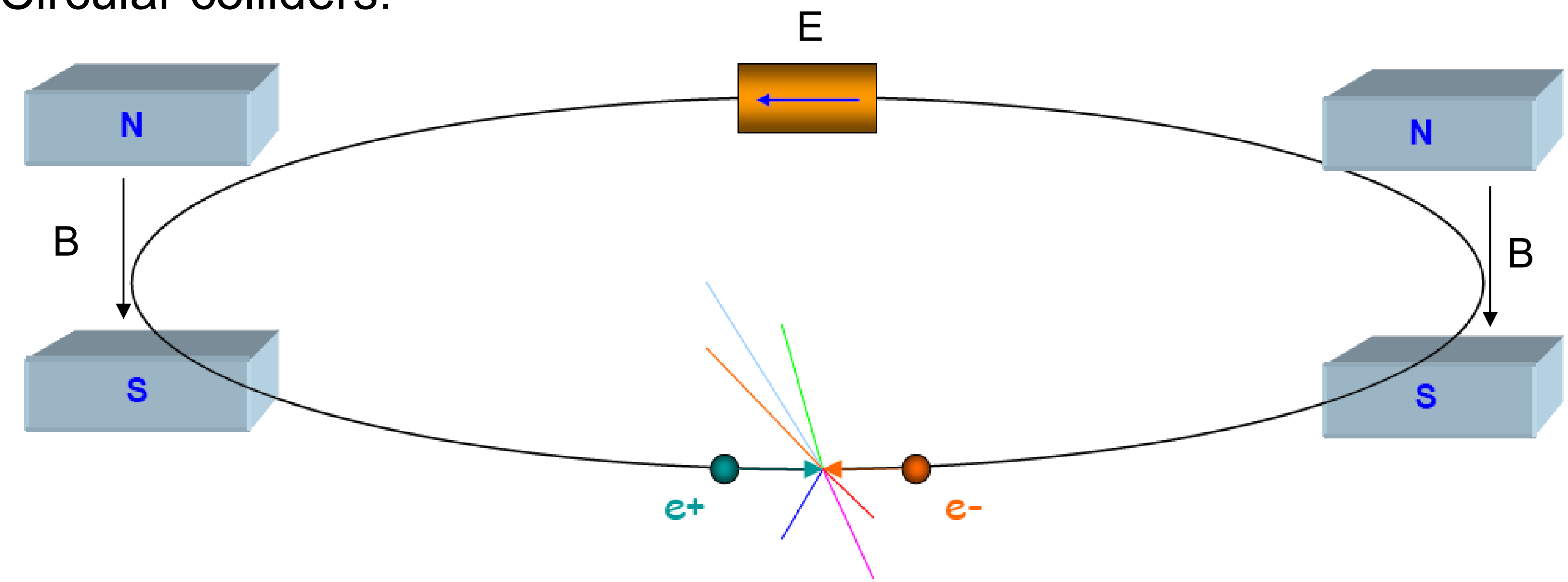


Damping rings

Linear colliders:



Circular colliders:



HERA: the super electron microscope

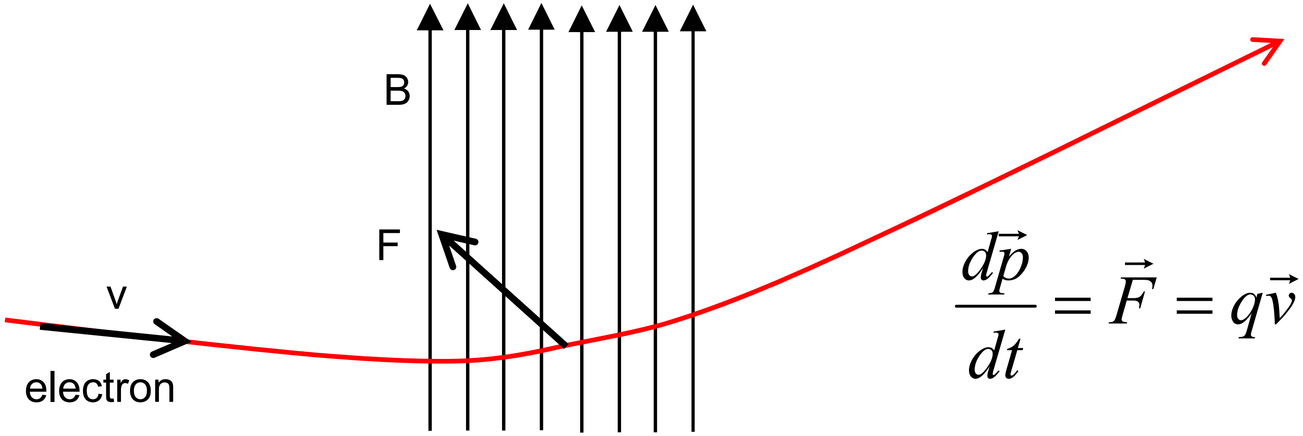
HERA (Hadron Electron Ring Accelerator) tunnel:

protons
(“samples”)
at 920 GeV

electrons at 27.5 GeV

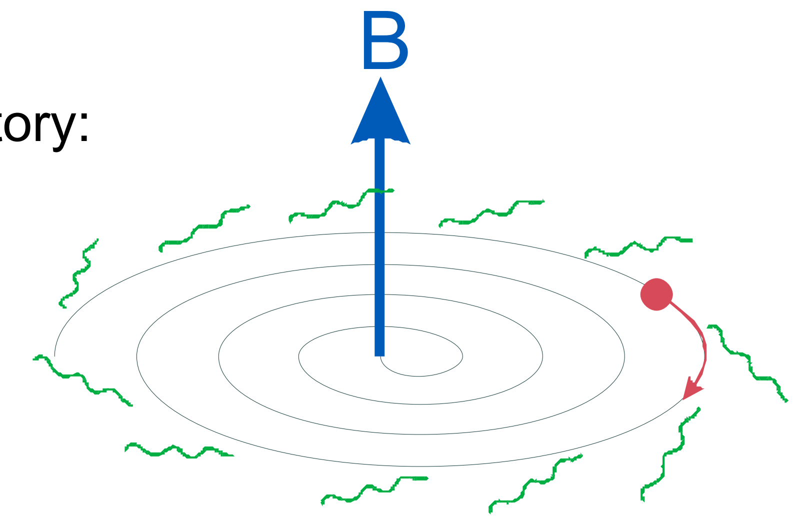
Why are the energies so different?

Particles moving in a magnetic field



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

Charged particles when accelerated,
emit radiation tangential to the trajectory:

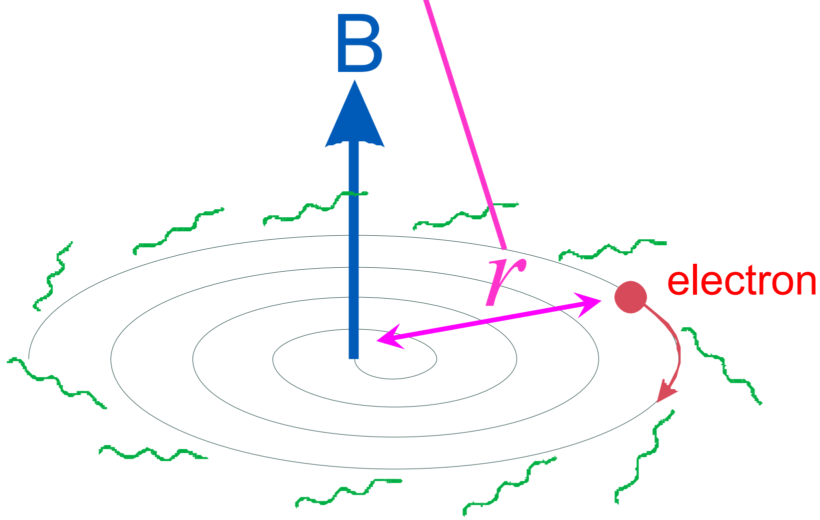


Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}}[\text{GeV}] = \frac{6.034 \times 10^{-18}}{r[\text{m}]} \gamma^4 \qquad \gamma = \frac{E}{m_0 c^2}$$

ALL charged particles when accelerated, emit radiation tangential to the trajectory:



Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}}[\text{GeV}] = \frac{6.034 \times 10^{-18}}{r[\text{m}]} \gamma^4 \quad \leftarrow \quad \gamma = \frac{E}{m_0 c^2}$$

HERA electron ring:

$$r = 580 \text{ m}$$

$$E = 27.5 \text{ GeV}$$

$$\Delta E \cong 80 \text{ MeV } (0.3\%)$$

need acceleration = 80 MV per turn

HERA proton ring:

$$r = 580 \text{ m}$$

$$E = 920 \text{ GeV}$$

$$\Delta E \cong 10 \text{ eV } (10^{-9}\%)$$

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}}[\text{GeV}] = \frac{6.034 \times 10^{-18}}{r[\text{m}]} \gamma^4$$

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

HERA electron ring:

$$r = 580 \text{ m}$$

$$E = 27.5 \text{ GeV}$$

$$\Delta E \cong 80 \text{ MeV } (0.3\%)$$

need acceleration = 80 MV per turn

HERA proton ring:

$$r = 580 \text{ m}$$

$$E = 920 \text{ GeV}$$

the limit is the max. dipole field = 5.5 Tesla

$$\frac{1}{r} = \frac{qB}{p}$$

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}}[\text{GeV}] = \frac{6.034 \times 10^{-18}}{r[\text{m}]} \gamma^4 \quad \leftarrow \quad \gamma = \frac{E}{m_0 c^2}$$

HERA electron ring:

$$r = 580 \text{ m}$$

$$E = 27.5 \text{ GeV}$$

$$\Delta E \cong 80 \text{ MeV } (0.3\%)$$

need acceleration = 80 MV per turn

x5 →

LEP collider:

$$r = 2800 \text{ m}$$

$$E = 105 \text{ GeV}$$

$$\Delta E \cong 3 \text{ GeV } (3\%)$$

need 3 GV per turn !!

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}}[\text{GeV}] = \frac{6.034\times 10^{-18}}{r[\text{m}]}\gamma^4 \qquad \gamma = \frac{E}{m_0 c^2}$$

HERA electron ring:

$r = 580\ \text{m}$ —— x5 ——→

$E = 27.5\ \text{GeV}$

$\Delta E \cong 80\ \text{MeV}\ (0.3\%)$

need acceleration = 80 MV per turn

LEP collider:

r …

… eV

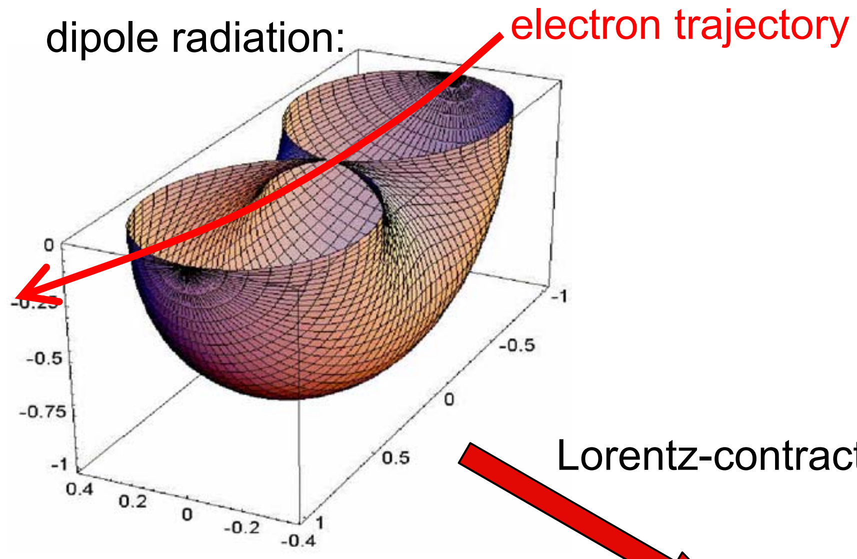
… $\cong 3\ \text{GeV}\ (3\%)$

need 3 GV per turn !!

LEP = Last Electron-Positron Collider ?

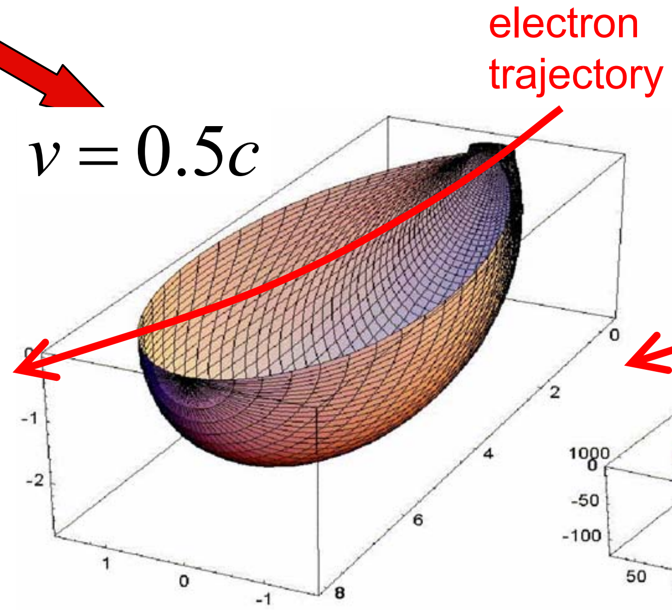
Radiation of a Hertz dipole under relativistic conditions

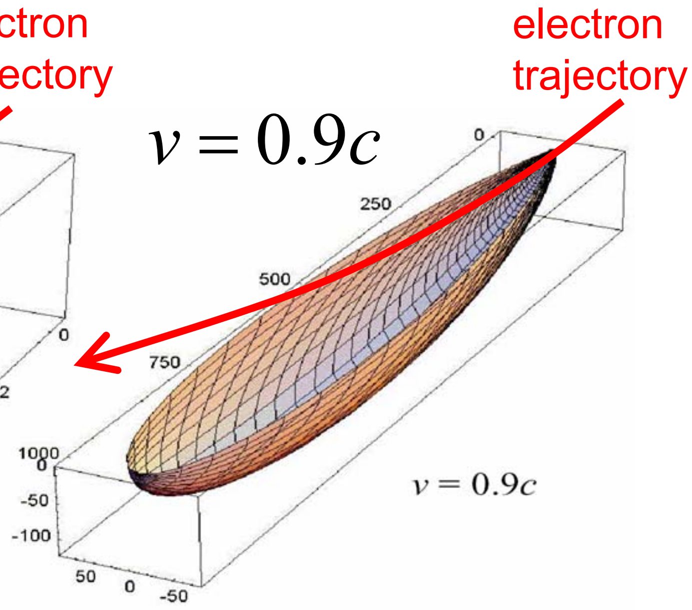
dipole radiation:



PETRA: γ =14000

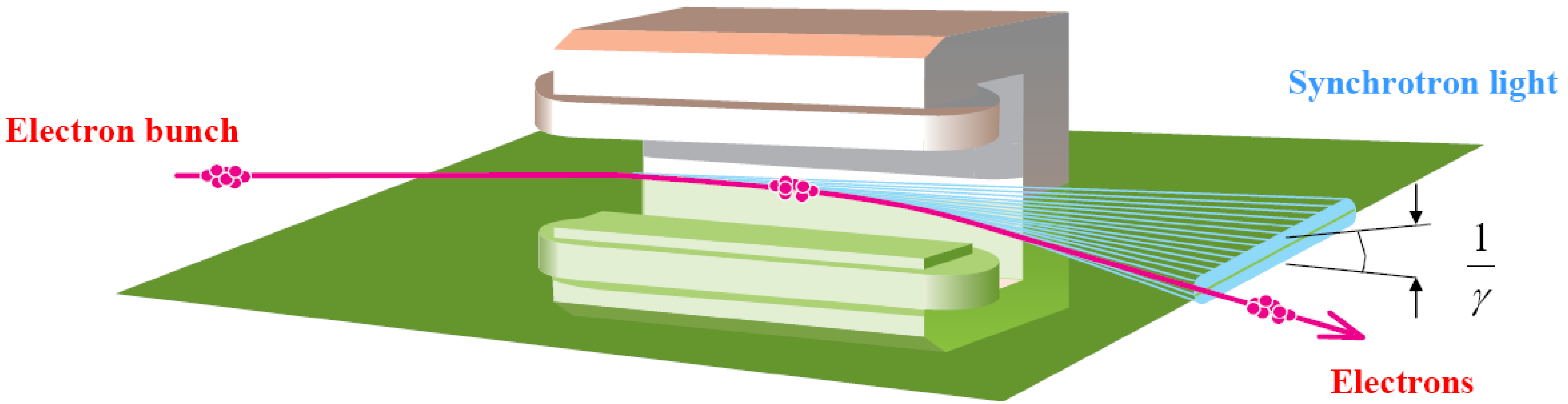
Lorentz-contraction



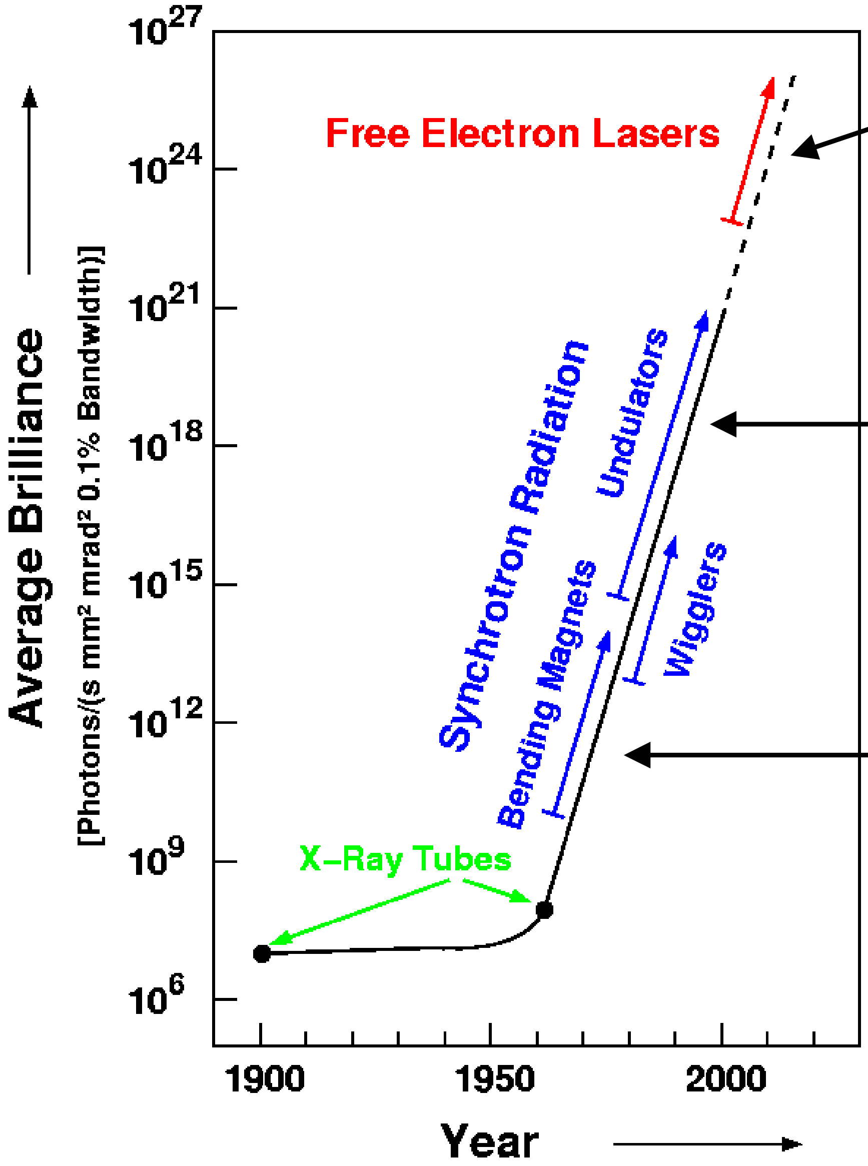


Synchrotron radiation

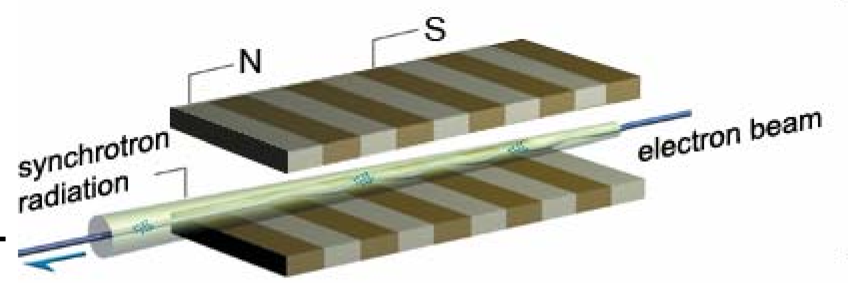
Bending Magnet

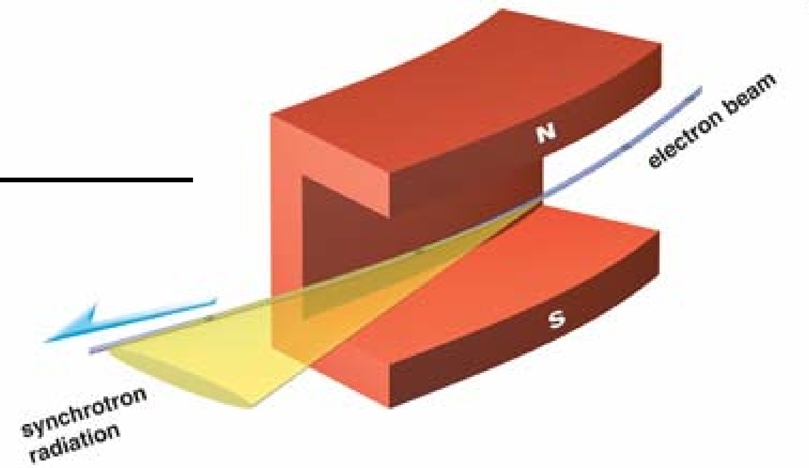


Development of synchrotron light sources

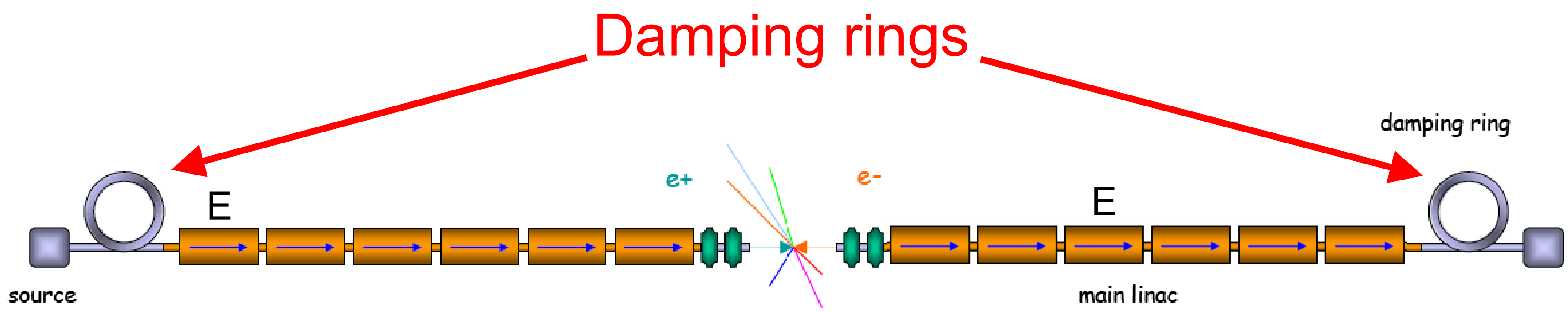


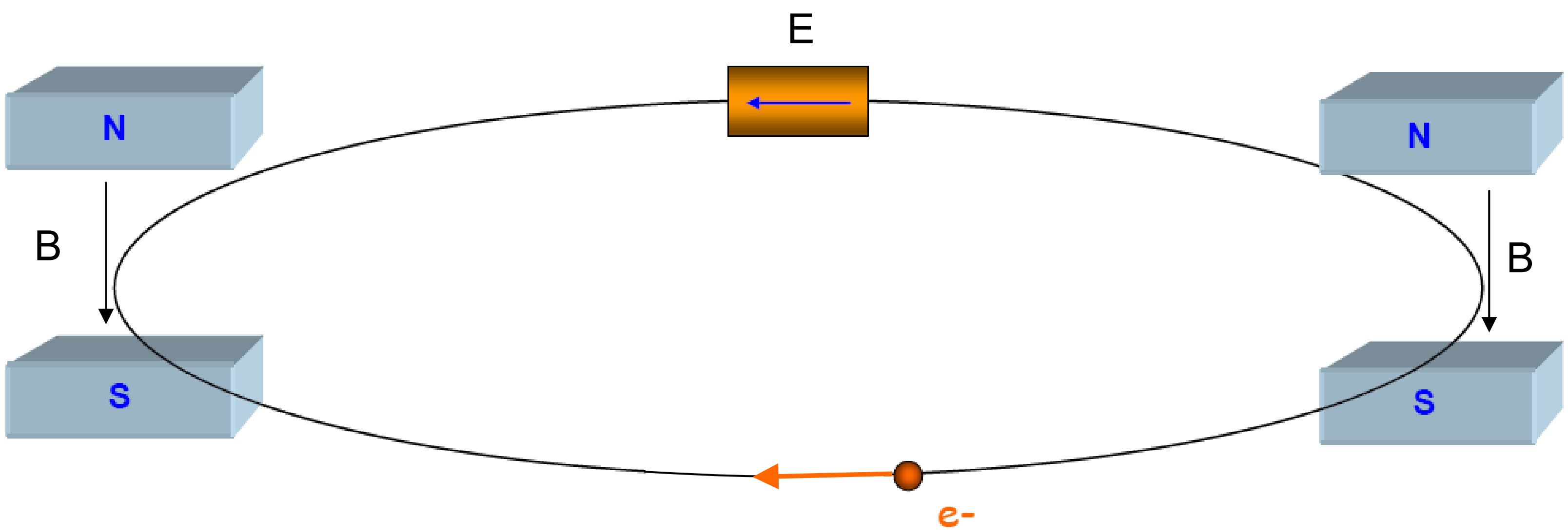
FELs lecture on Friday, by M. Dohlus



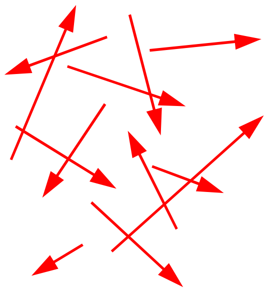


Damping rings

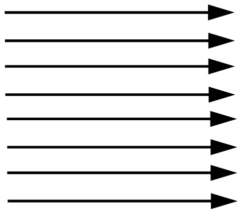




Concept of beam emittance

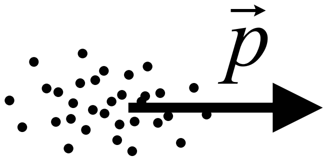


plasma

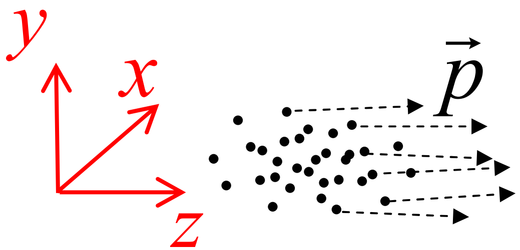


beam

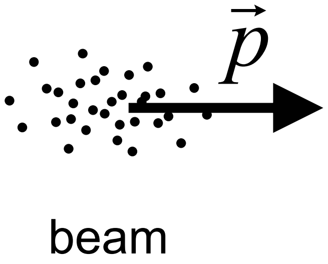
Concept of beam emittance

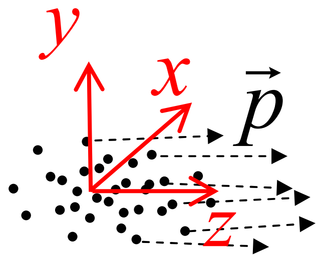


beam



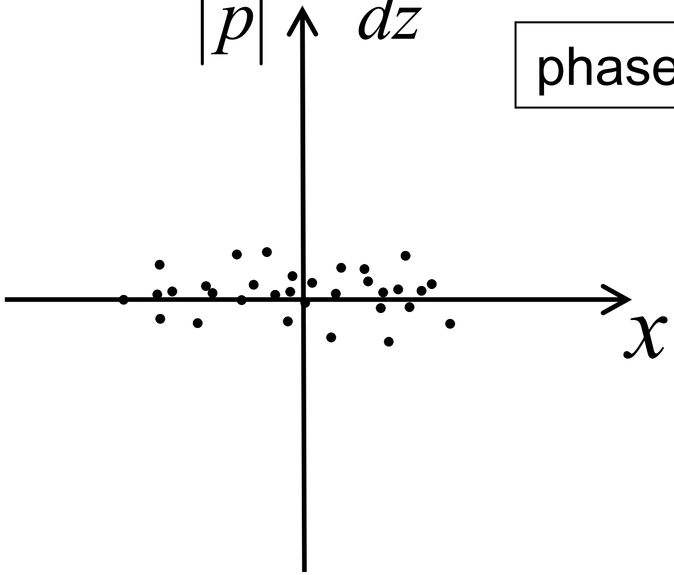
Concept of beam emittance



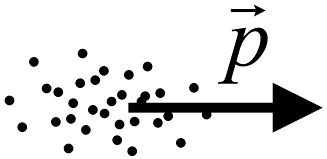


$$\frac{p_x}{|\vec{p}|} = \frac{dx}{dz} \cong x'$$

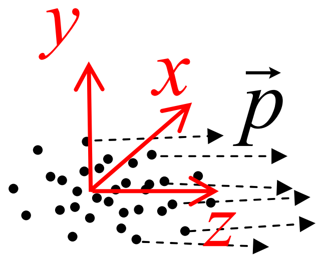
phase space diagram



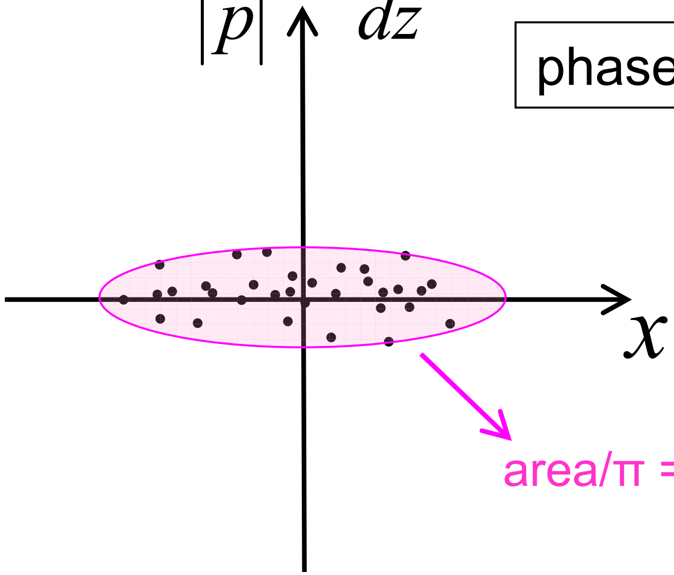
Concept of beam emittance



beam



$$\frac{p_x}{|\vec{p}|} = \frac{dx}{dz} \cong x'$$



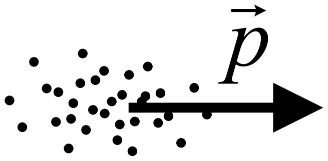
phase space diagram

emittance definition:

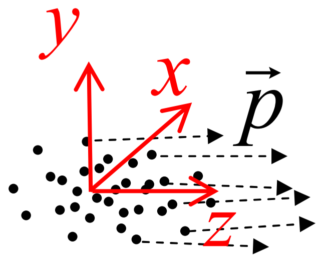
$$\varepsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

area/π = emittance (units: mm.mrad)

Concept of beam emittance



beam

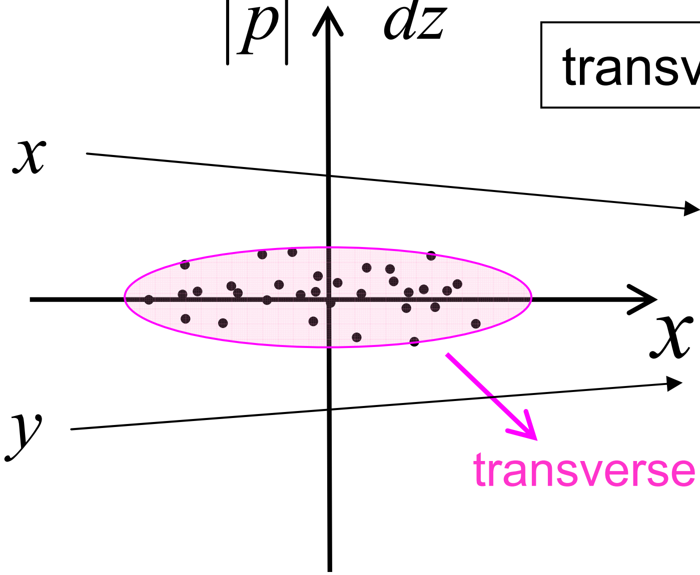


$$\frac{p_x}{|\vec{p}|} = \frac{dx}{dz} \cong x'$$

transverse phase space diagram

x' as function of x

$$\varepsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

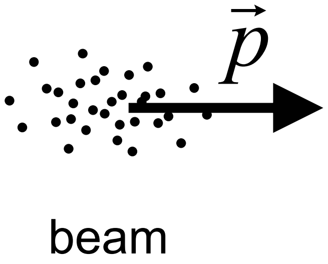


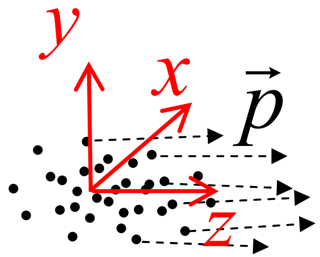
y' as function of y

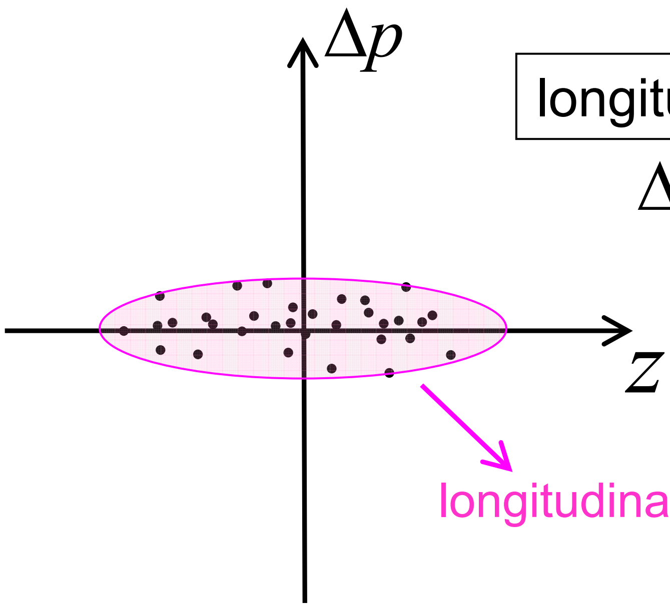
$$\varepsilon_y = \sqrt{\langle y^2 \rangle \langle y'^2 \rangle - \langle yy' \rangle^2}$$

transverse emittance (units: mm.mrad)

Concept of beam emittance







longitudinal phase space diagram

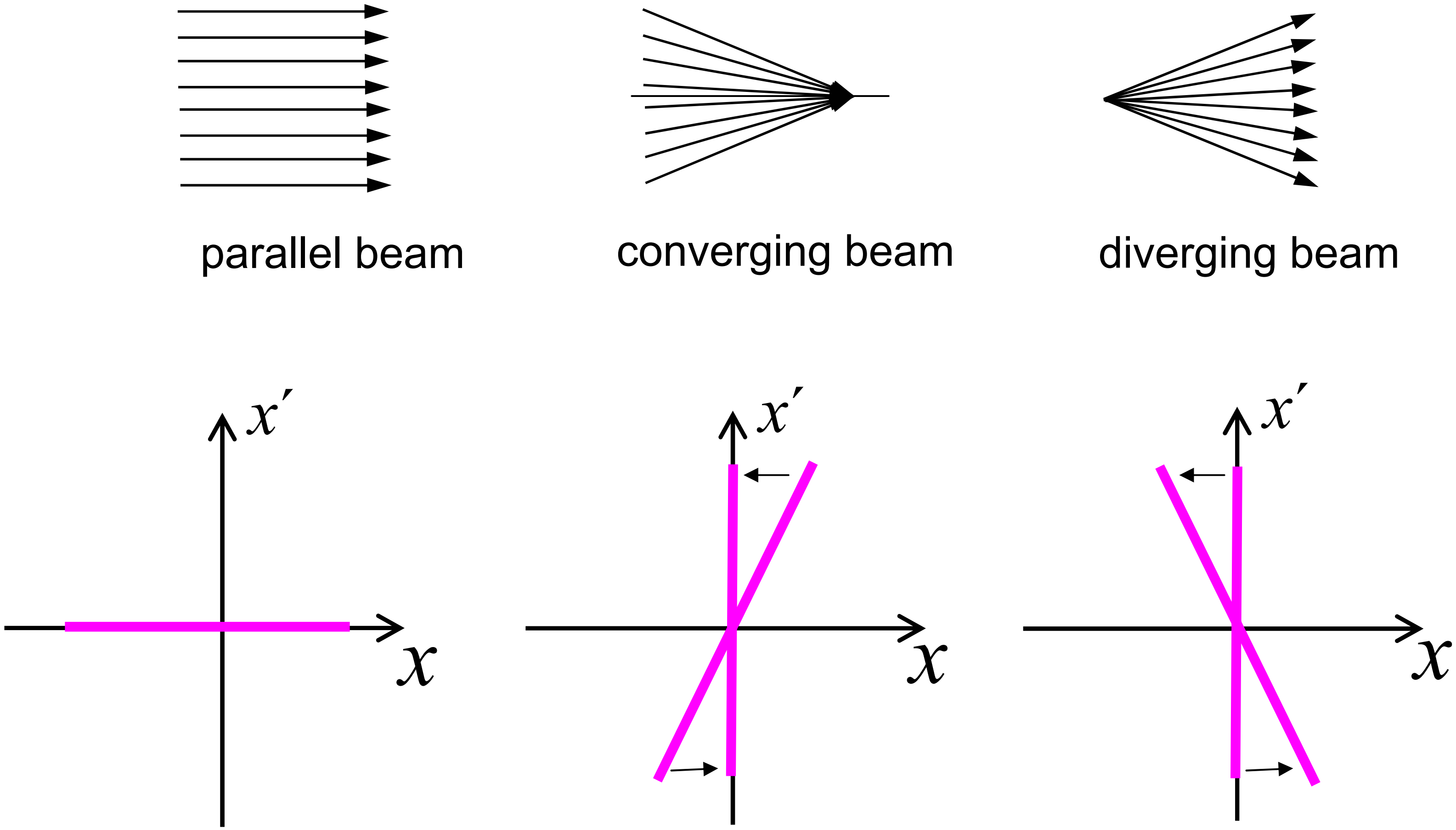
Δp as function of z

$\downarrow$

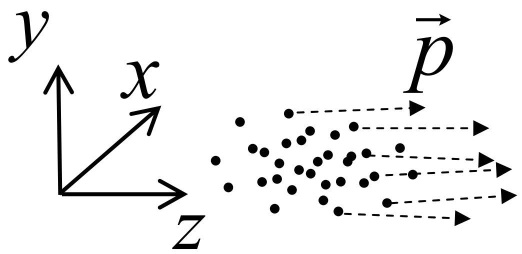
ε_z

longitudinal emittance (units: mm.eV/c)

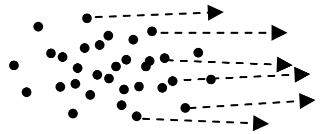
Concept of beam emittance



Concept of beam emittance



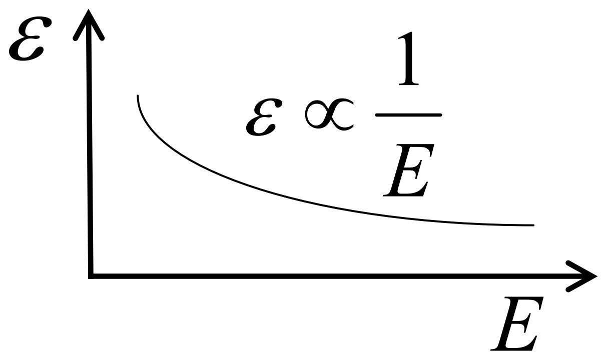
$$\vec{p}' = \vec{p} + \Delta\vec{p}_z$$



acceleration (only in z direction)

$\frac{p_x}{|\vec{p}|}$ gets smaller

linear accelerators:



$$\varepsilon \propto \frac{1}{E}$$

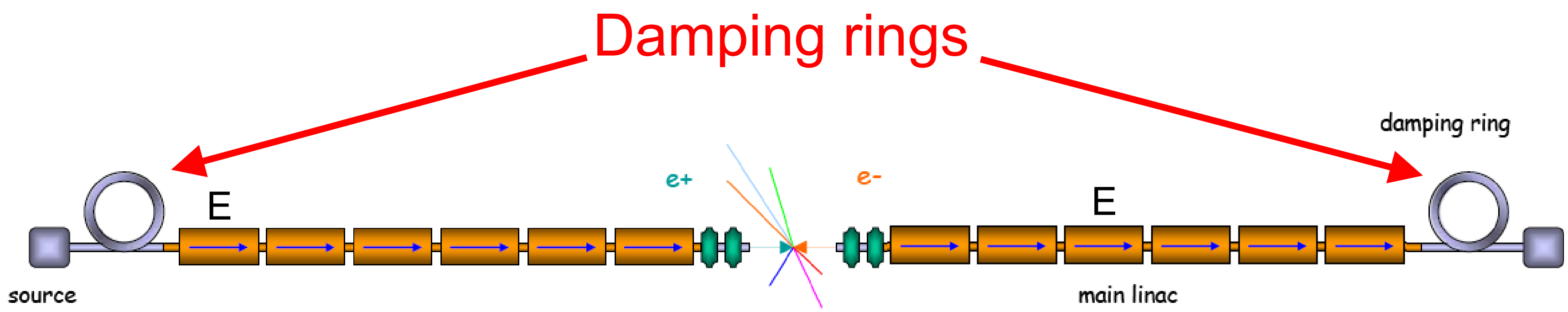
definition:

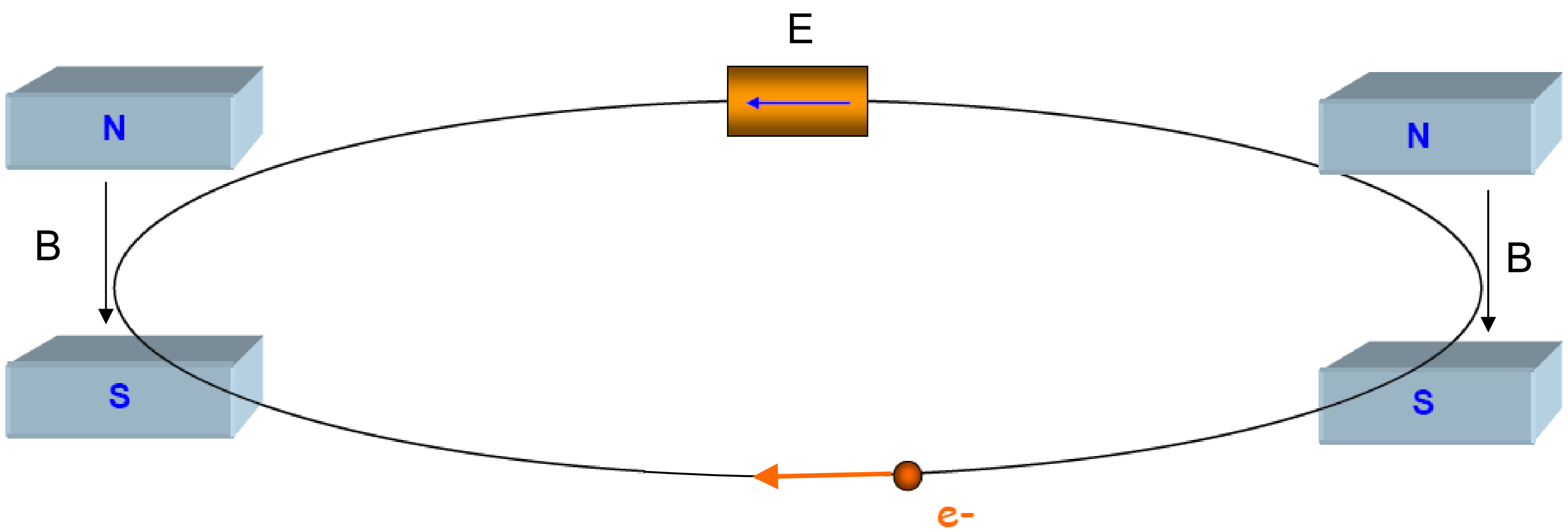
normalized emittance:

$$\varepsilon_{\mathrm{N}} = \varepsilon \cdot \gamma = \text{constant}$$

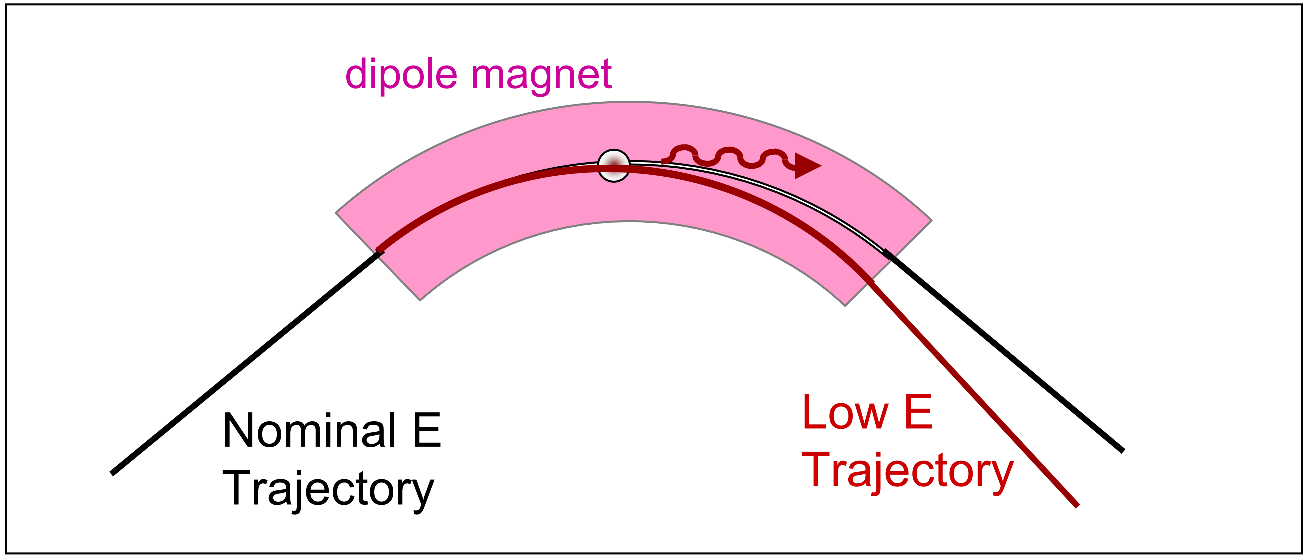
geometrical emittance

Damping rings





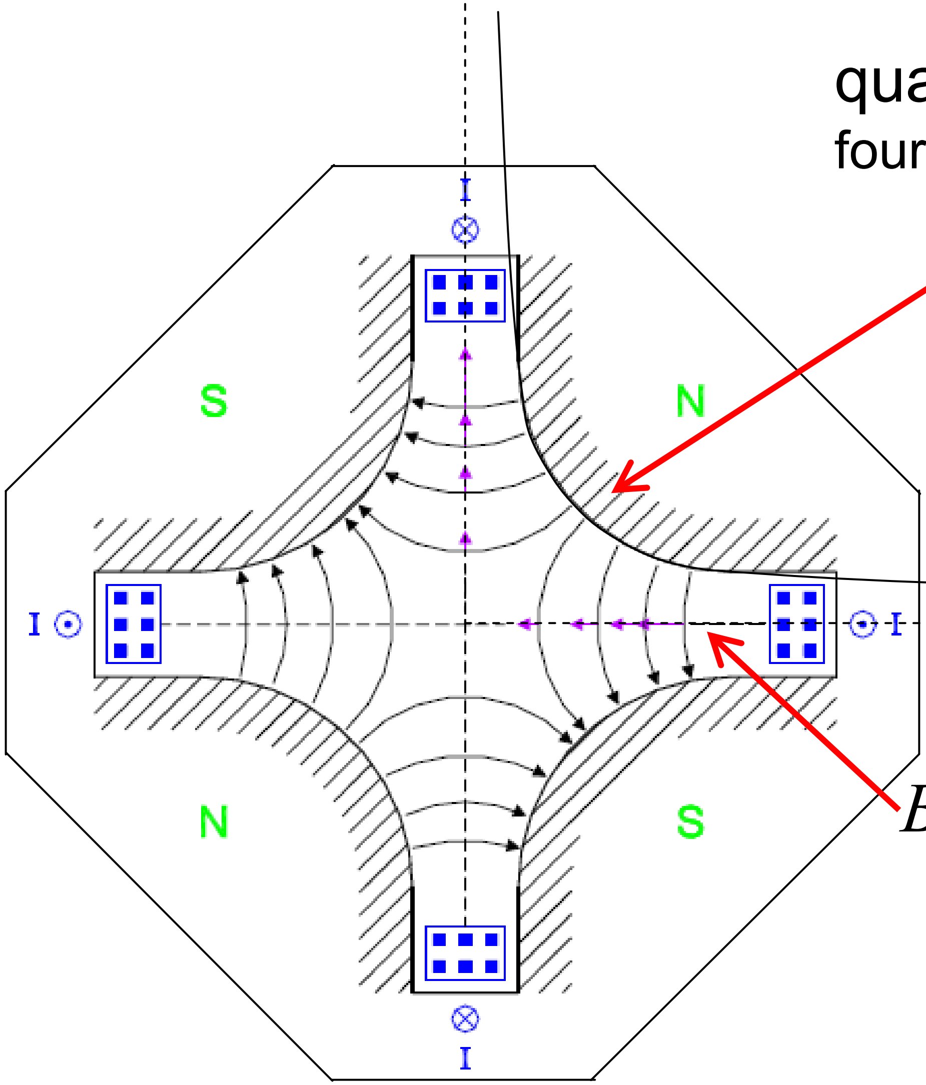
Quatum excitation



> Quantum excitation

- Radiation is emitted in discrete quanta
- Number and energy distribution etc. of photons obey statistical laws
- Increase emittance

Need of focusing



quadrupole magnet:

four iron pole shoes of hyperbolic contour

hyperbola

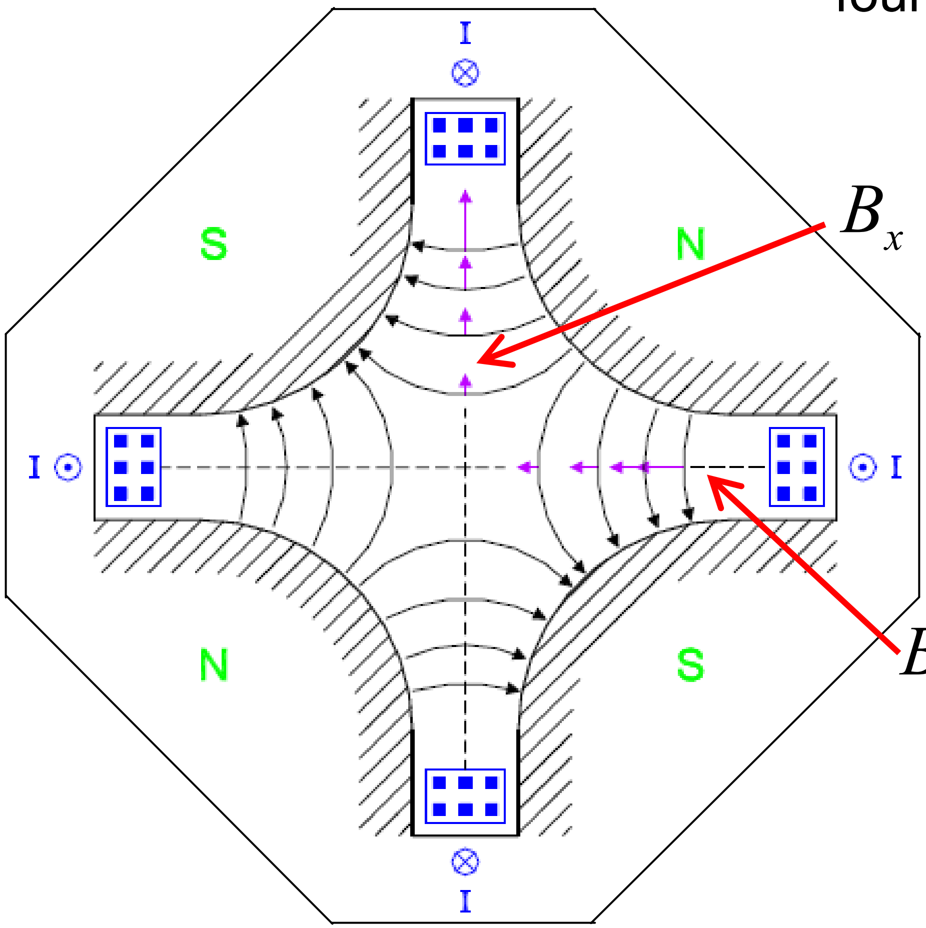
$$B_y = -g \cdot x \quad \Rightarrow \quad F_x = -g \cdot x$$

focusing !

Quadrupole magnets

quadrupole magnet:

four iron pole shoes of hyperbolic contour



$$B_x = g \cdot y \quad \Rightarrow \quad F_y = g \cdot y$$

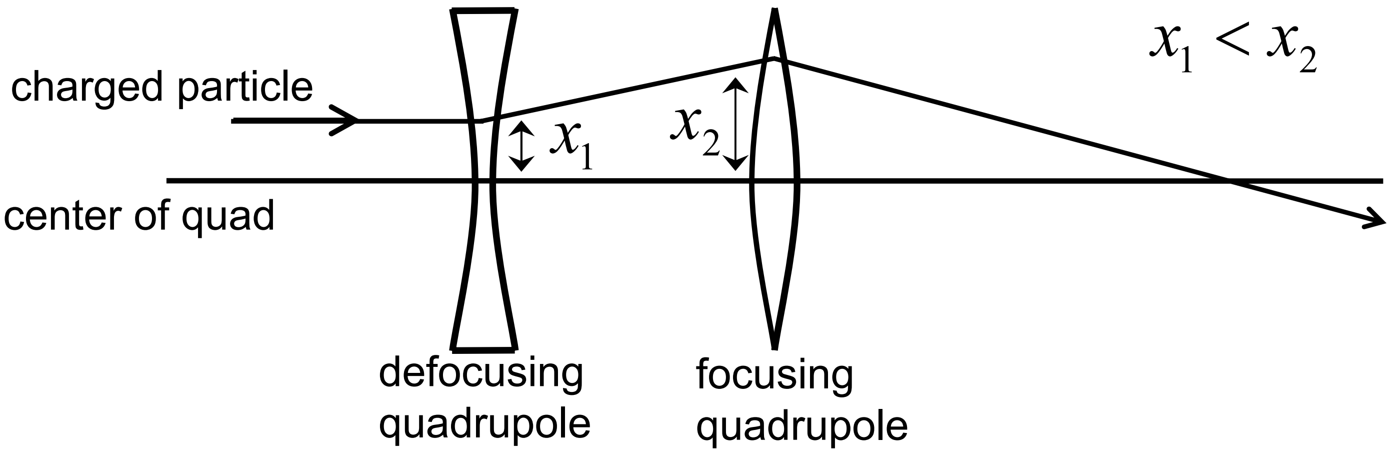
defocusing

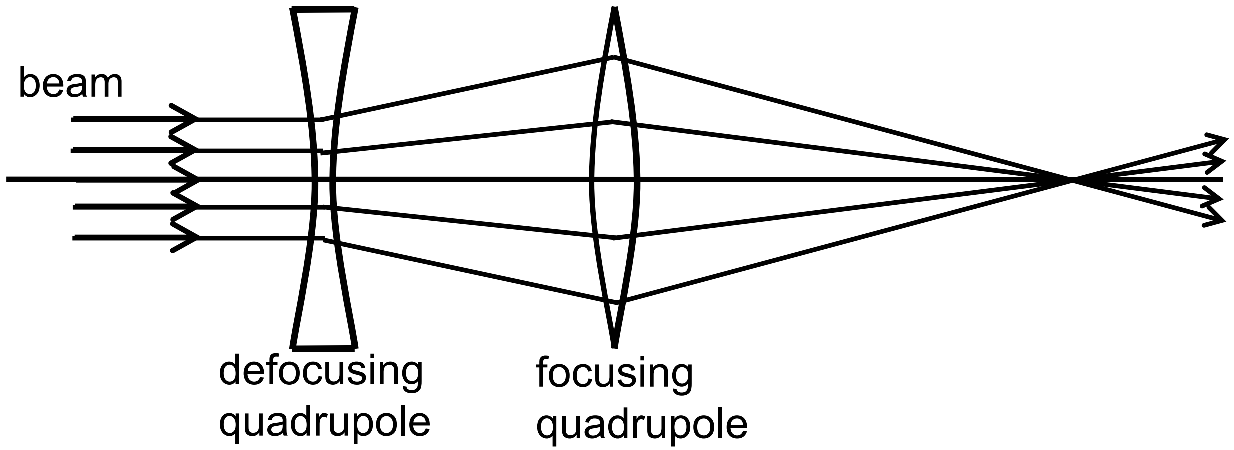
$$B_y = -g \cdot x \quad \Rightarrow \quad F_x = -g \cdot x$$

focusing !

Quadrupole magnets

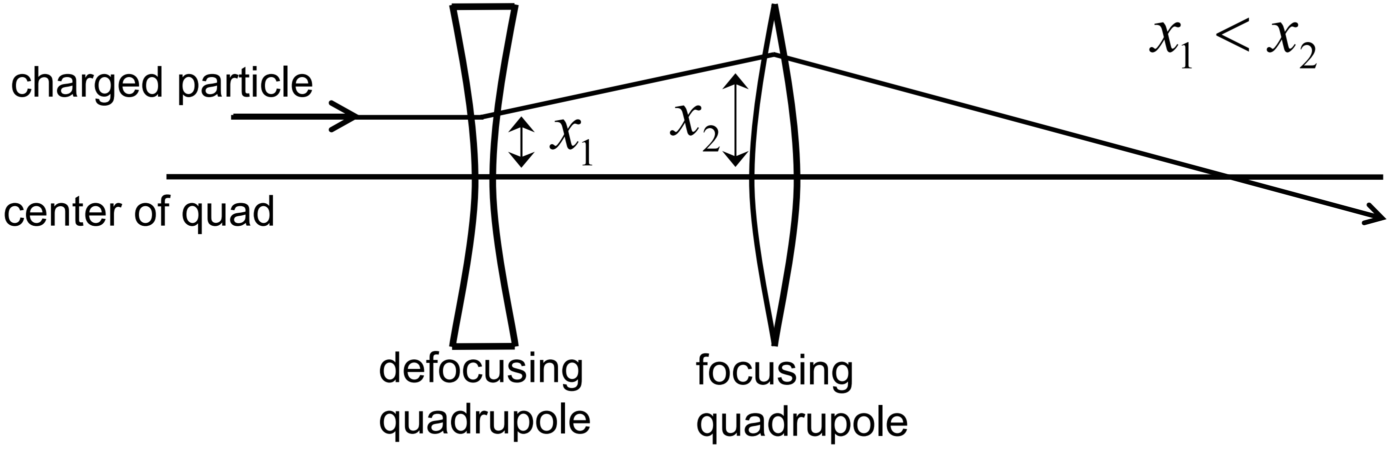
QD + QF = net focusing effect:

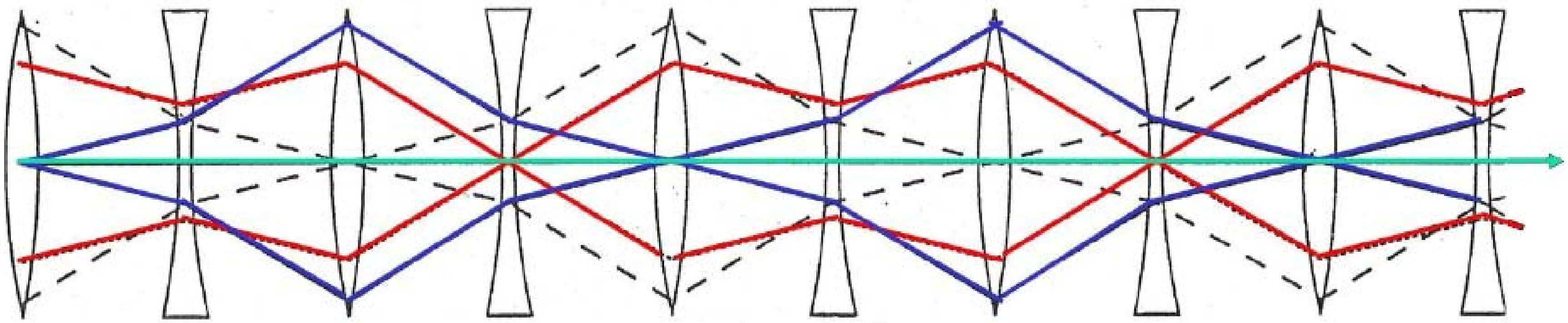




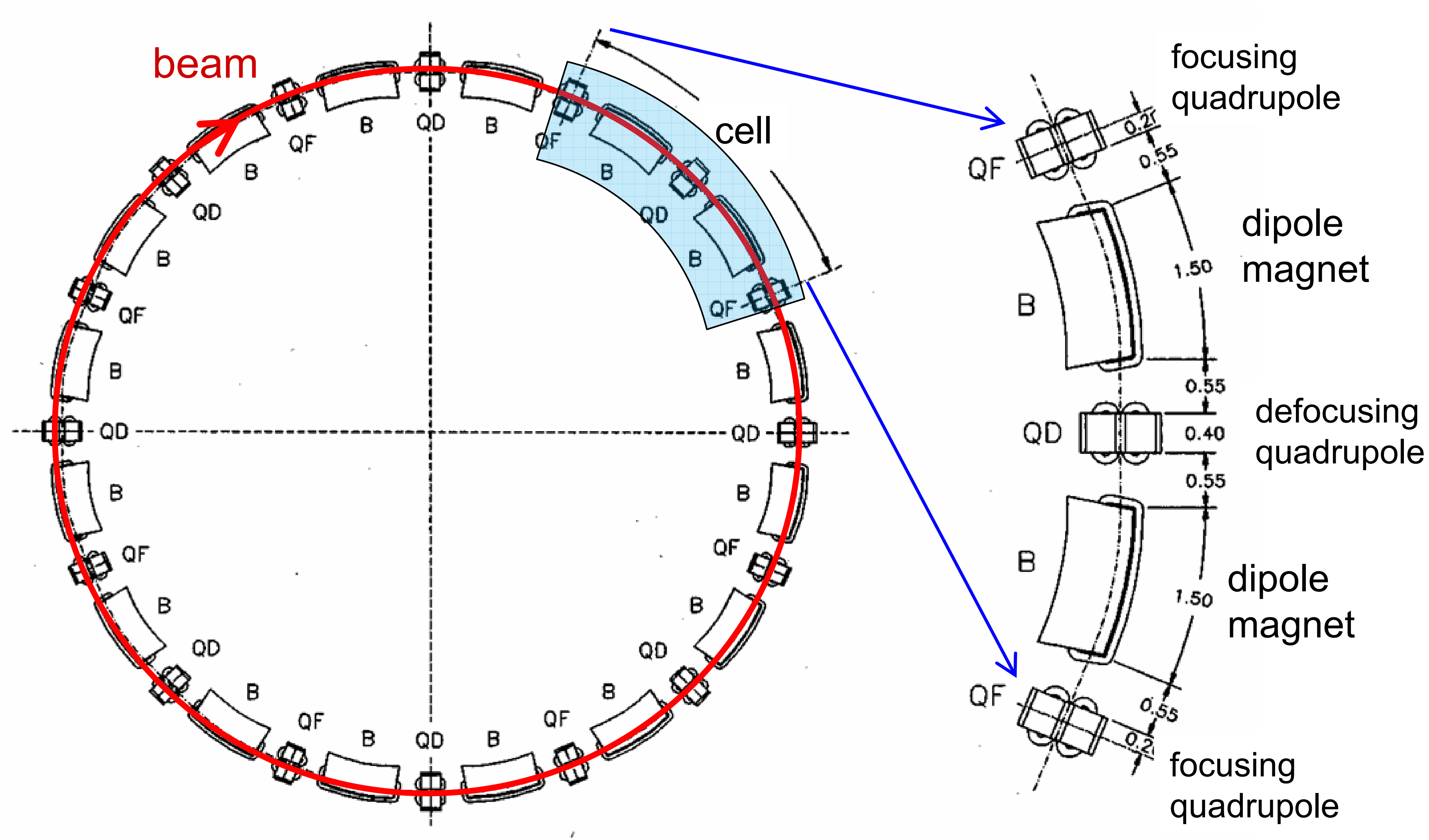
Quadrupole magnets

QD + QF = net focusing effect:



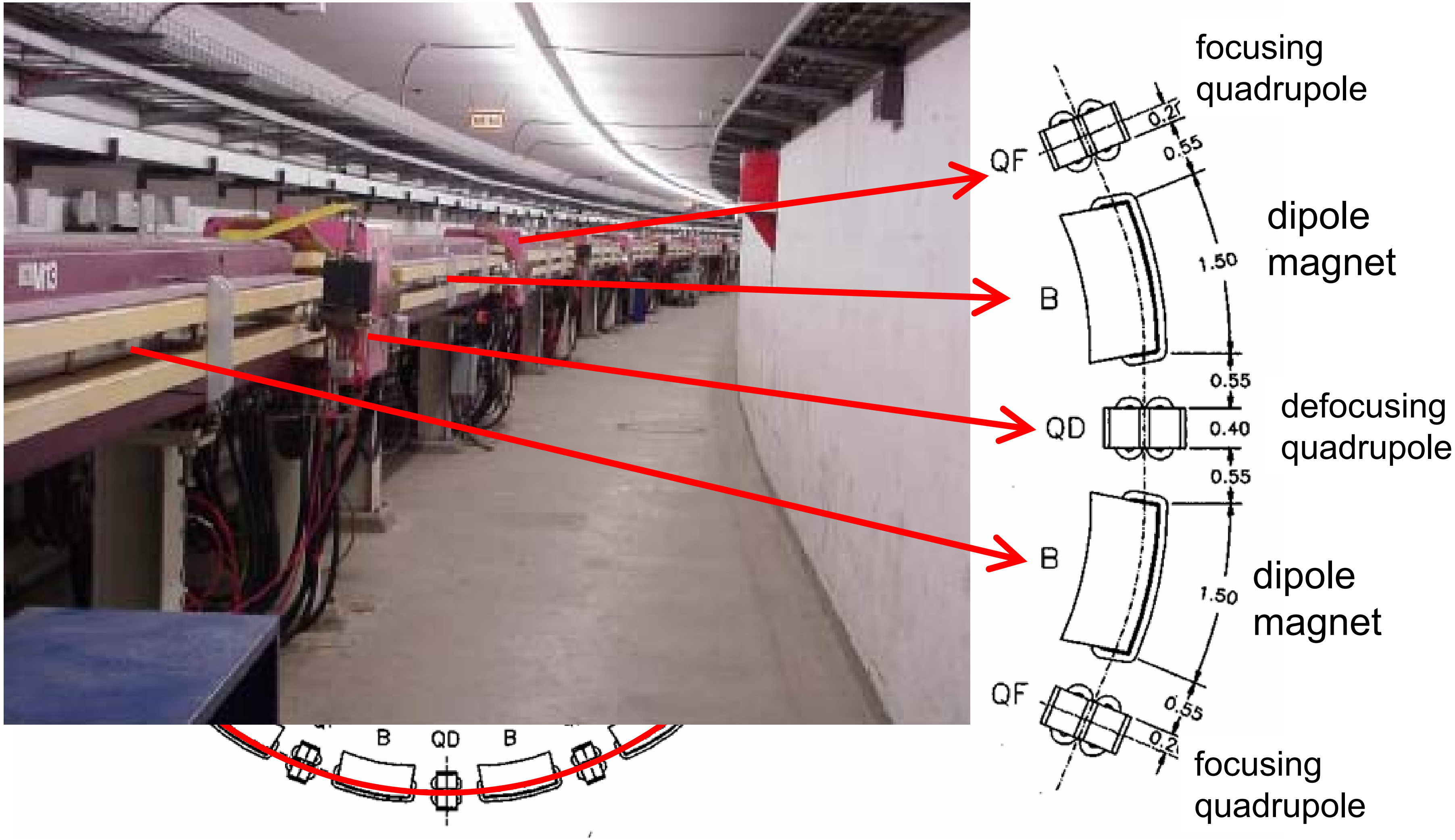


Circular accelerator



Circular accelerator

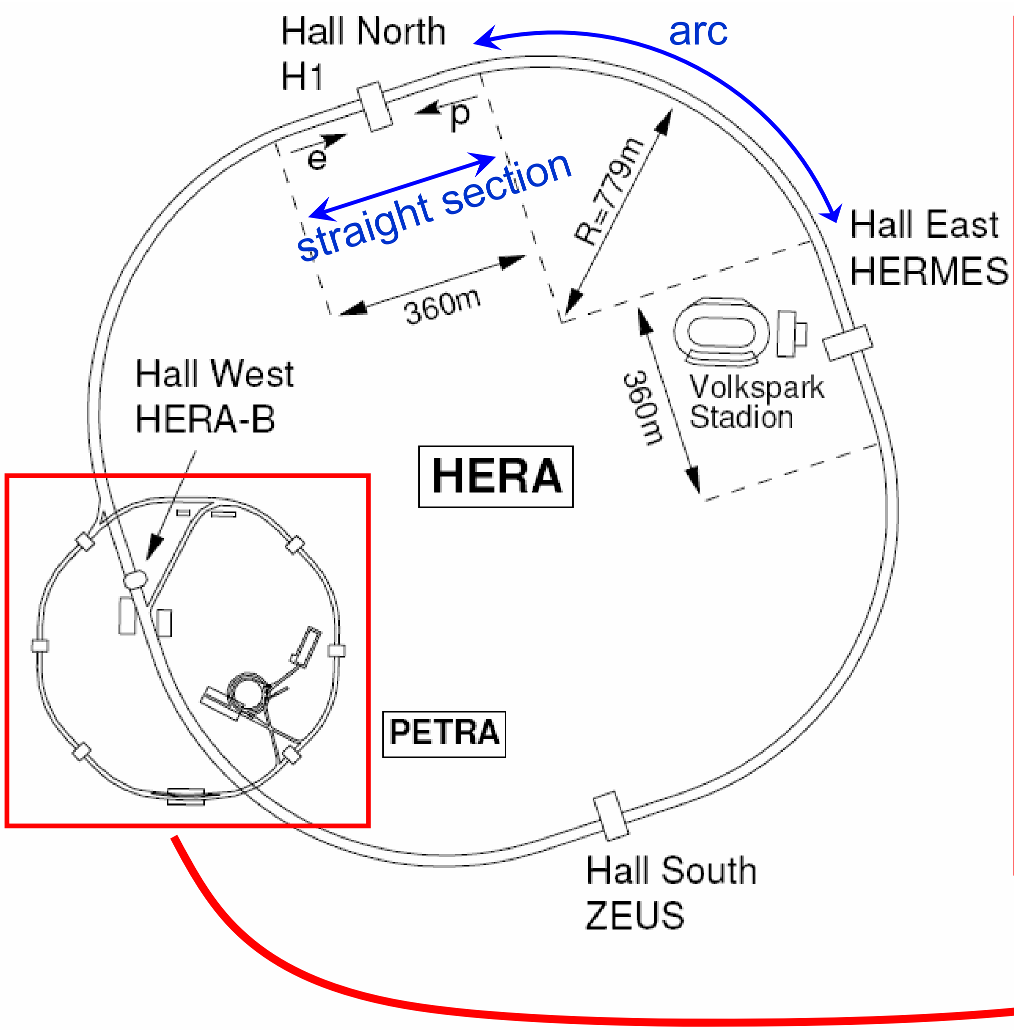
PETRA

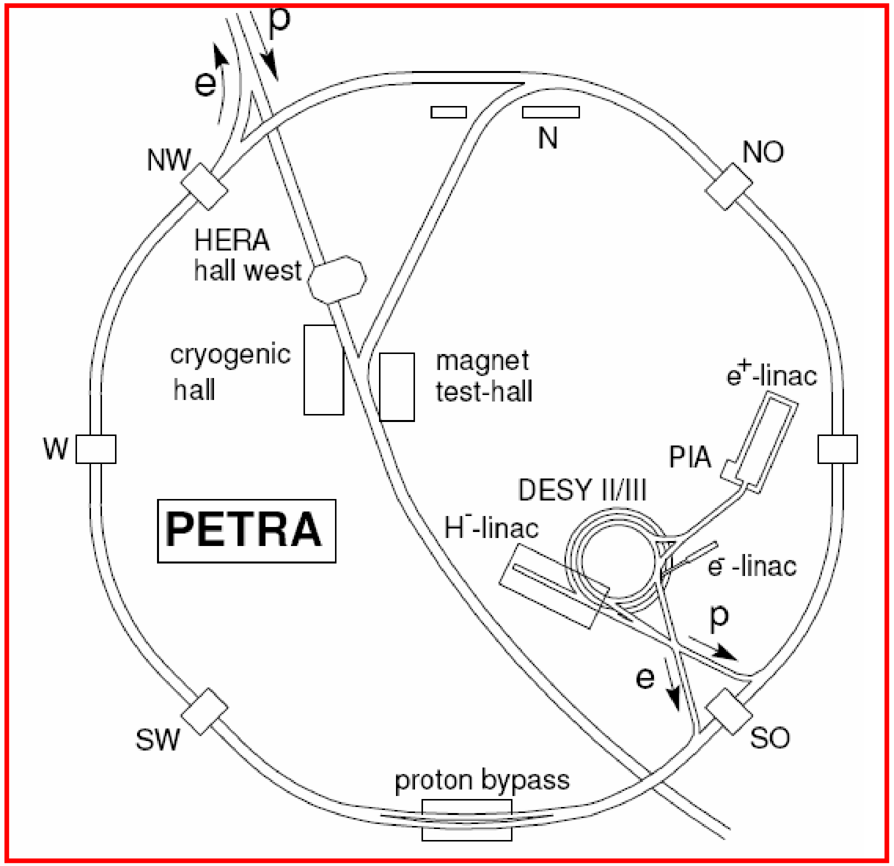


HERA collider and injector chain

HERA: 4 arcs + 4 straight sections

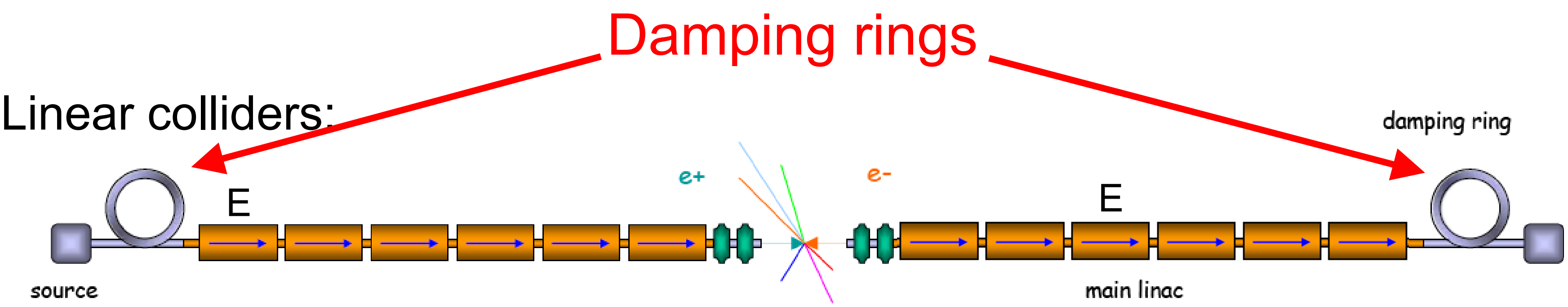
PETRA: 8 arcs + 8 straight sections

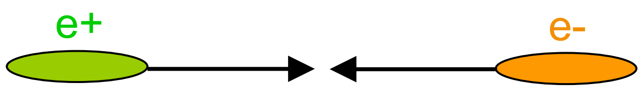




Damping rings for high luminosity

Linear colliders:





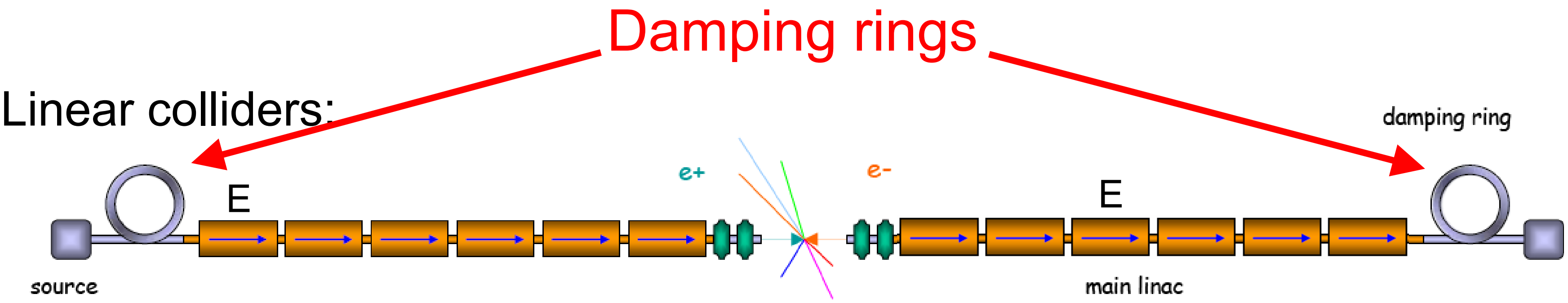
production rate of a given event (for example, Z particle production):

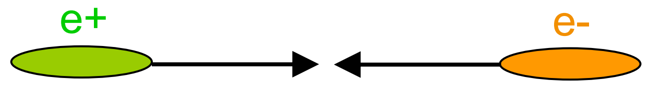
$$R_Z = \frac{dN_z}{dt} = \Sigma_z \cdot L$$

- R_Z: production rate
- dN_z: number of events
- L: luminosity (independent of the event type)
- Σ_z: cross section of Z production

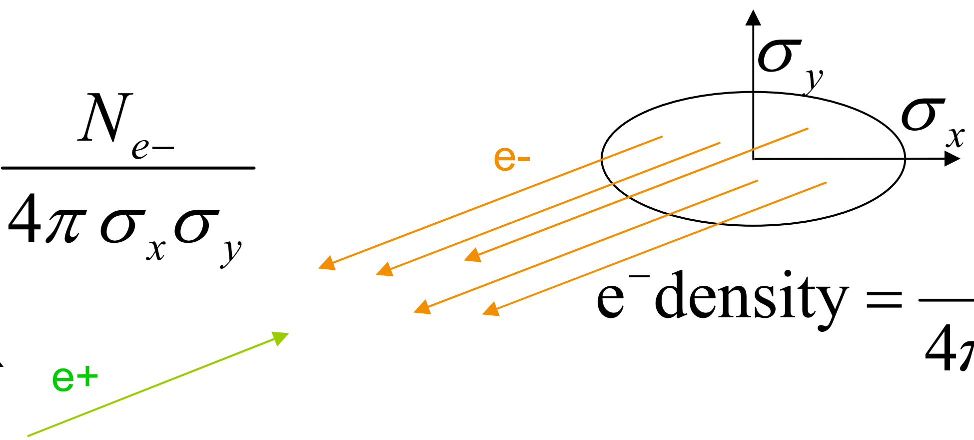
Damping rings for high luminosity

Linear colliders:





$$P_Z(1\,e^+) = \Sigma_z \cdot \frac{N_{e-}}{4\pi\,\sigma_x\sigma_y}$$

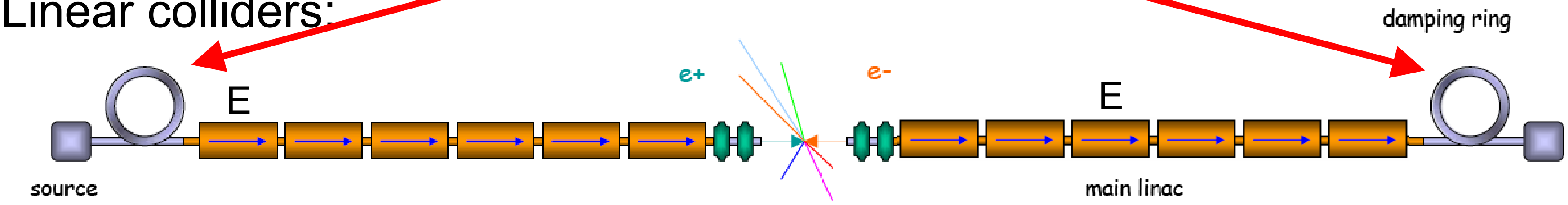


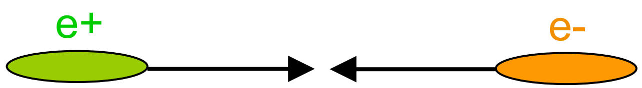
$$\text{e}^-\text{density} = \frac{N_{e-}}{4\pi \cdot \sigma_x\sigma_y}$$

Damping rings for high luminosity

Damping rings

Linear colliders:





number of colliding bunches per second

number of positrons per bunch

number of electrons per bunch

$$R_Z = \Sigma_z \cdot L = \Sigma_z \cdot \frac{n_b N_{e+} N_{e-}}{4\pi \sigma_x \sigma_y}$$

luminosity

transverse bunch sizes (at the collision point)

Certification of knowledge

in accelerator physics and technology:

- magnet dipoles basics (normal conducting and superconducting)
- RF cavity basics (normal conducting and superconducting)
- synchrotron radiation effects
- quadrupole focusing
- concept of emittance
- concept of luminosity

Hamburg, 21st July 2010

Thank you for your attention

pedro.castro@desy.de