Introduction to Accelerator Physics (part 1)

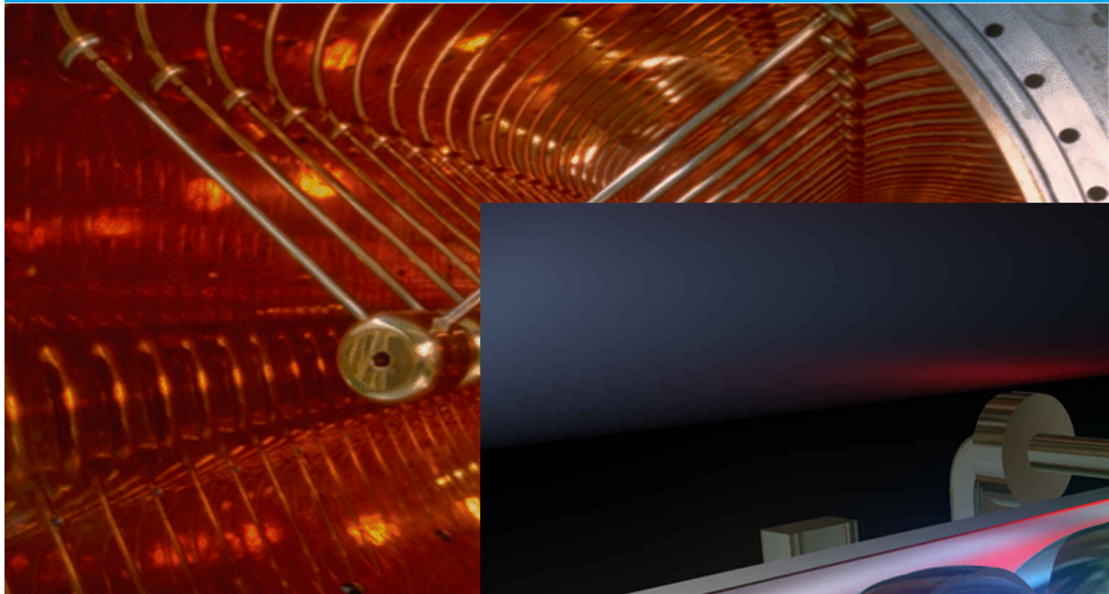
Scientific Tools for High Energy Physics, Synchrotron Radiation Research and Medicine Applications

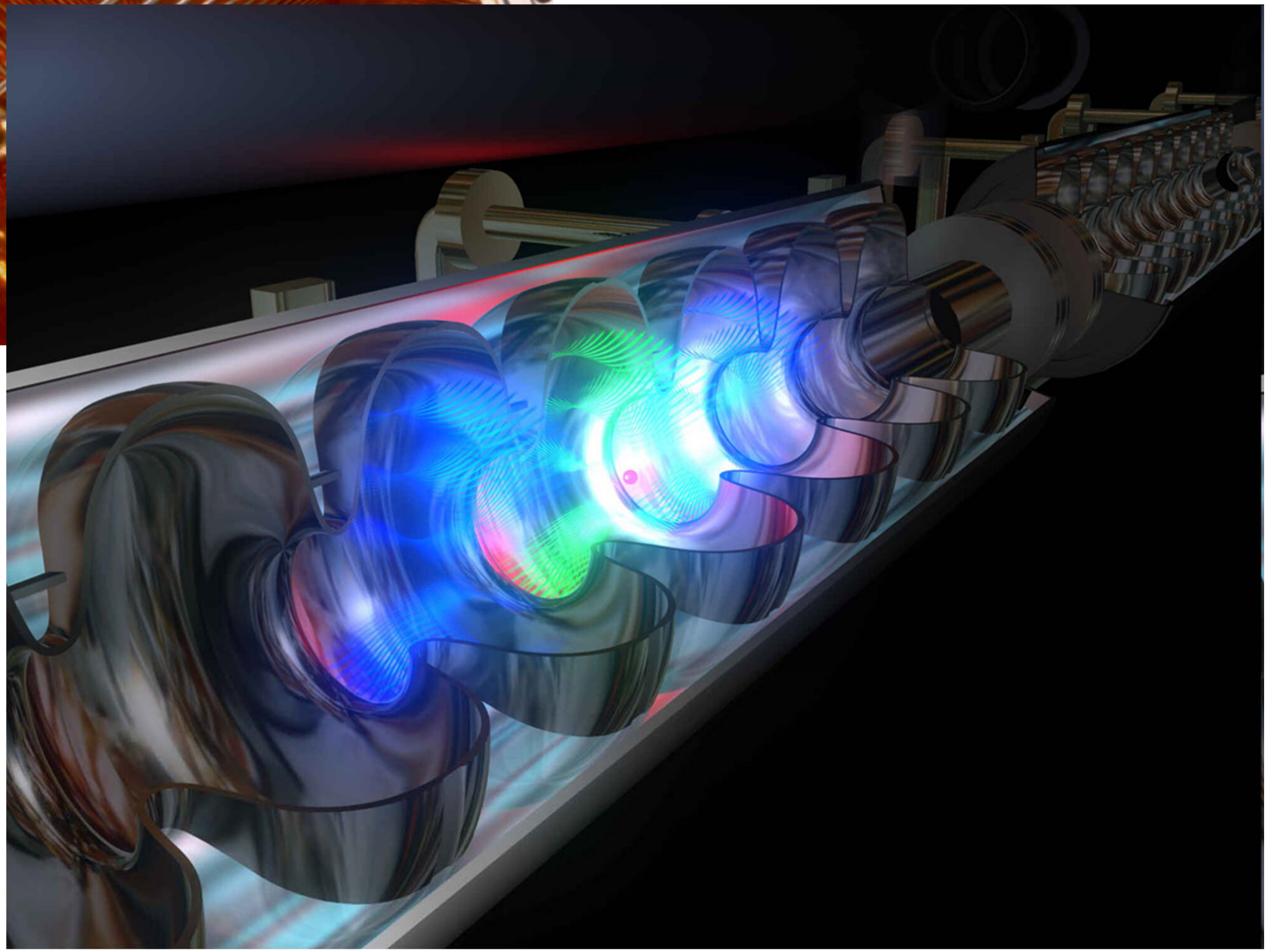
Pedro Castro / Accelerator Physics Group (MPY)
Introduction to Accelerator Physics (part 1)
DESY, 5th August 2011

HELMHOLTZ ASSOCIATION

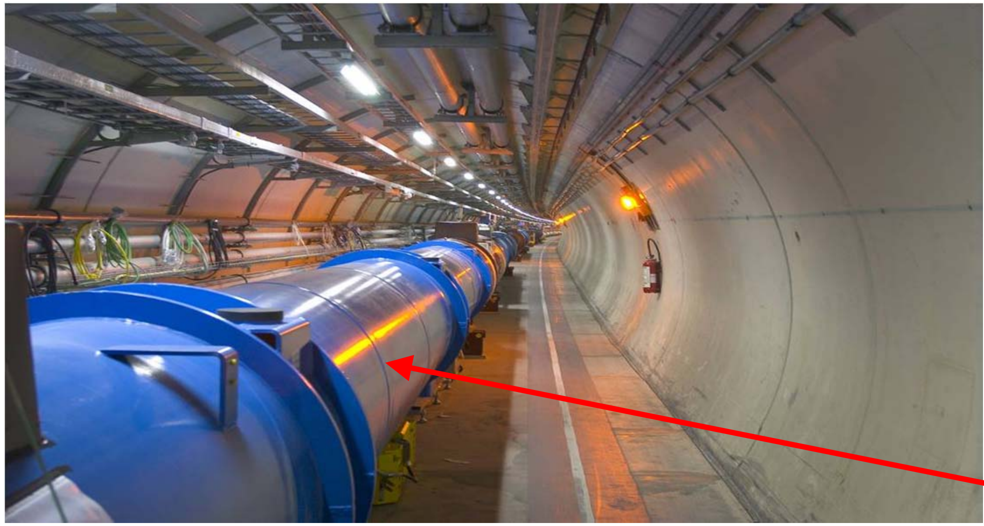
DESY

How electromagnetic fields accelerate particles





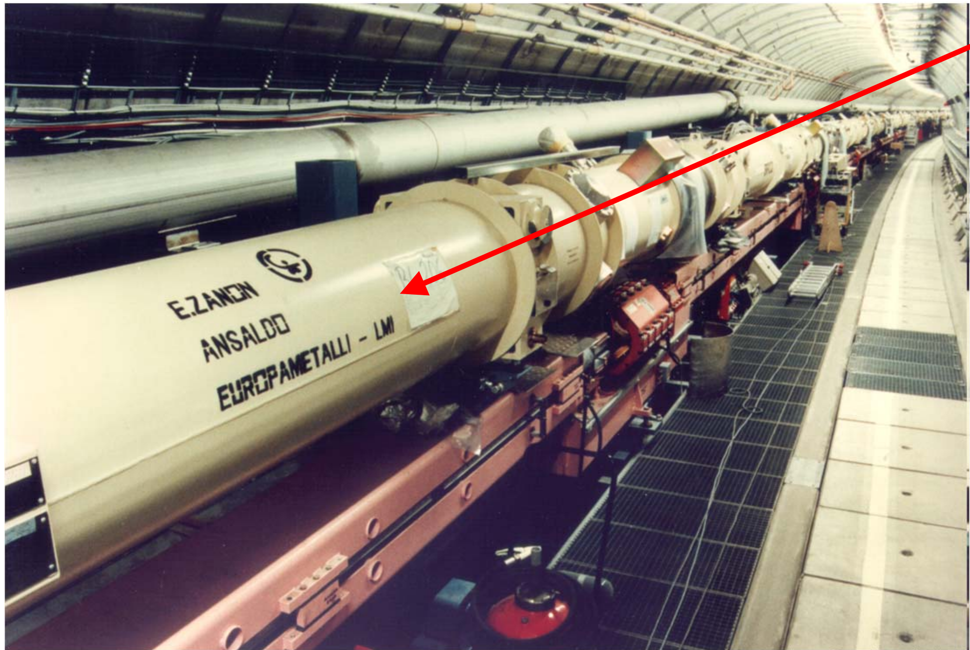
Why we need superconducting magnets



LHC: Large Hadron Collider
at CERN

p: 7 TeV

superconducting magnets



HERA: Hadron-Electron Ring Accelerator
at DESY

p: 920 GeV
e: 27.5 GeV

Differences between proton and electron accelerators

HERA (Hadron Electron Ring Accelerator) tunnel:

proton accelerator

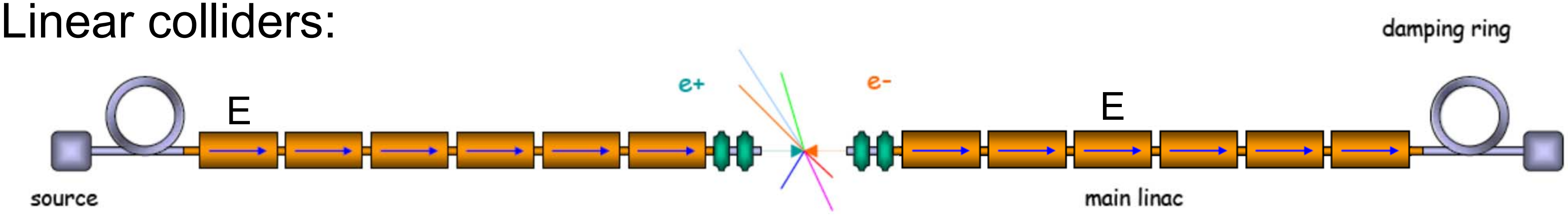
920 GeV

electron accelerator

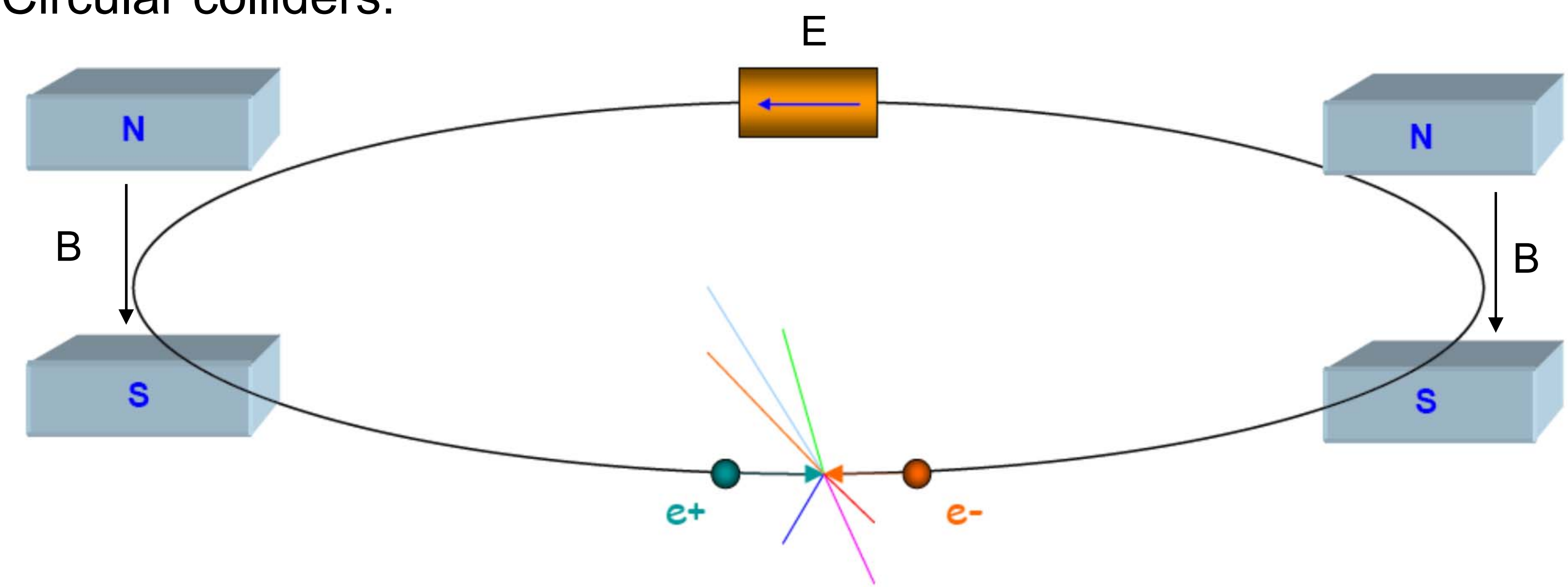
27.5 GeV

Which collider is better?

Linear colliders:



Circular colliders:



Applications of accelerators

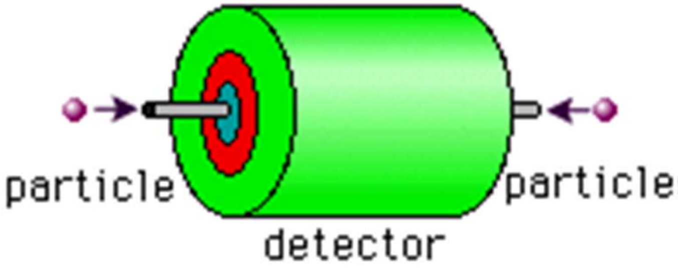
(

Applications of Accelerators (1)

Particle colliders for High Energy Physics (HEP) experiments

- fix target experiments:

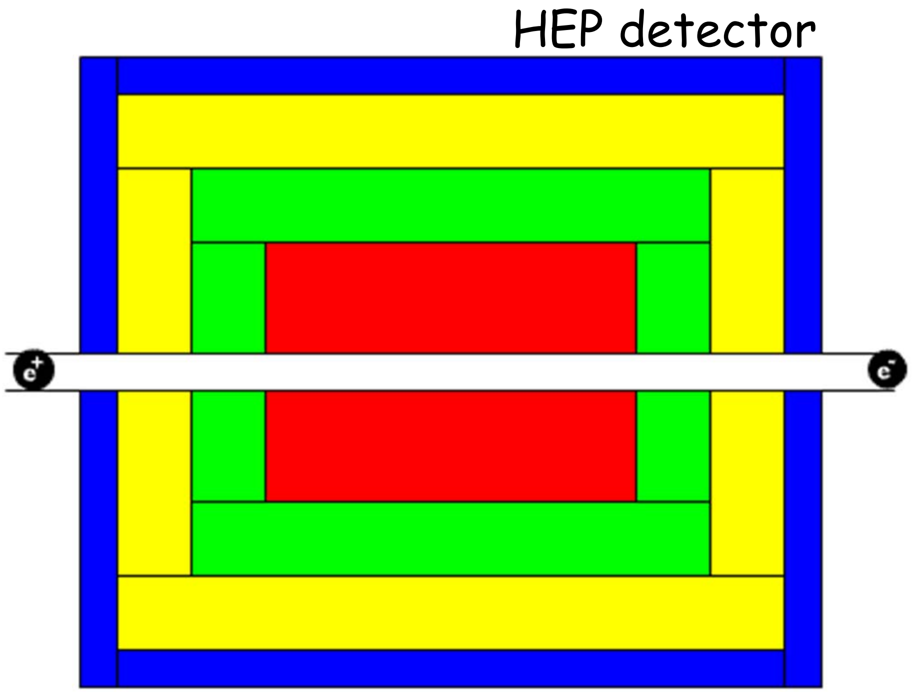
- two beams collision experiments:



Applications of Accelerators (1)

Particle colliders for High Energy Physics (HEP) experiments

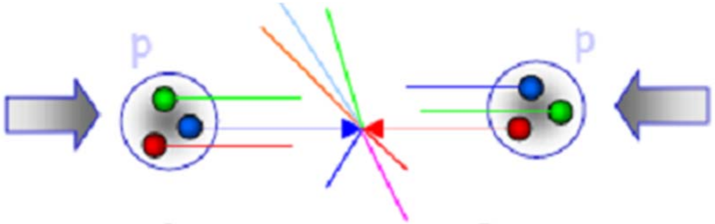
- fix target experiments:



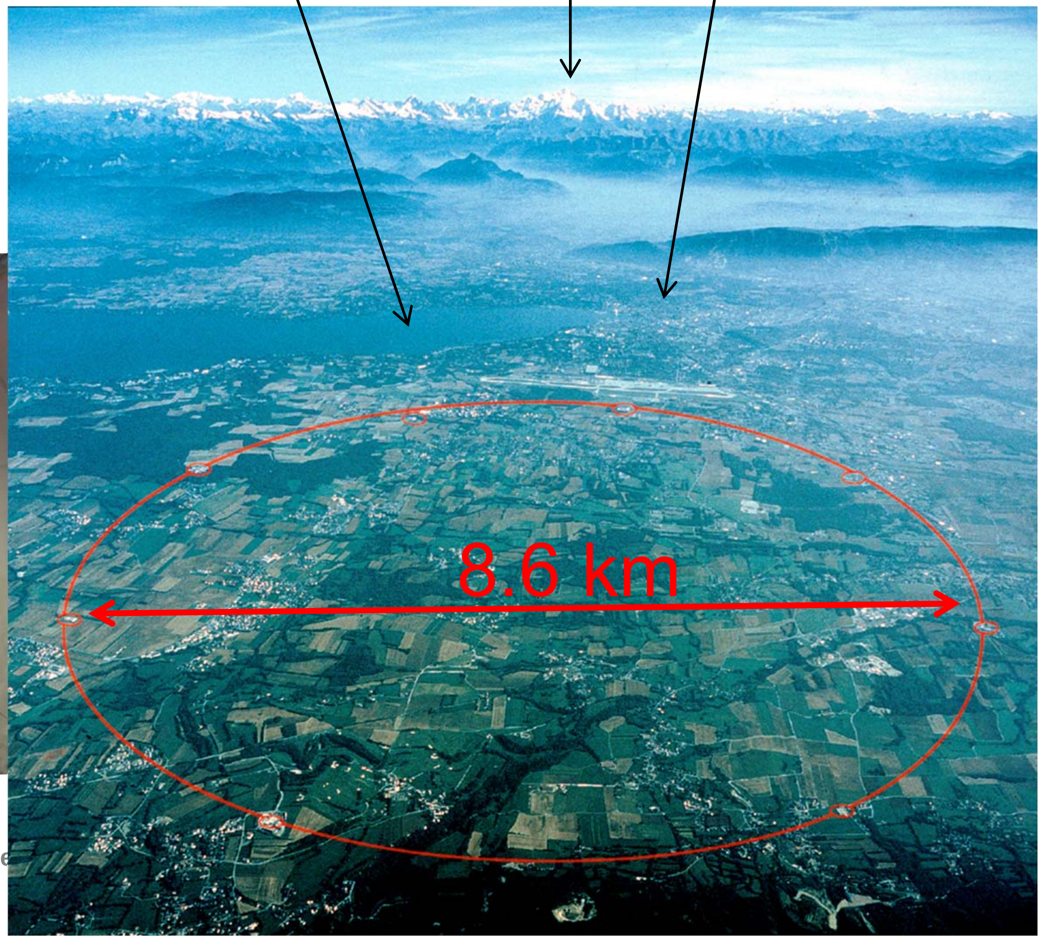
Applications of Accelerators (1)

Particle colliders for High Energy Physics experiments

Example: the Large Hadron Collider (LHC) at CERN

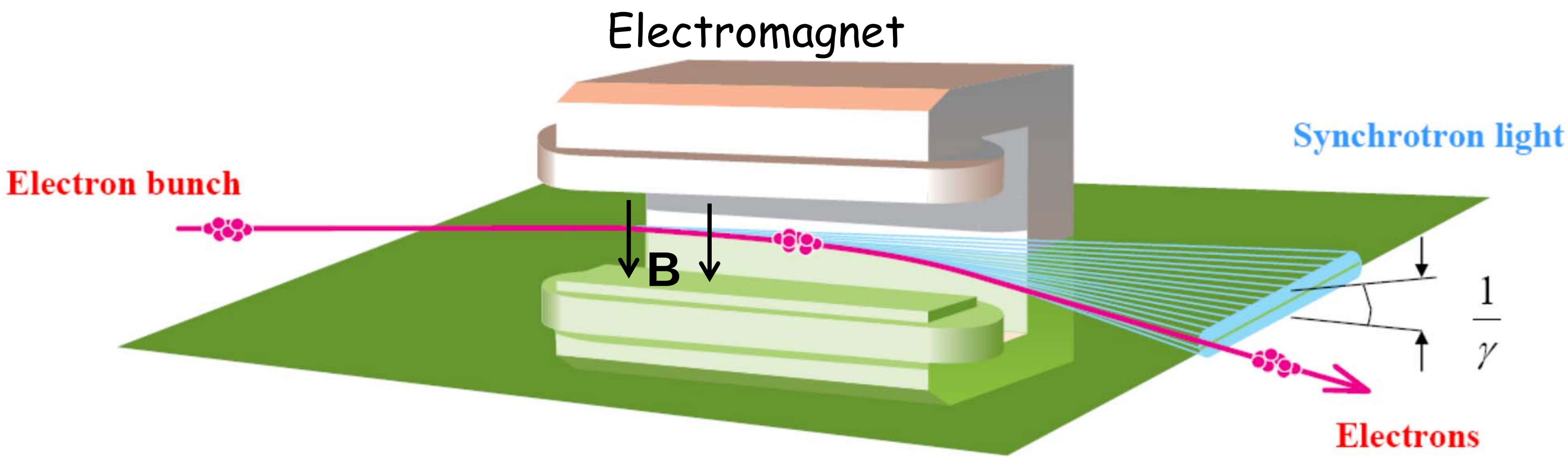


superconducting magnets
(inside a cryostat)



Applications of Accelerators (2)

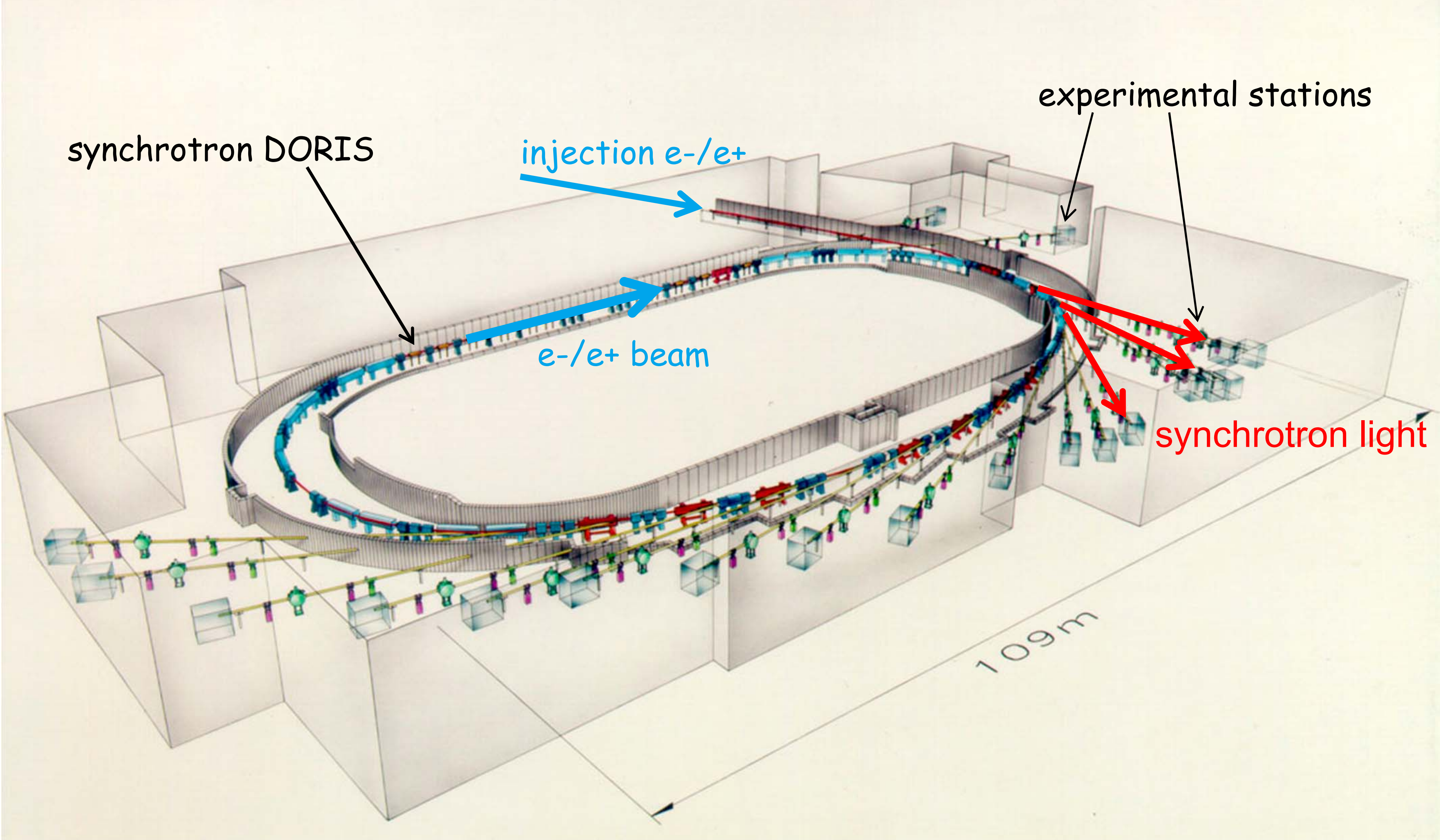
Light sources for biology, physics, chemistry… experiments



- structural analysis of crystalline materials
- X-ray crystallography (of proteins)
- X-ray microscopy
- X-ray absorption (or emission) spectroscopy
- …

Example: Doppel-Ring-Speicher (DORIS)
'double ring store' at DESY

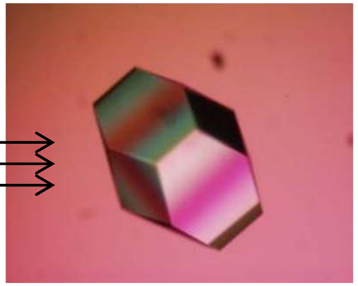
built between 1969 and 1974
HEP exp. until 1983
synchrotron rad. since 1980

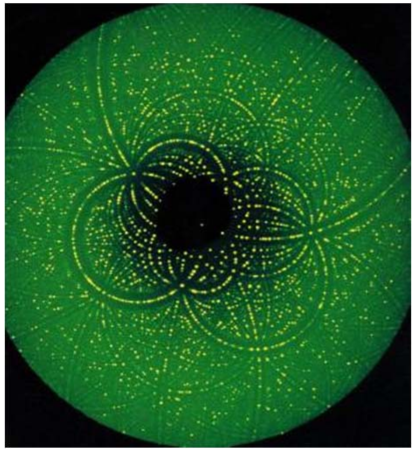


Applications of Accelerators (2)

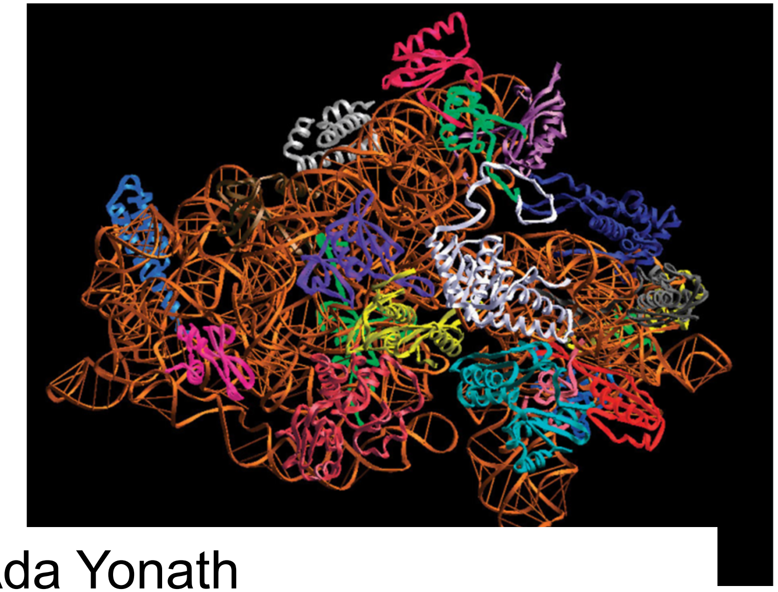
X-ray crystallography

X-rays





Ribosome



Ada Yonath

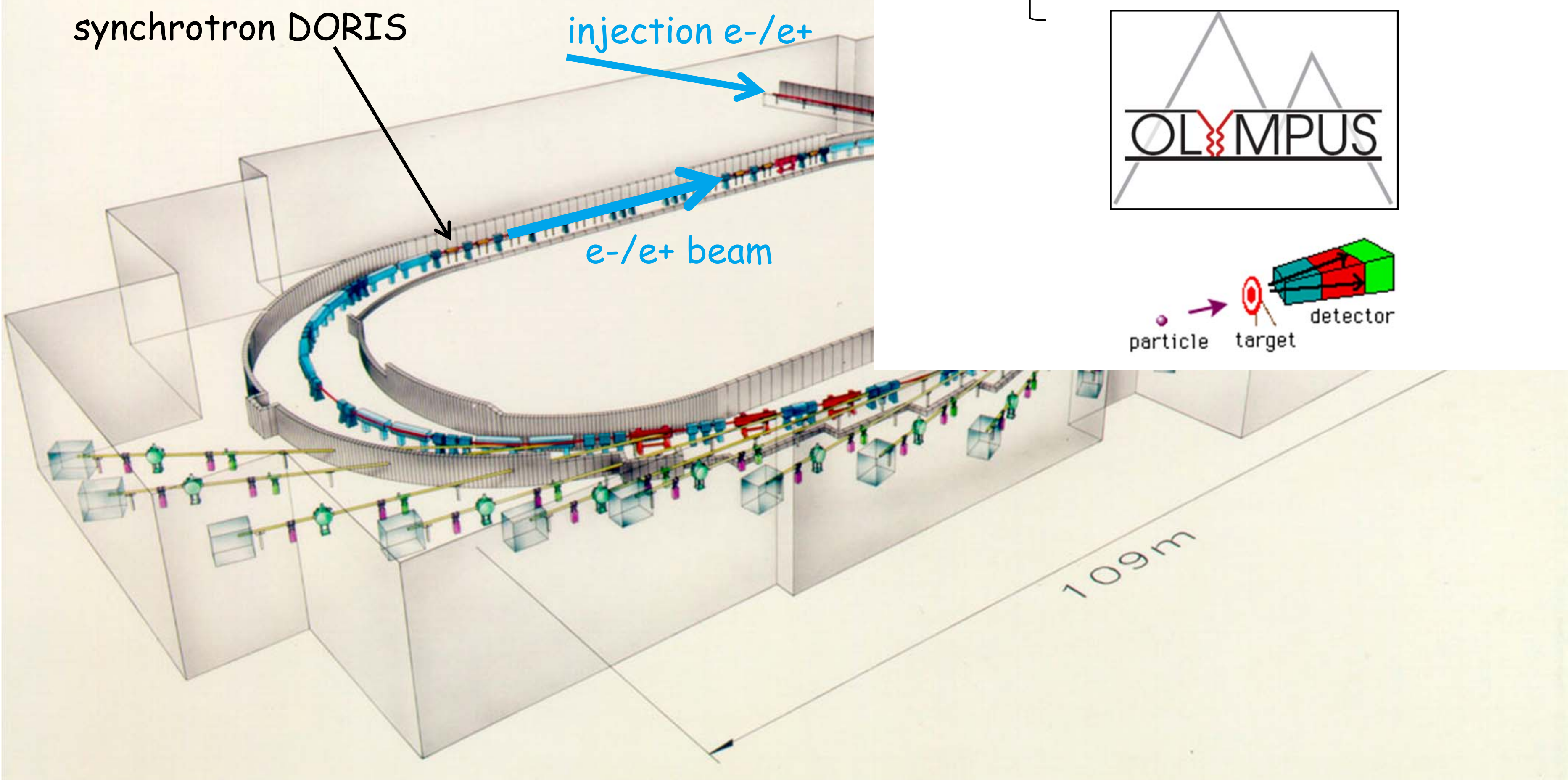
Leader of MPG Ribosome Structure Group at DESY 1986-2004

2009 Nobel Prize of Chemistry together with T. Steitz and V. Ramakrishnan

Example: Doppel-Ring-Speicher (DORIS)
'double ring store' at DESY

history:
- built between 1969 and 1974
- HEP exp. until 1983
- synchrotron rad. since 1980

future:
- synchrotron rad. until 2012
- HEP exp. from 2012



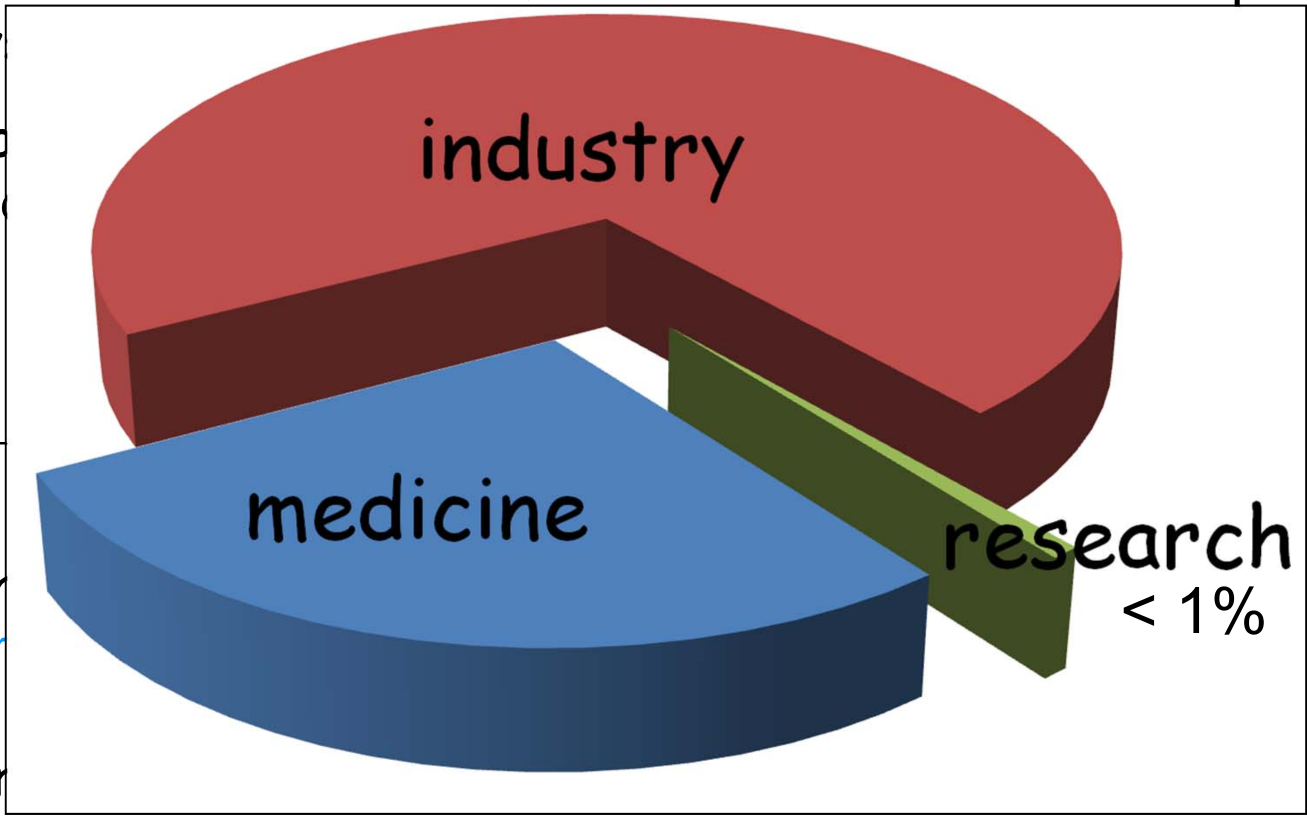
> About 120 accelerators for research in "nuclear and particle physics"
> About 70 electron storage rings and electron linear accelerators used as light sources (so-called 'synchrotron radiation sources')

> 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) …

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

> Abo … elerators
use … ources')



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

Applications of Accelerators (3)

Medical applications

For radioisotope production

proton beam + stable isotope $\xrightarrow{\text{transmutation}}$ radioactive isotope

For radiotherapy and radiosurgery:

- x-rays and gamma-rays
- ions (from protons to atoms with atomic number up to 18, Argon)
- neutrons

Applications of Accelerators (3)

Medical applications

For radioisotope production

For example:

18 MeV proton accelerator → p → target: Oxygen-18 (stable)

(transmutation)

Fluorine-18 (half-life time = 110 min.)

↓ 97% of decays

Oxygen-18 + positron

Applications of Accelerators (3)

Medical applications

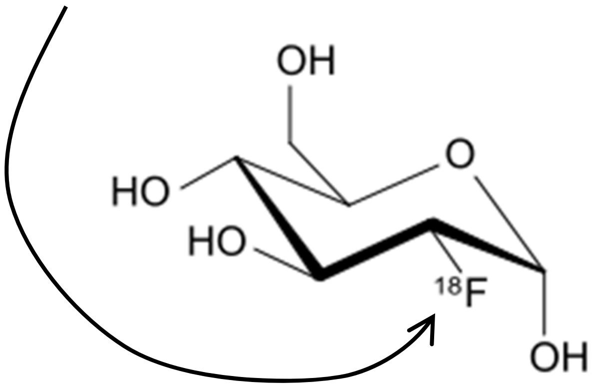
For radioisotope production

For example:

18 MeV proton accelerator —p→ target: Oxygen-18

(transmutation)

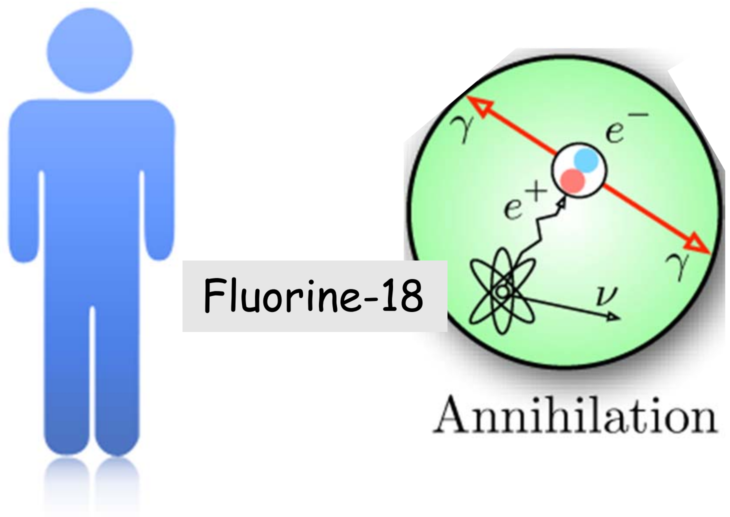
Fluorine-18 (half-life time = 110 min.)



Fludeoxyglucose (^{18}F)

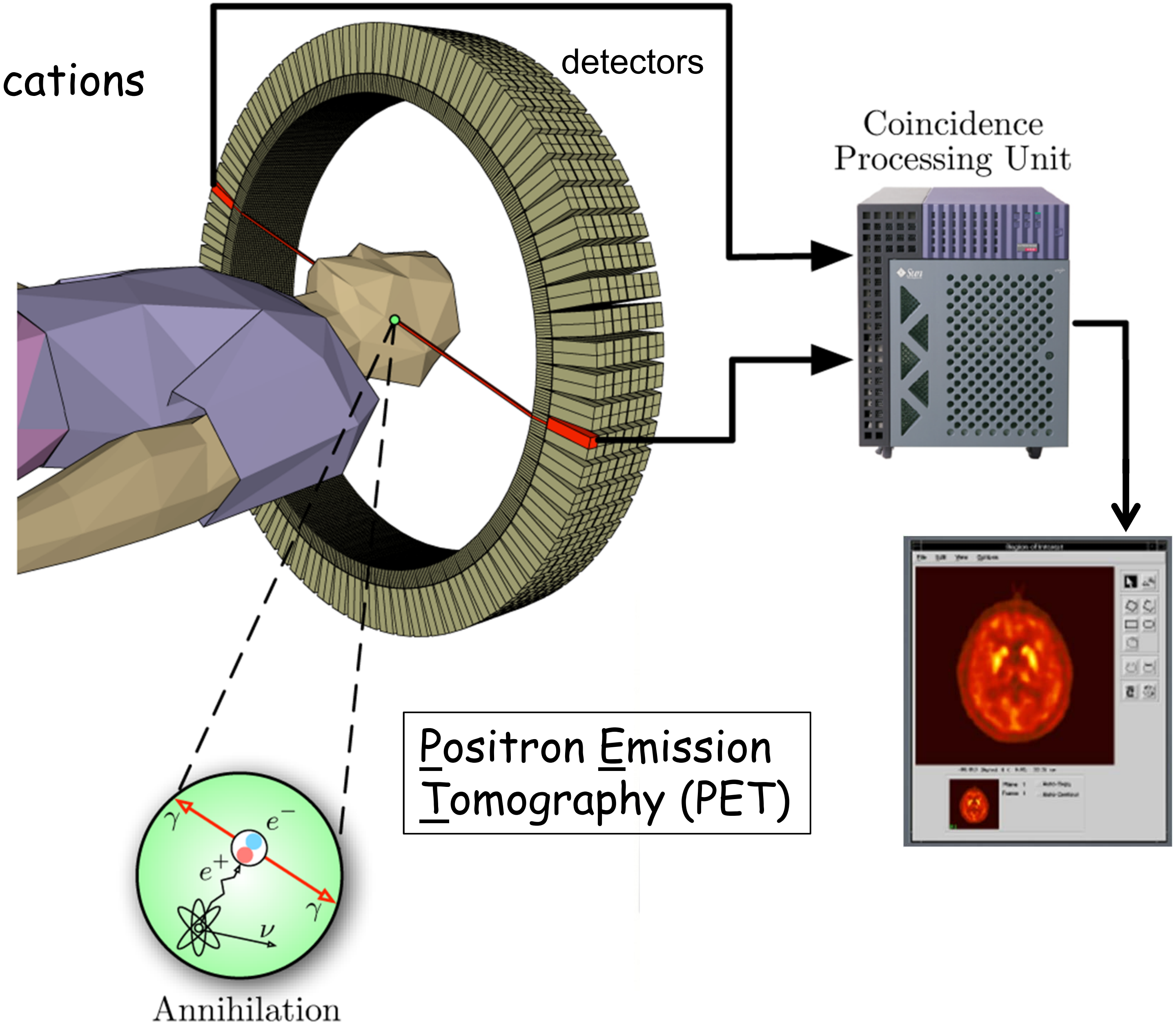
Applications of Accelerators (3)

Medical applications



Applications of Accelerators (3)

Medical applications



Positron Emission Tomography (PET)

Applications of Accelerators (4)

For industrial applications:

Application	
Ion implantation	~ 9500
Electron cutting and welding	~ 4500
Electron beam and x-ray irradiators	~ 2000
Ion beam analysis (including AMS)	~ 200
Radioisotope production (including PET)	~ 900
Nondestructive testing (including security)	~ 650
Neutron generators (including sealed tubes)	~ 1000

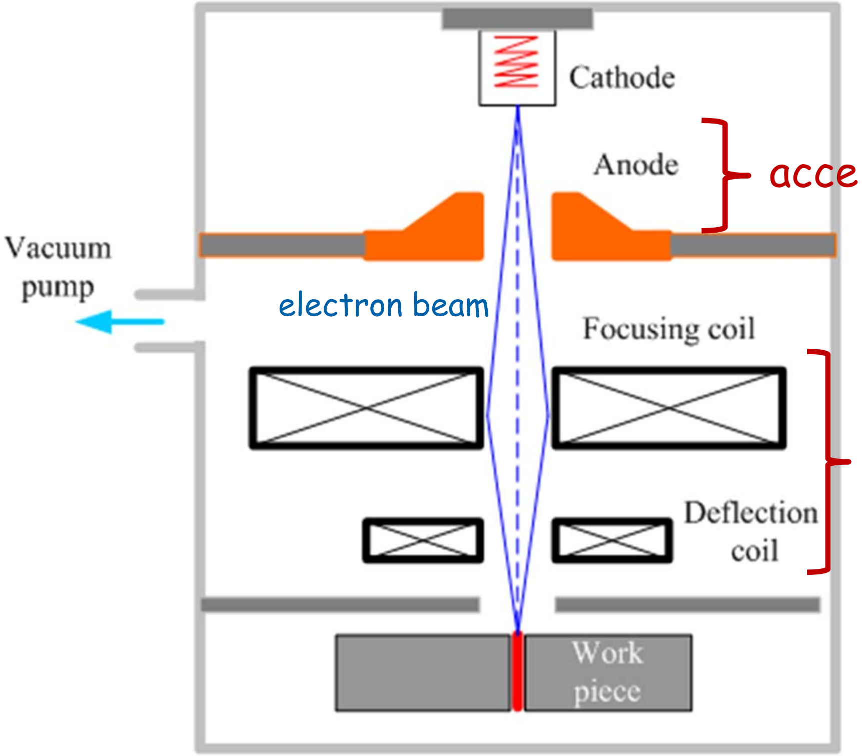
approx. numbers from 2007 (worldwide)

with energies up to 15 MeV

Applications of Accelerators (4)

For industrial applications:

an example: electron beam welding



acceleration up to 60-200 keV

magnets as 'focusing lenses' as well as 'deflectors'

up to 15 cm

'deep welding effect'

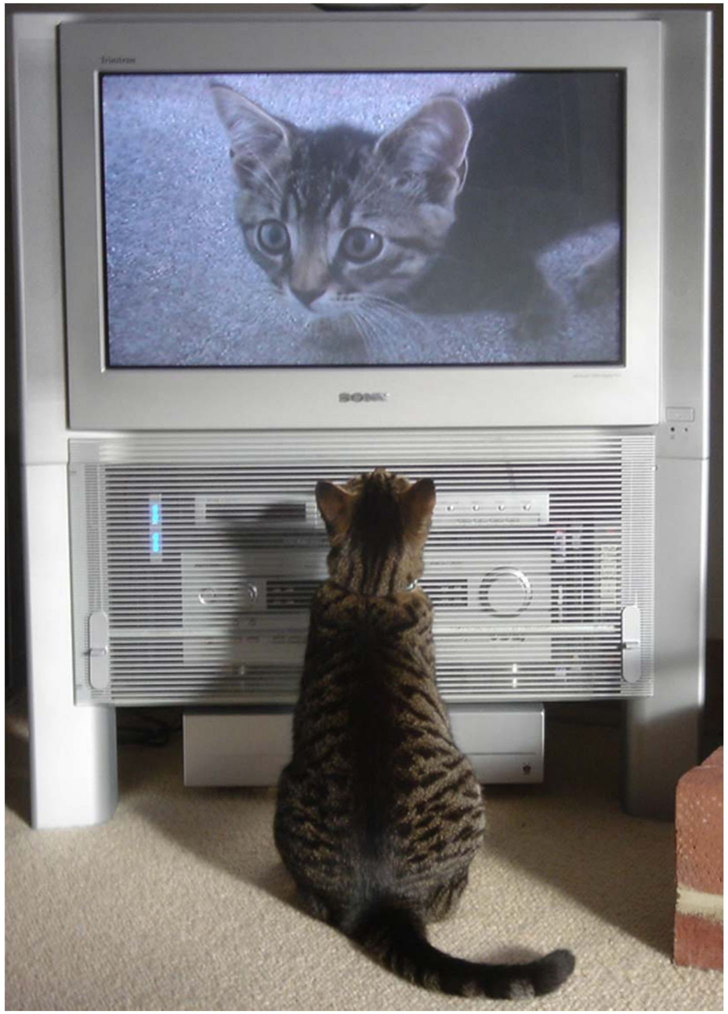
- About 120 accelerators for research in "nuclear and particle physics"
- About 70 electron storage rings and electron linear accelerators used as light sources (so-called 'synchrotron radiation sources')

...and there is more !!!

- 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) …

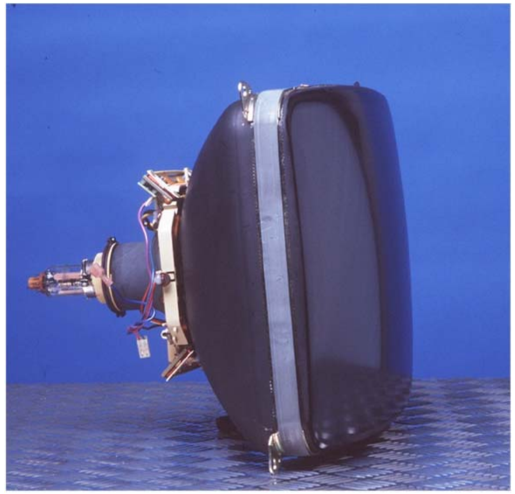
Applications of Accelerators (5)

Many millions of television sets, oscilloscopes using CRTs (Cathode Ray Tube)



TV

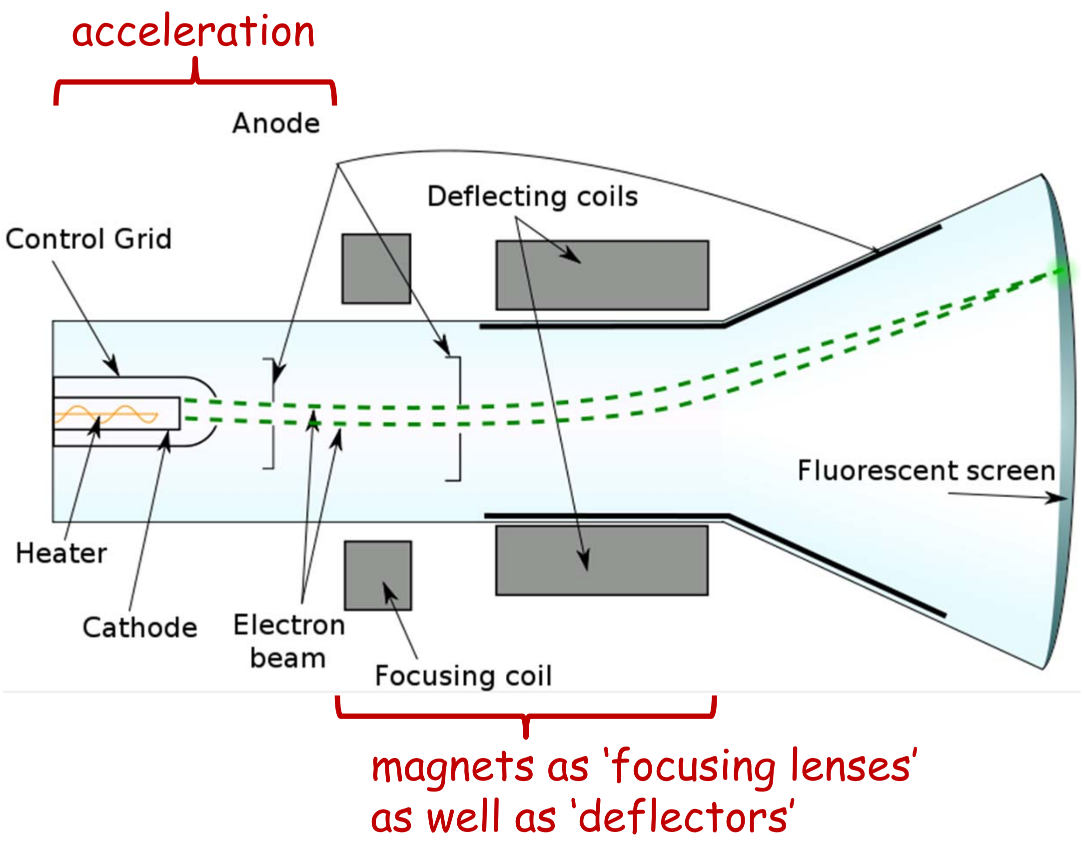
CRT (Cathode Ray Tube)

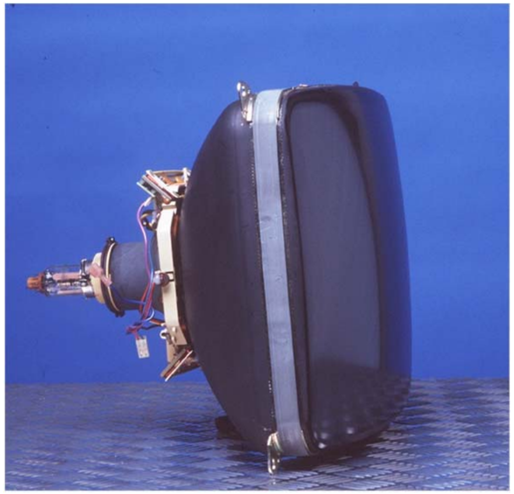


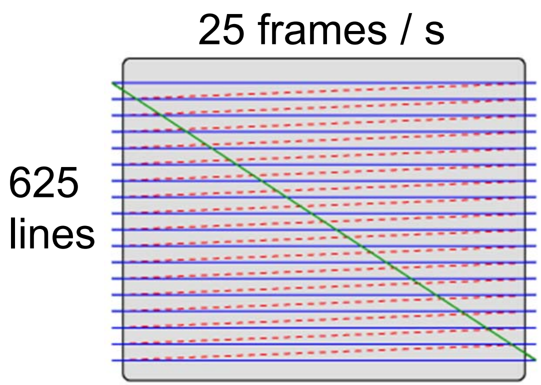
oscilloscope

Applications of Accelerators (5)

Many millions of television sets, oscilloscopes using CRTs (Cathode Ray Tube)



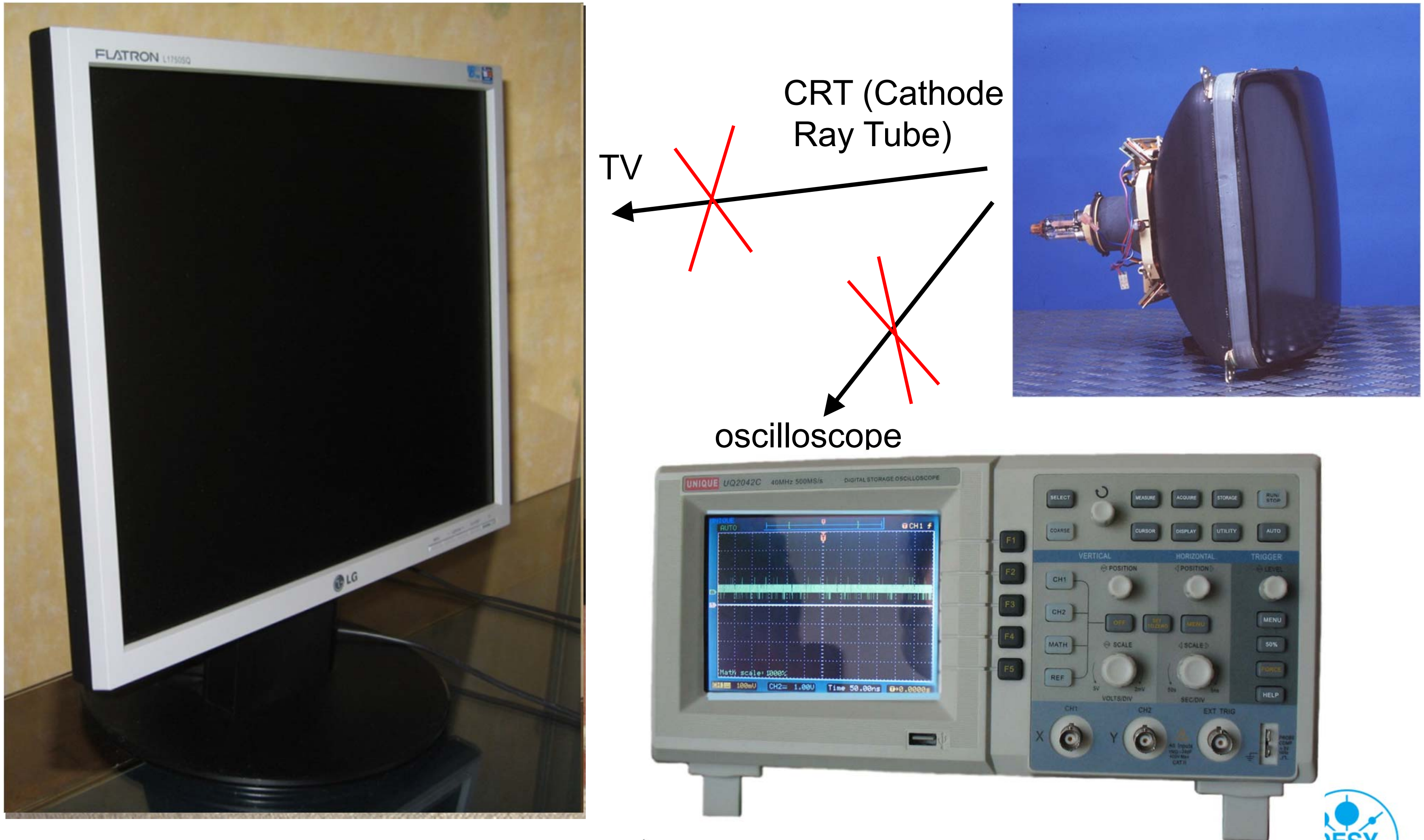




Applications of Accelerators (5)

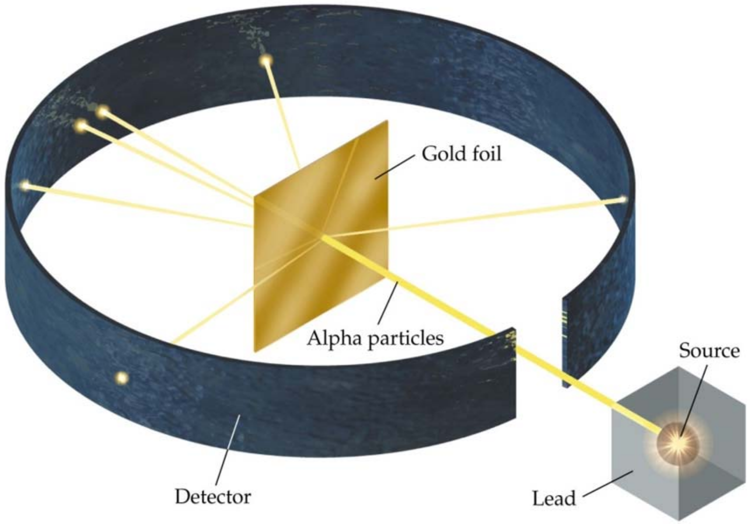
Many millions of television sets, oscilloscopes using CRTs (Cathode Ray Tube)

(tending to disappear, replaced by LCD and plasma screens)

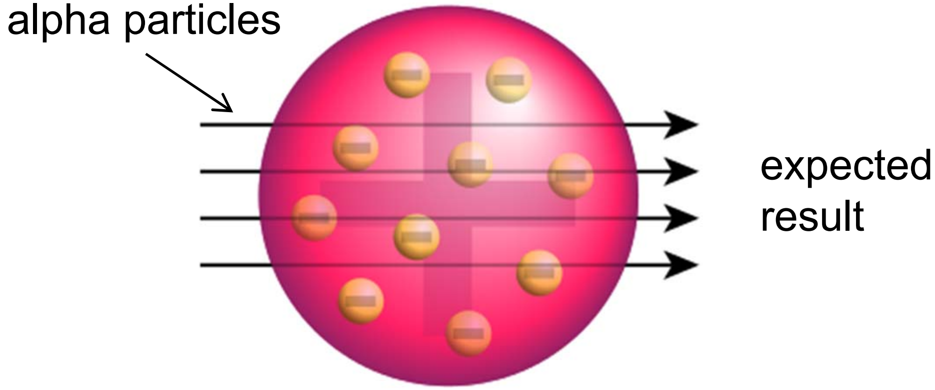


Applications of accelerators

Geiger-Marsden experiment:
the gold foil experiment (1909)

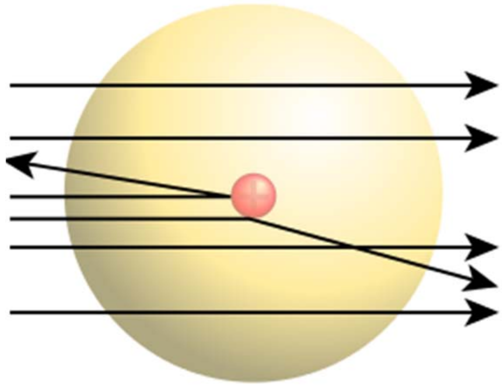


Thomson model of the atom (1904)



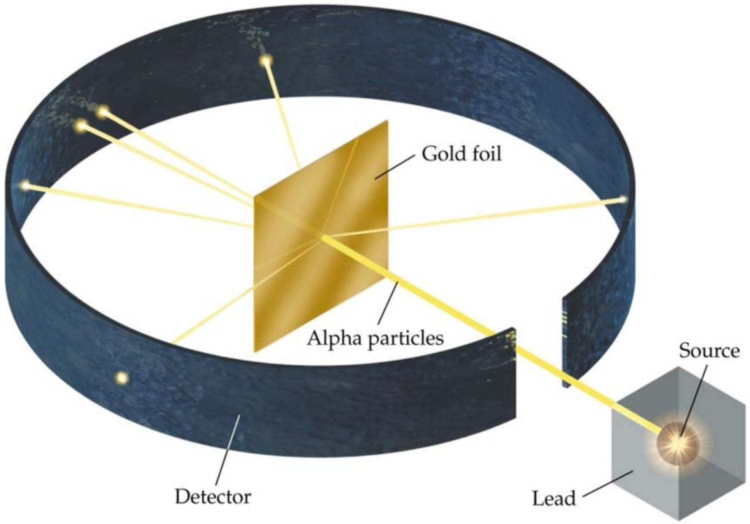
1 in 8000 reflected with θ > 90°

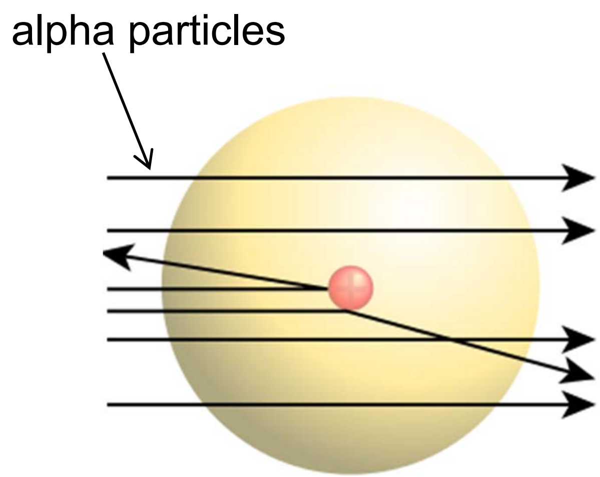
shooting with 10000 km/s, a few coming back !



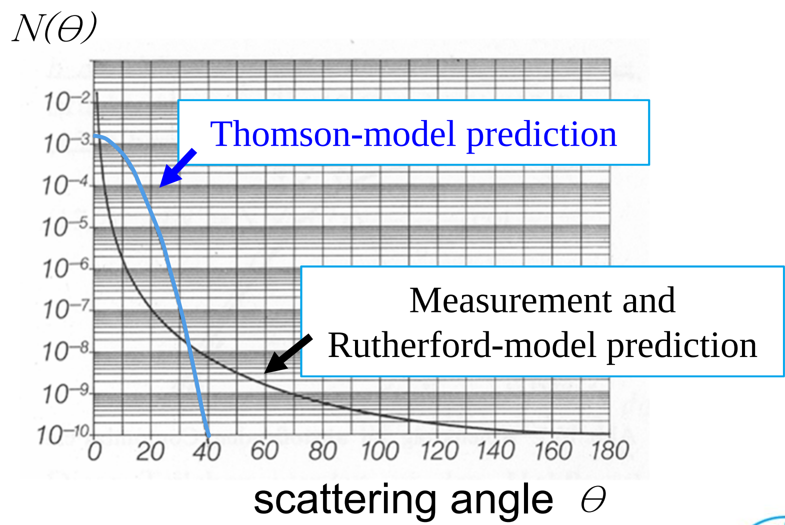
Rutherford model of the atom (1911)

Geiger-Marsden experiment:
the gold foil experiment (1909)





Rutherford model of the atom (1911)



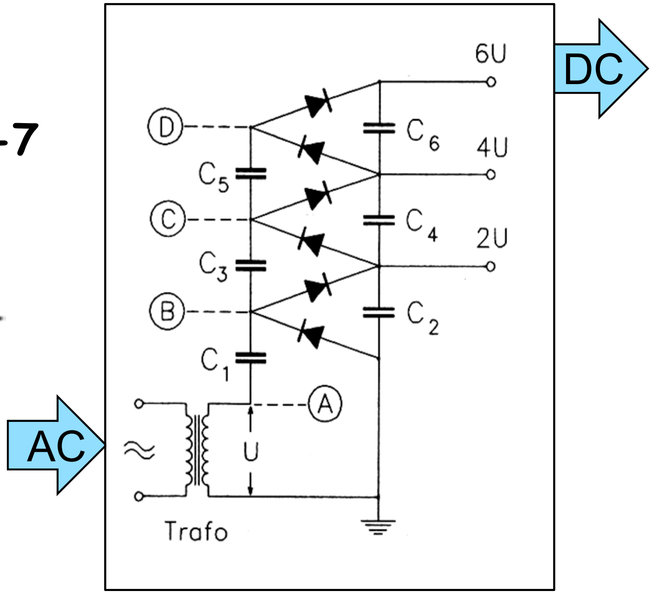
Cockcroft-Walton generator

(1932)

400 keV p → Lithium-7

↓

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} + 17{,}35\ \mathrm{MeV}$$



voltage multiplier

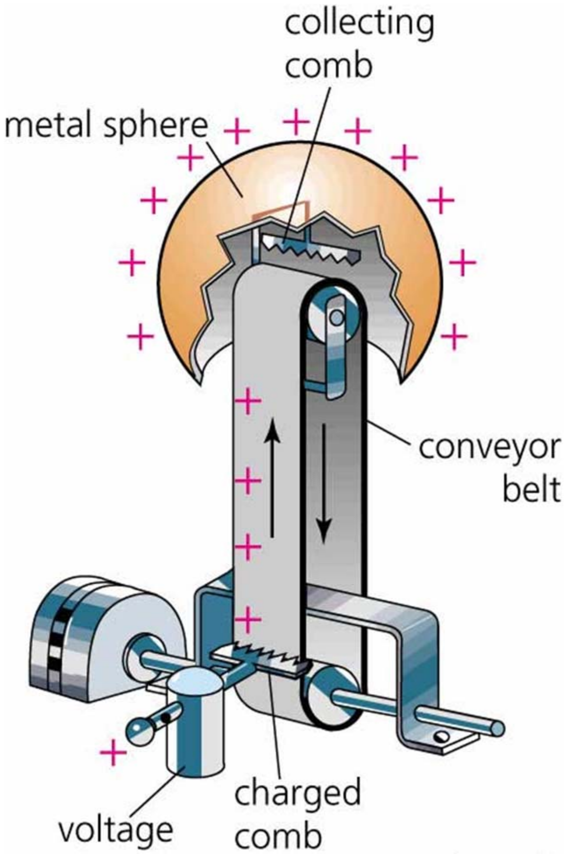
maximum voltage < 1 MV

maximum voltage ~ 25 MV

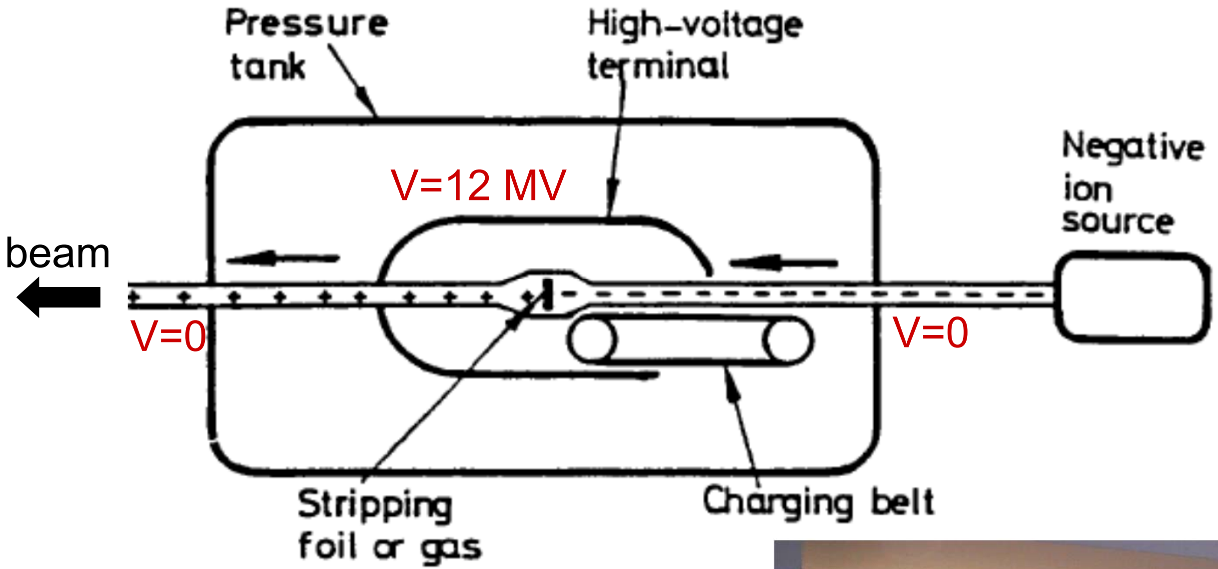
→ **Van de Graaff generator**

Acceleration with an electrostatic field

Van der Graaff generator: invented in 1929



Acceleration with an electrostatic field



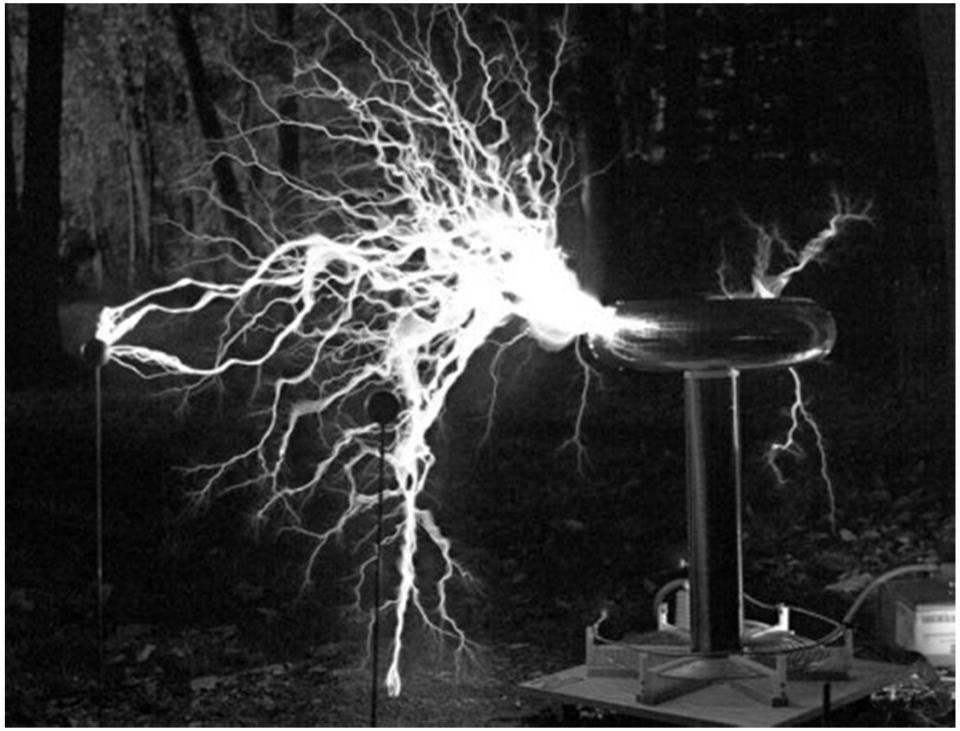
12 MV-Tandem Van de Graaff Accelerator
at MPI Heidelberg, GE

Acceleration with an electrostatic field

20 MV-Tandem
at Daresbury, UK

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

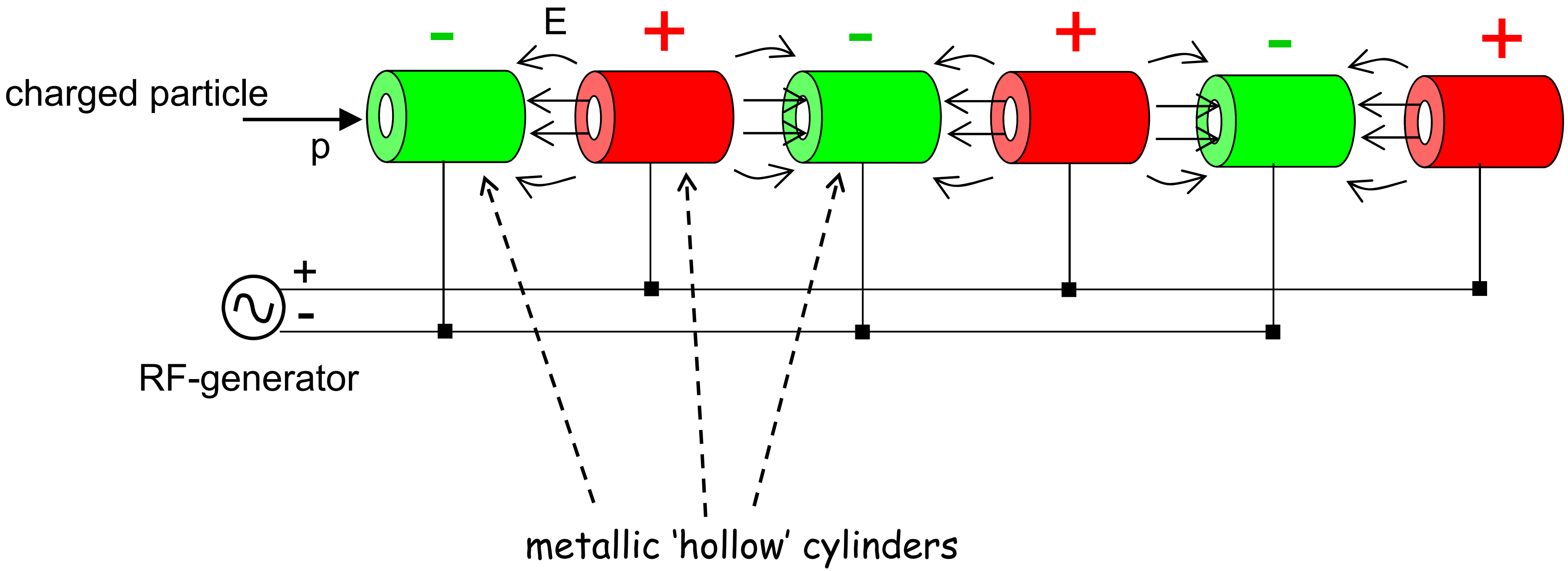
Limitation of electrostatic fields



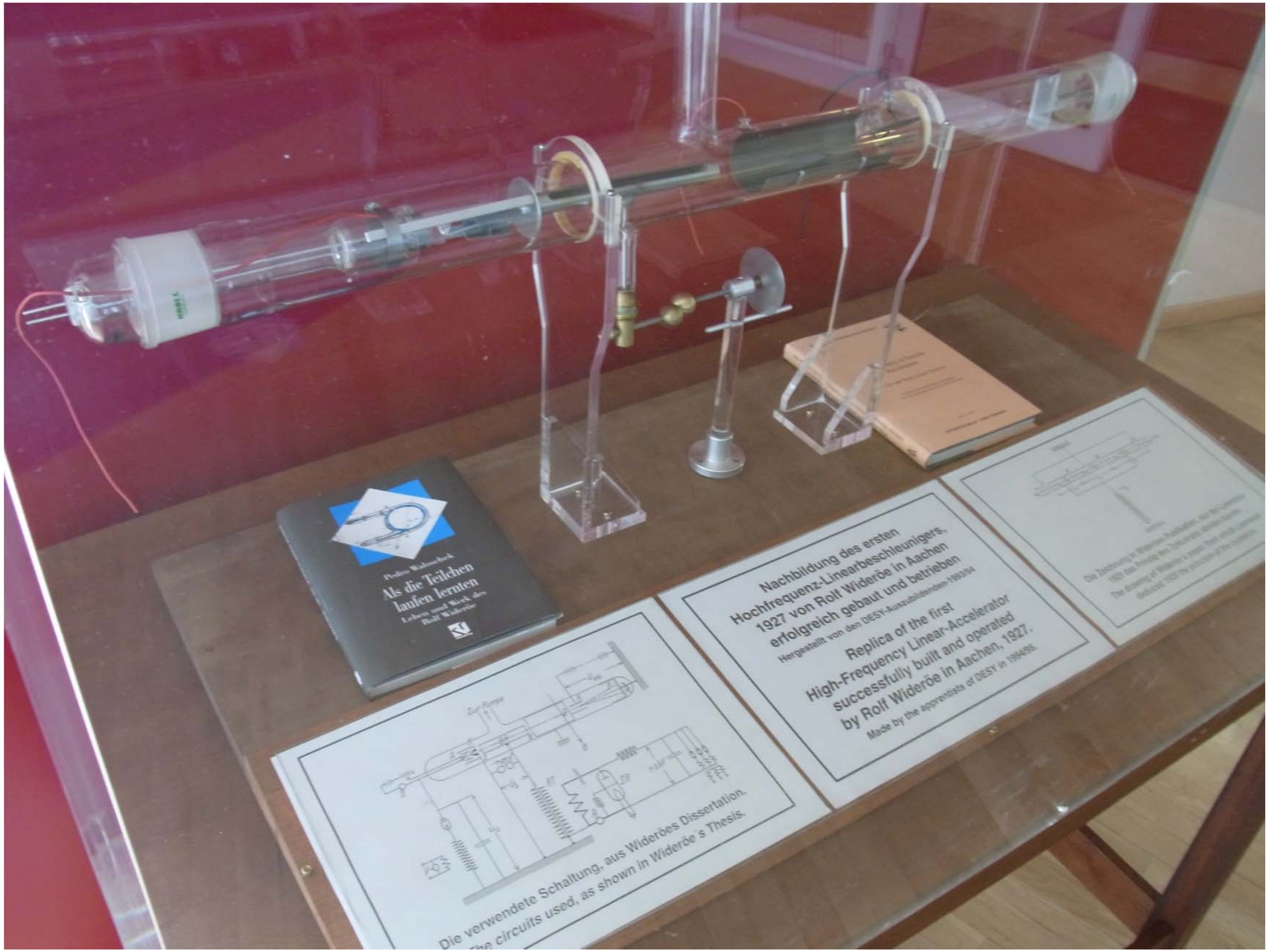
breakdown

Acceleration using Radio-Frequency (RF) generators

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



Replica of the Widerøe accelerator



Acceleration using Radio-Frequency (RF) generators

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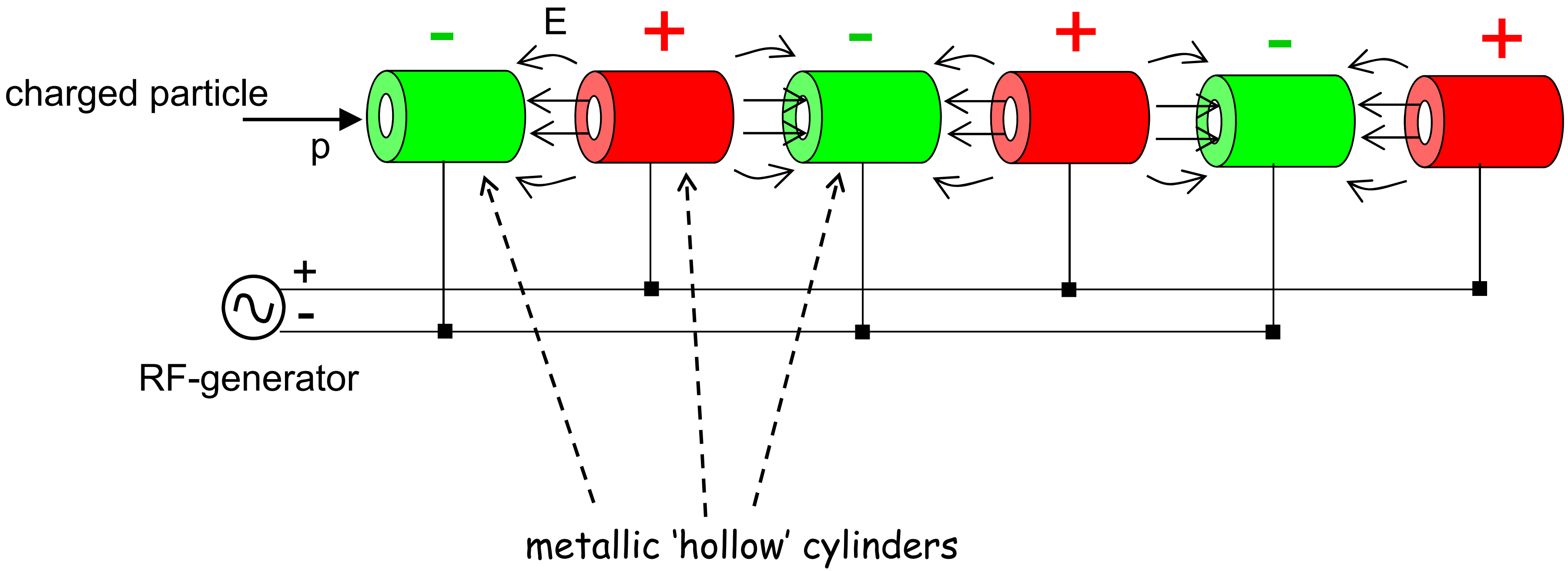
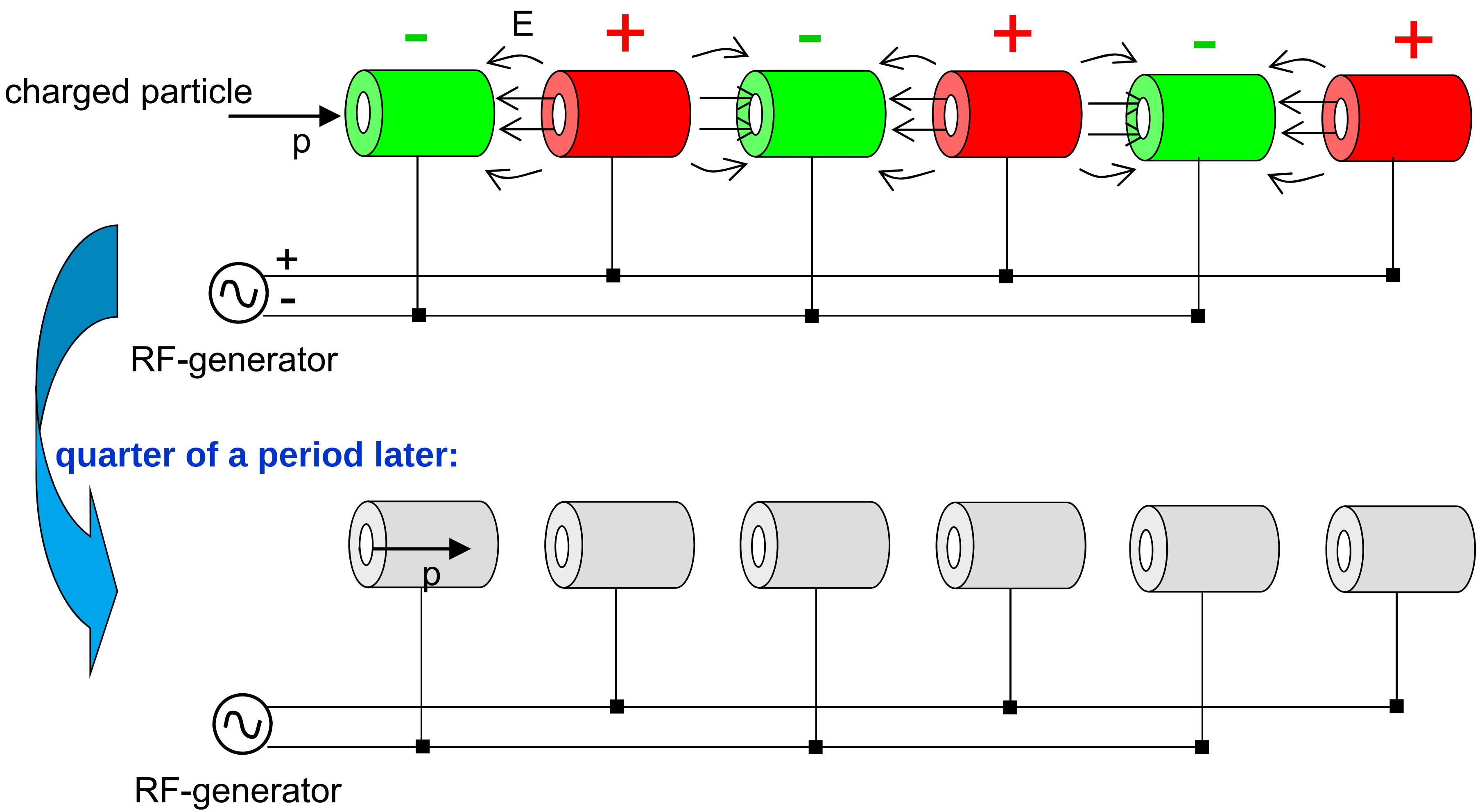
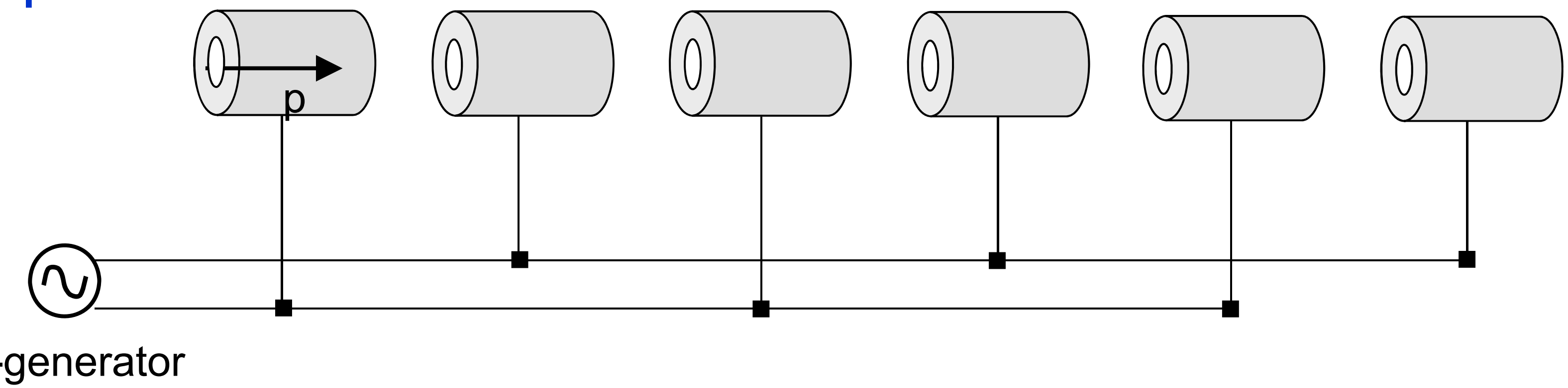


Acceleration using Radio-Frequency (RF) generators

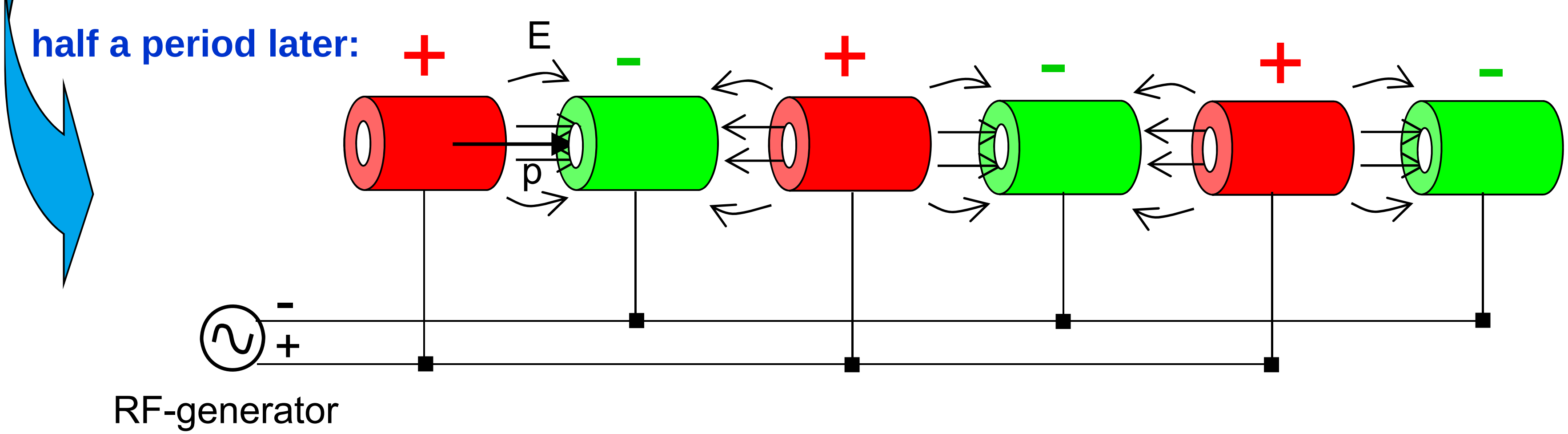


Acceleration using Radio-Frequency (RF) generators

quarter of a period later:



half a period later:

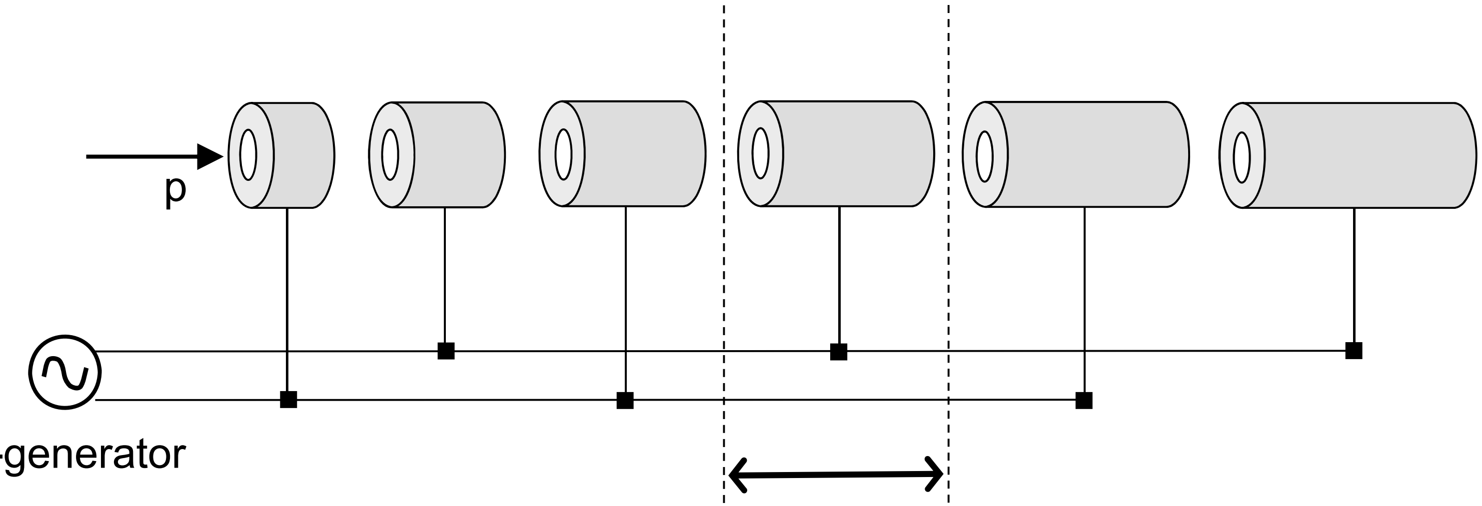


Restrictions of RF

- particles travel in groups → called bunches
- bunches are travelling synchronous with RF cycles
- $\Delta E \quad \rightarrow \quad \Delta v$

Acceleration using Radio-Frequency (RF) generators

$\beta < 1$



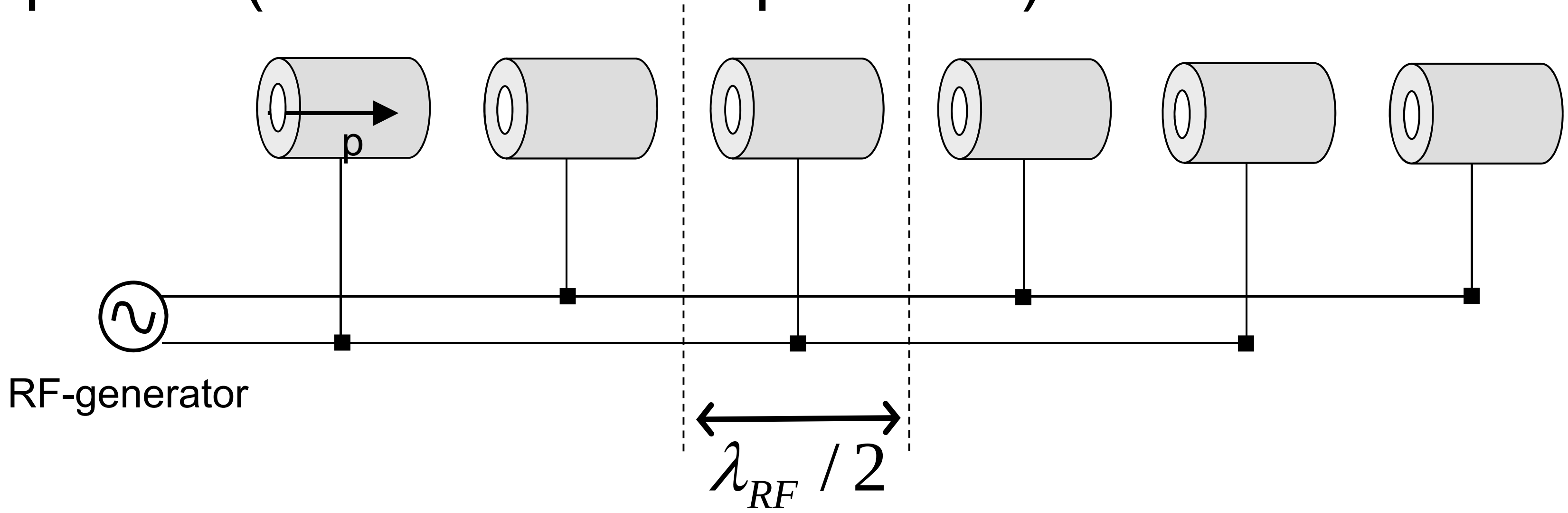
$$v_p \cdot \frac{T_{RF}}{2} = v_p \cdot \frac{\lambda_{RF}}{2c} = \beta_p \cdot \frac{\lambda_{RF}}{2}$$

relativistic β

original Widerøe drift-tube principle

Acceleration using Radio-Frequency (RF) generators

$\beta \approx 1$ (ultra relativistic particles)



Limitations of drift tube accelerators:

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

$$L_{tube} = \beta \frac{\lambda_{RF}}{2} = \beta \frac{c}{2 f_{RF}}$$ → 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

First summing-up

Applications:

- HEP (example: LHC)
- light source (example: DORIS, Ribosome)
- medicine (example: PET)
- industry (example: electron beam welding)
- cathode ray tubes (example: TV)

Electrostatic accelerators:

- Cockcroft-Walton generator
- Tandem Van der Graaff accelerator

Radio-frequency accelerators:

- Widerøe drift-tube

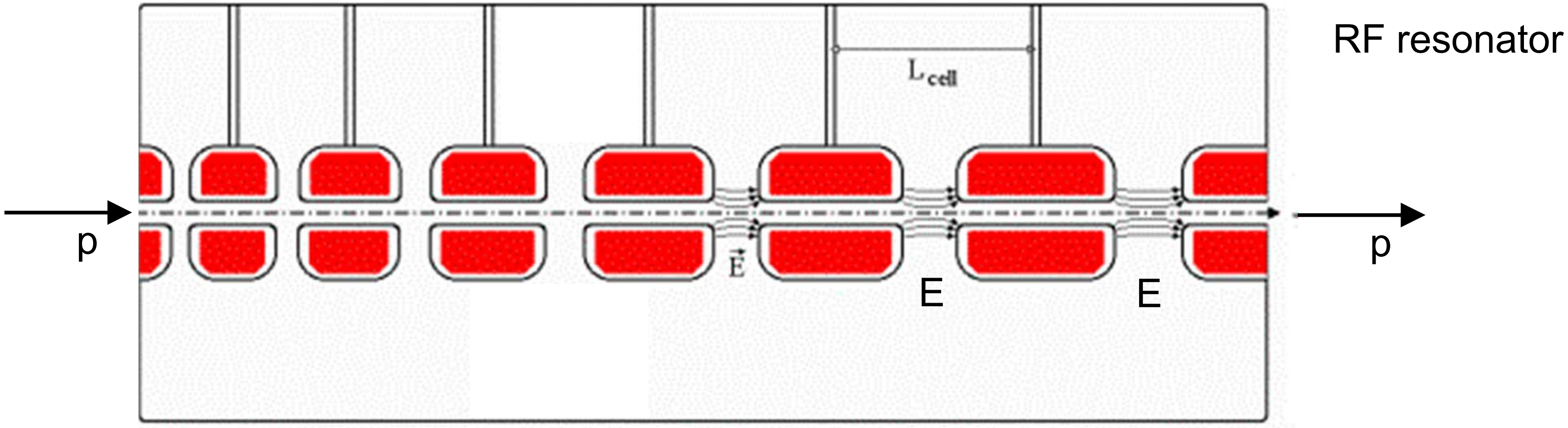
Alvarez drift-tube (1946) structure

Widerøe drift-tube principle

Cyclotron (1929), E. Lawrence

Resonant cavities

Alvarez drift-tube (1946) structure:

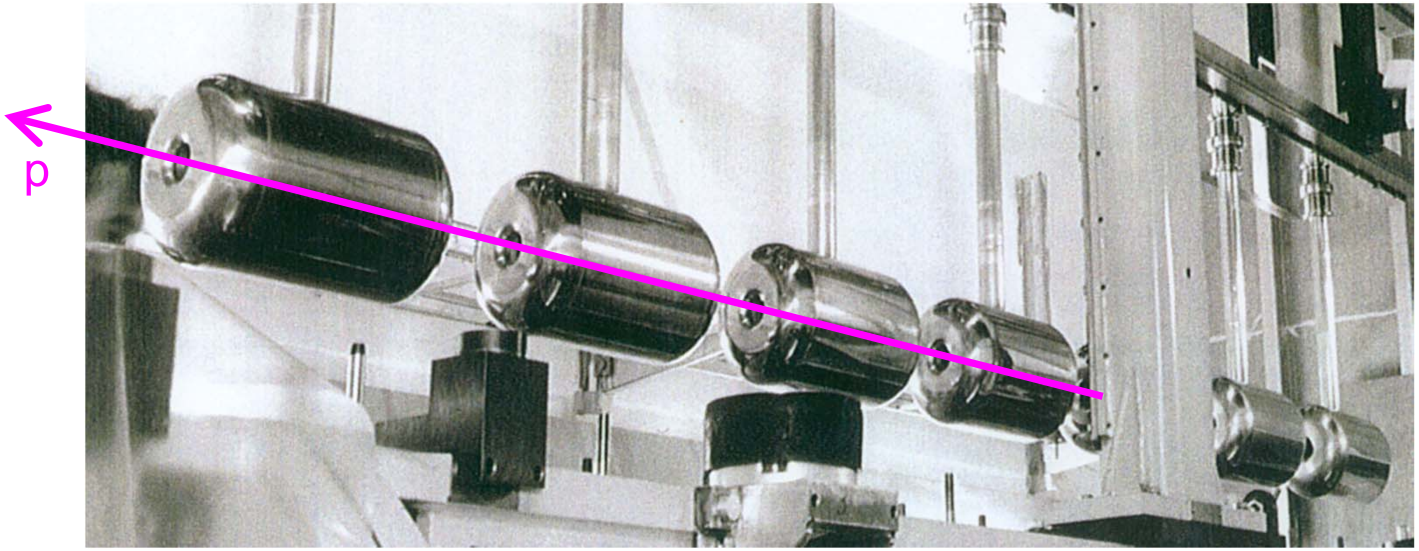


Examples

DESY proton linac (LINAC III)

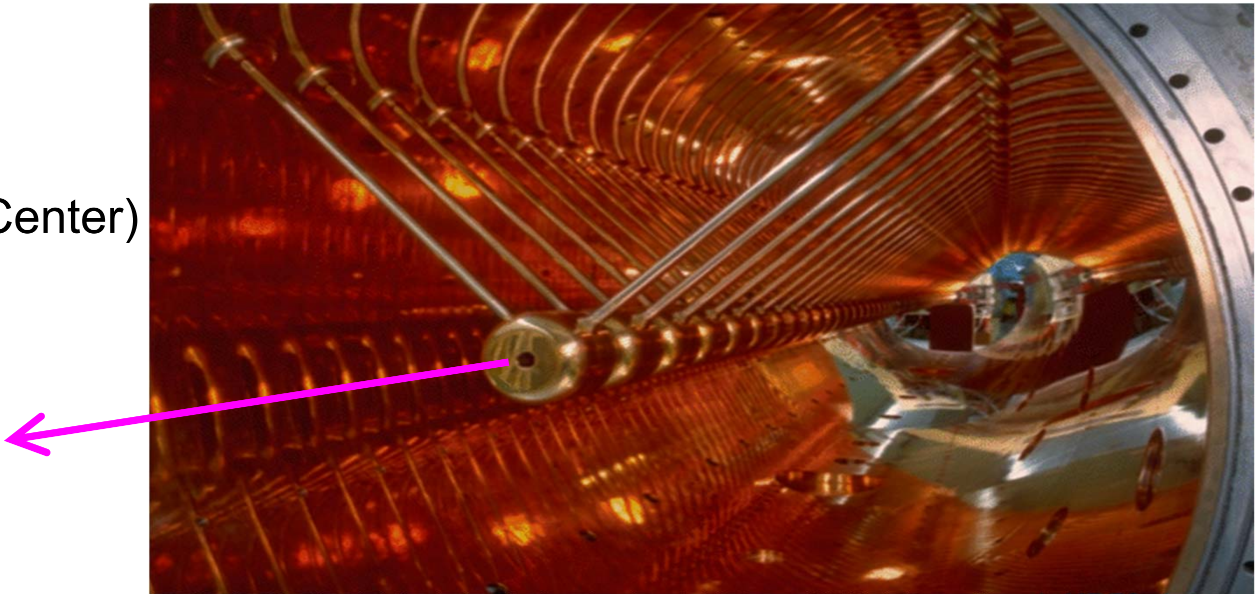
$$E_{kin} = 50\,MeV$$

$\beta \approx 0.3$

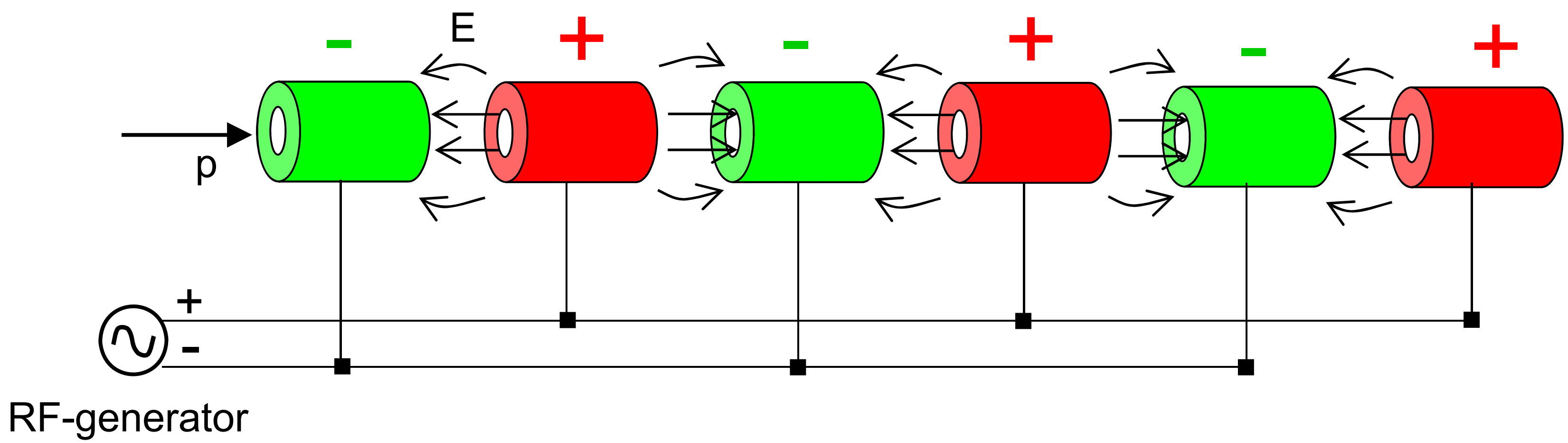


GSI Unilac
(GSI: Heavy Ion Research Center)
Darmstadt, Germany

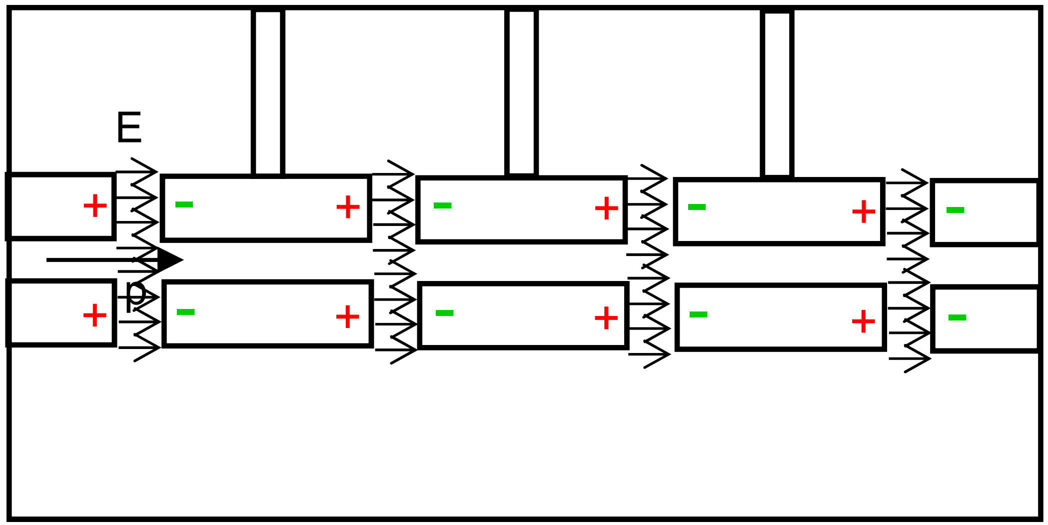
Protons/Ions
E ≈ 20 MeV per nucleon
$\beta \approx 0.04 \ldots 0.2$



Widerøe drift-tube

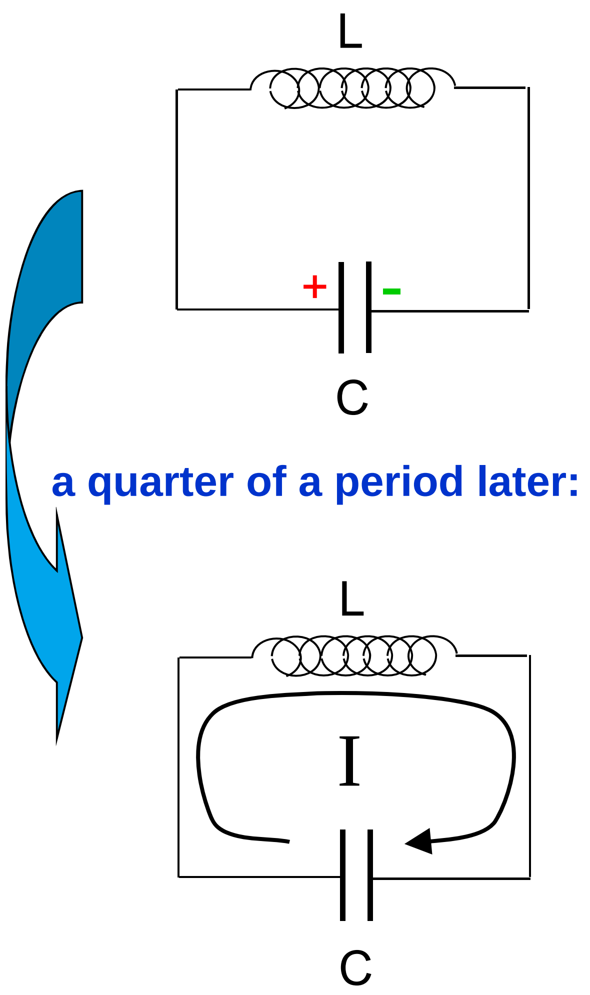


Alvarez drift-tube

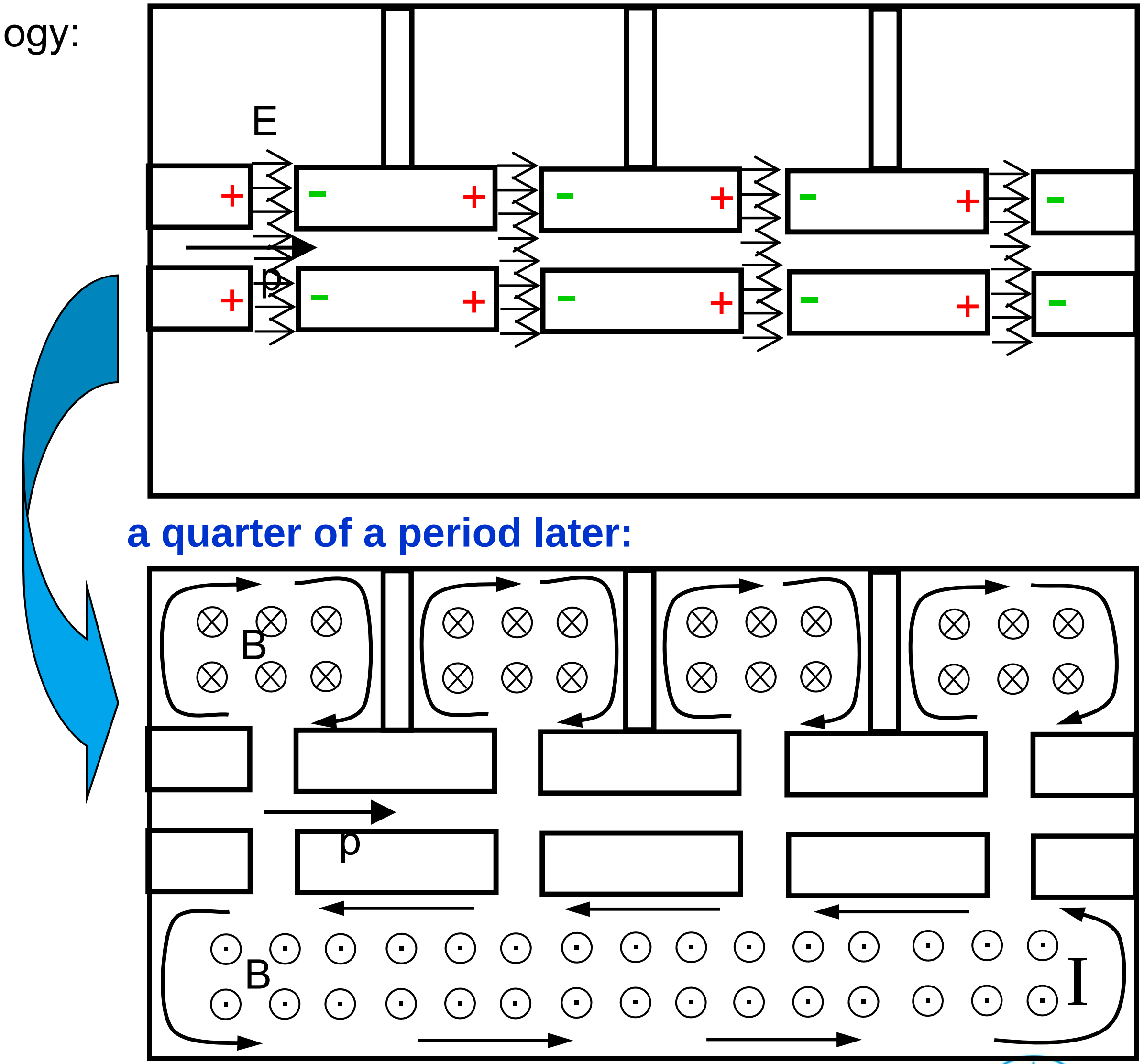


Charges, currents and electromagnetic fields

LC circuit (or resonant circuit) analogy:



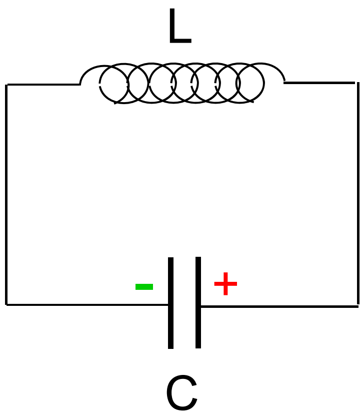
Alvarez drift-tube



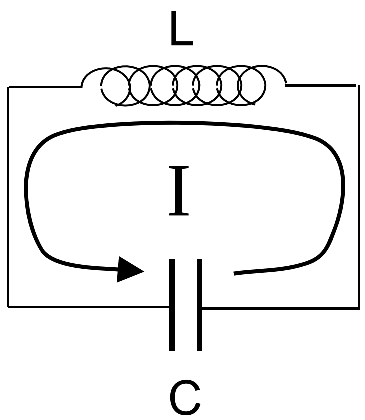
Charges, currents and electromagnetic fields

Alvarez drift-tube

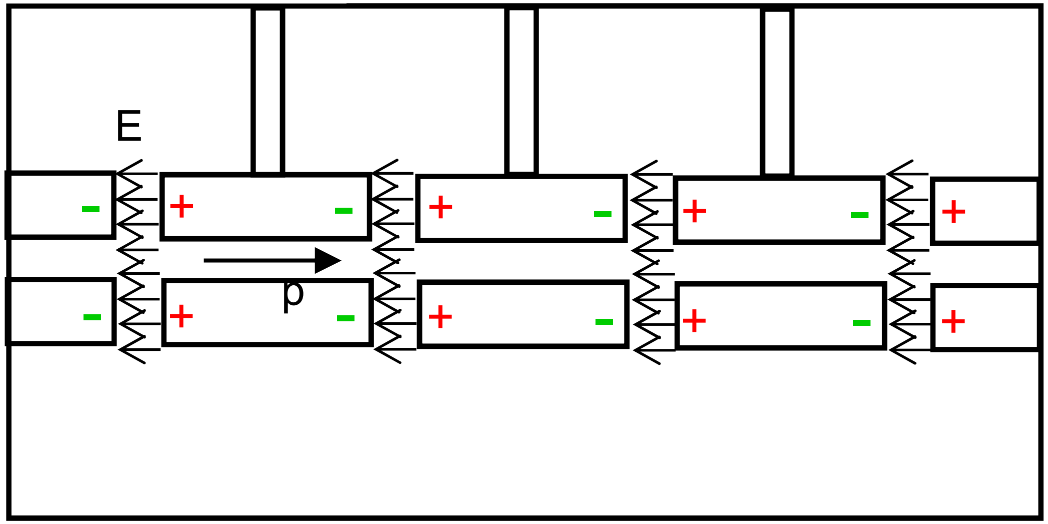
half a period later:



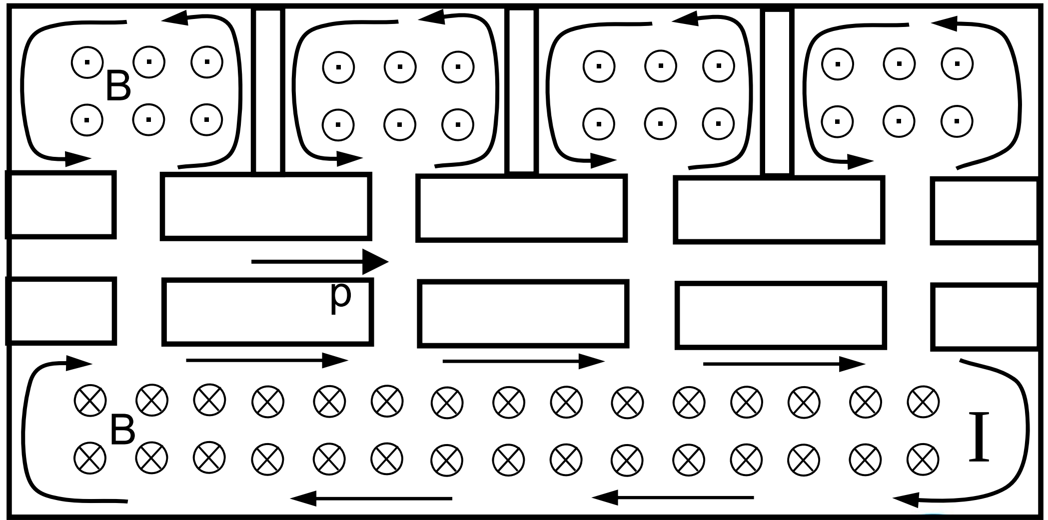
3 quarters of a period later:



half a period later:

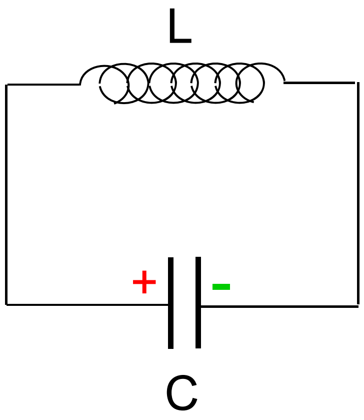


3 quarters of a period later:



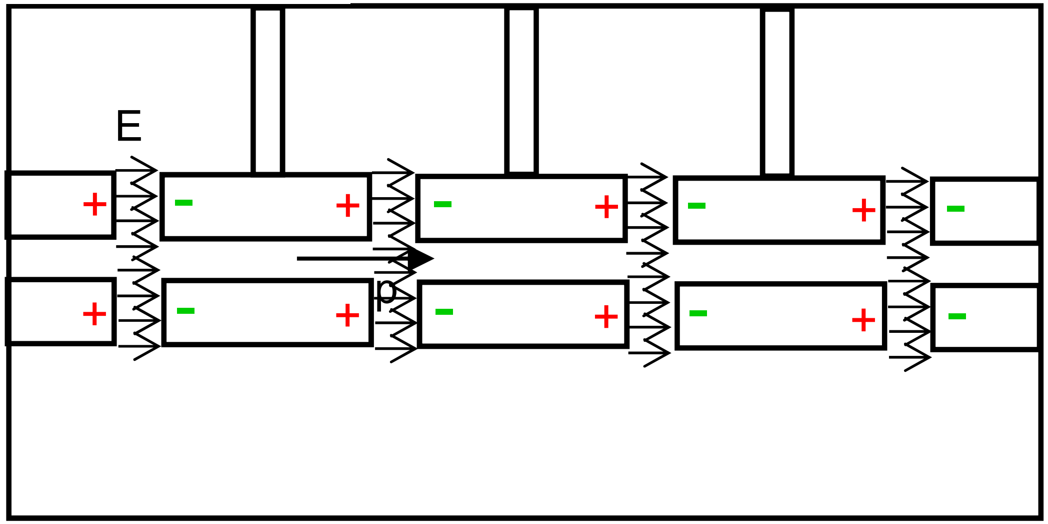
Charges, currents and electromagnetic fields

a full period later:



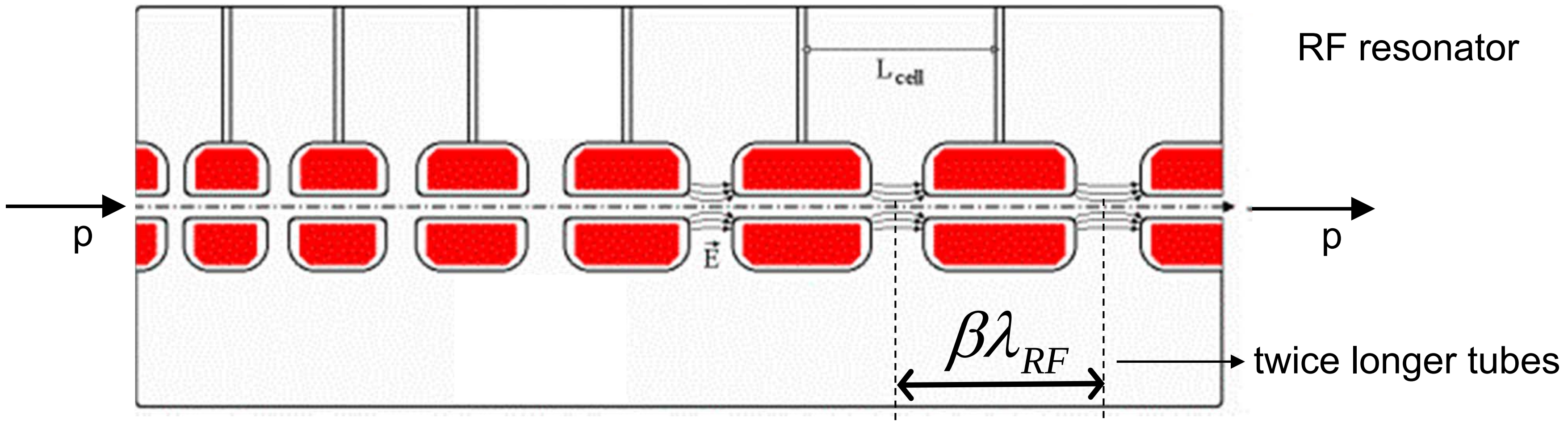
a full period later:

Alvarez drift-tube



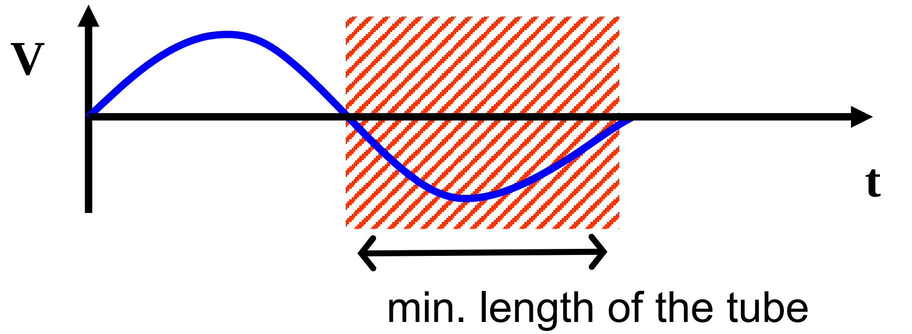
Resonant cavities

Alvarez drift-tube structure:



higher frequencies possible → shorter accelerator

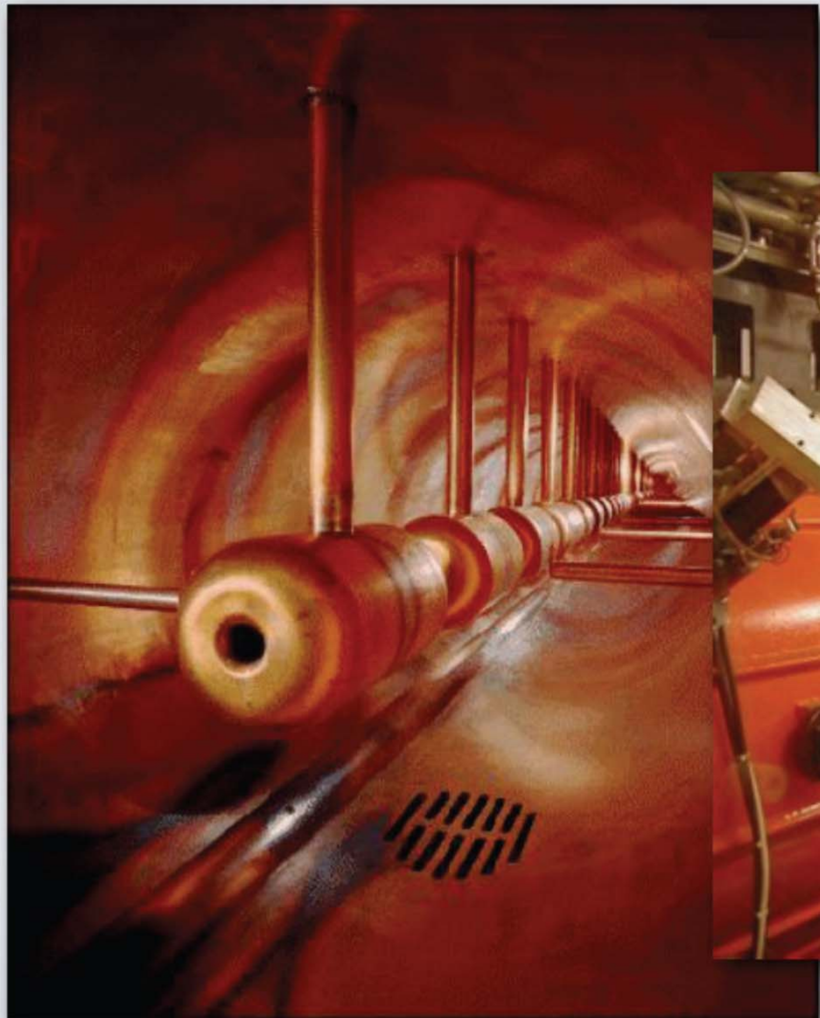
voltage between tubes



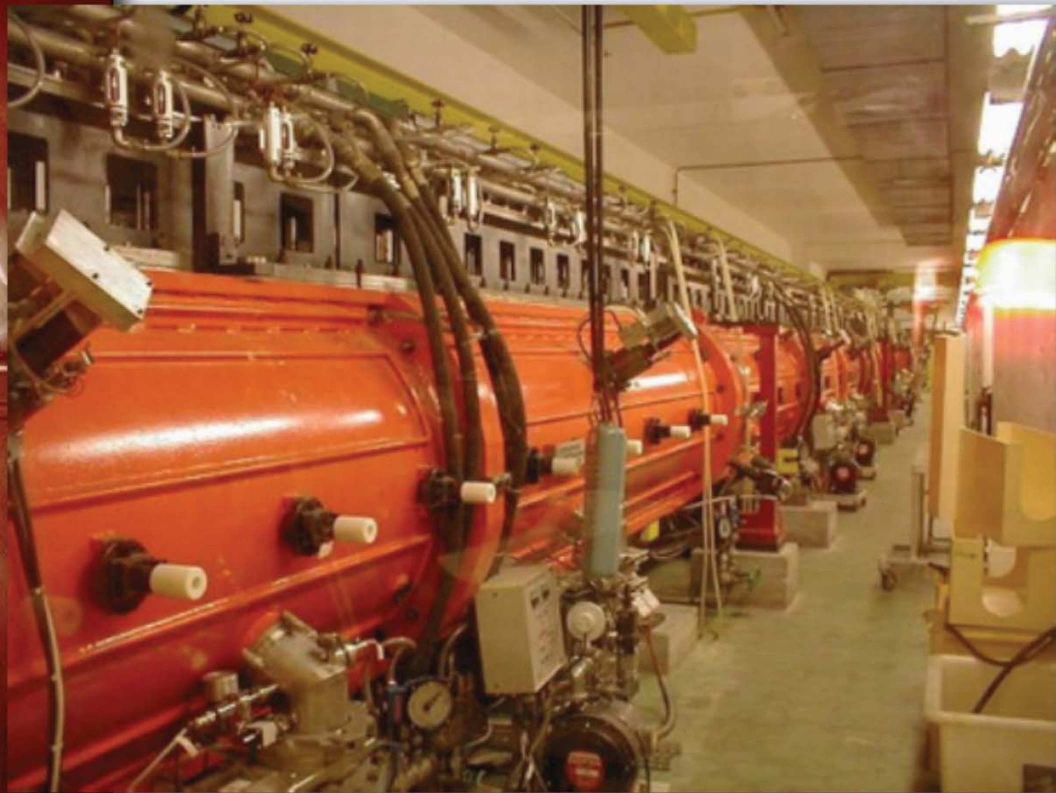
preferred solution
for ions and protons
up to few hundred MeV

Examples

inside a drift tube linac

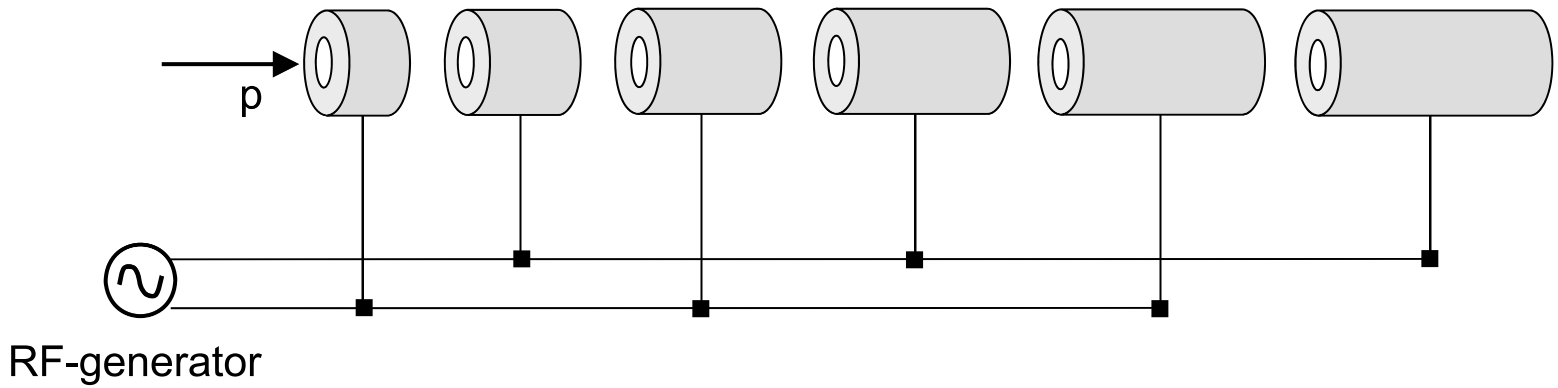


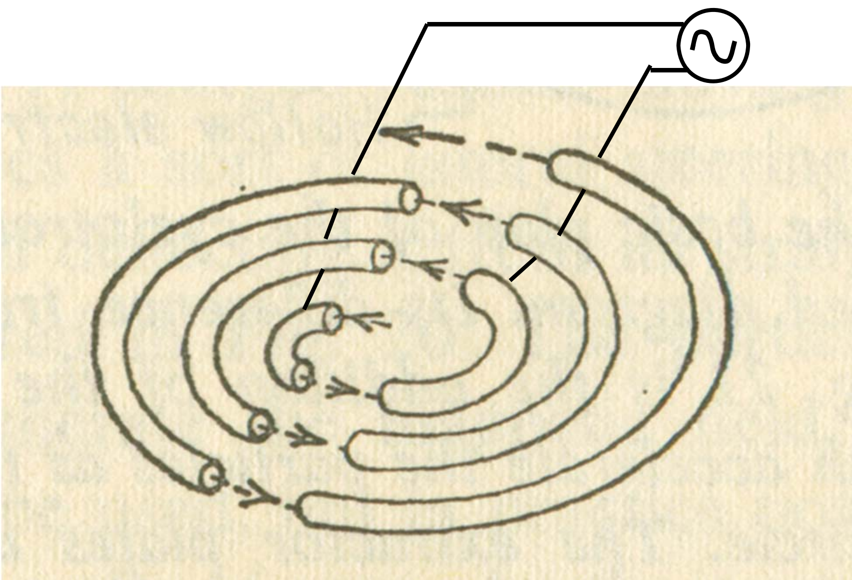
Linac2 at CERN, 50 MeV



Acceleration using Radio-Frequency (RF) generators

original Widerøe drift-tube principle



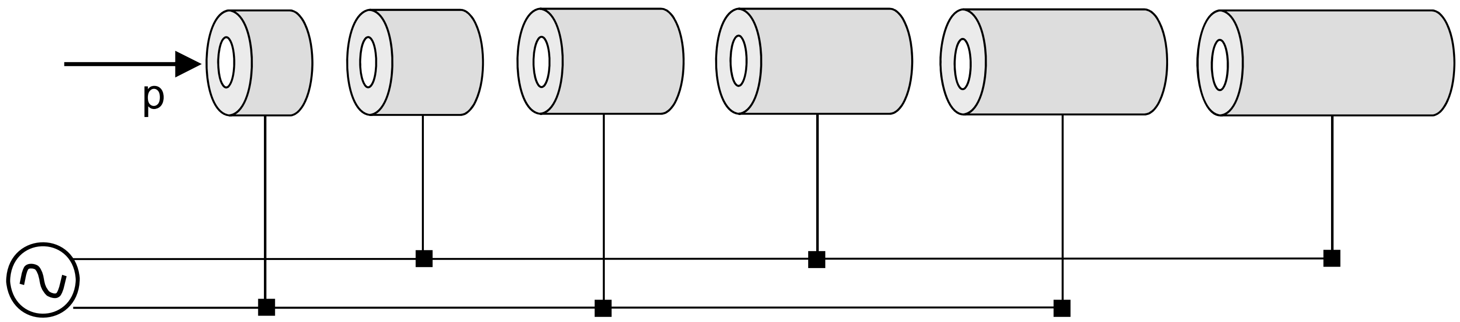


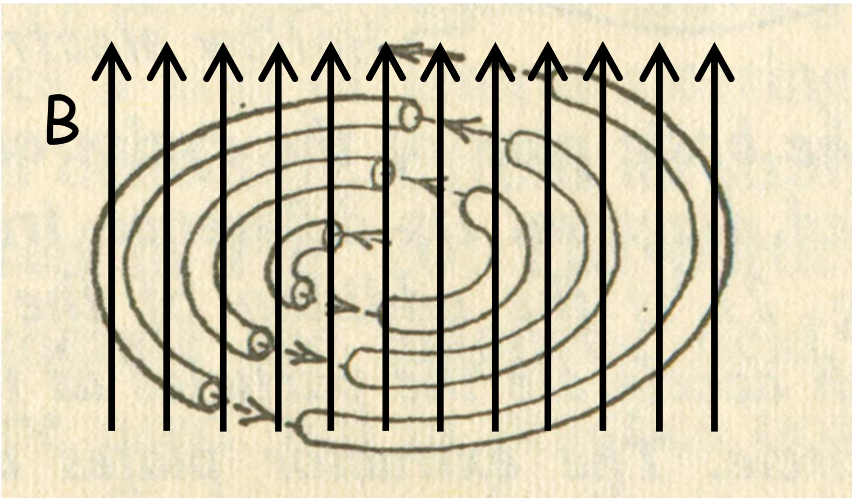
first concept of the 'cyclotron' (1929)
(from E. Lawrence)

drift-tube linac "rolled up"

Acceleration using Radio-Frequency (RF) generators

original Widerøe drift-tube principle

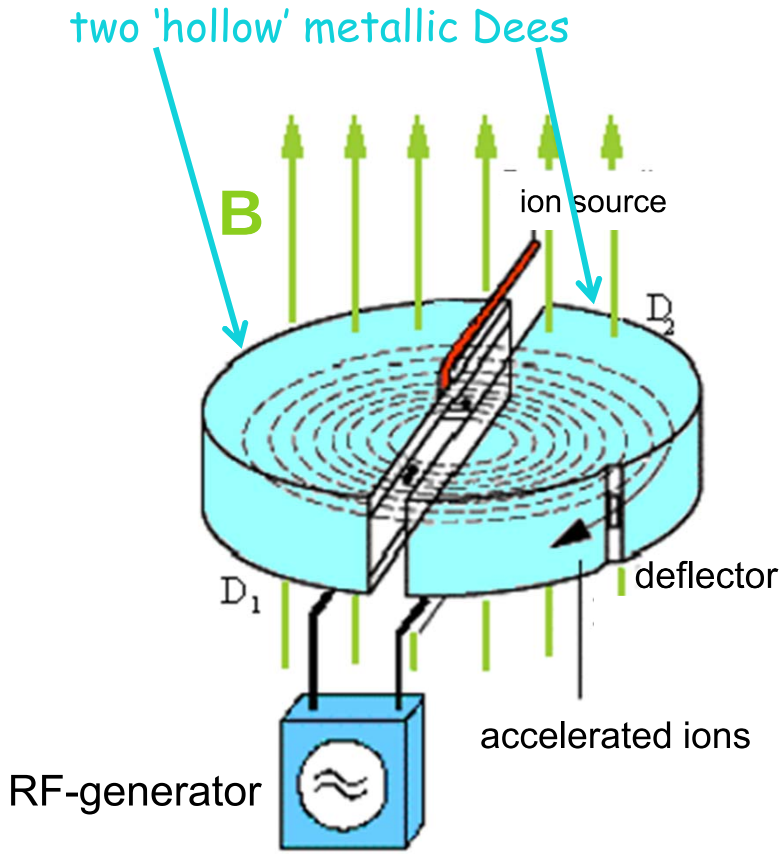




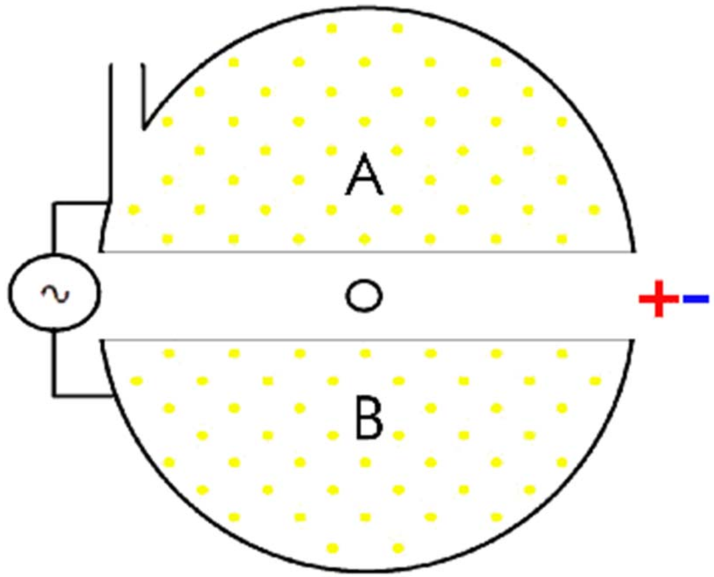
first concept of the 'cyclotron' (1929)
(from E. Lawrence)

drift-tube linac "rolled up"

Cyclotron

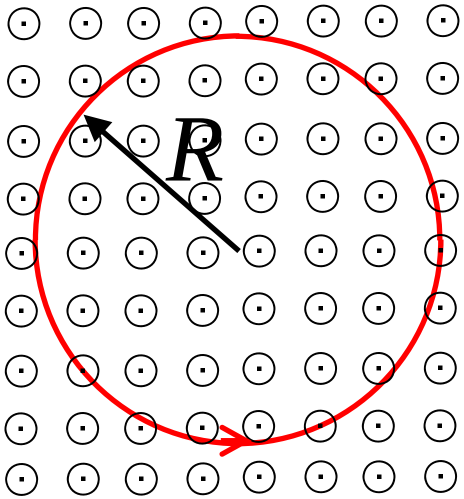


two 'hollow' metallic Dees
B
ion source
D_2
D_1
deflector
accelerated ions
RF-generator



A
O
B
+ -

B (perpendicular)



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

momentum, charge, velocity — of the particle; magnetic field

circular motion:

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

time for one revolution: $T = \frac{2\pi\,R}{v} = 2\pi\frac{m}{q\,B} = const.$

Cyclotron

… in a uniform constant magnetic field:

$$T = 2\pi \frac{m}{q\,B} = const.$$ (for non-relativistic velocities)

cyclotron frequency: $$\omega = \frac{2\pi}{T} = \frac{q}{m} B = const.$$

→ protons up to 15 MeV (β = 0.1)

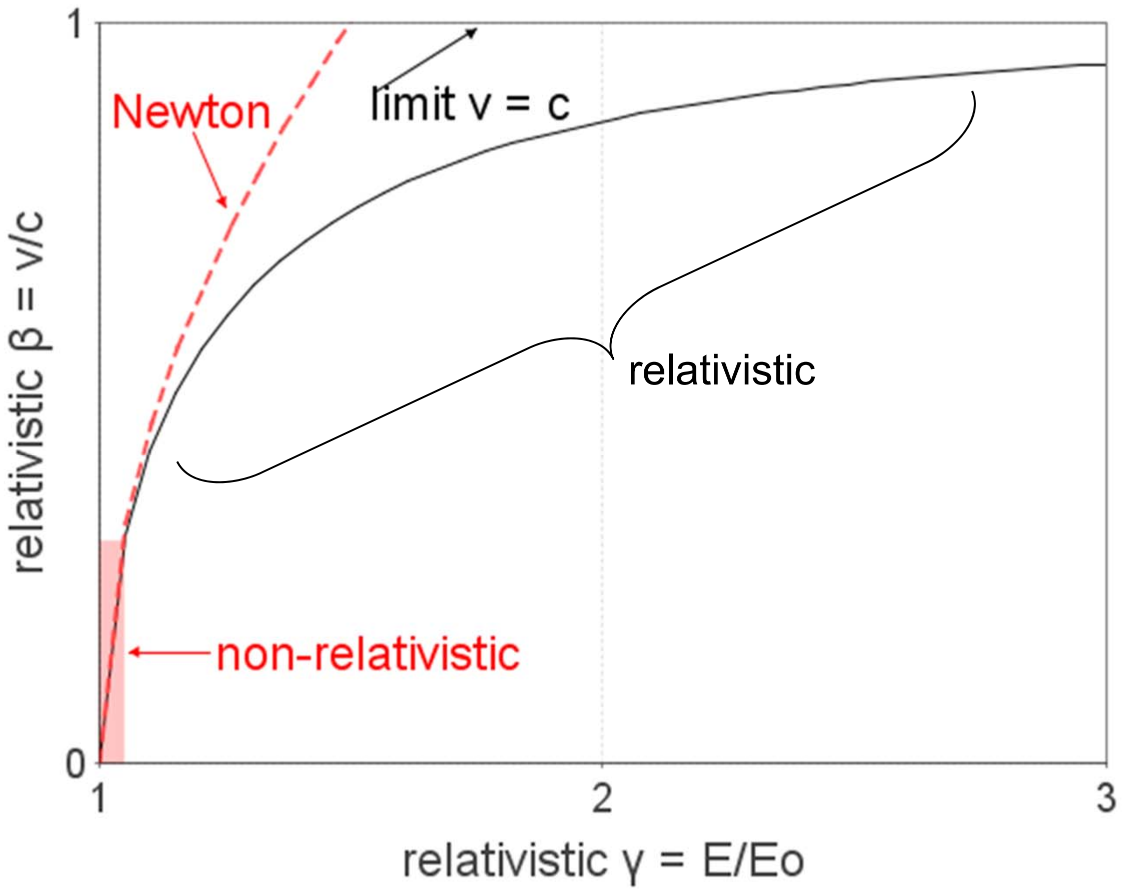
Velocity as function of energy → β as function of γ

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

Einstein:

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

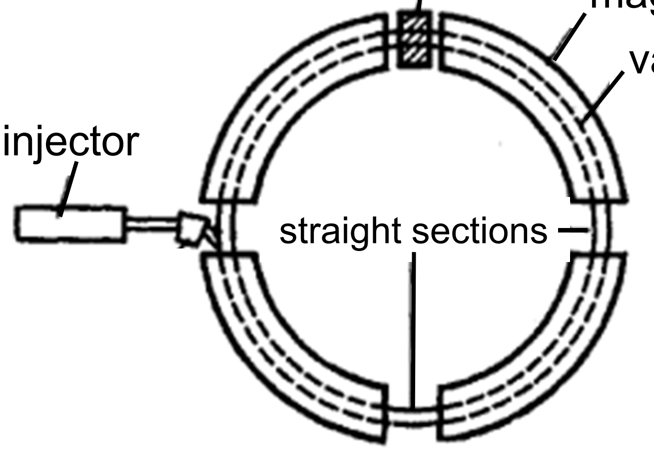
$$\beta = \frac{v}{c}$$



relativistic γ = 3 :
2.8 GeV protron
1.5 MeV electron

Cyclotron at Fermilab, Chicago IL, USA

Circular accelerators

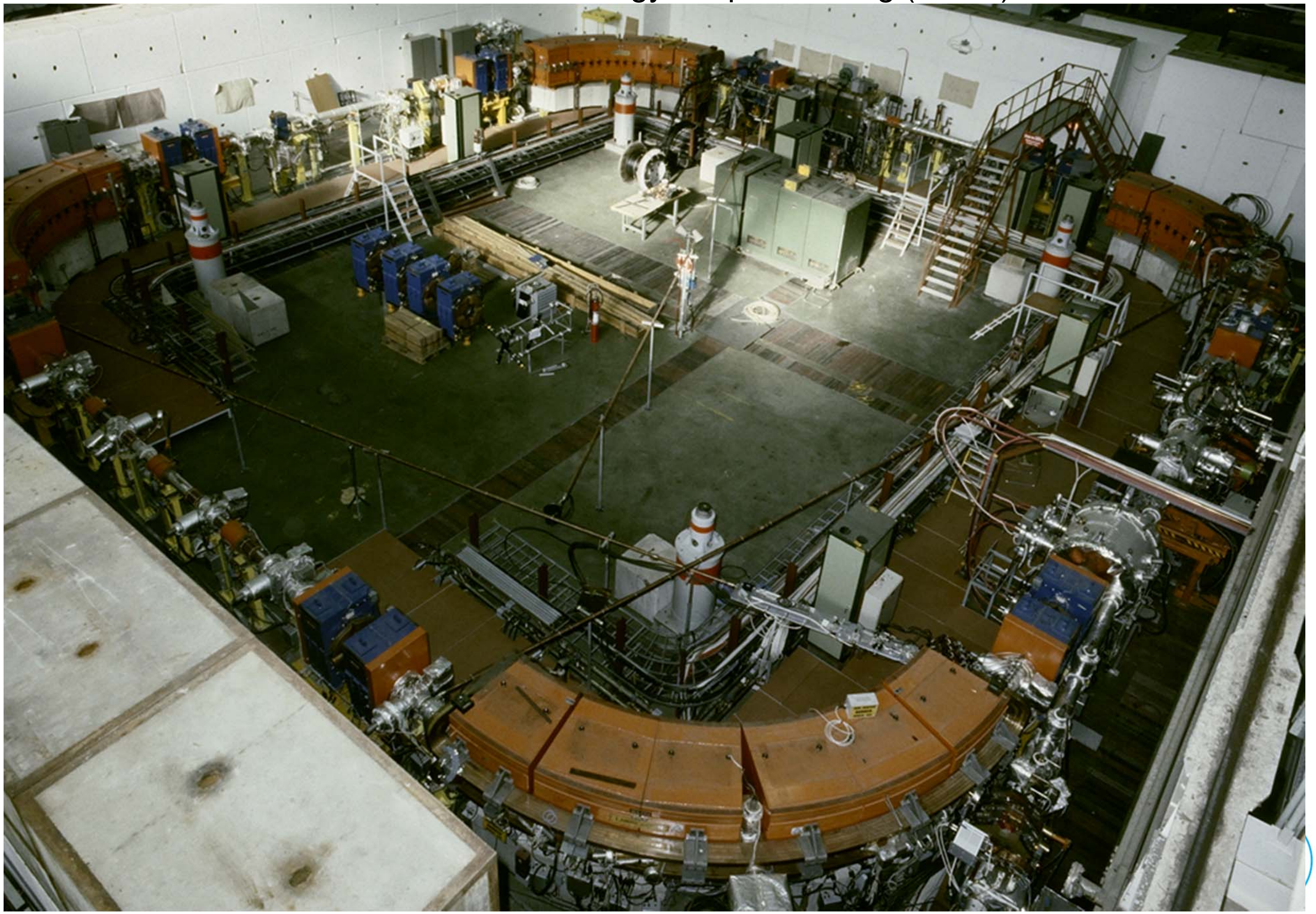


$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = q\,v\,B = m\frac{v^2}{R} \quad \Rightarrow \quad R = \frac{m\,v}{q\,B}$$

synchrotron: R is constant,
→ increase B synchronously with E of particle

Circular accelerators

Low Energy Antiproton Ring (LEAR) at CERN

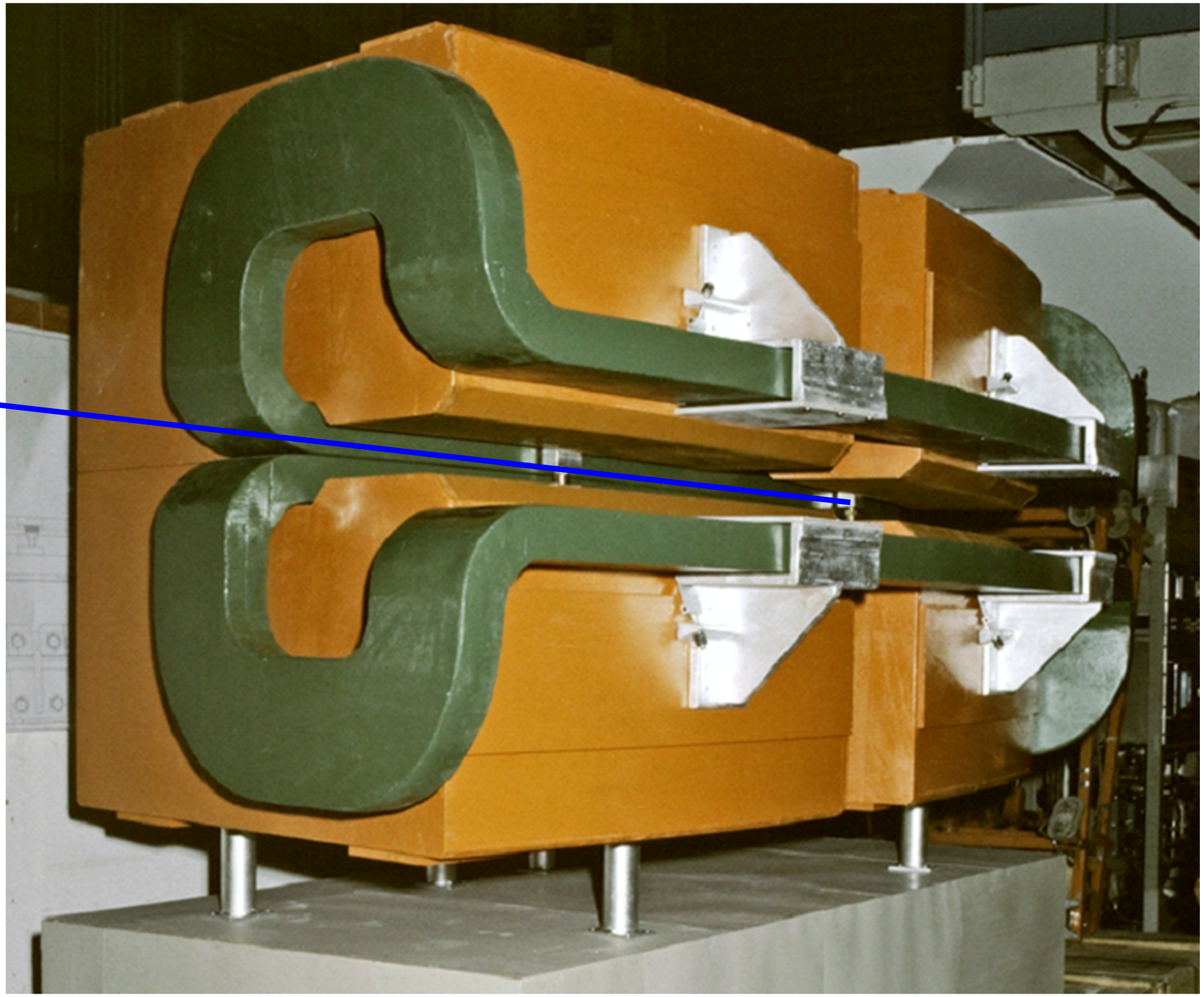


DESY (Deutsches Elektronen Synchrotron)

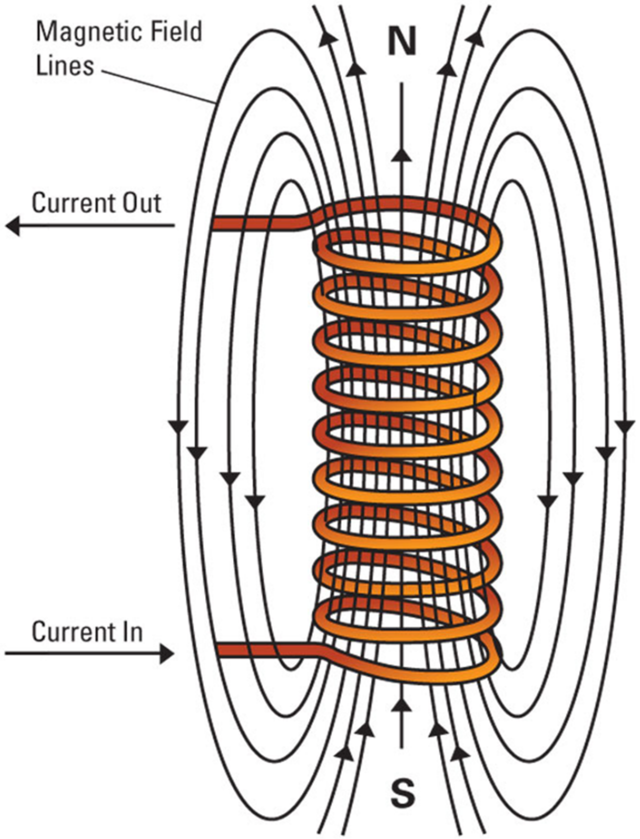
DESY: German electron synchrotron, 1964, 7.4 GeV

Dipole magnet

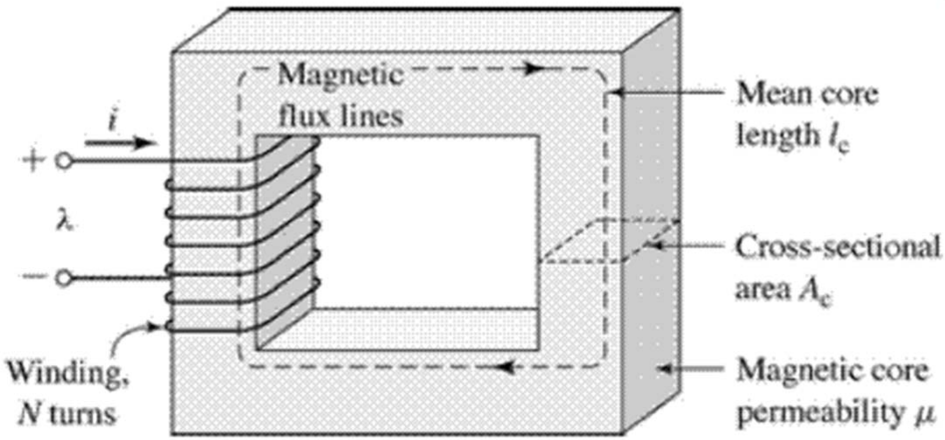
beam



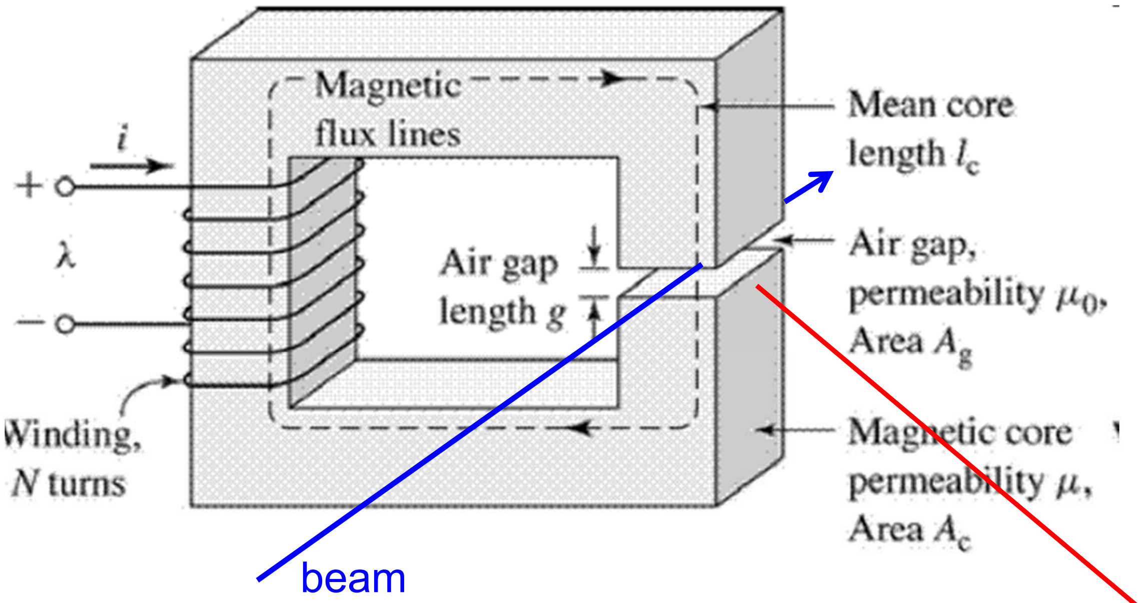
Electromagnet

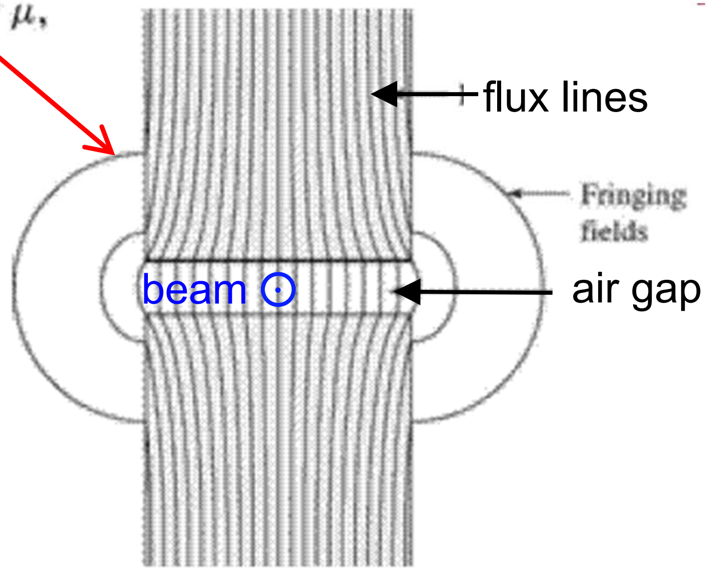


permeability of iron = 300…10000 larger than air



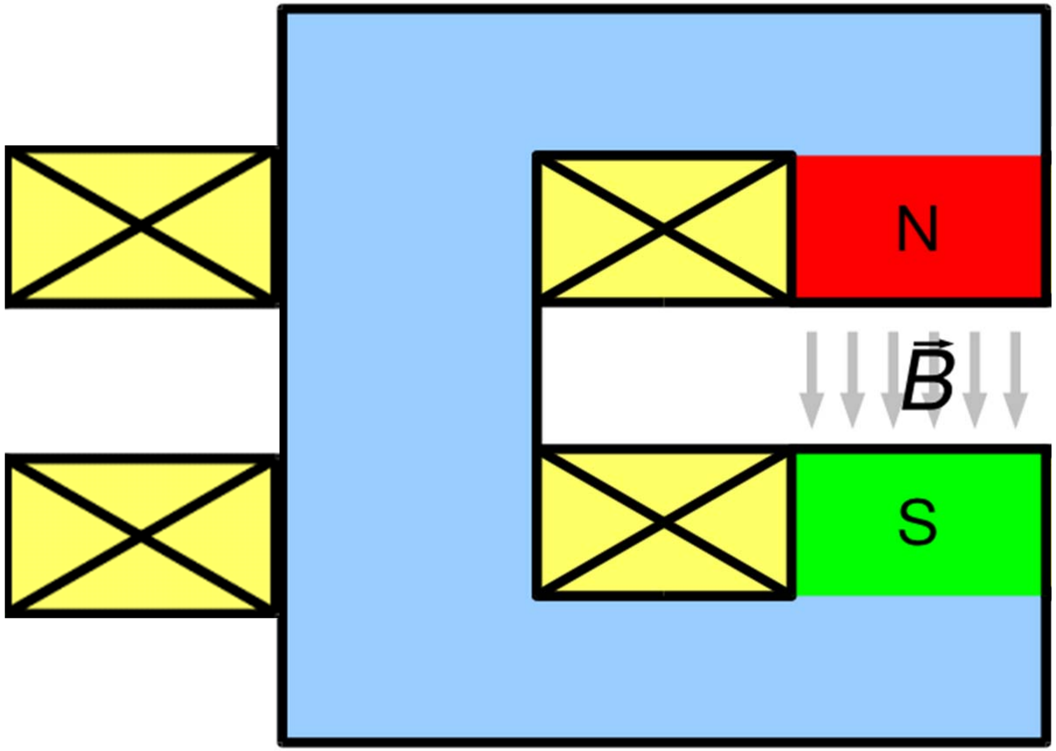
Dipole magnet





DESY

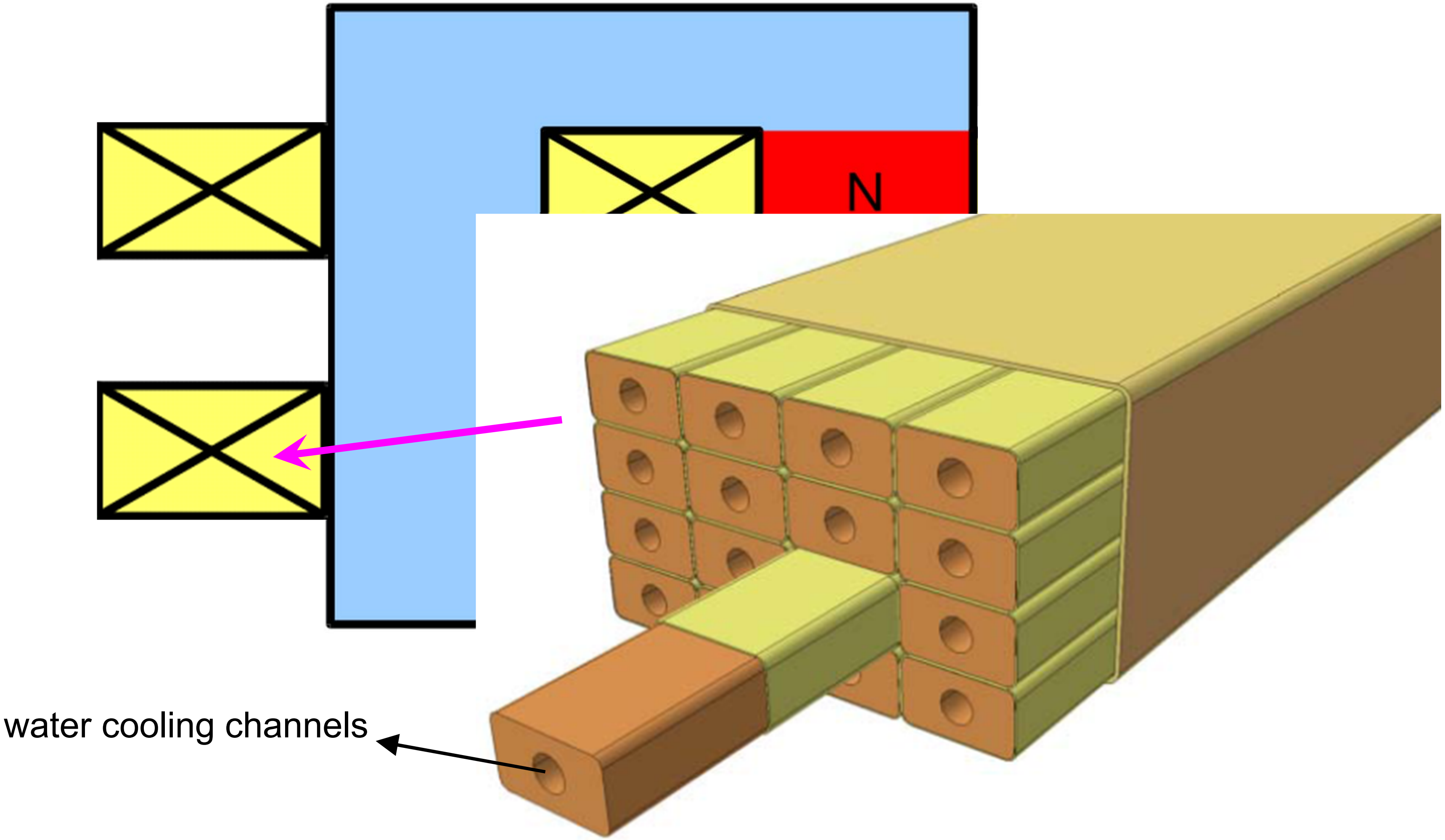
Dipole magnet cross section



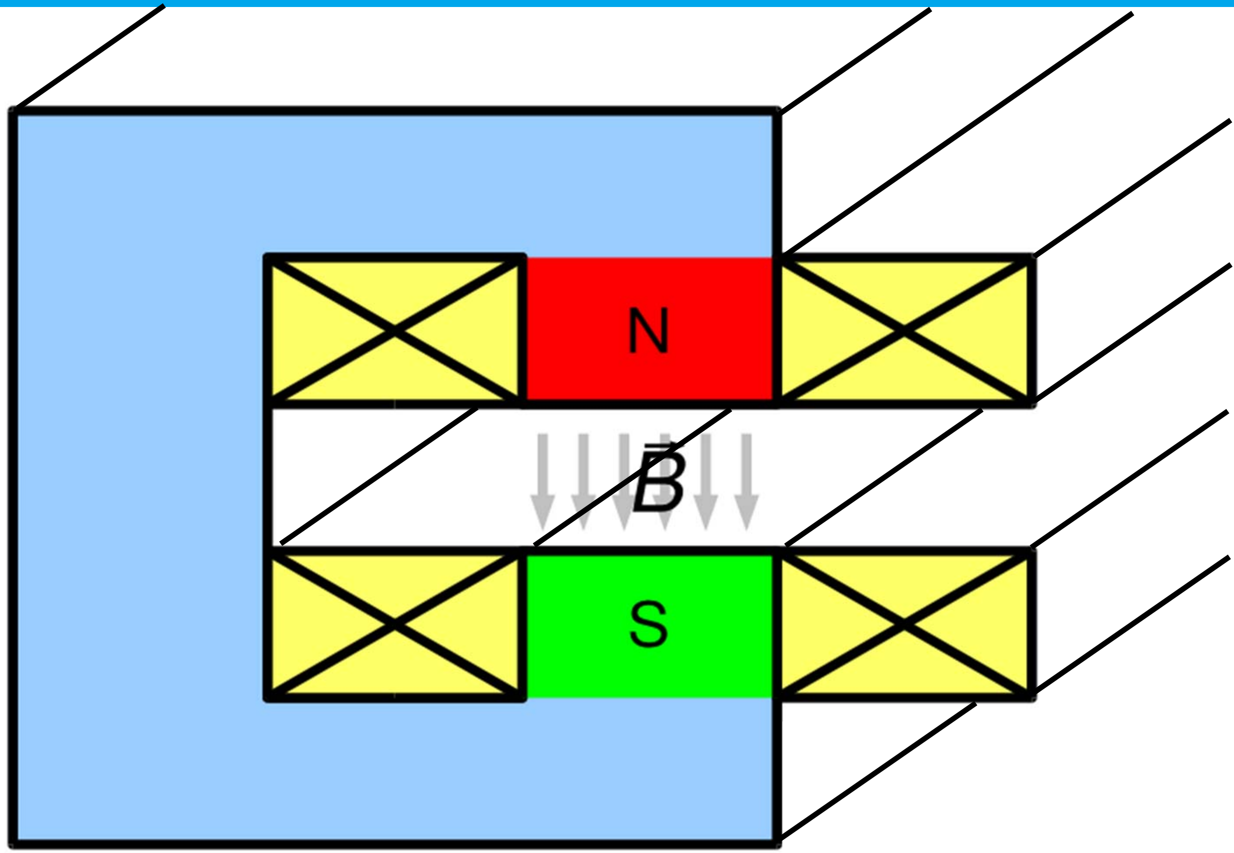
Max. B ➔ max. current ➔ large conductor cables

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

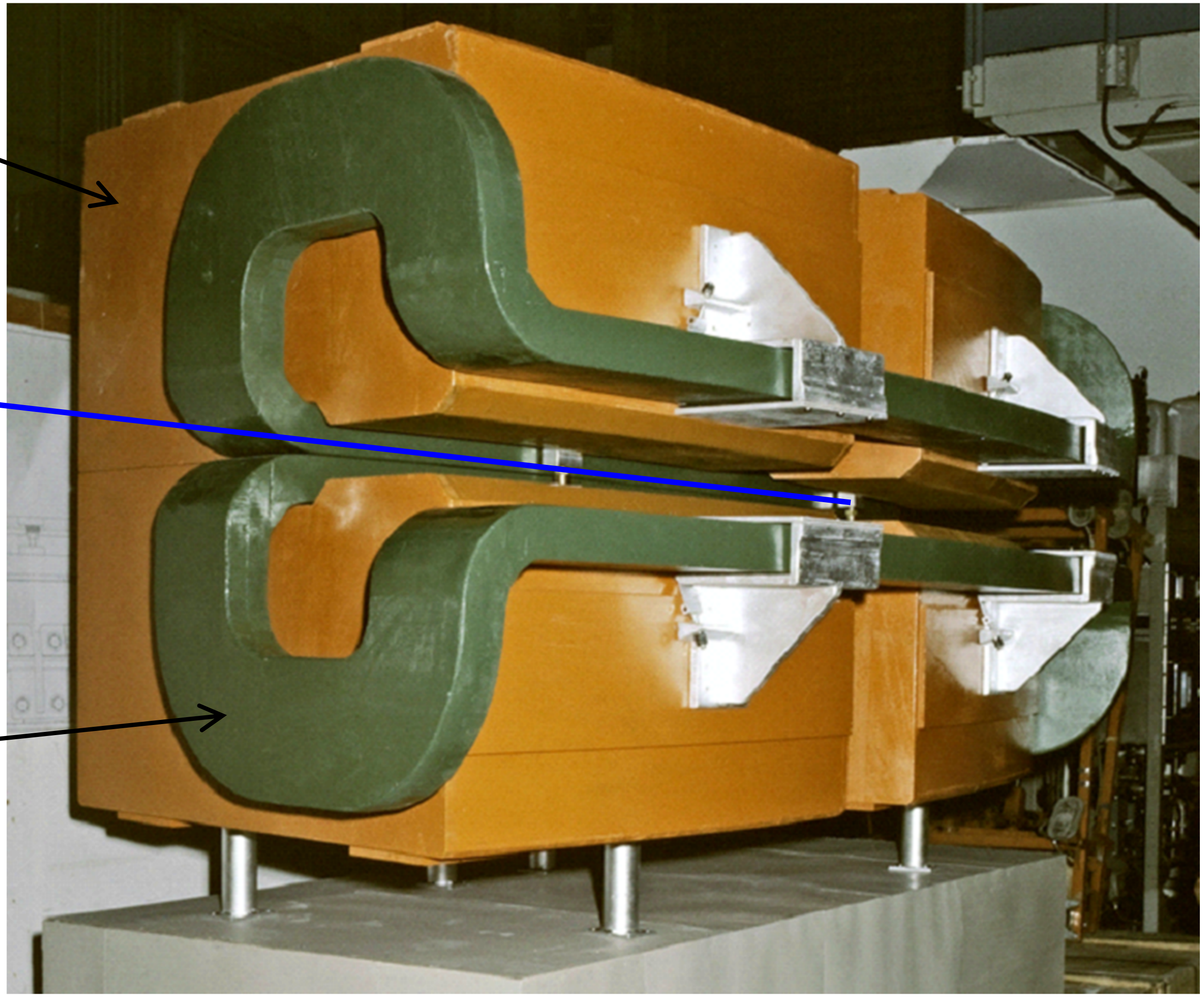
Dipole magnet cross section



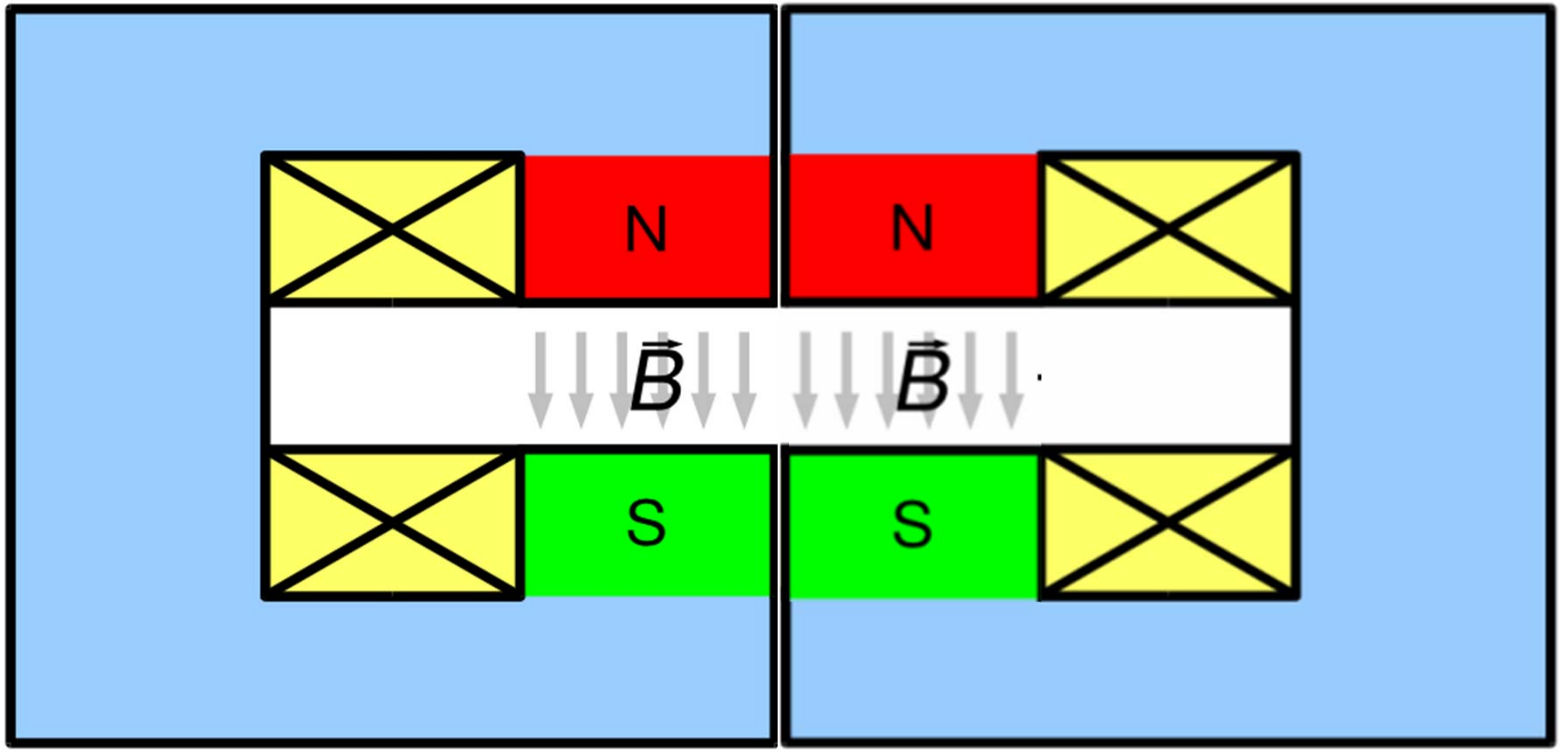
Dipole magnet cross section



Dipole magnet

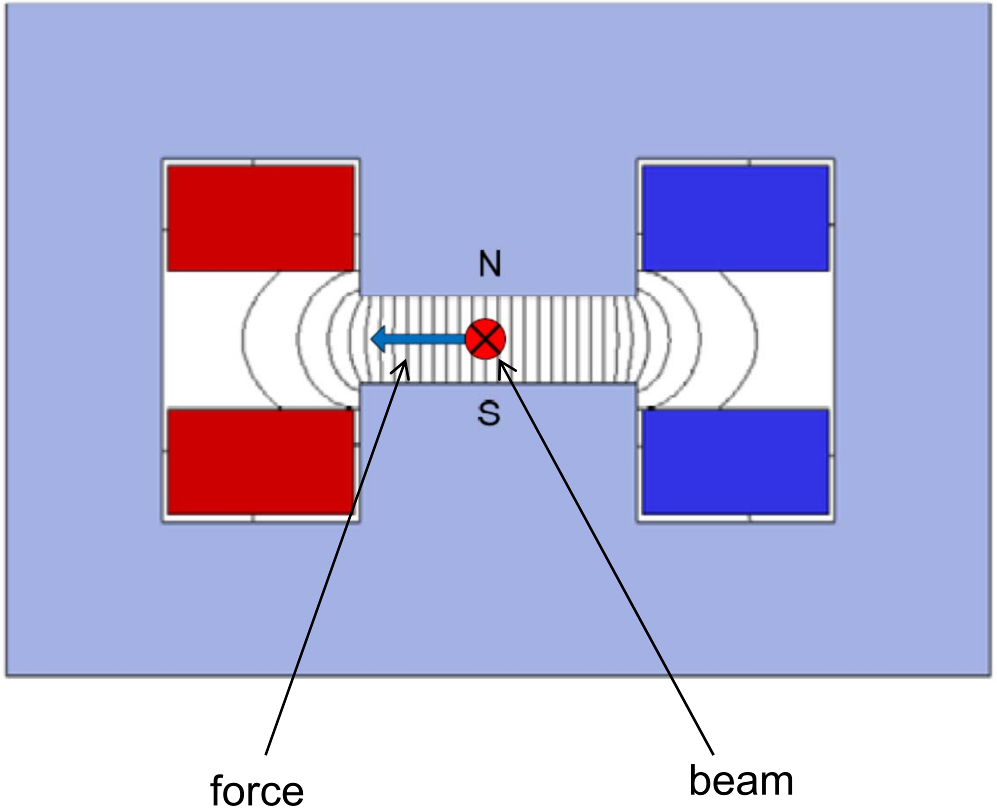


Dipole magnet cross section

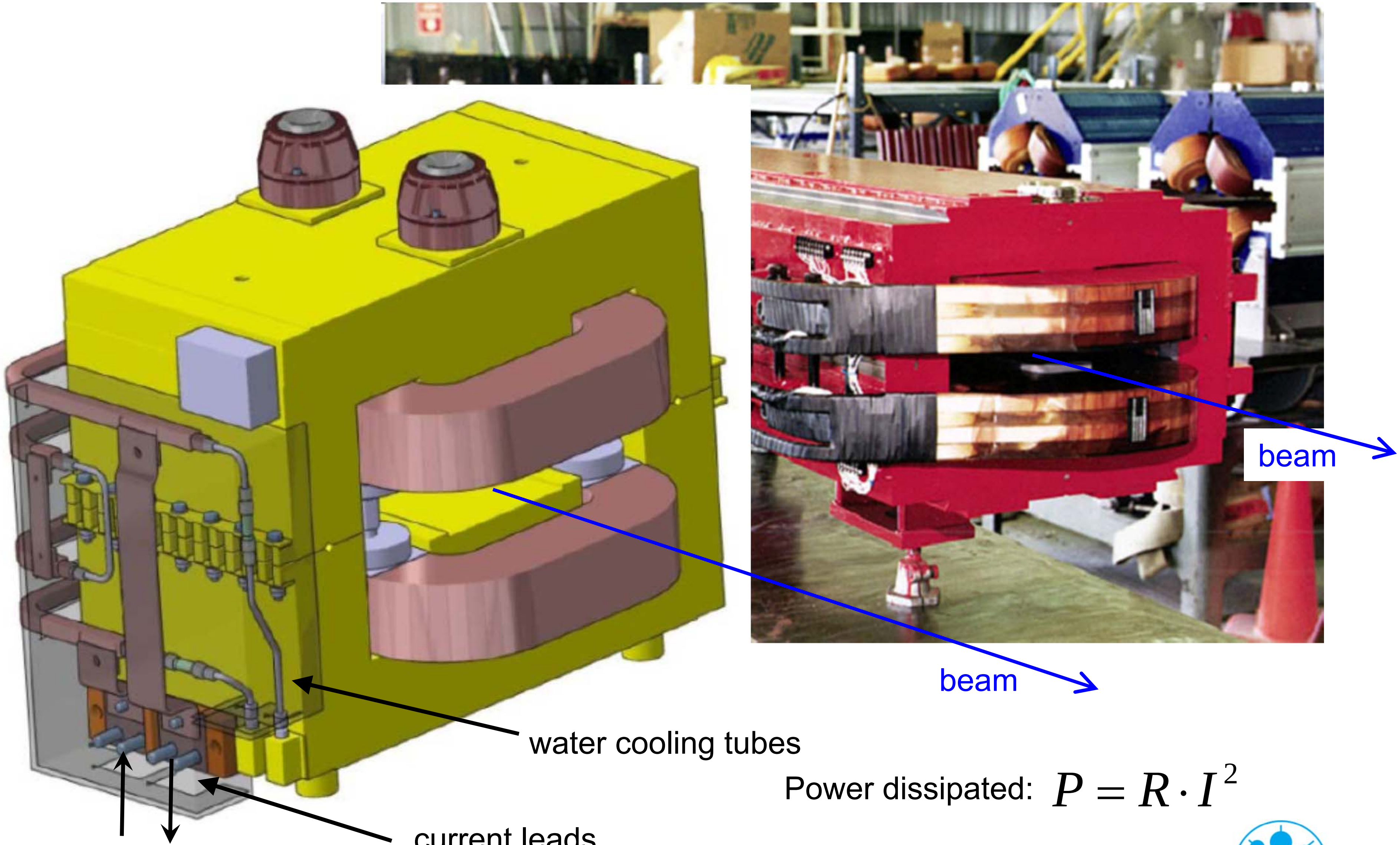


C magnet + C magnet = H magnet

Dipole magnet cross section (another design)



Dipole magnet cross section (another design)

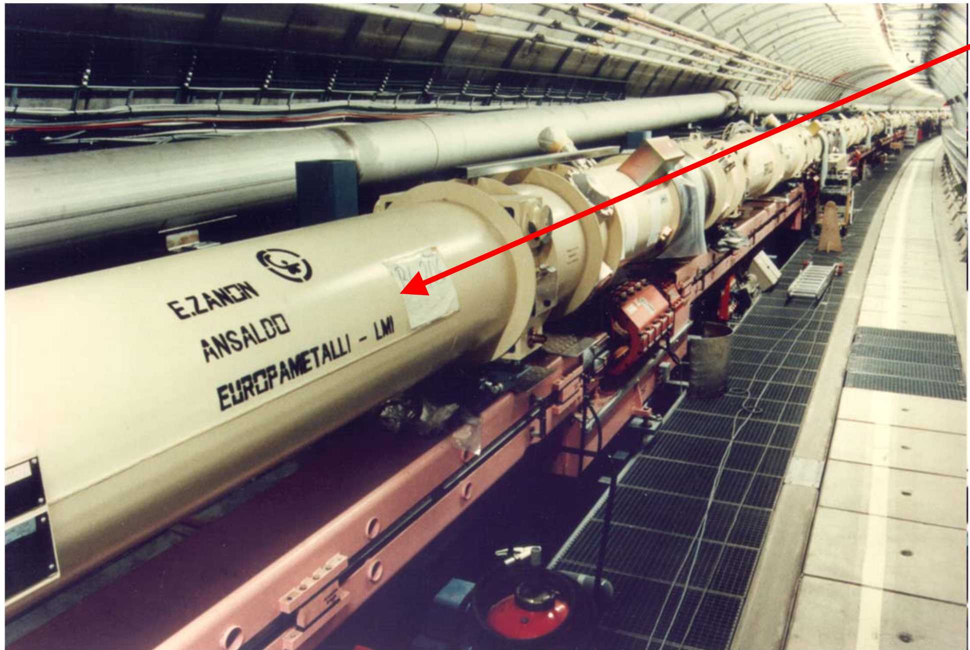


Power dissipated: $P = R \cdot I^2$

Superconducting dipole magnets

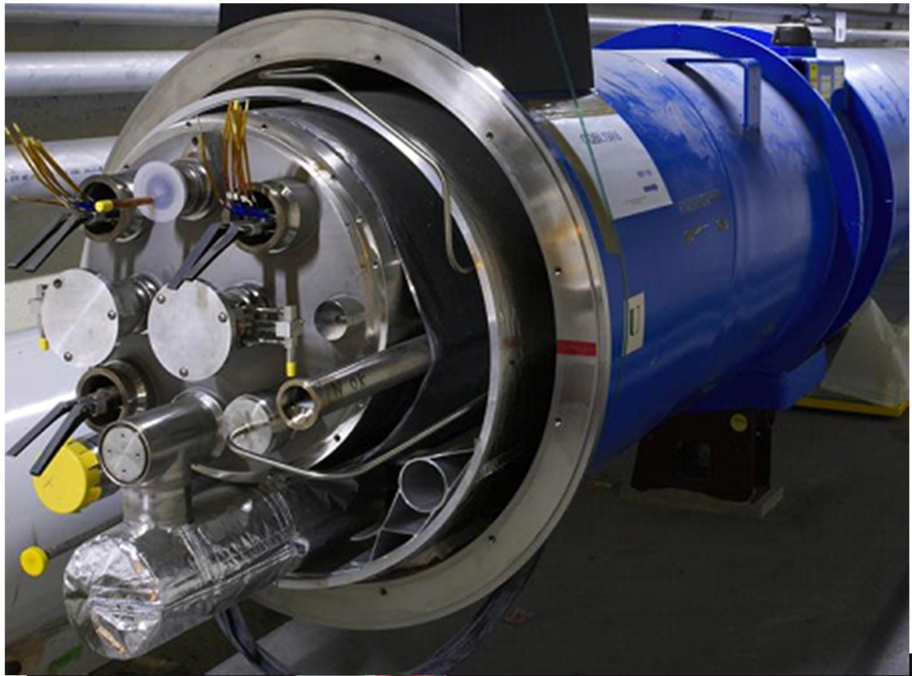
LHC

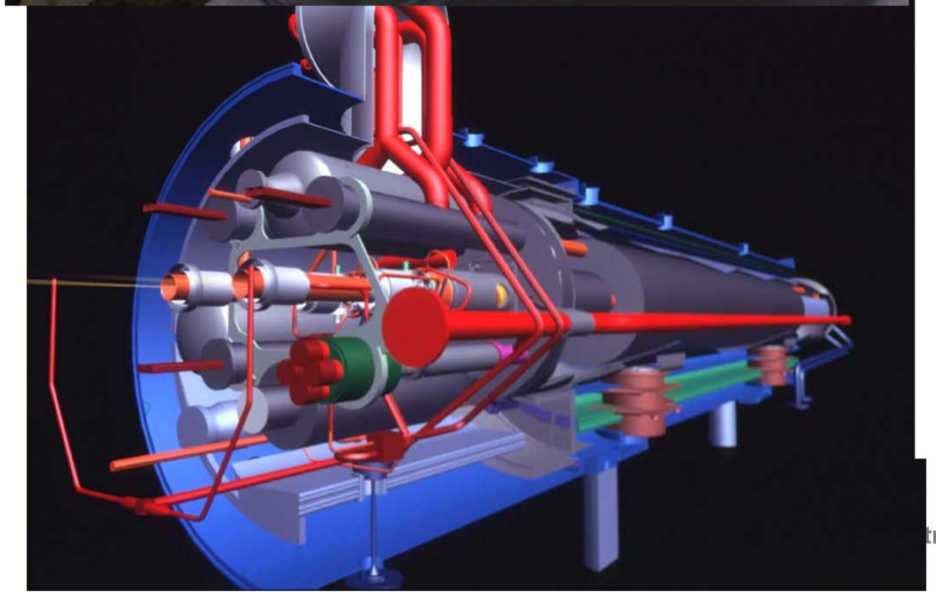
superconducting dipoles

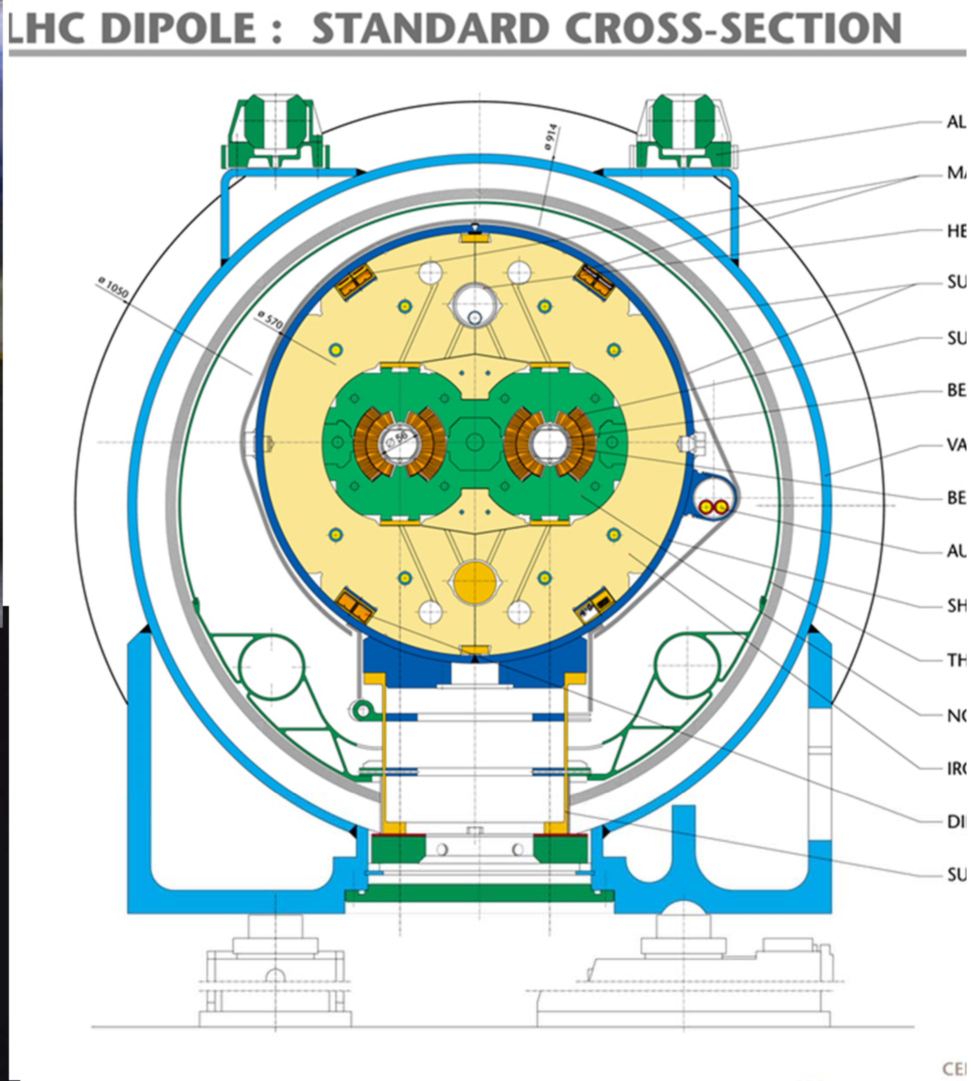


HERA

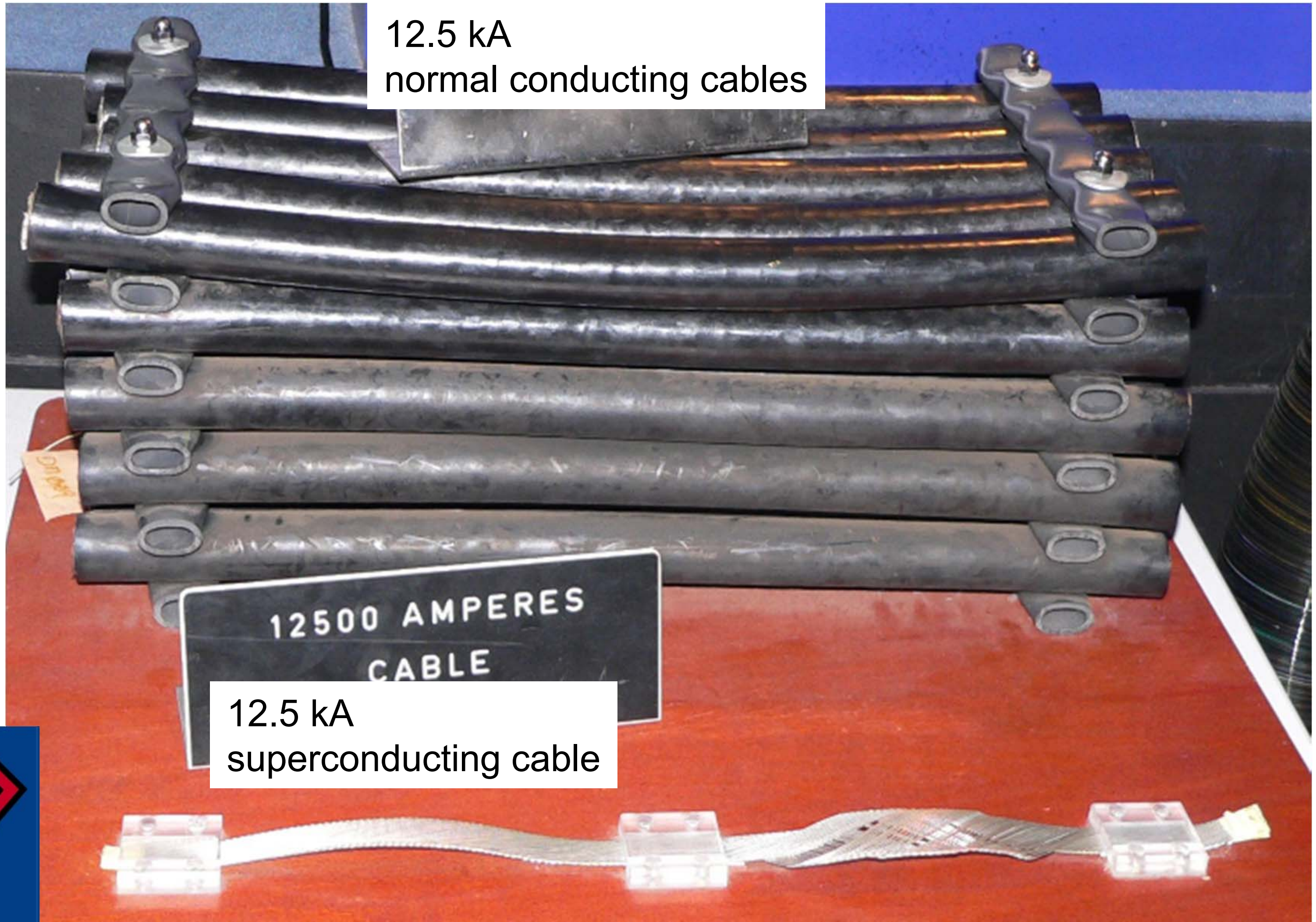
Superconducting dipole magnets





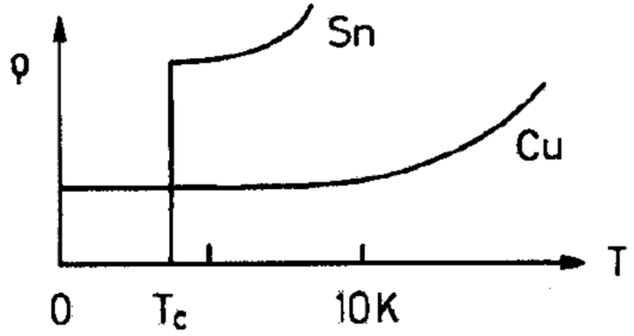


Superconductivity



Superconductivity

resistance



critical temperature (Tc):

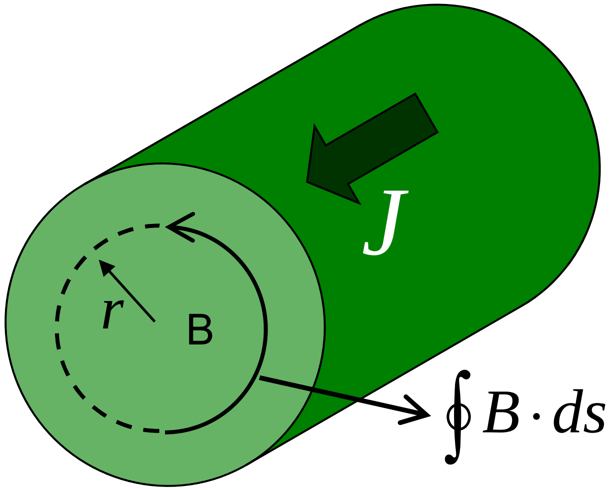
Dipole field from 2 conductors

J = uniform current density

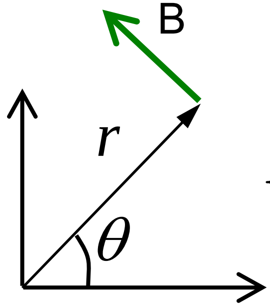
Ampere's law:

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

current through the circle



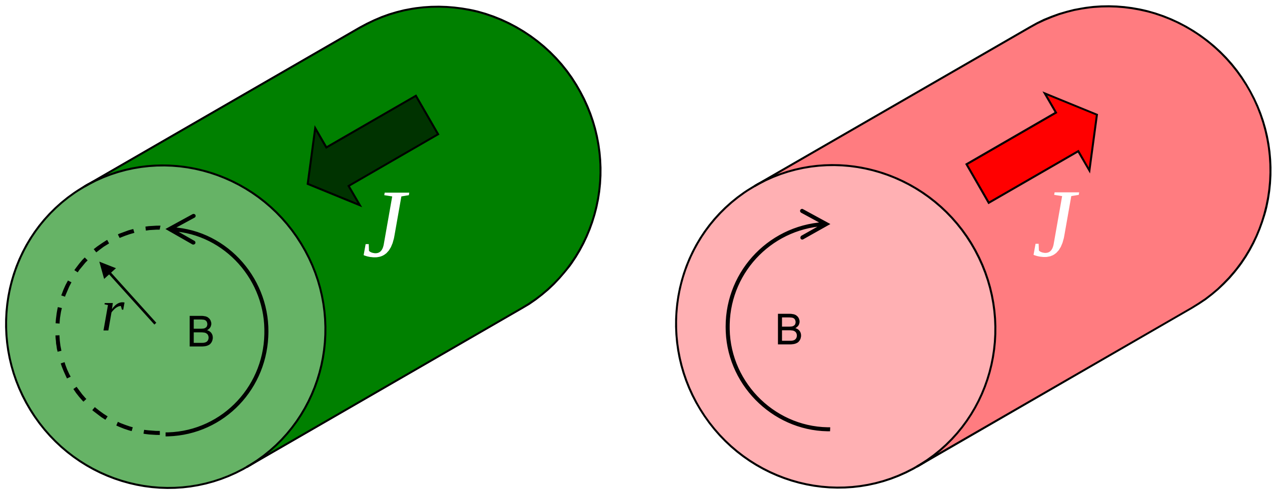
$$\oint B \cdot ds = 2\pi r B = \mu_0 \pi r^2 J \quad \rightarrow \quad B = \frac{\mu_0 J}{2} r$$



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

Dipole field from 2 conductors

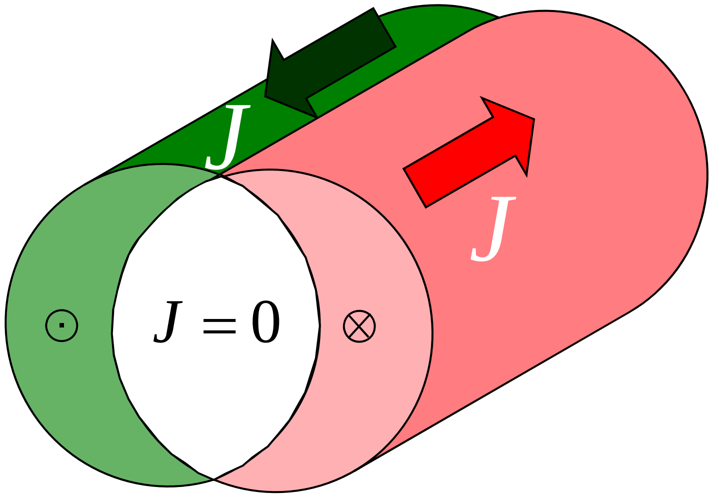
J = uniform current density



Dipole field from 2 conductors

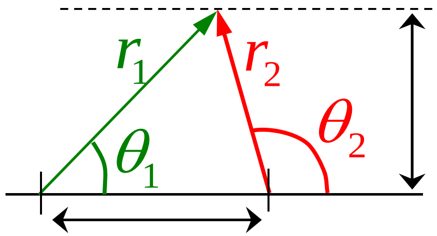
$$J = \text{uniform current density}$$

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



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

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

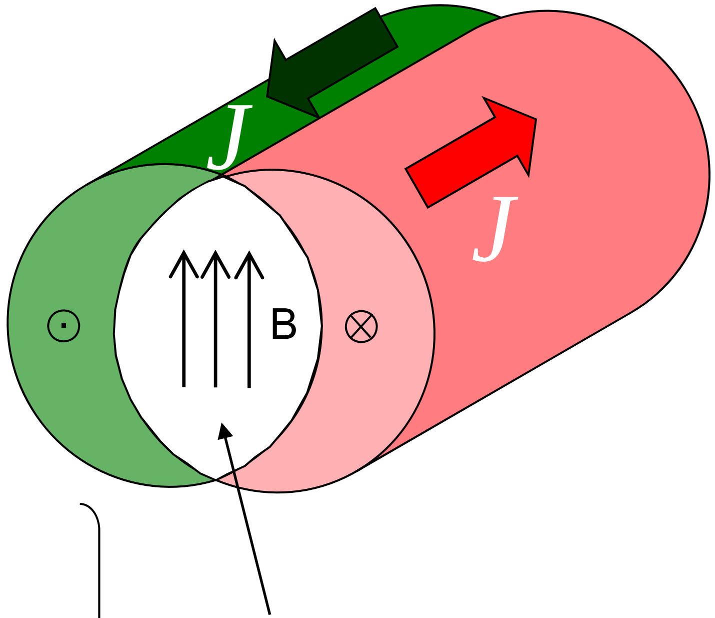


$$h = r_1 \sin\theta_1 = r_2 \sin\theta_2$$

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

Dipole field from 2 conductors

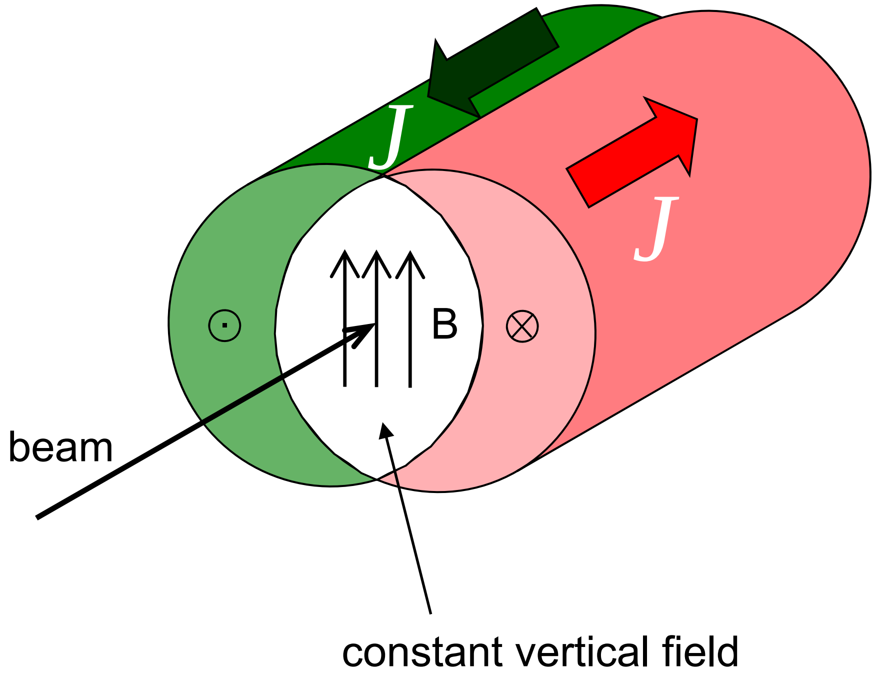
J = uniform current density



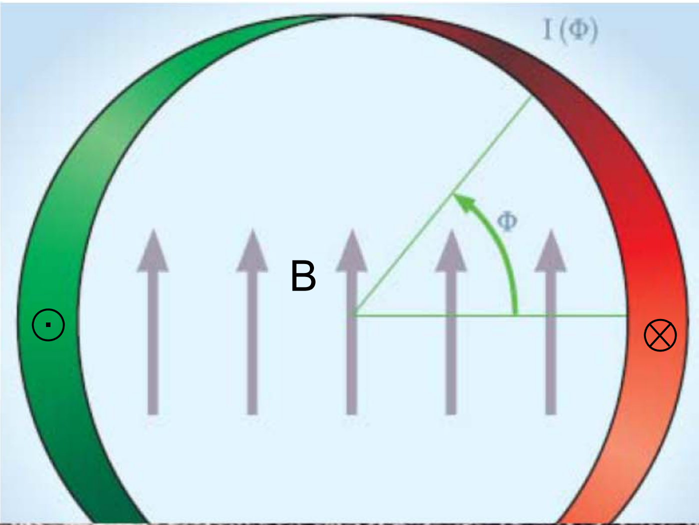
$$B_x = \frac{\mu_0 J}{2}(r_1 \sin\theta_1 - r_2 \sin\theta_2) = 0$$

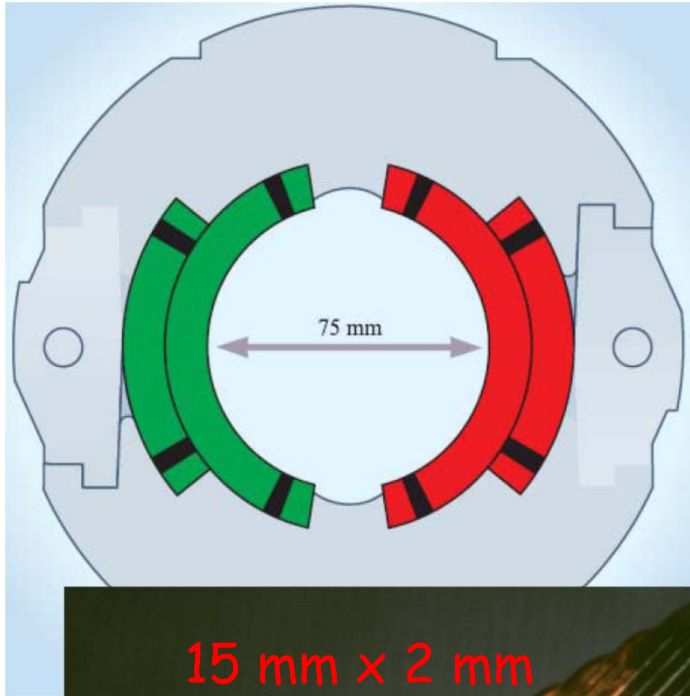
$$B_y = \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2) = \frac{\mu_0 J}{2} d$$

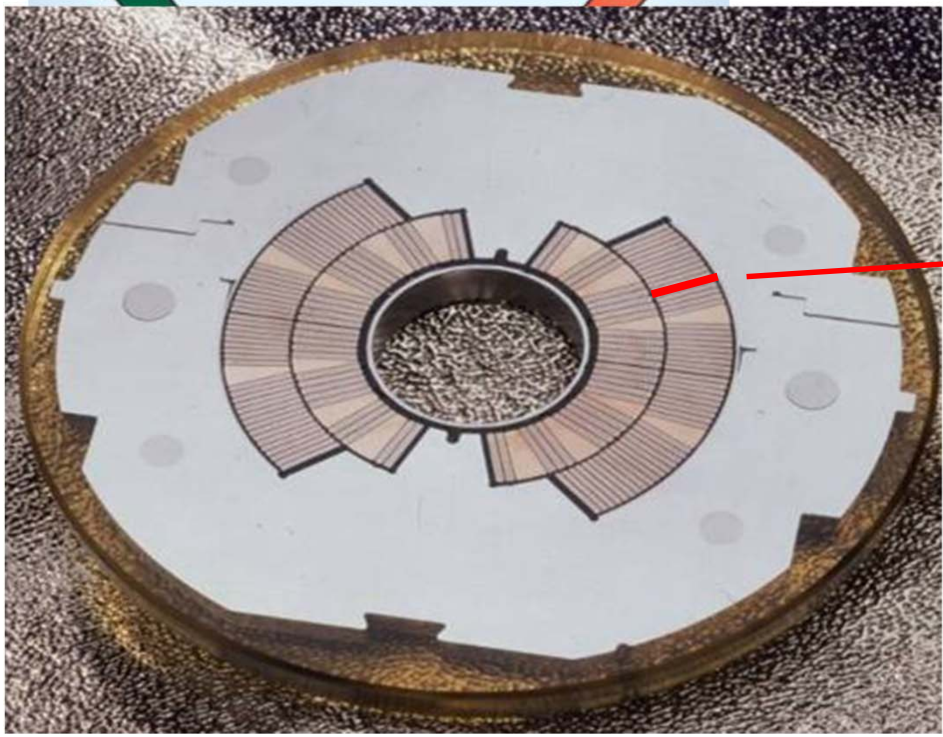
Dipole field from 2 conductors

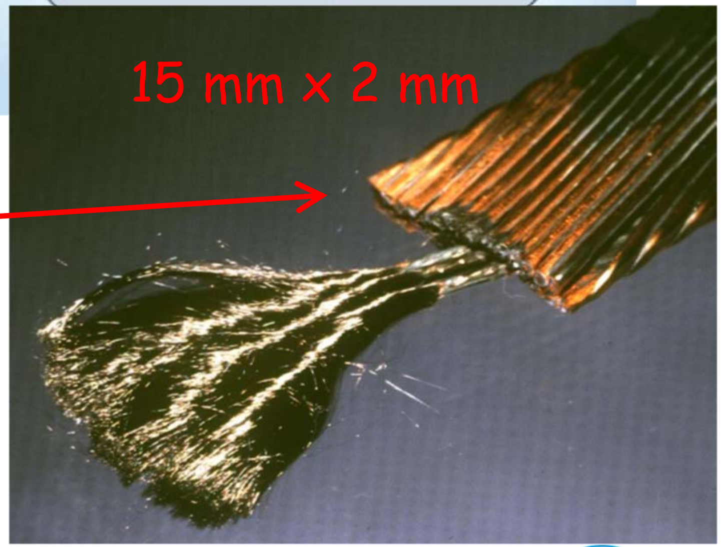


From the principle to the reality…



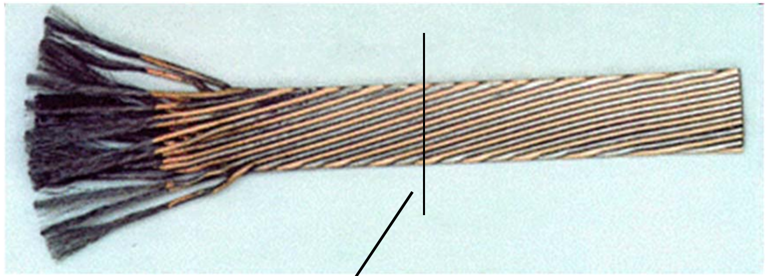






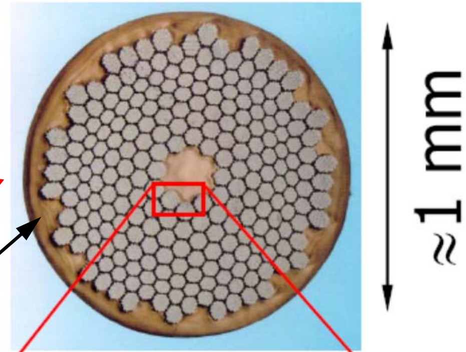
LHC cables

1 cable houses 36 strands



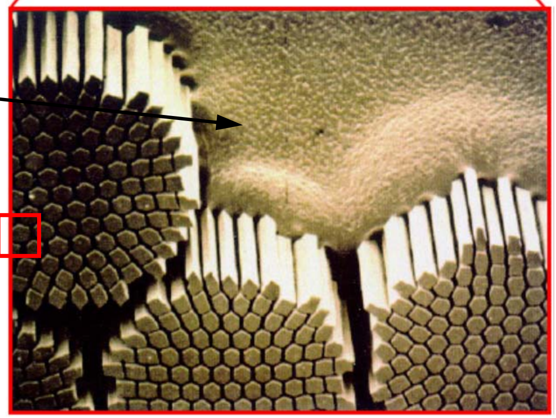
cross section

1 strand = 0.825 mm diameter
houses 6300 filaments



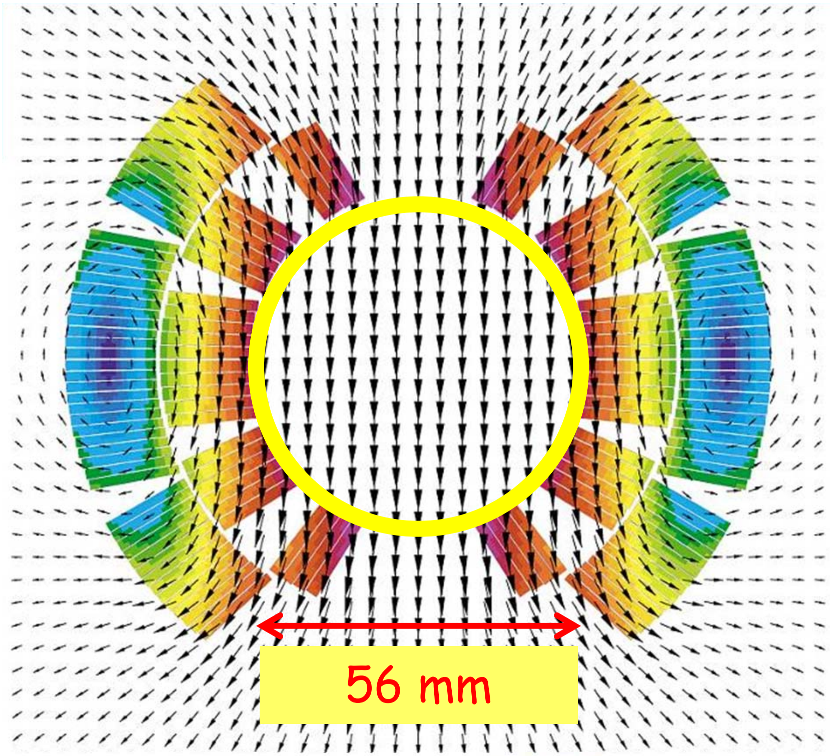
Copper is the insulation material
between two filaments

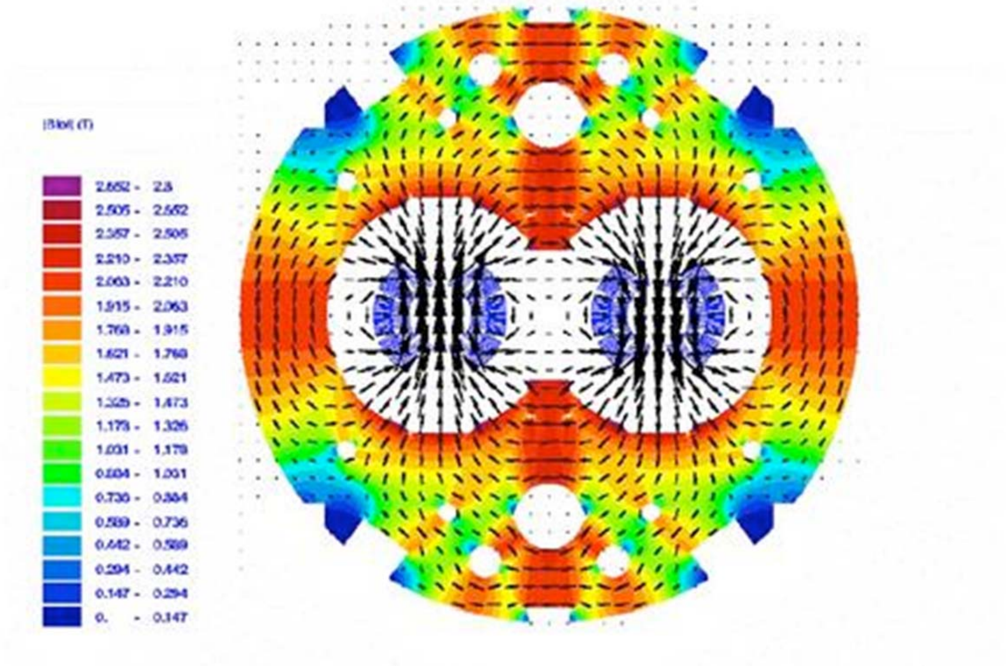
(around each filament: 0.5 μm Cu)

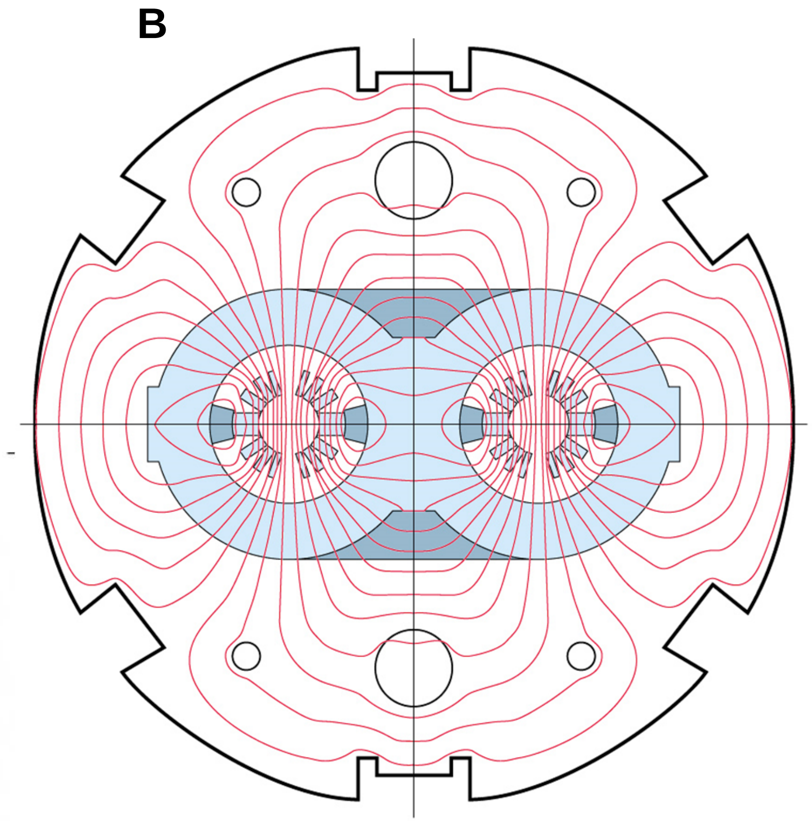


1 filament = 6 μm

Computed magnetic field

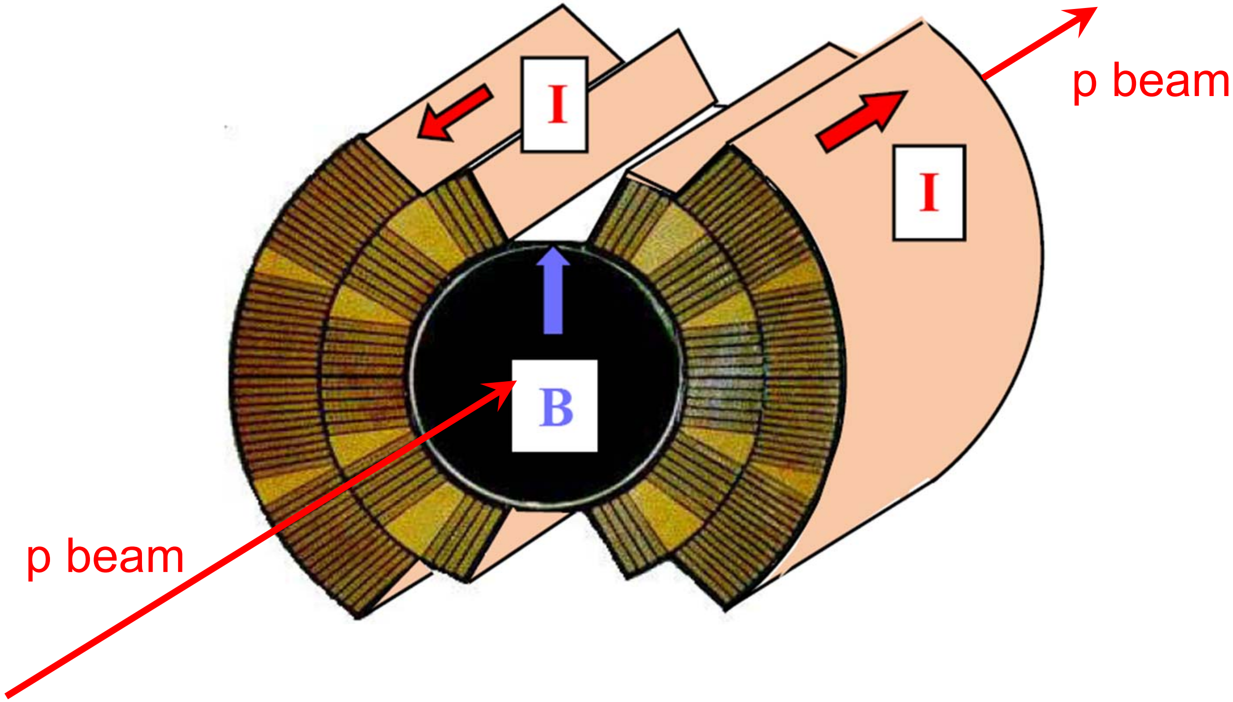




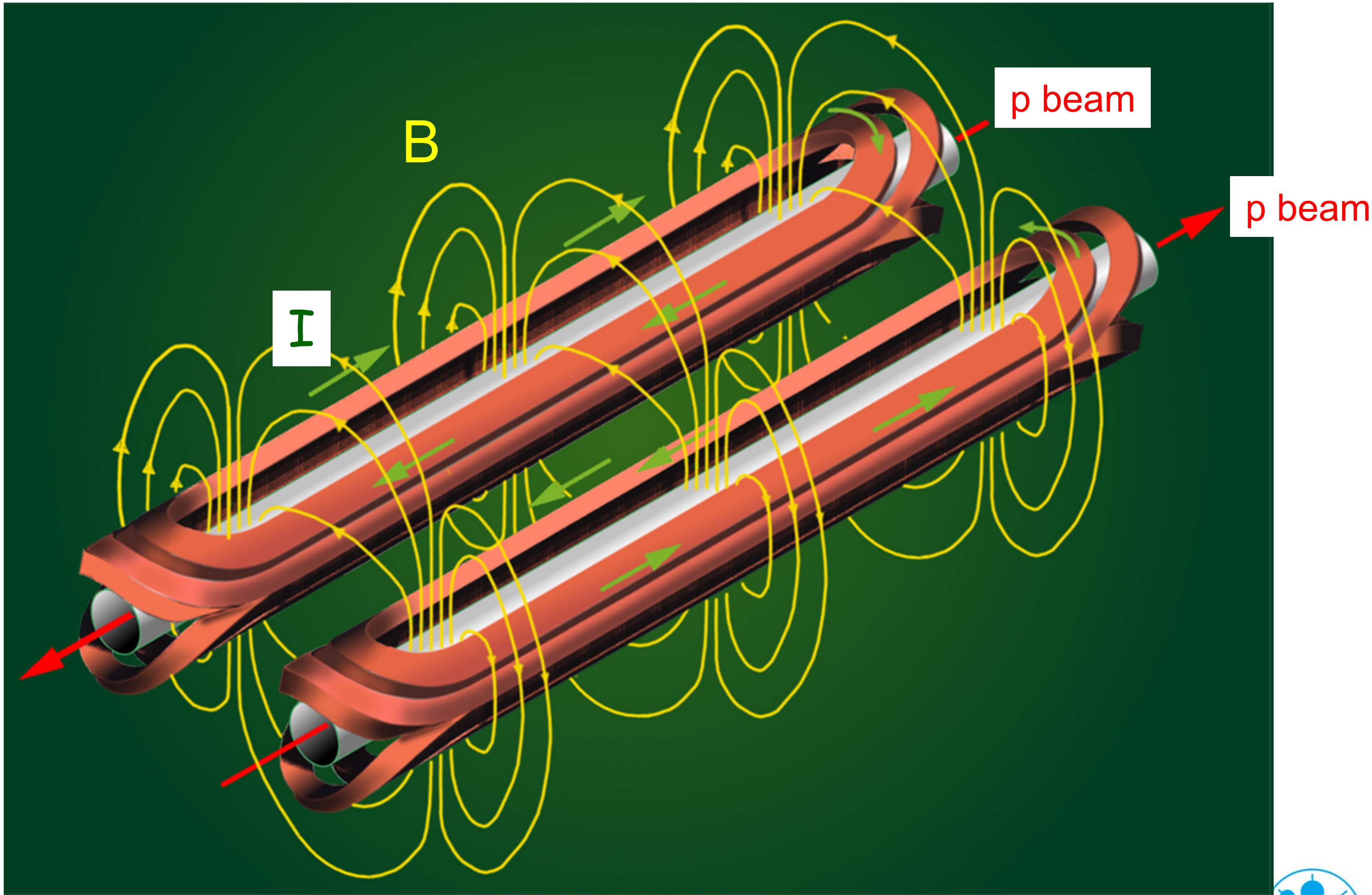


Computed magnetic flux map

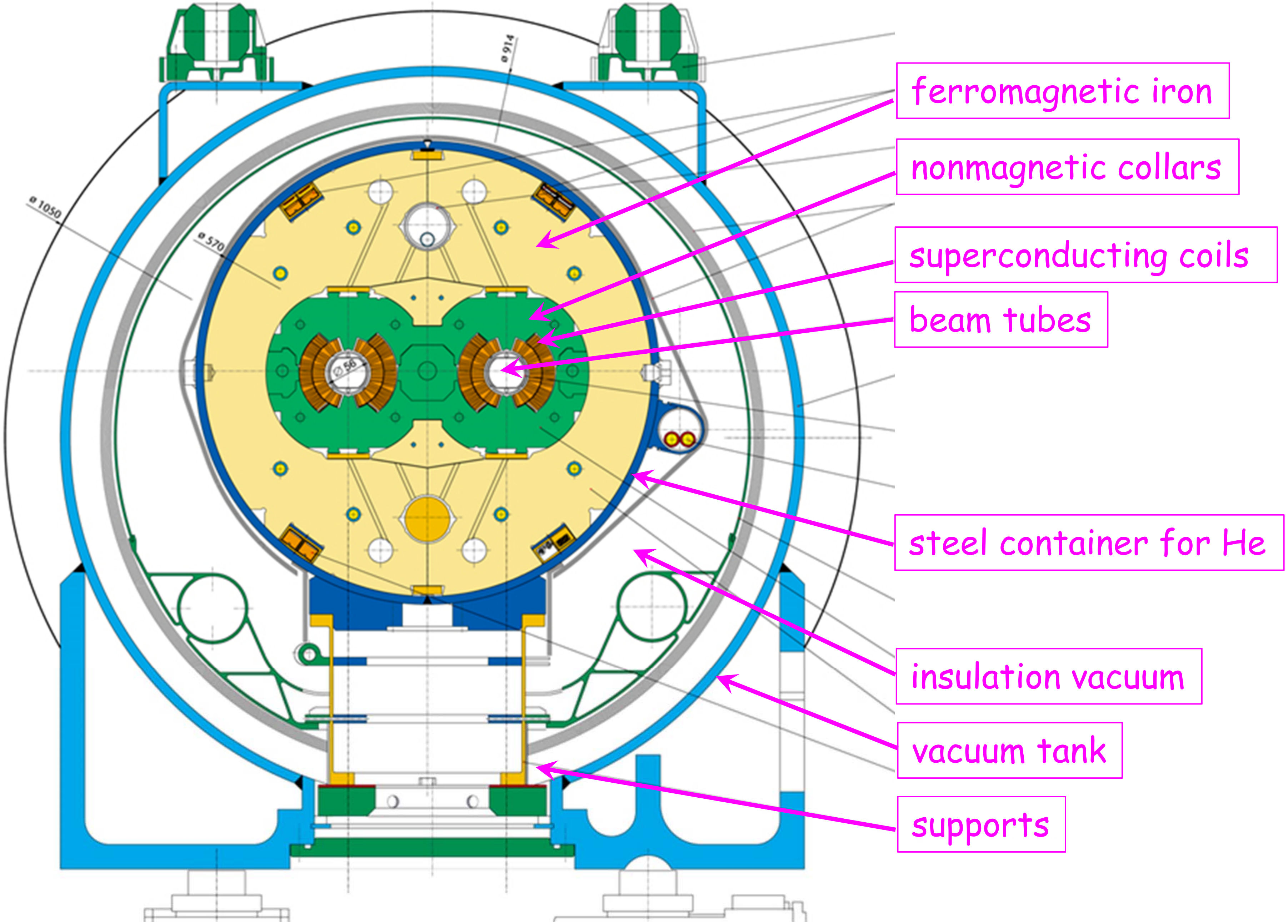
LHC dipole coils in 3D



LHC dipole coils in 3D

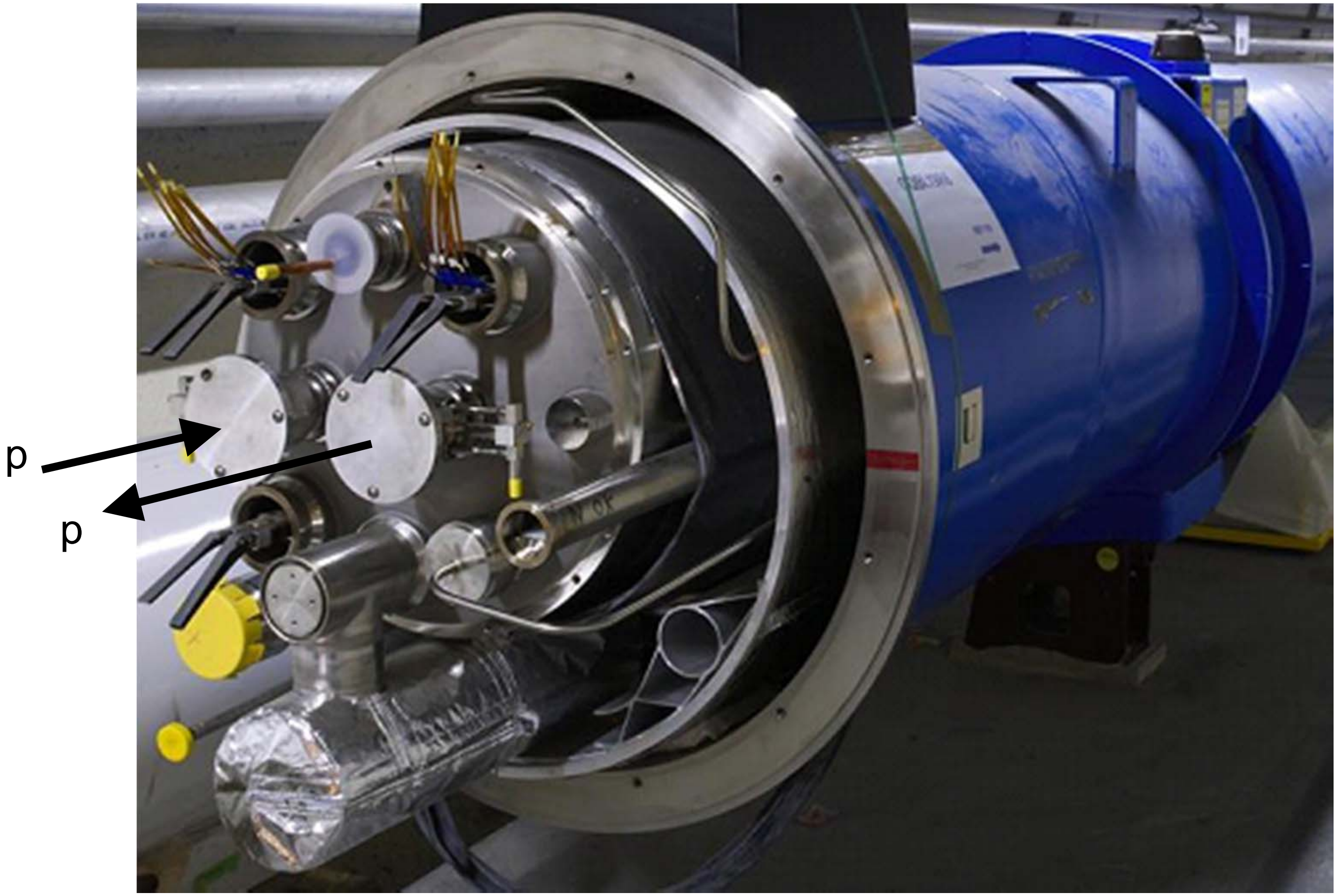


LHC DIPOLE : STANDARD CROSS-SECTION



Superconducting dipole magnets

LHC dipole magnet interconnection:



Second summing-up

Linear accelerators:

- Alvarez drift-tube structure

Circular accelerators:

- Cyclotron, E. Lawrence
- Synchrotron

Dipole magnets:
- normal conducting dipoles
- superconducting dipoles