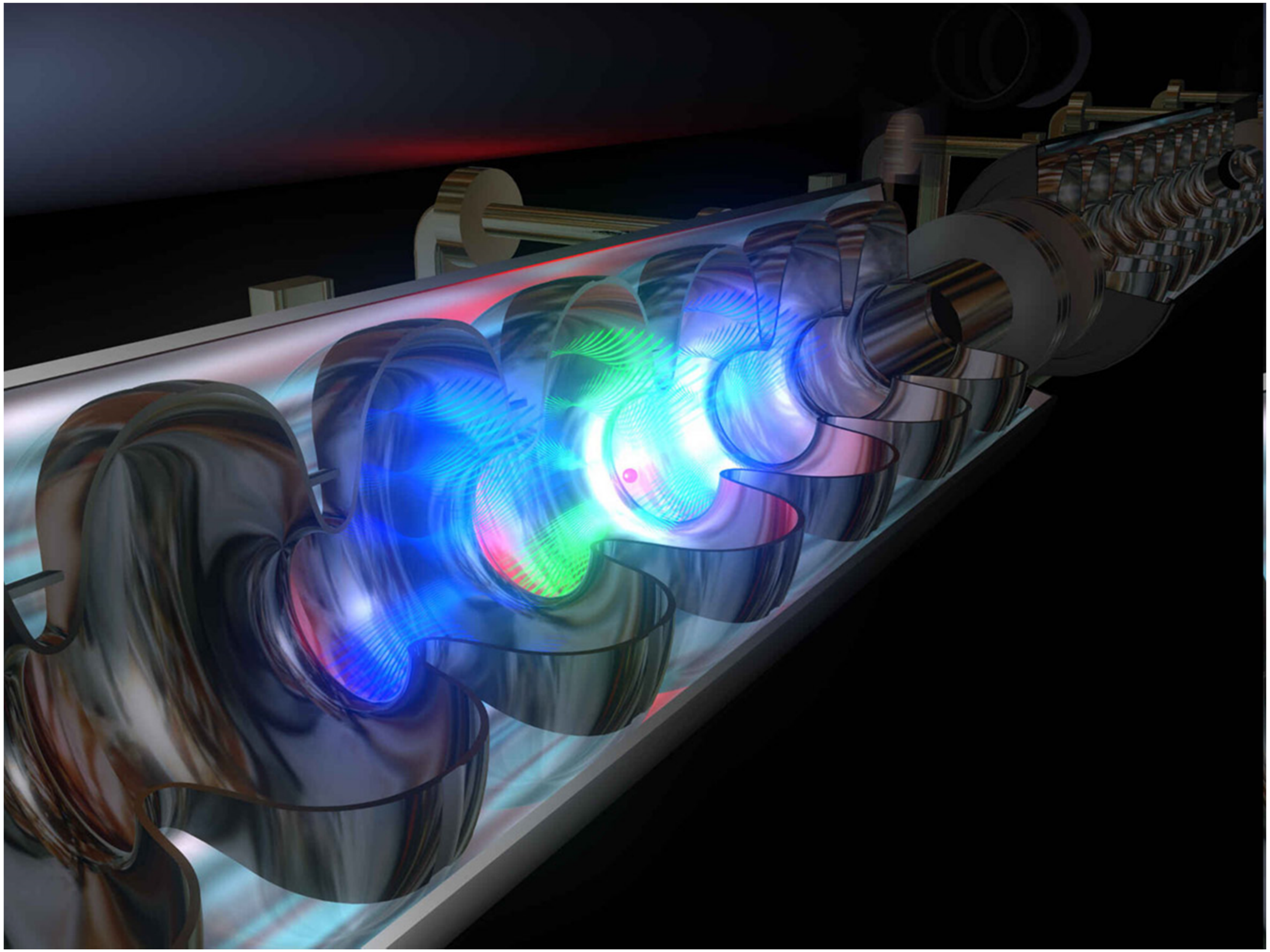
Colliders – part 1

Accelerator physics - Colliders

Pedro Castro / Accelerator Physics Group (MPY)
Introduction to Accelerator Physics
DESY, 30th July 2012

How electromagnetic fields accelerate particles

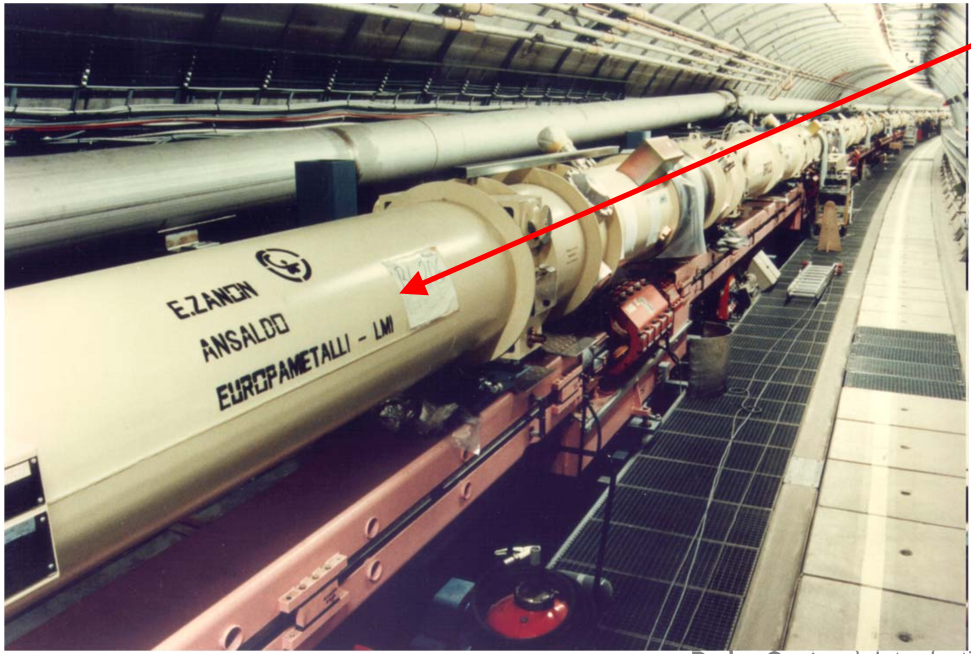


Why we need superconducting magnets

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:

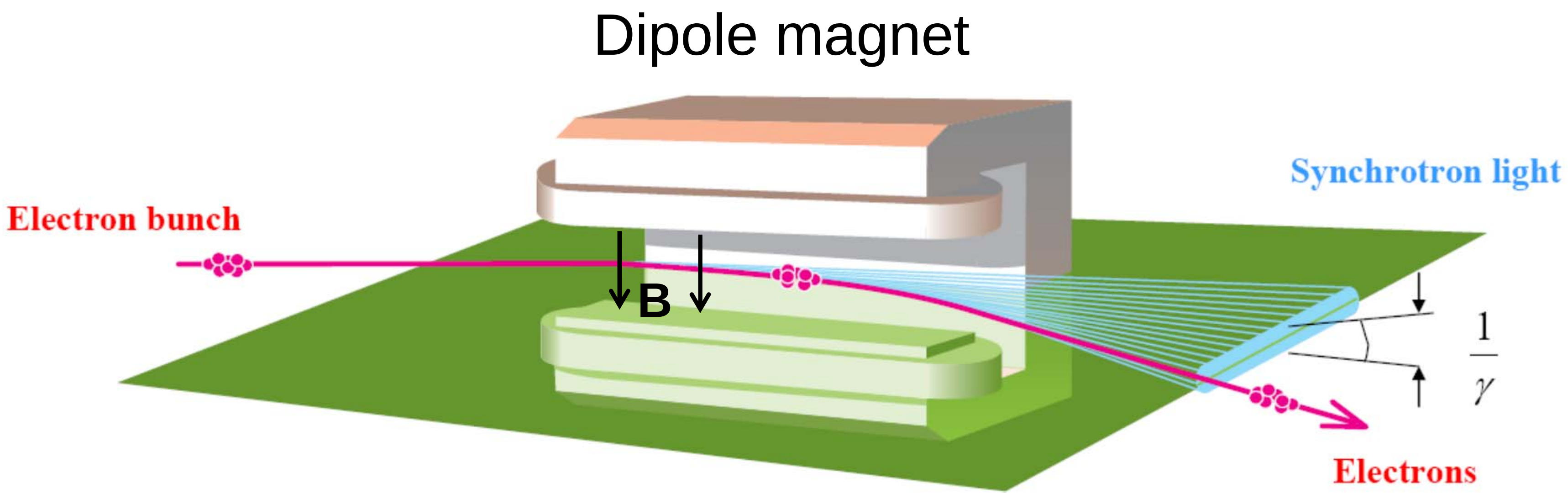
proton accelerator

920 GeV

electron accelerator

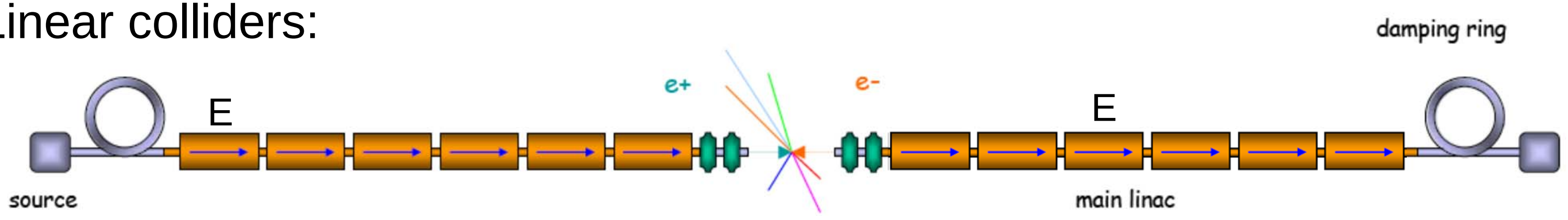
27.5 GeV

Synchrotron radiation

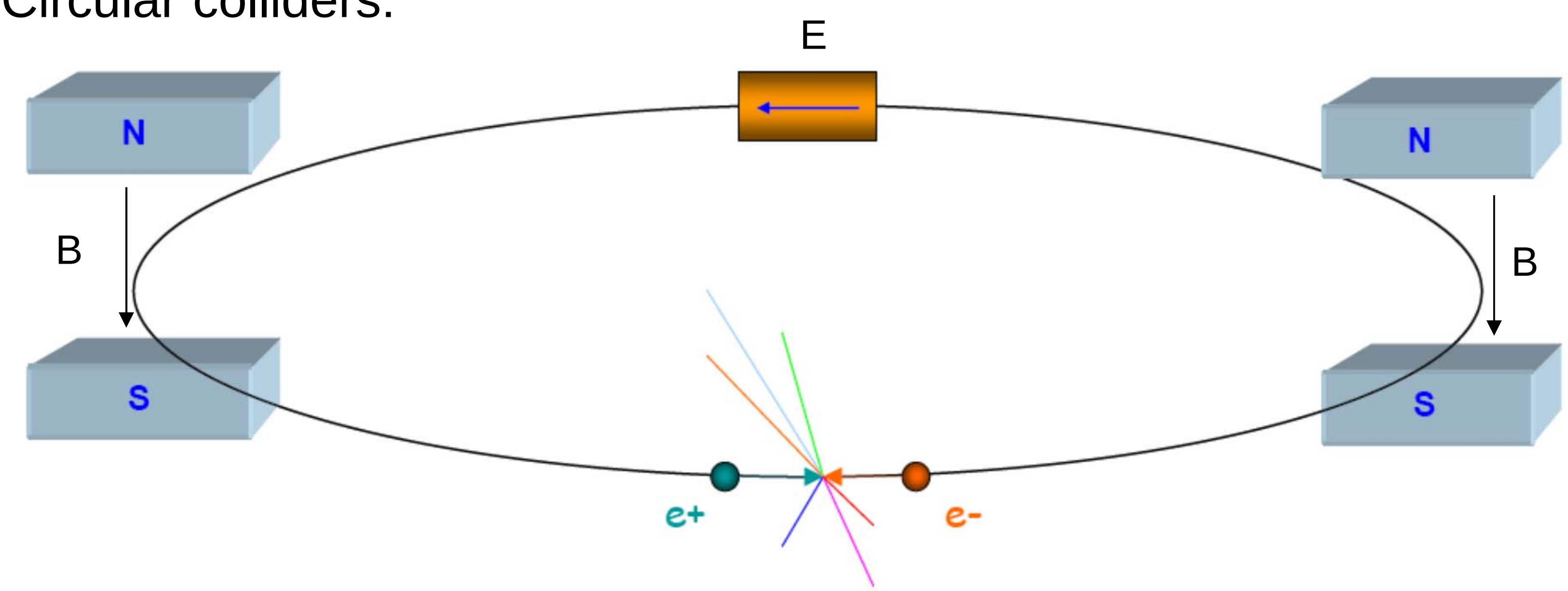


Which collider is better?

Linear colliders:



Circular colliders:

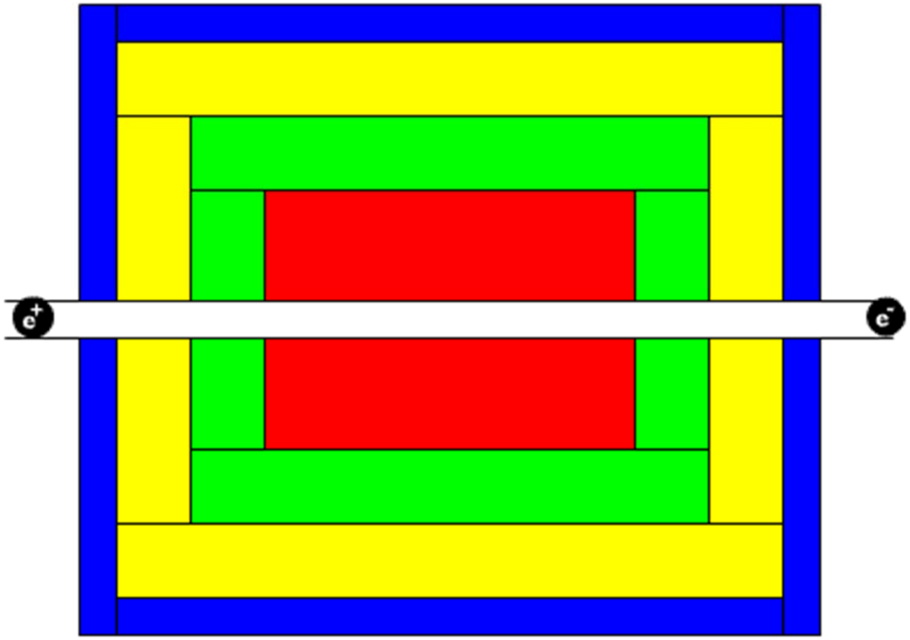


Applications of Accelerators (1)

Particle colliders for High Energy Physics (HEP) experiments

- fix target experiments:

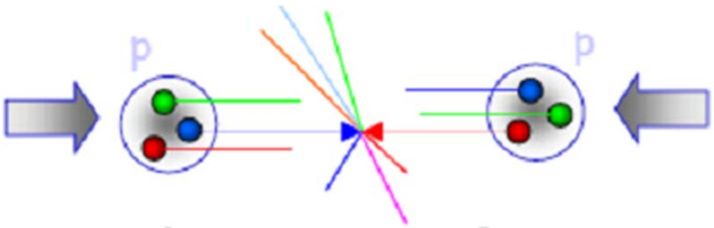
HEP detector

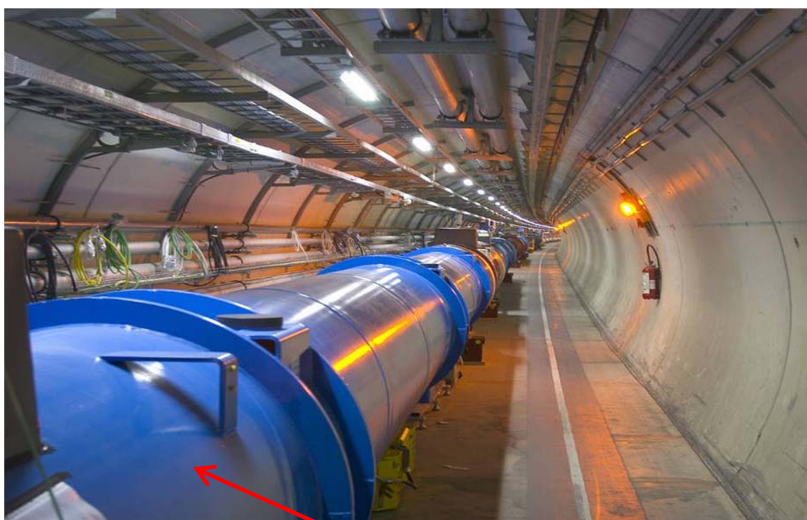


Applications of Accelerators (1)

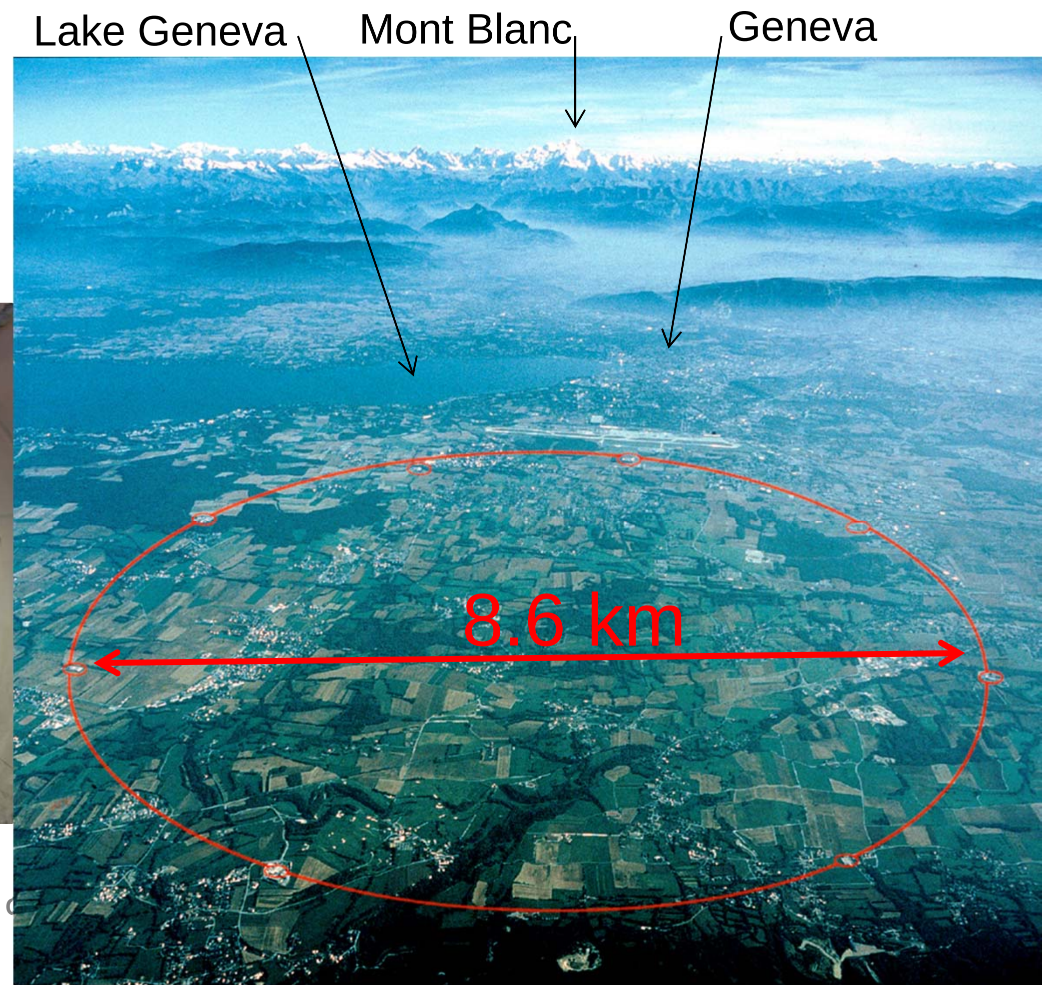
Particle colliders for High Energy Physics experiments

Example: the Large Hadron Collider (LHC) at CERN



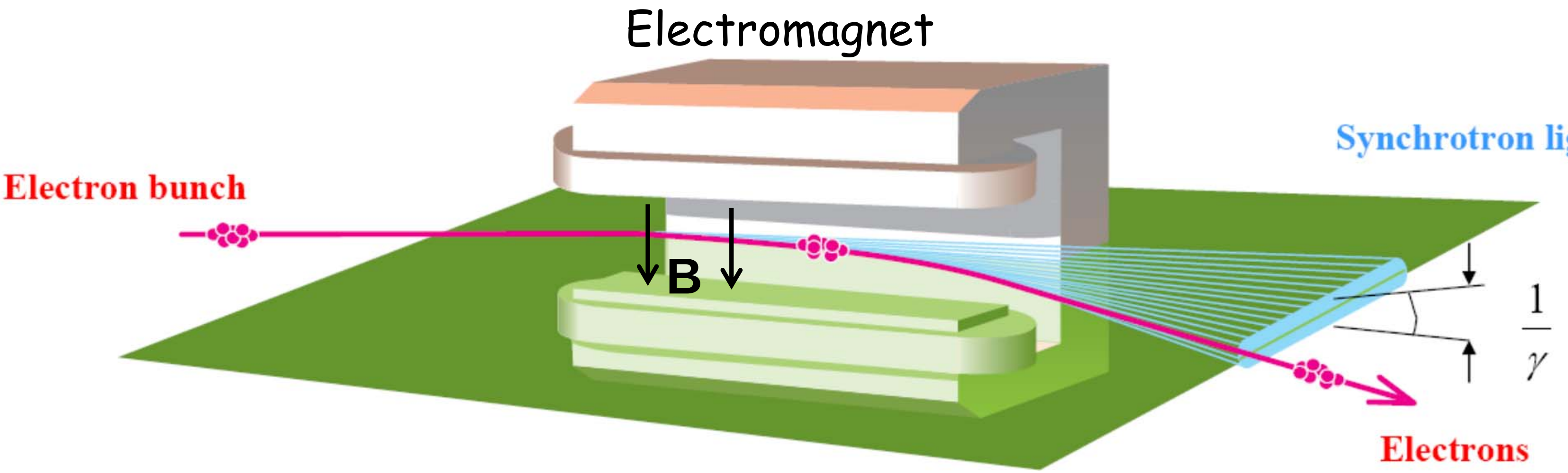


superconducting magnets
(inside a cryostat)

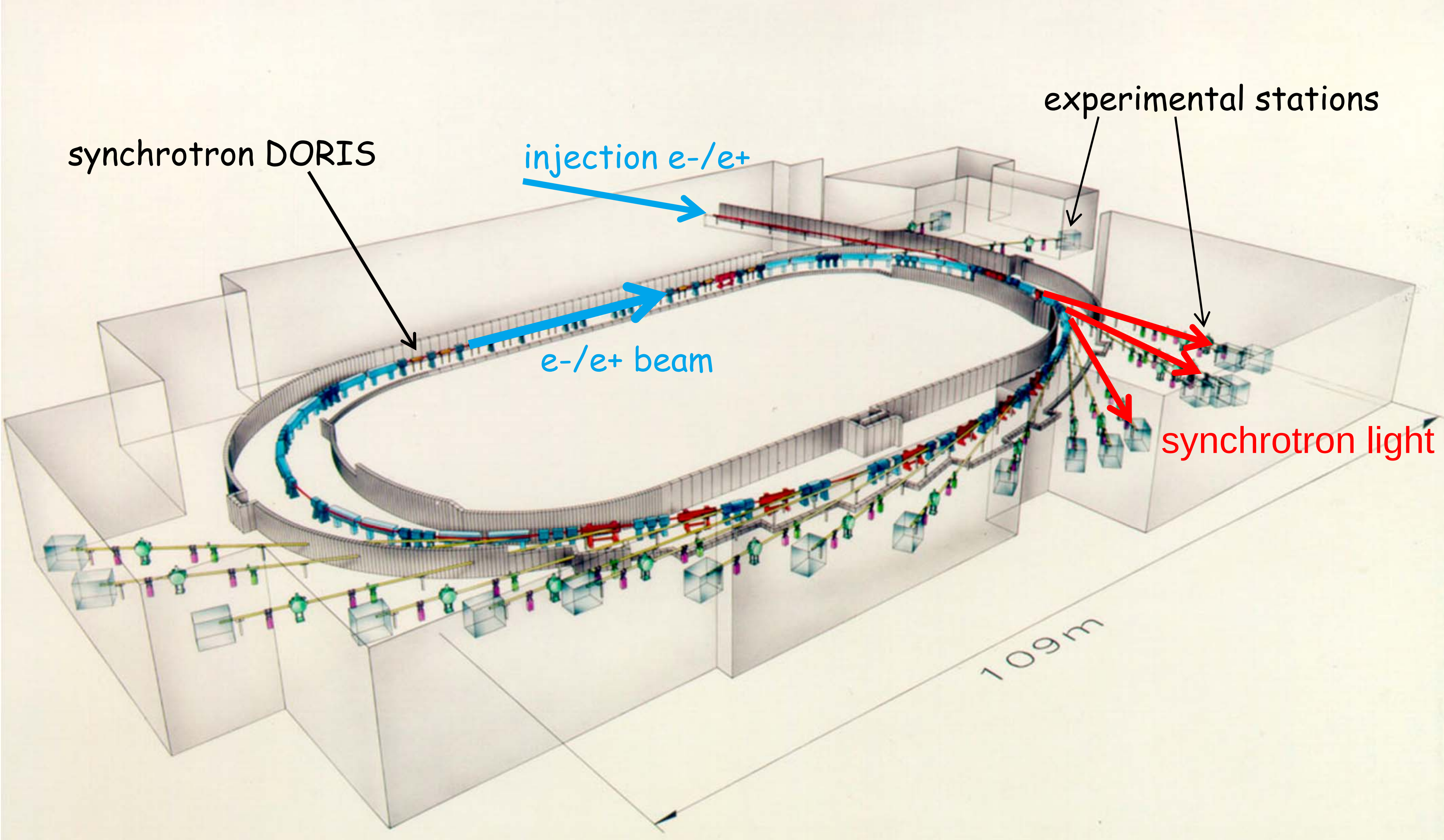


Applications of Accelerators (2)

Light sources for biology, physics, chemistry… experiments



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

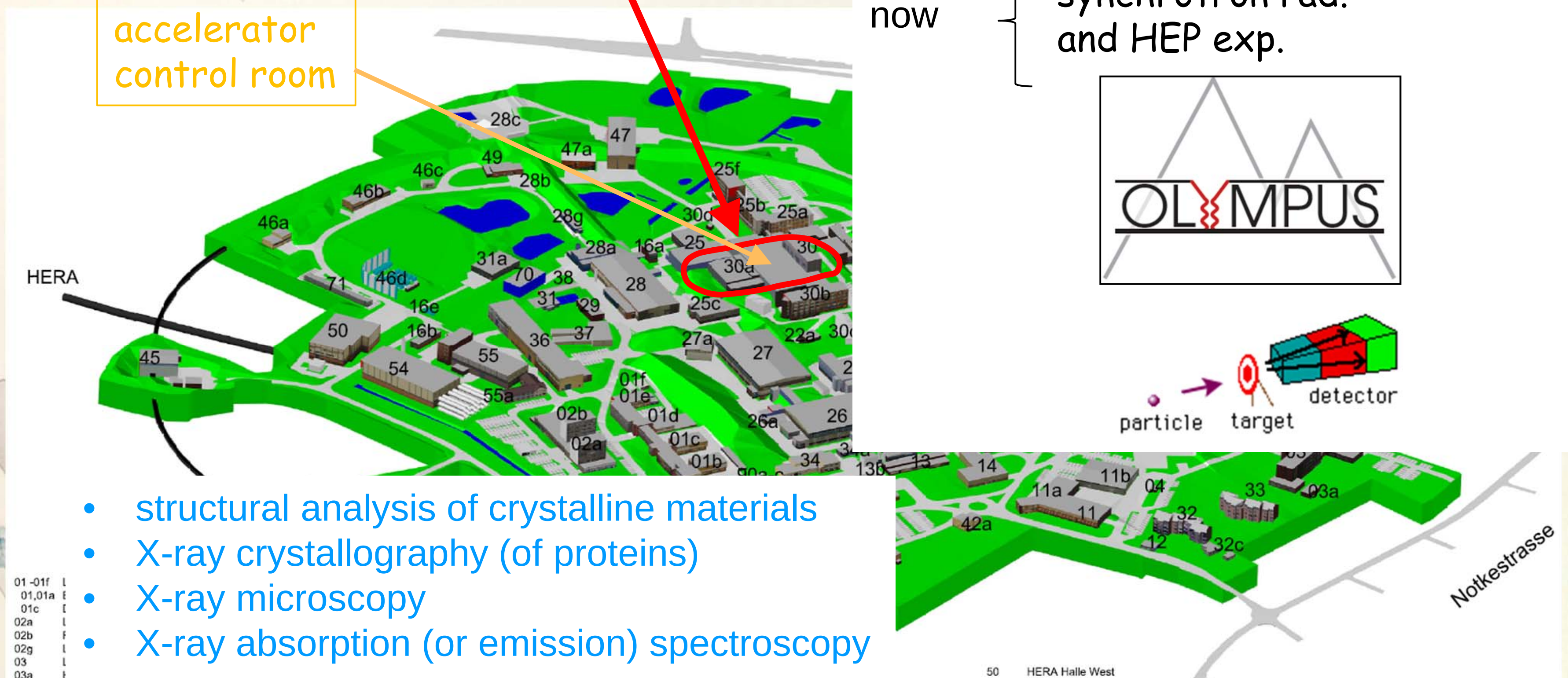


Example: Doppel-Ring-Speicher (DORIS)
'double ring store' at DESY

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

now
- synchrotron rad.
- and HEP exp.

accelerator control room



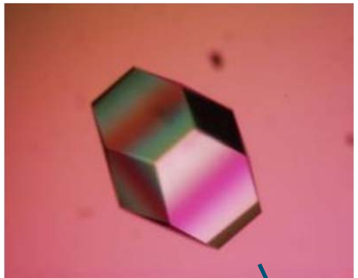
- structural analysis of crystalline materials
- X-ray crystallography (of proteins)
- X-ray microscopy
- X-ray absorption (or emission) spectroscopy
- …

Applications of Accelerators (2)

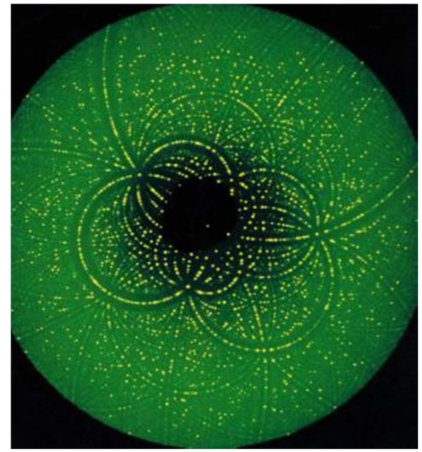
Example: X-ray crystallography

diffraction
pattern(s)

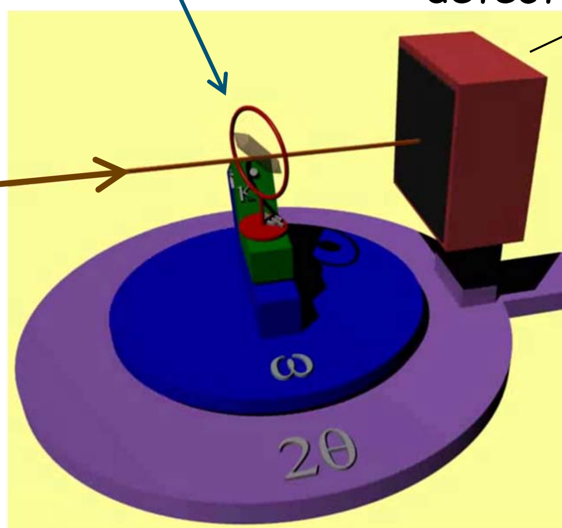
protein
crystal

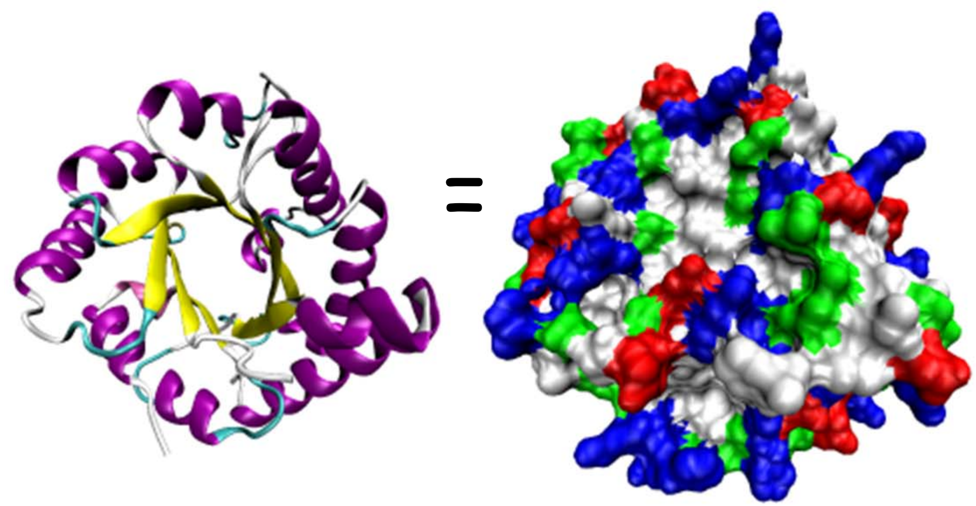


detector



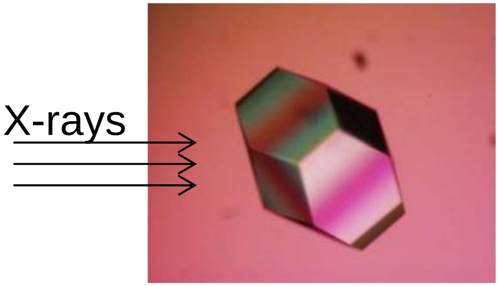
X-ray photons

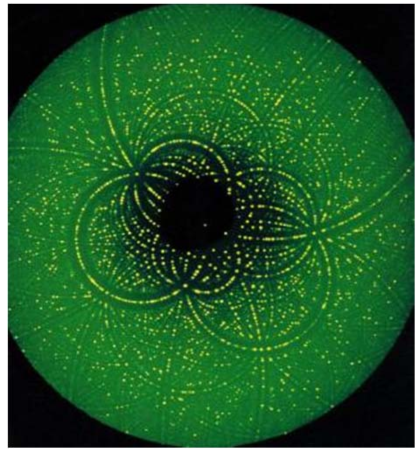




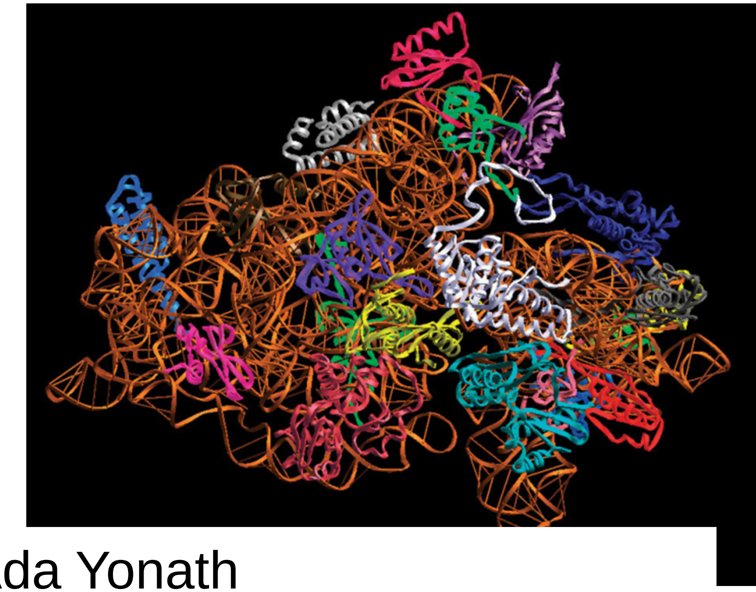
Applications of Accelerators (2)

X-ray crystallography





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

> 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) …

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

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

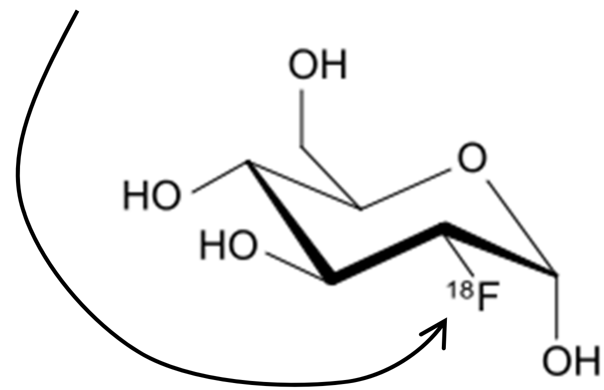
For radioisotope production

For example:

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

(transmutation)

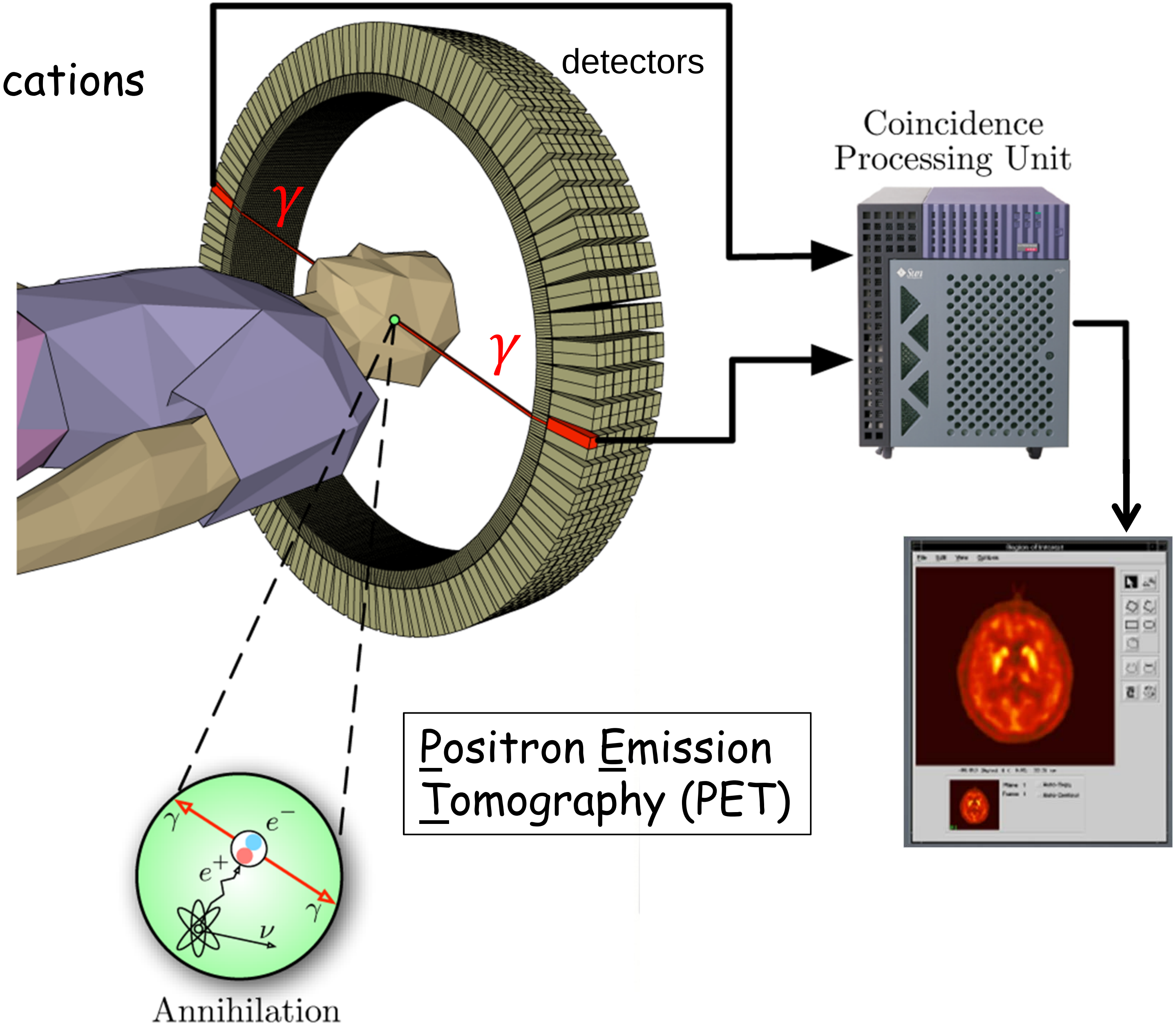
Fluorine-18 (half-life time = 110 min.)



Fludeoxyglucose (^{18}F)

Applications of Accelerators (3)

Medical applications



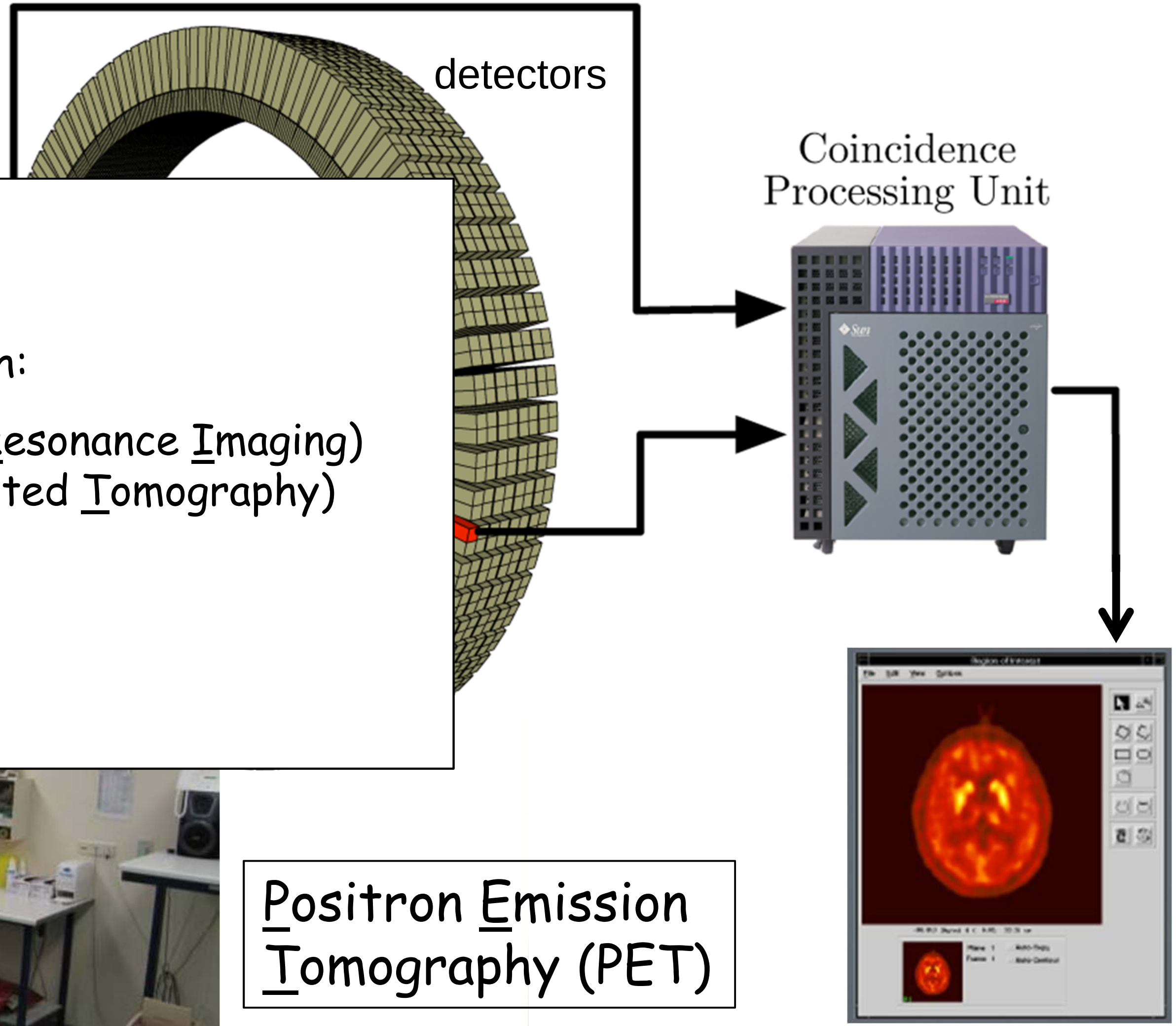
Positron Emission Tomography (PET)

Applications of Accelerators (3)

Medical applications

not to be confused with:

- MRI (Magnetic Resonance Imaging)
- CT (X-ray Computed Tomography)



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

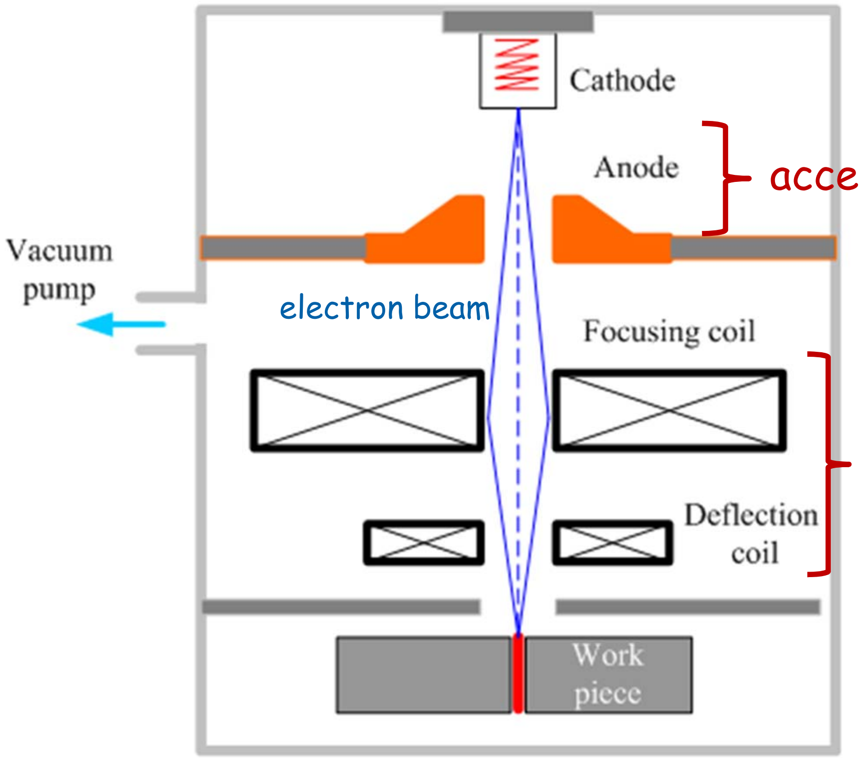
approx. numbers from 2007 (worldwide)

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'

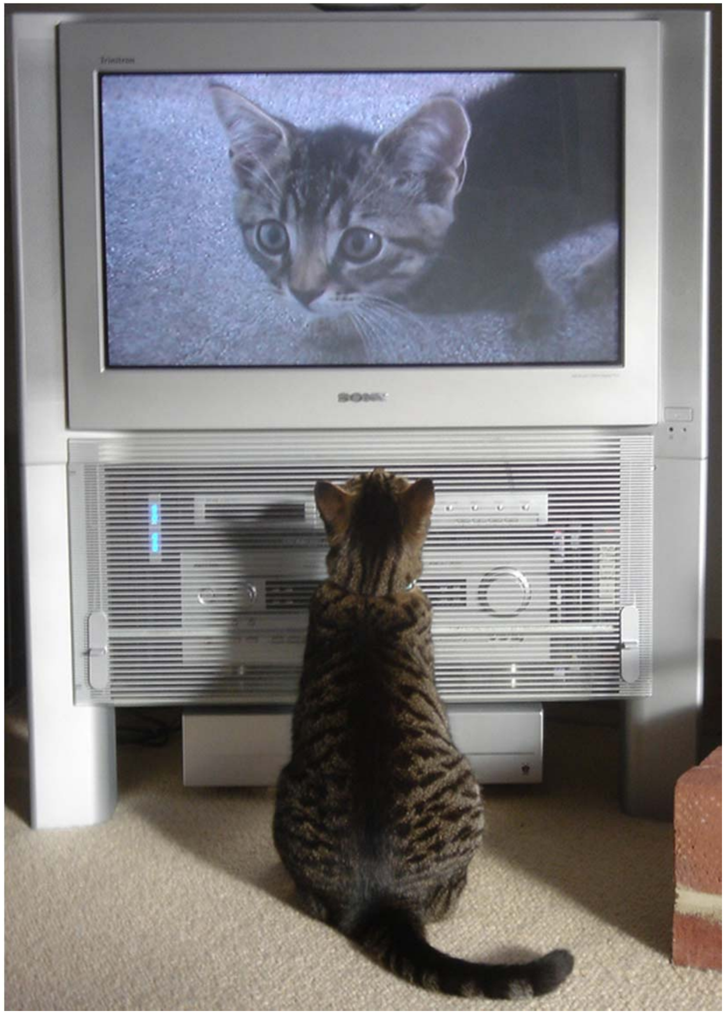
- About 120 accelerators for research in "nuclear and particle physics"
- About 70 electron storage rings and electron linear accelerators used as light sources (so-called 'synchrotron radiation sources')

...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) …

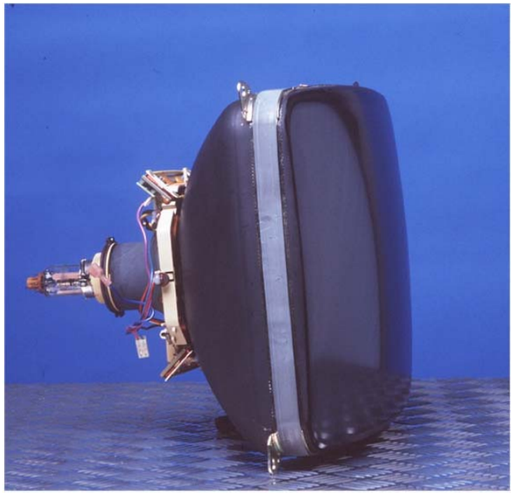
Applications of Accelerators (5)

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



TV

CRT (Cathode Ray Tube)

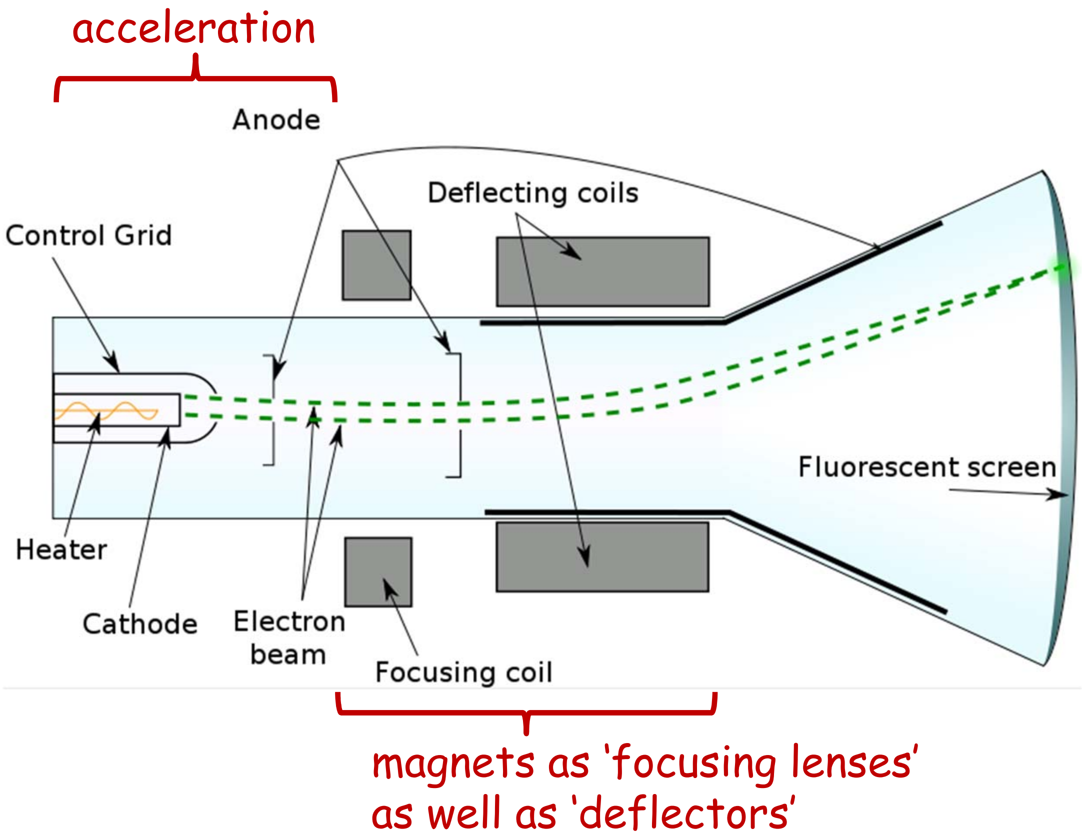


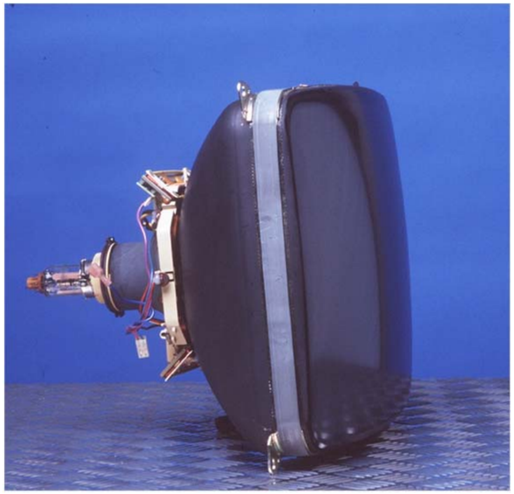
oscilloscope

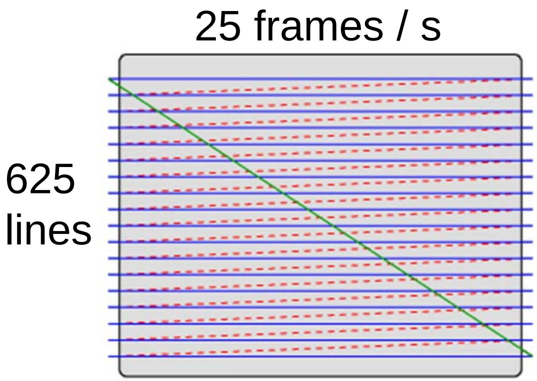
DESY

Applications of Accelerators (5)

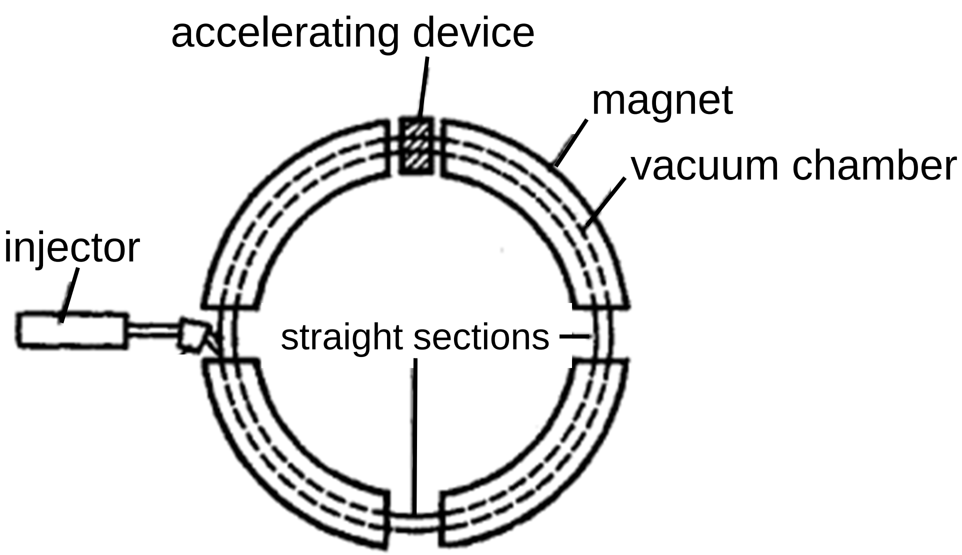
Many millions of television sets, oscilloscopes using CRTs (Cathode Ray Tube)





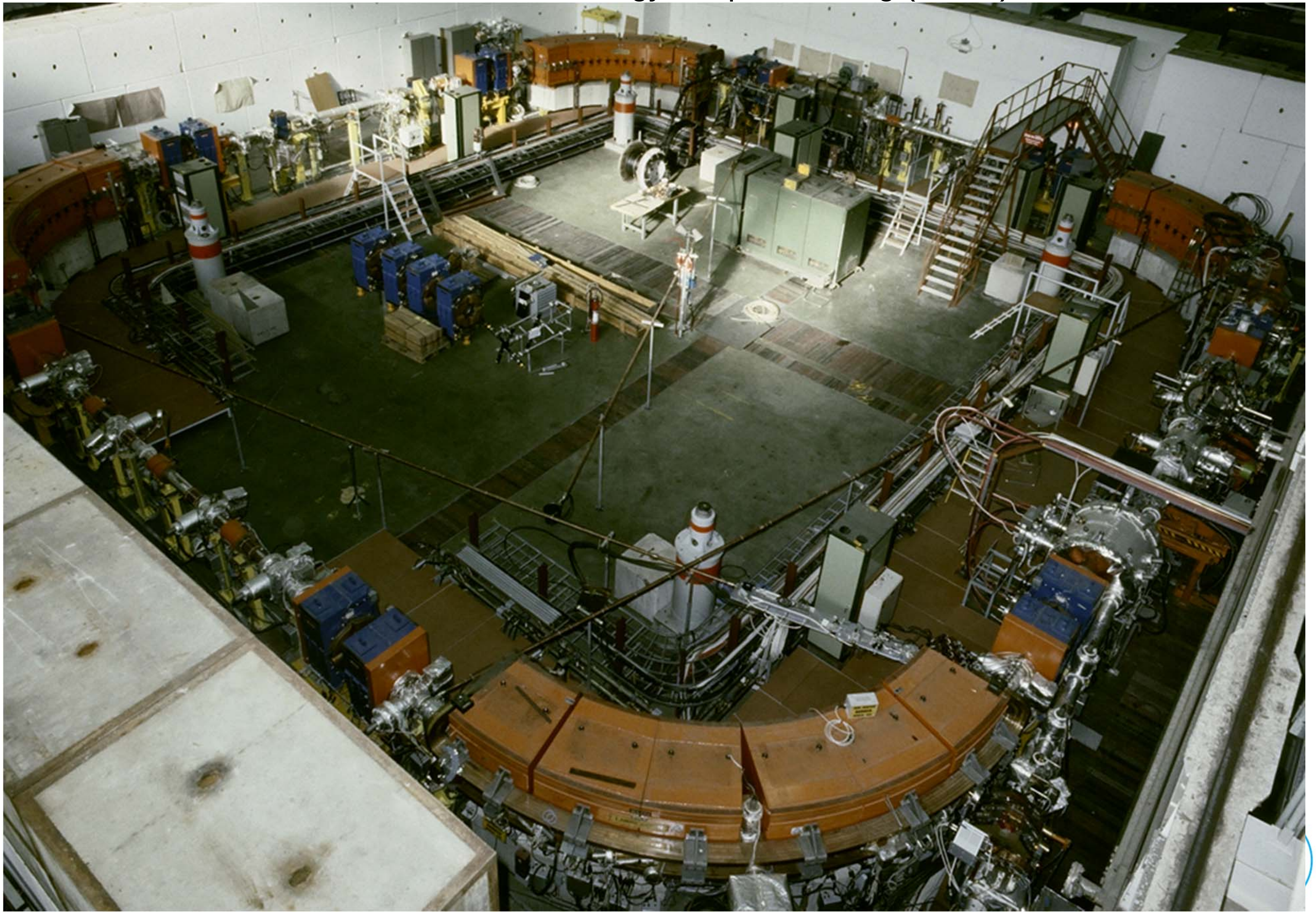


Circular accelerators: the synchrotron



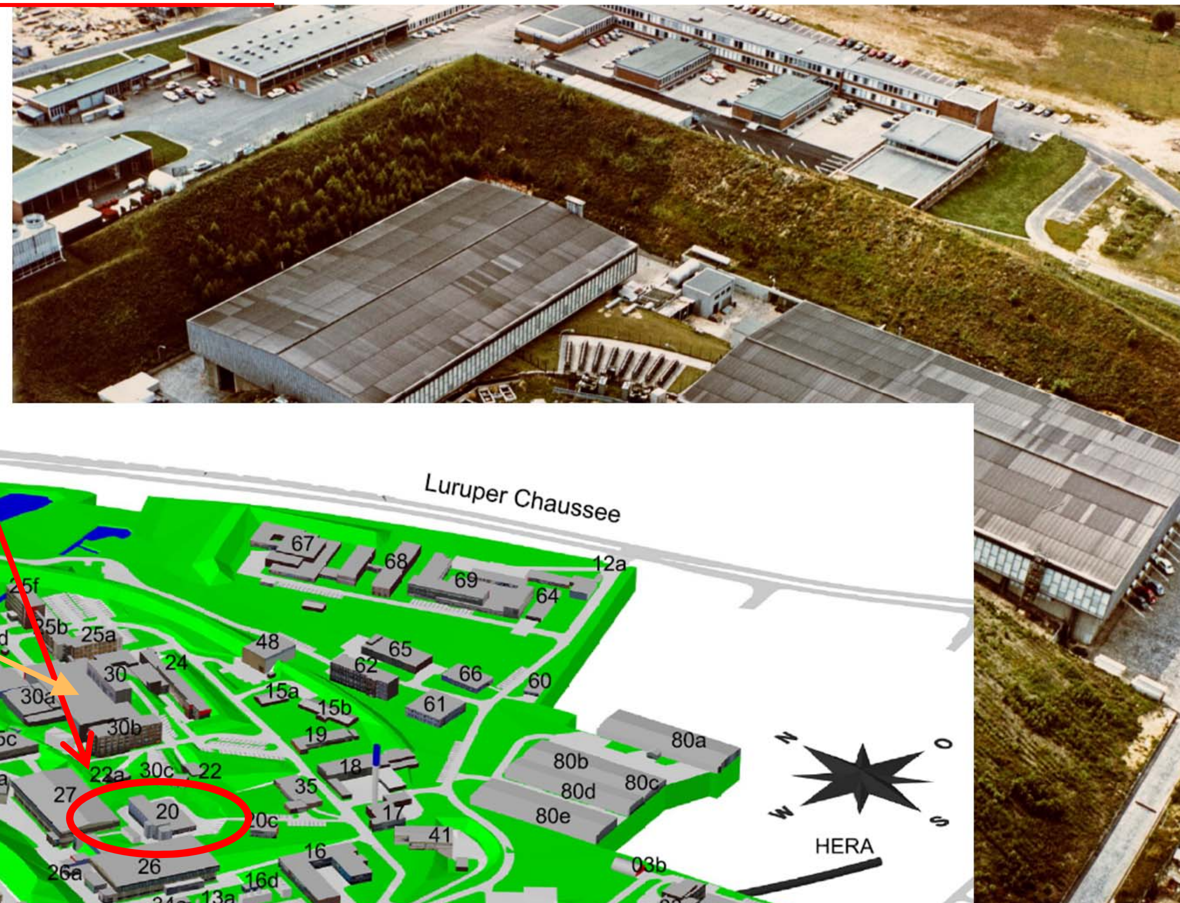
Circular accelerators

Low Energy Antiproton Ring (LEAR) at CERN

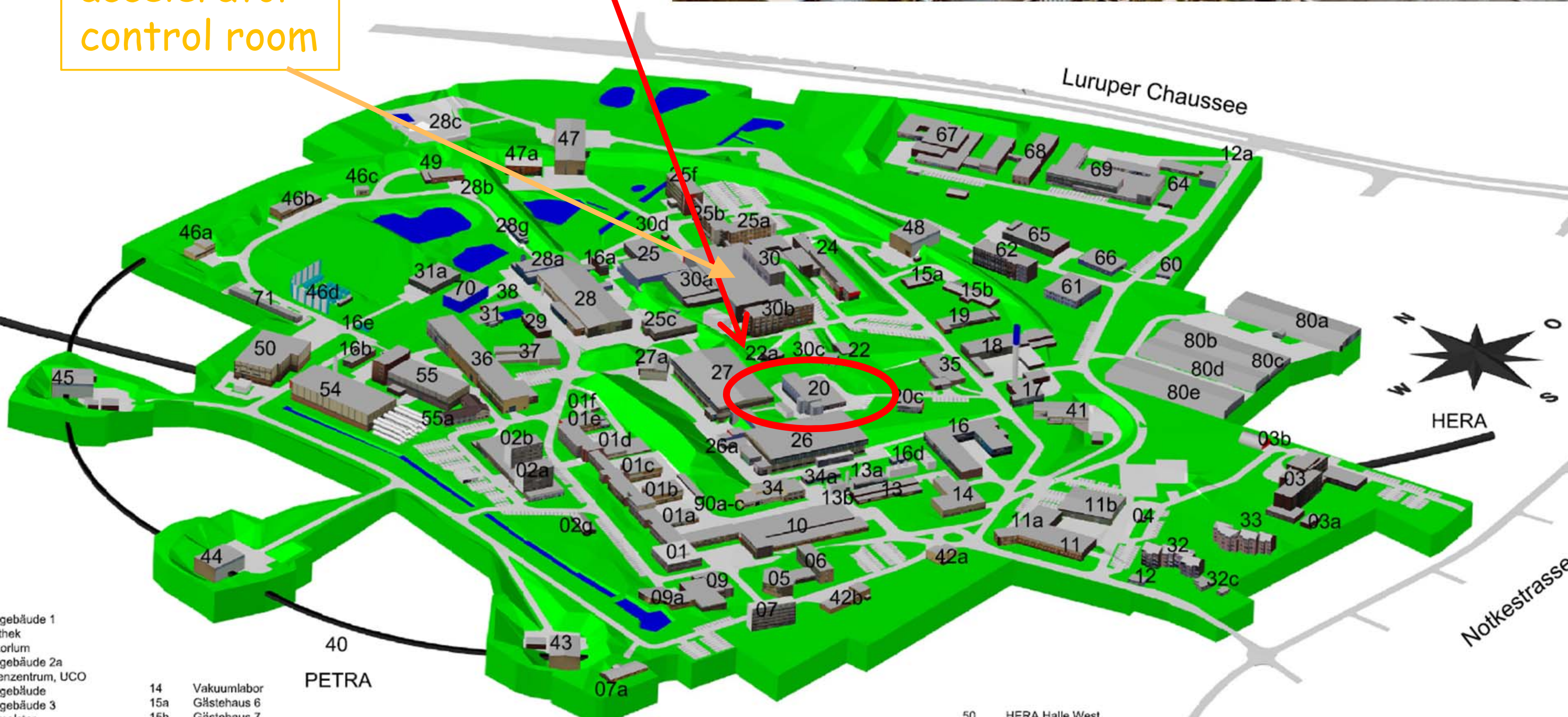


DESY (Deutsches Elektronen Synchrotron)

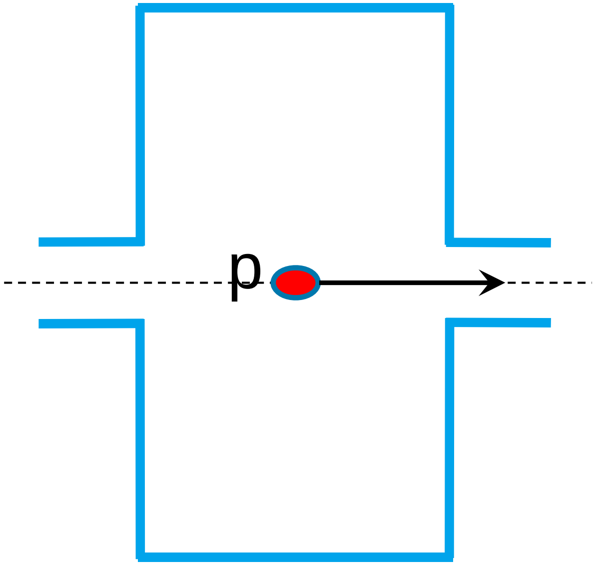
DESY: German electron synchrotron, 1964, 7.4 GeV

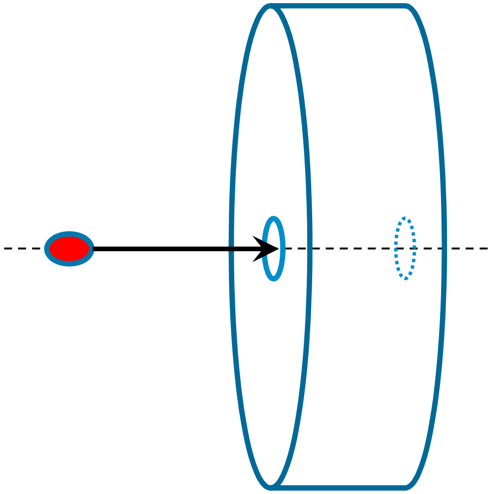


accelerator control room



RF cavity basics: the pill box cavity

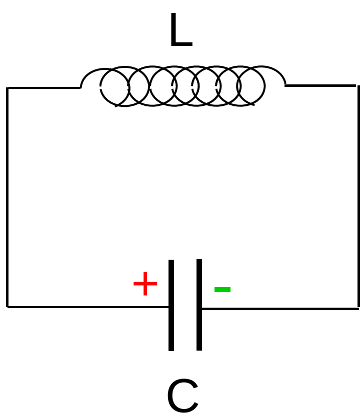




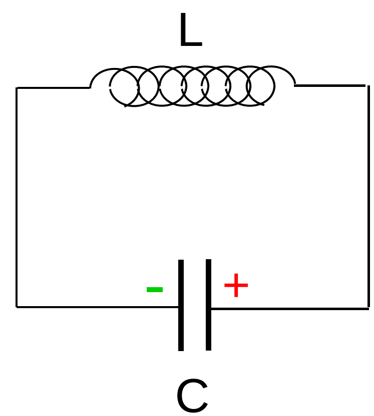
pill boxes

Charges, currents and electromagnetic fields

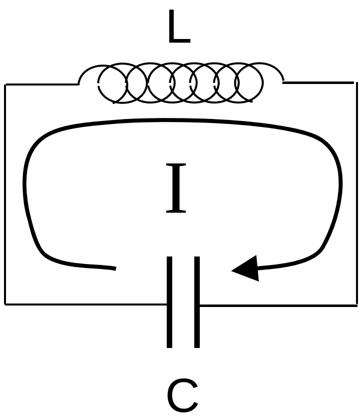
LC circuit (or resonant circuit) analogy:



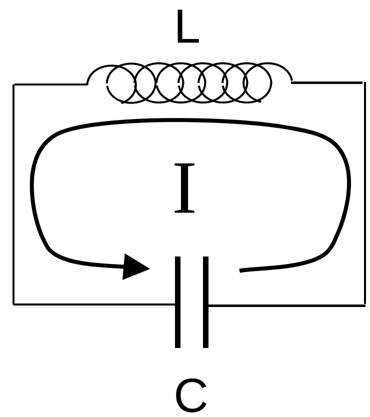
half a period later:



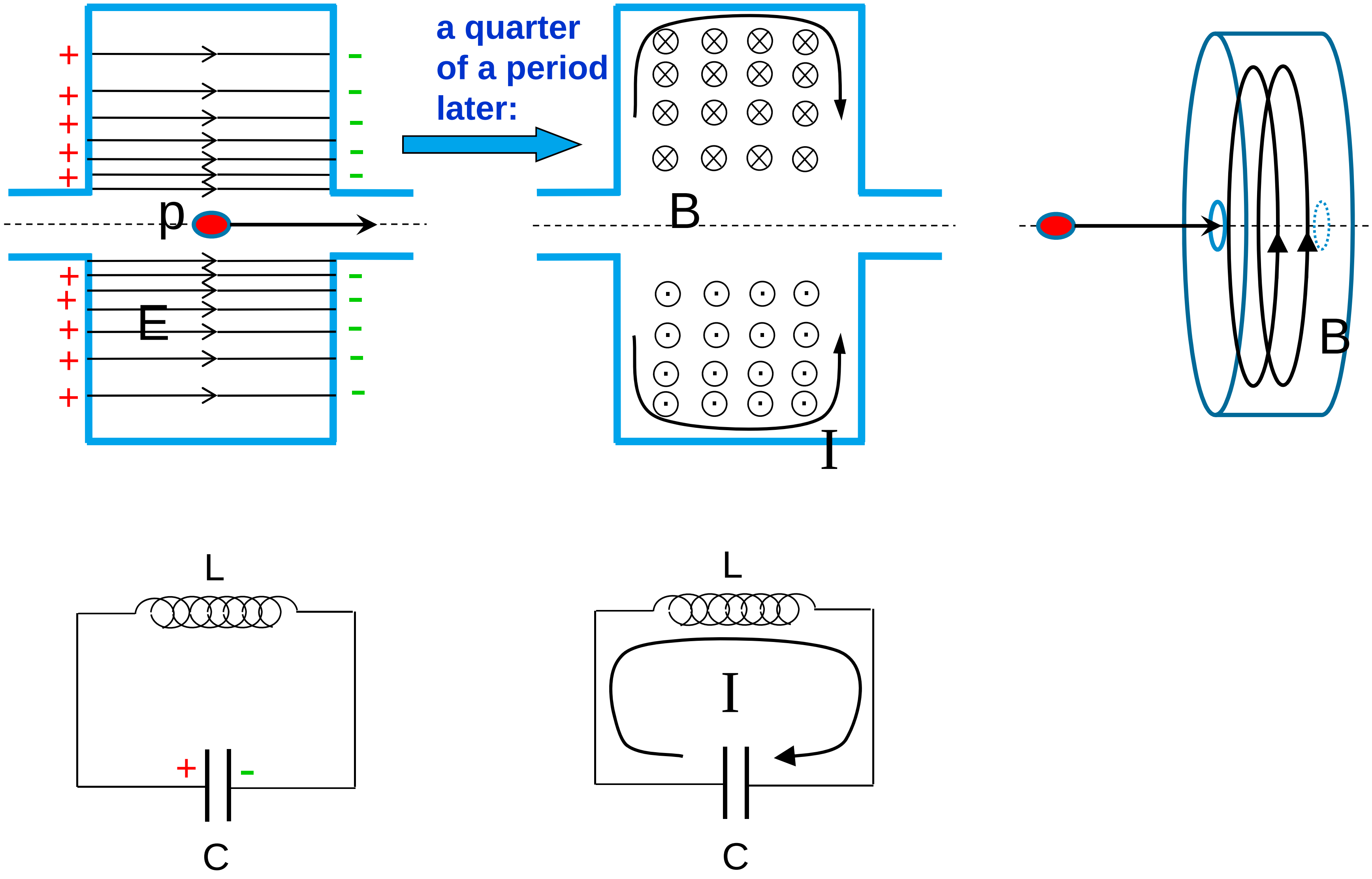
a quarter of a period later:



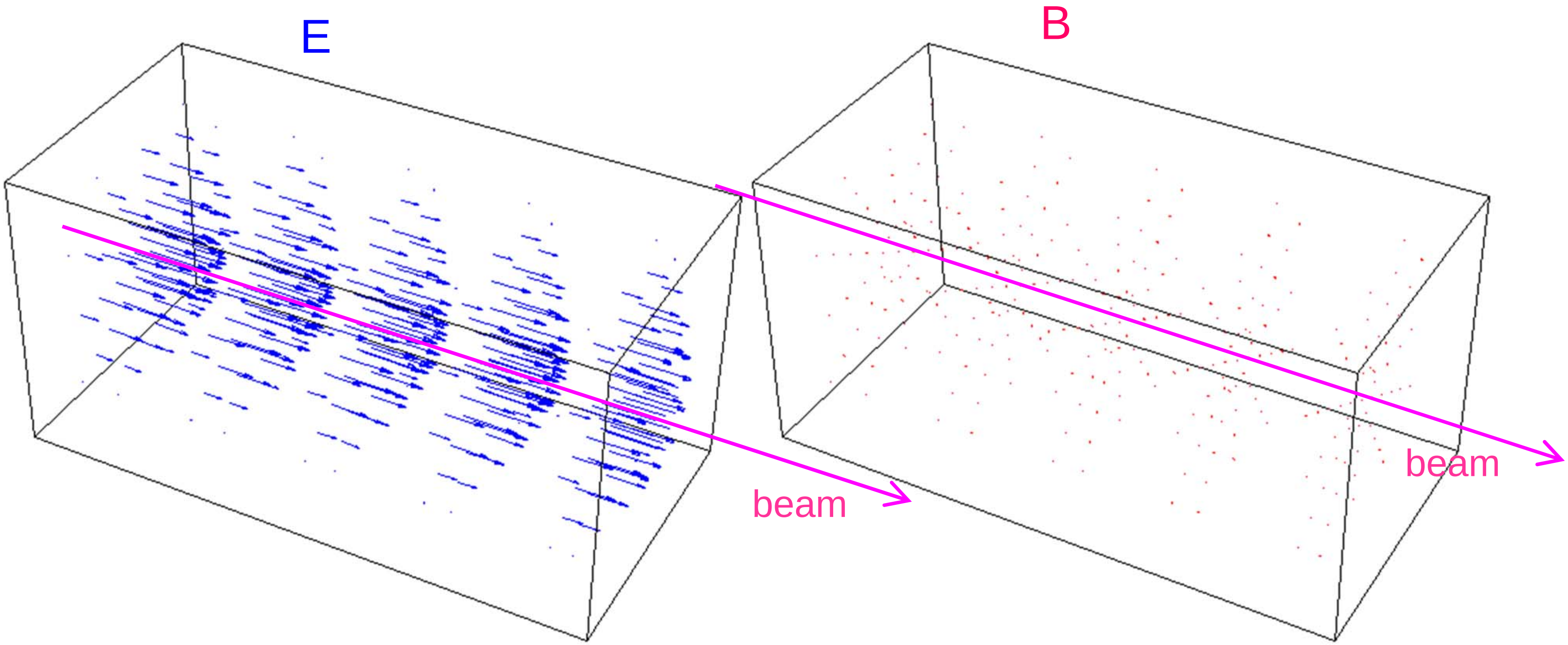
3 quarters of a period later:



RF cavity basics: the pill box cavity

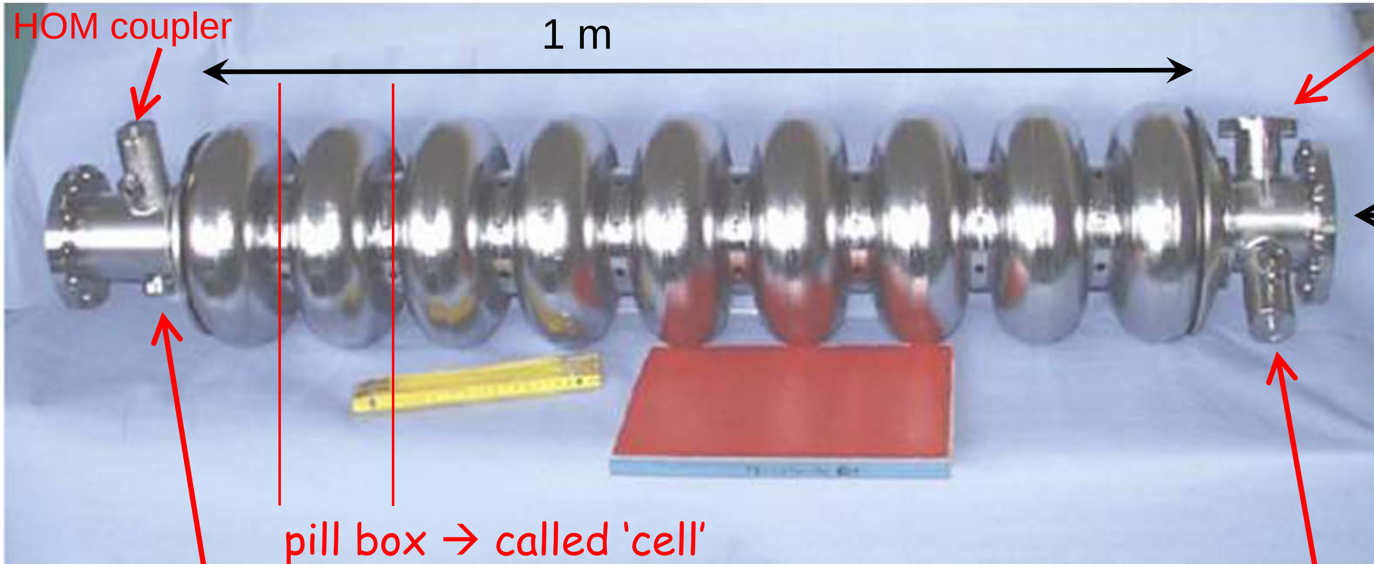


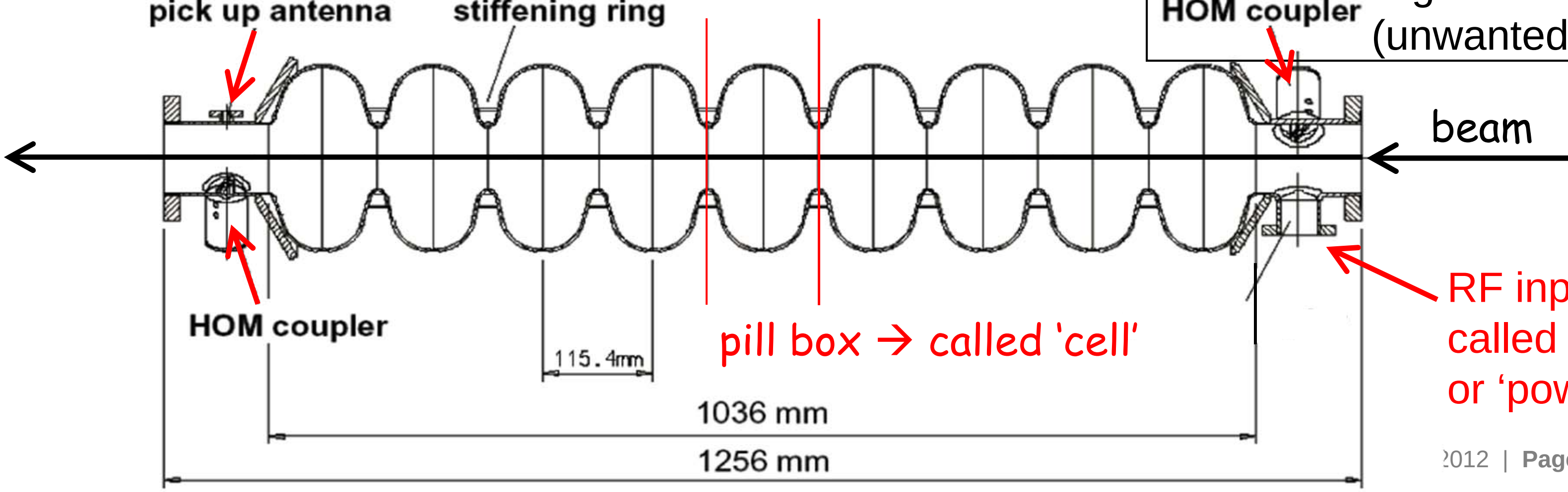
Pill box cavity: 3D visualisation of E and B



Superconducting cavity used in FLASH and in XFEL

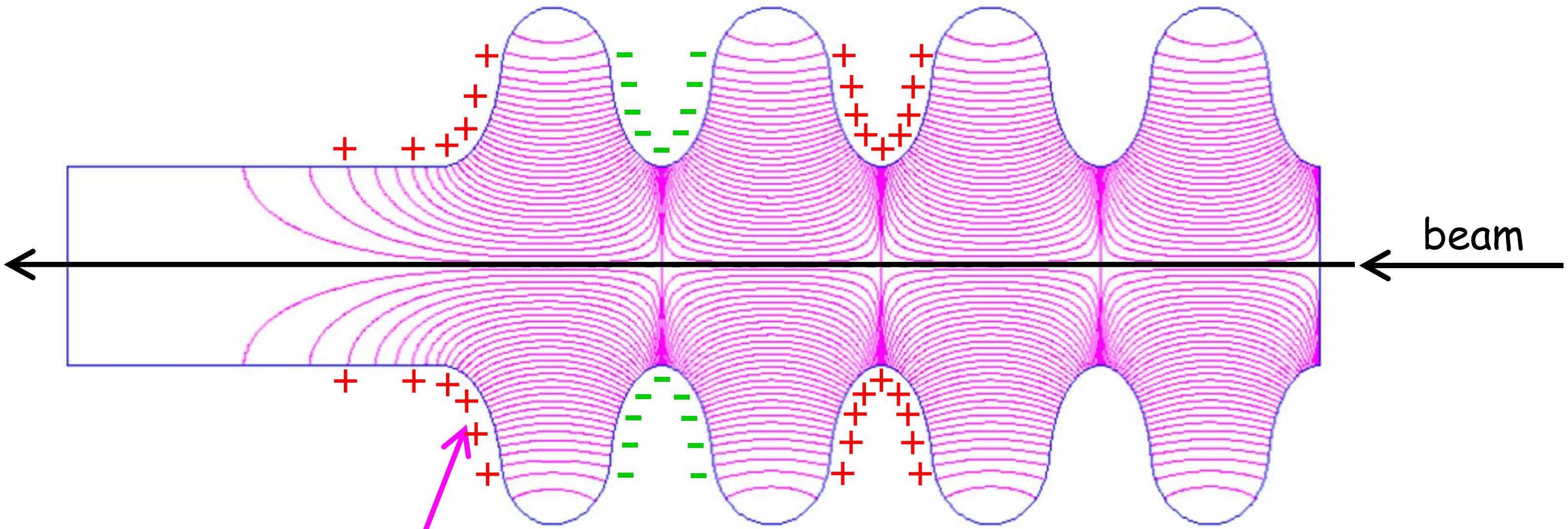
Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)

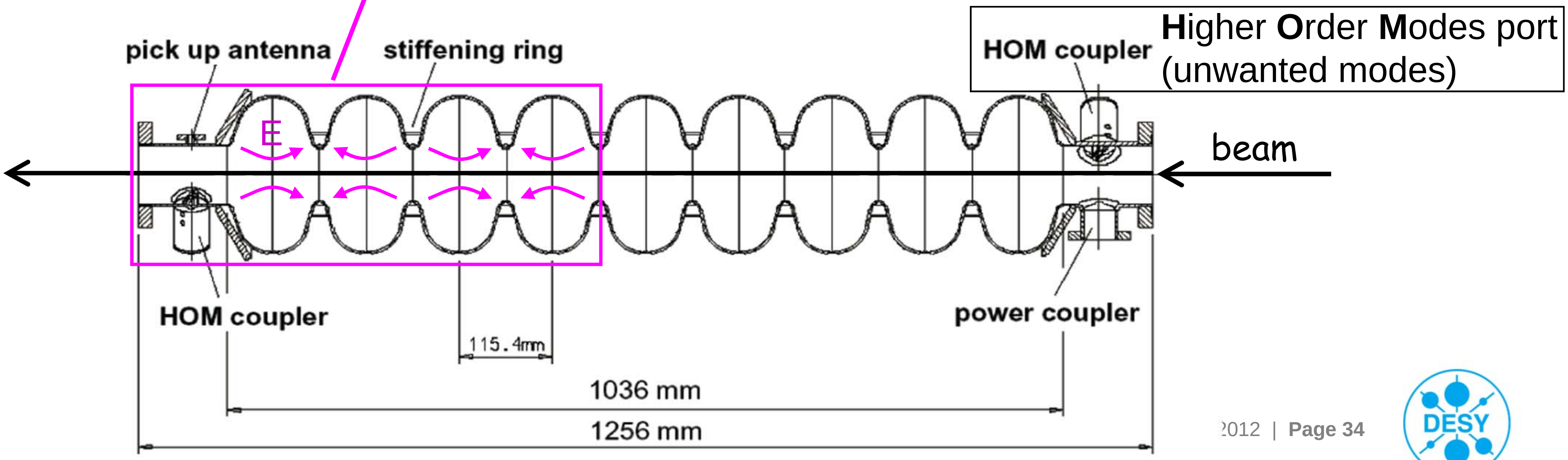




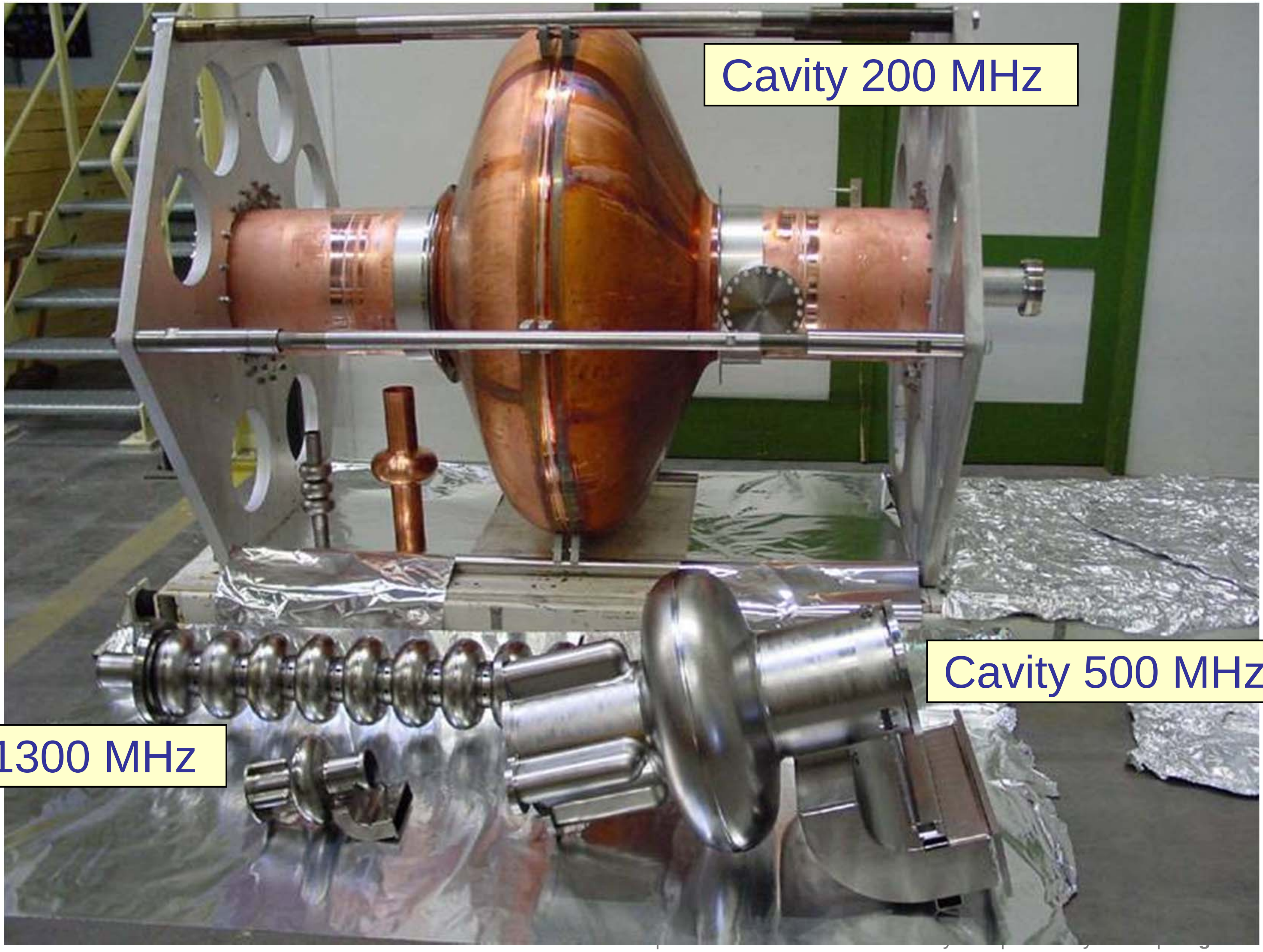
Accelerating field map

Simulation of the fundamental mode: electric field lines

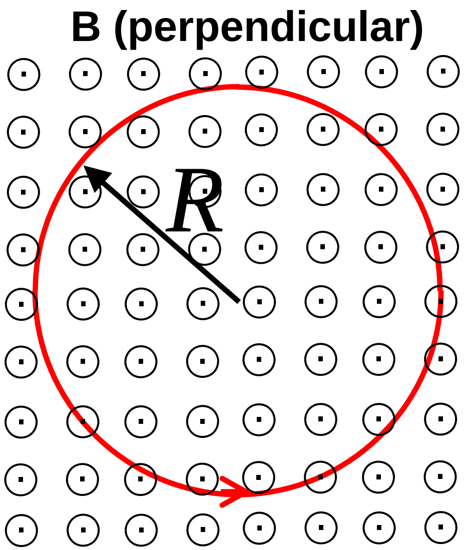




A collection of SRF cavities developed at Cornell University with frequencies spanning 200 MHz to 3 GHz



Circular accelerators: the synchrotron



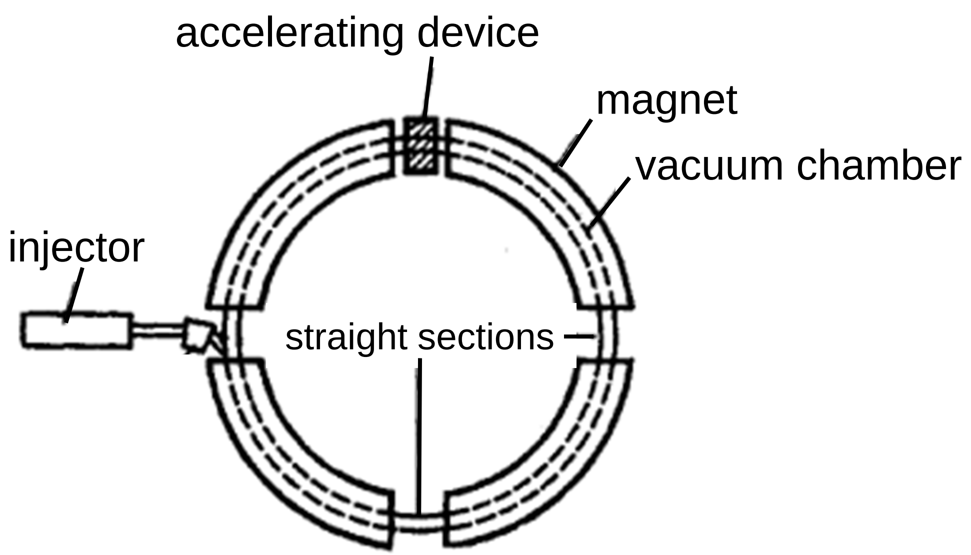
$$\vec{F} = \frac{d\vec{p}}{dt} = q\,\vec{v} \times \vec{B}$$

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

circular motion:

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

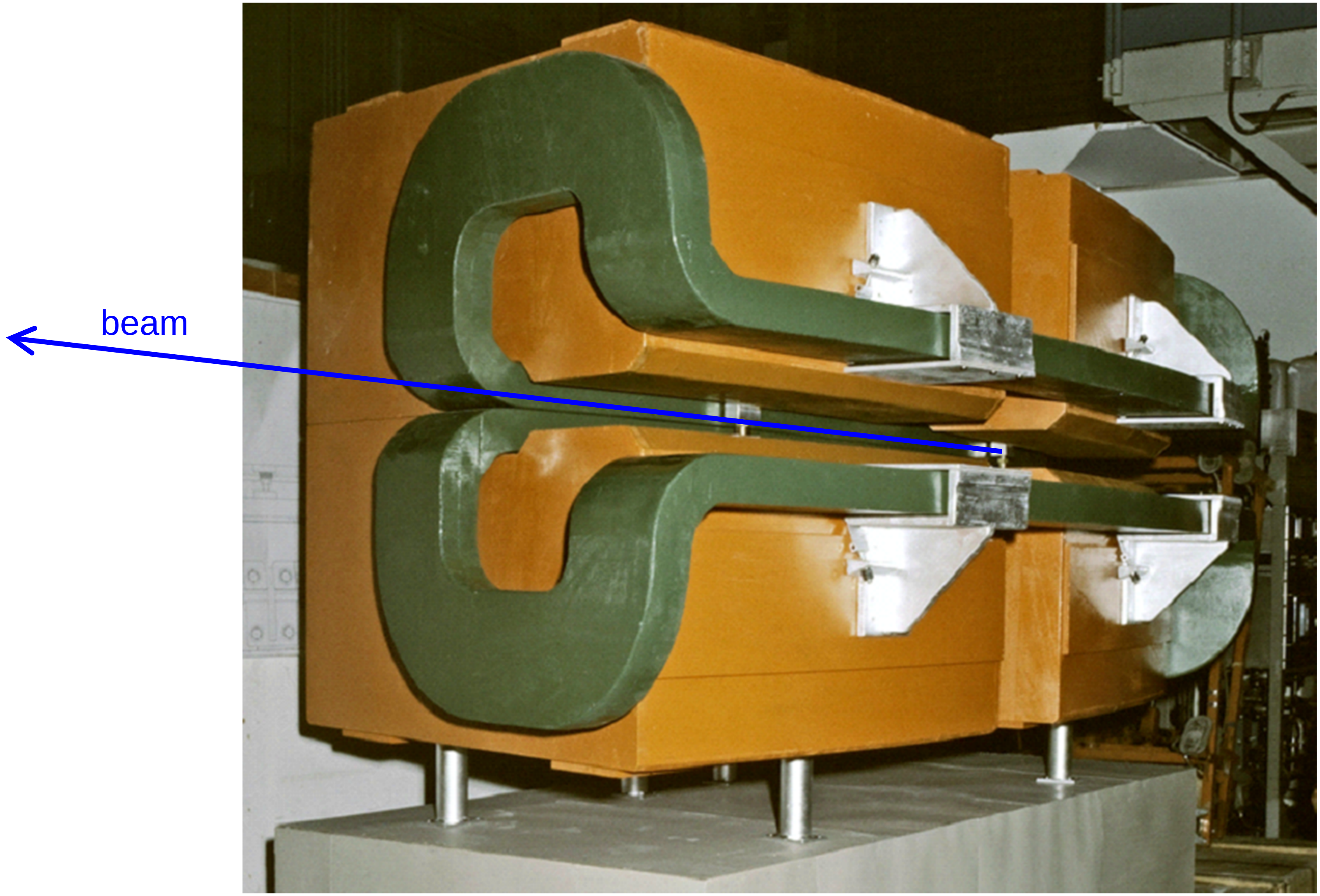
Circular accelerators: the synchrotron



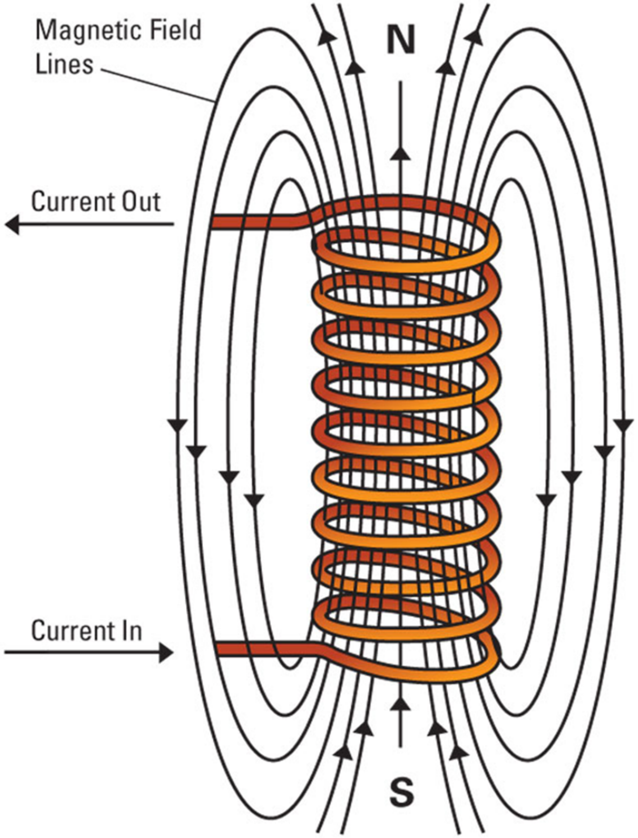
$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = q\,v\,B = m\frac{v^2}{R} \quad \Rightarrow \quad R = \frac{p}{q\,B}$$

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

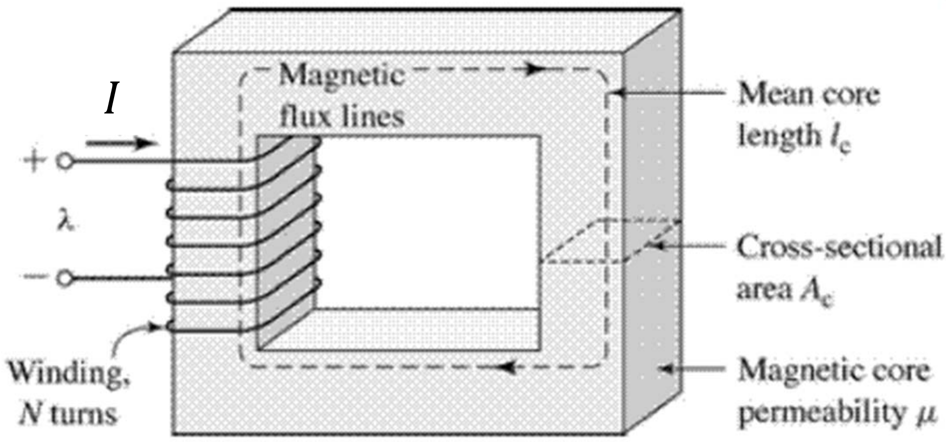
Dipole magnet



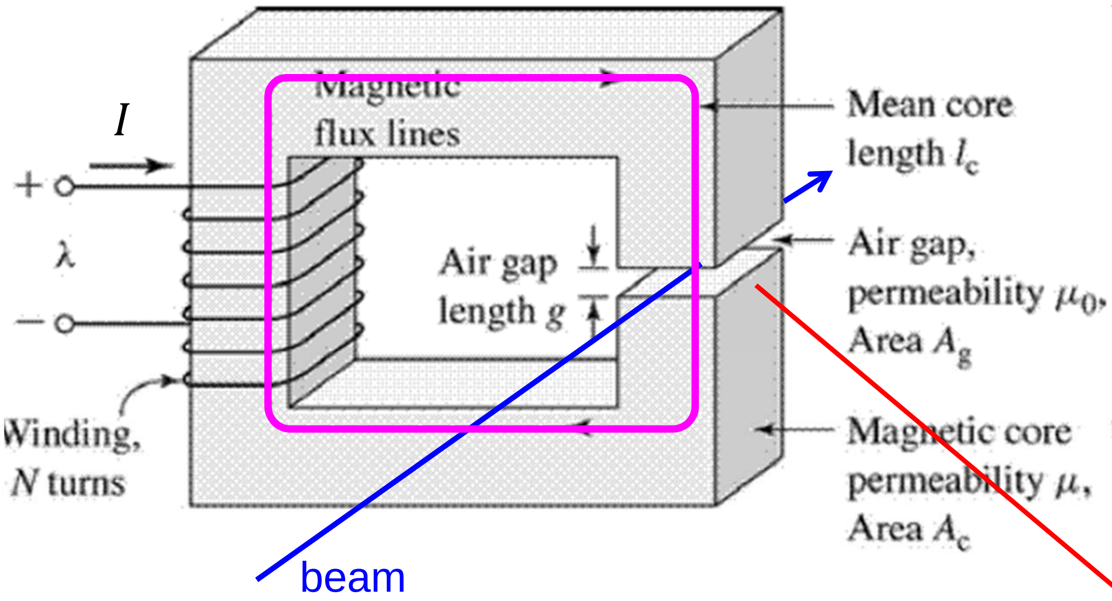
Electromagnet



permeability of iron = 300…10000 larger than air

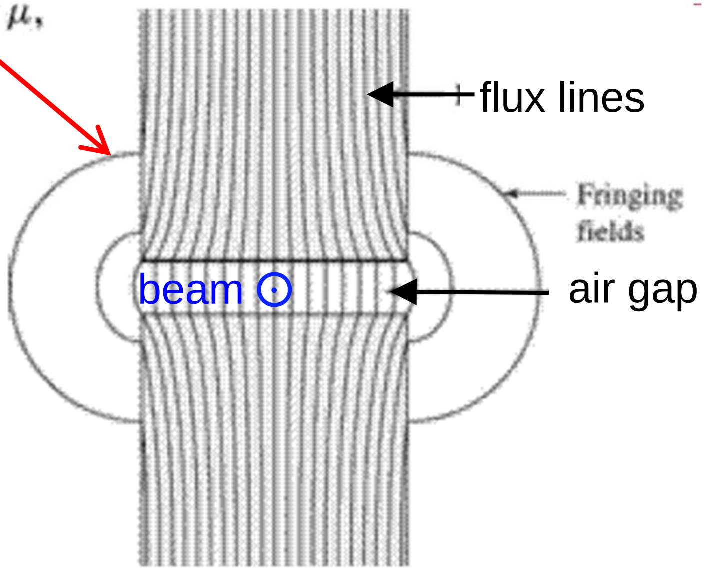


Dipole magnet



$$\int_{gap} \frac{\vec{B}}{\mu_0} \overrightarrow{ds} = \frac{B g}{\mu_0} = N\, I$$

$$\boxed{B = \frac{\mu_0 N\, I}{g}}$$



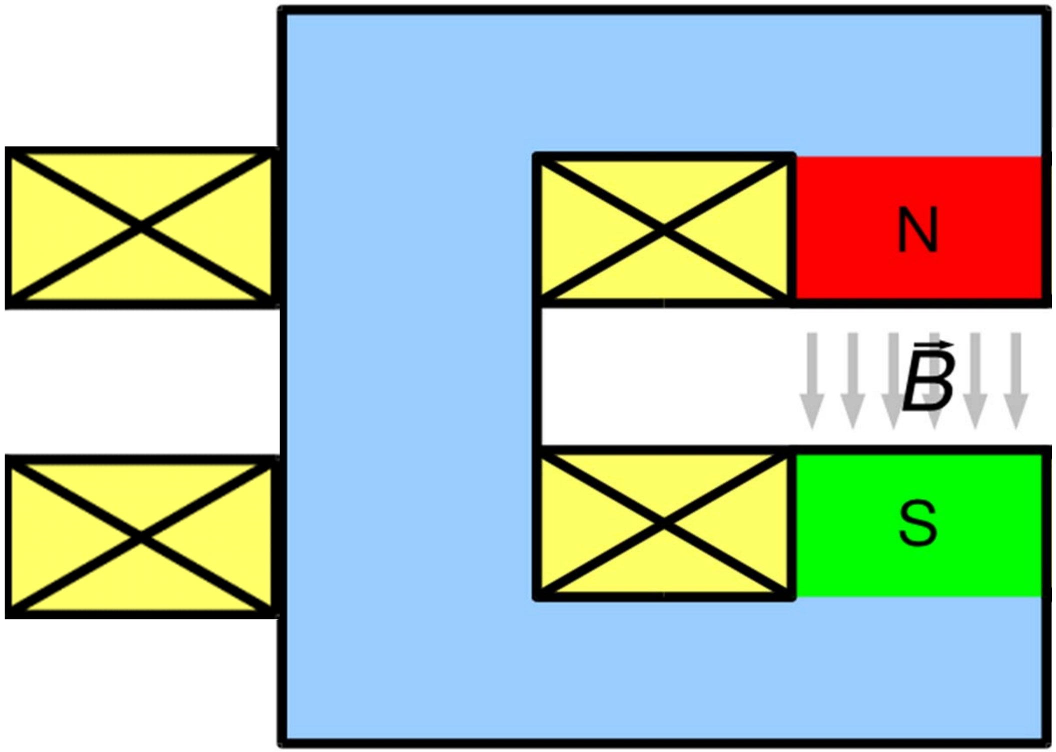
Ampere's law:

$$\oint \vec{H}\, \overrightarrow{ds} = N\, I$$

$$\oint \vec{H}\, \overrightarrow{ds} = \int_{iron} \vec{H}\, \overrightarrow{ds} + \int_{gap} \vec{H}\, \overrightarrow{ds} = N\, I$$

$$\int_{iron} \frac{\vec{B}}{\mu_{iron}} \overrightarrow{ds} + \int_{gap} \frac{\vec{B}}{\mu_0} \overrightarrow{ds} = N\, I$$

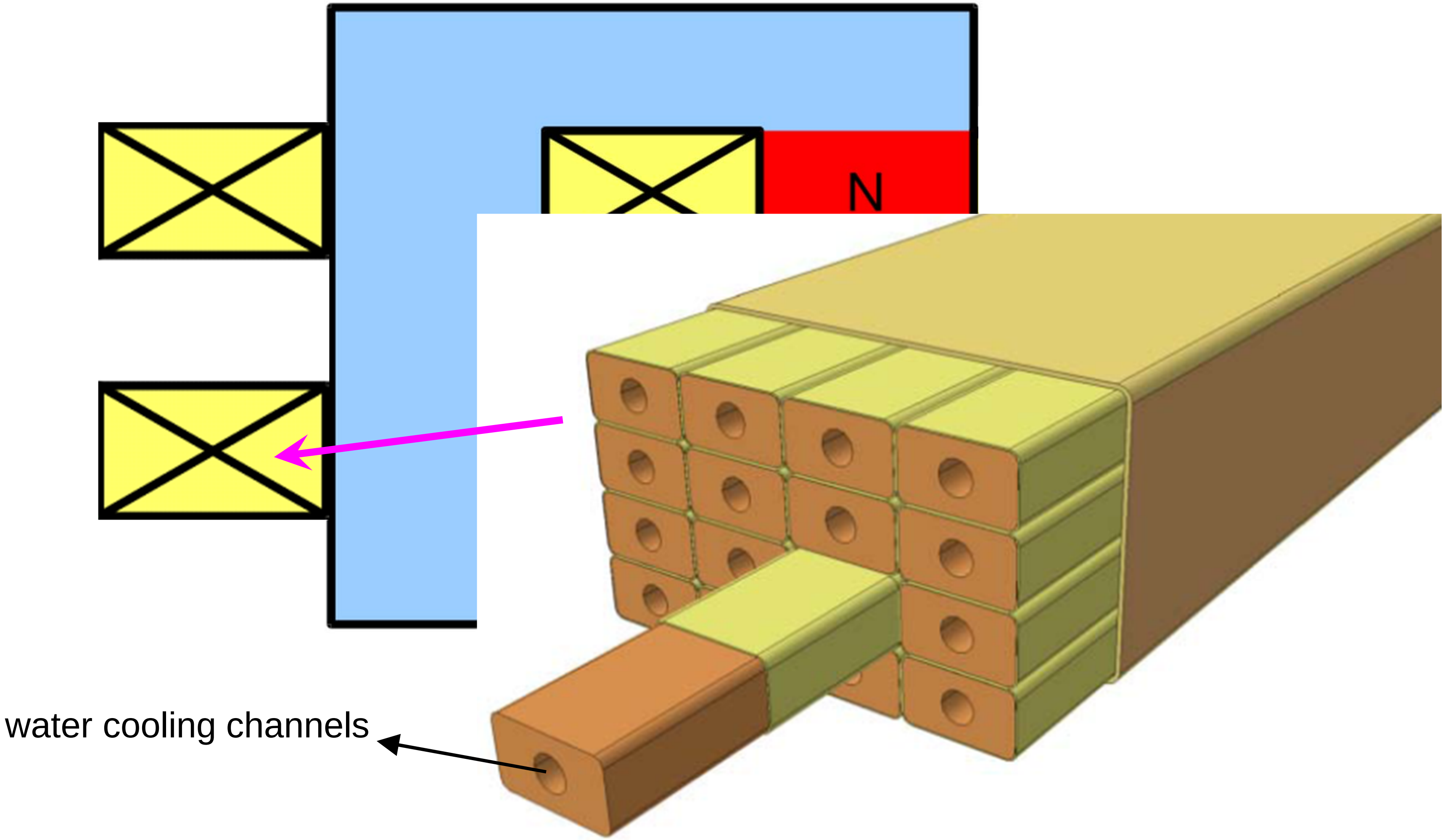
Dipole magnet cross section



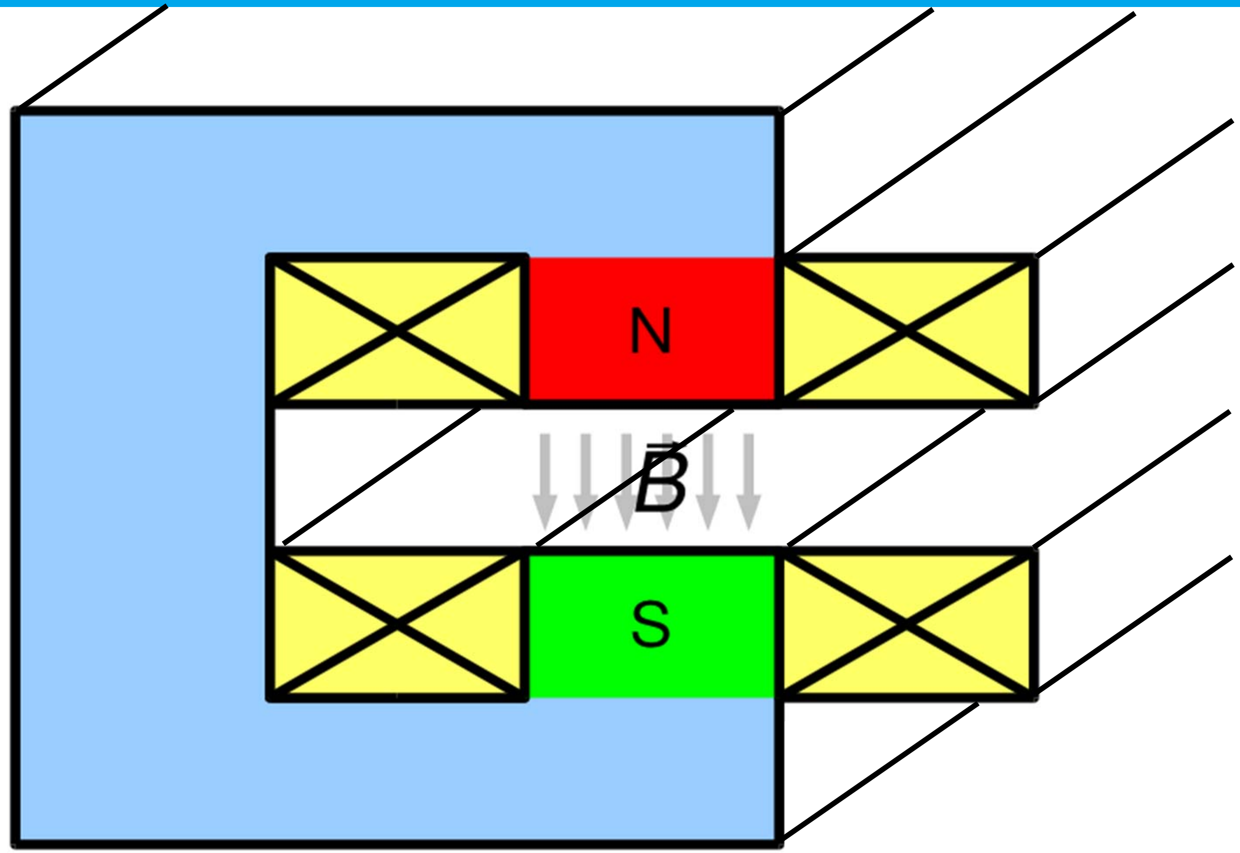
Max. B ➔ max. current ➔ large conductor cables

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

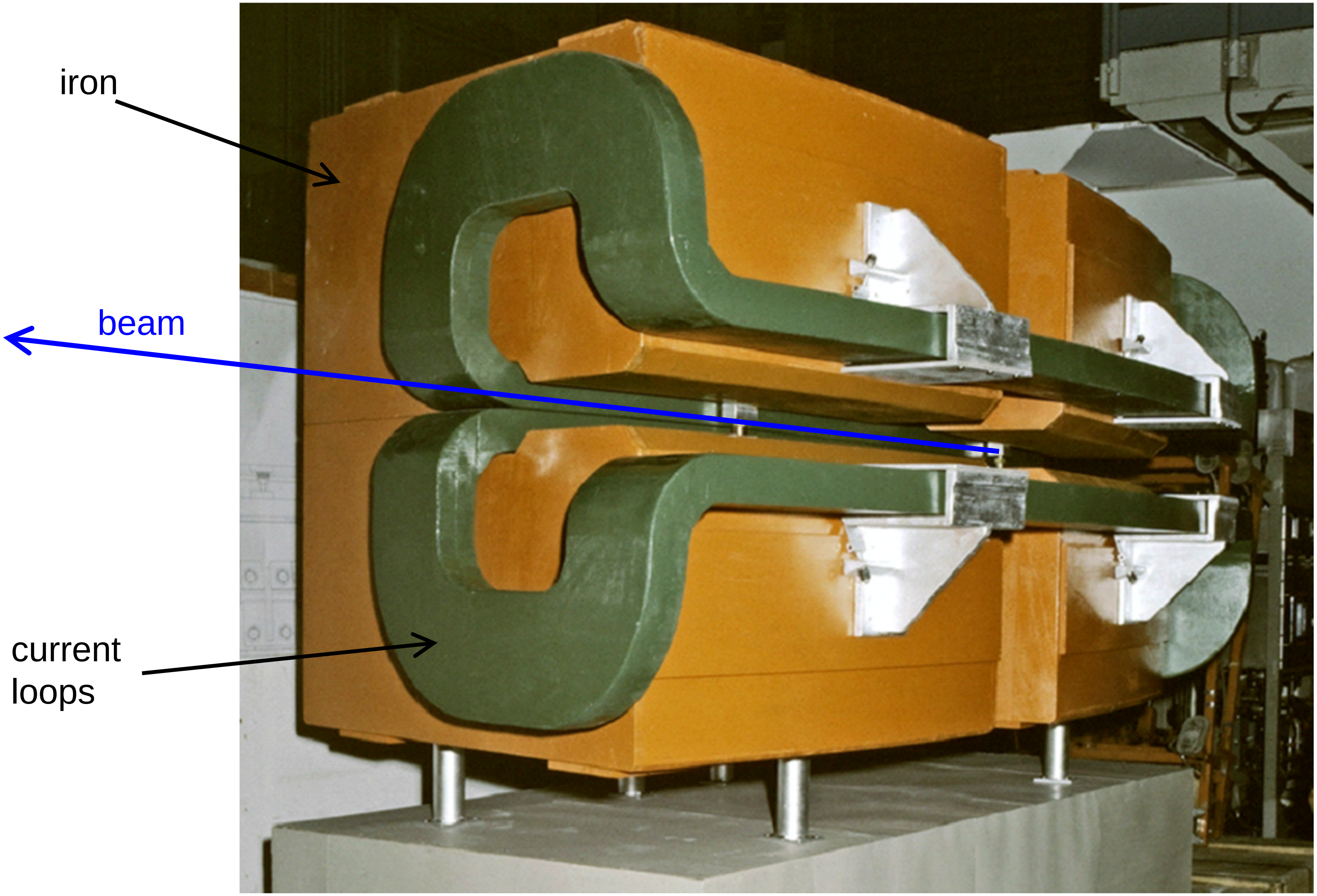
Dipole magnet cross section



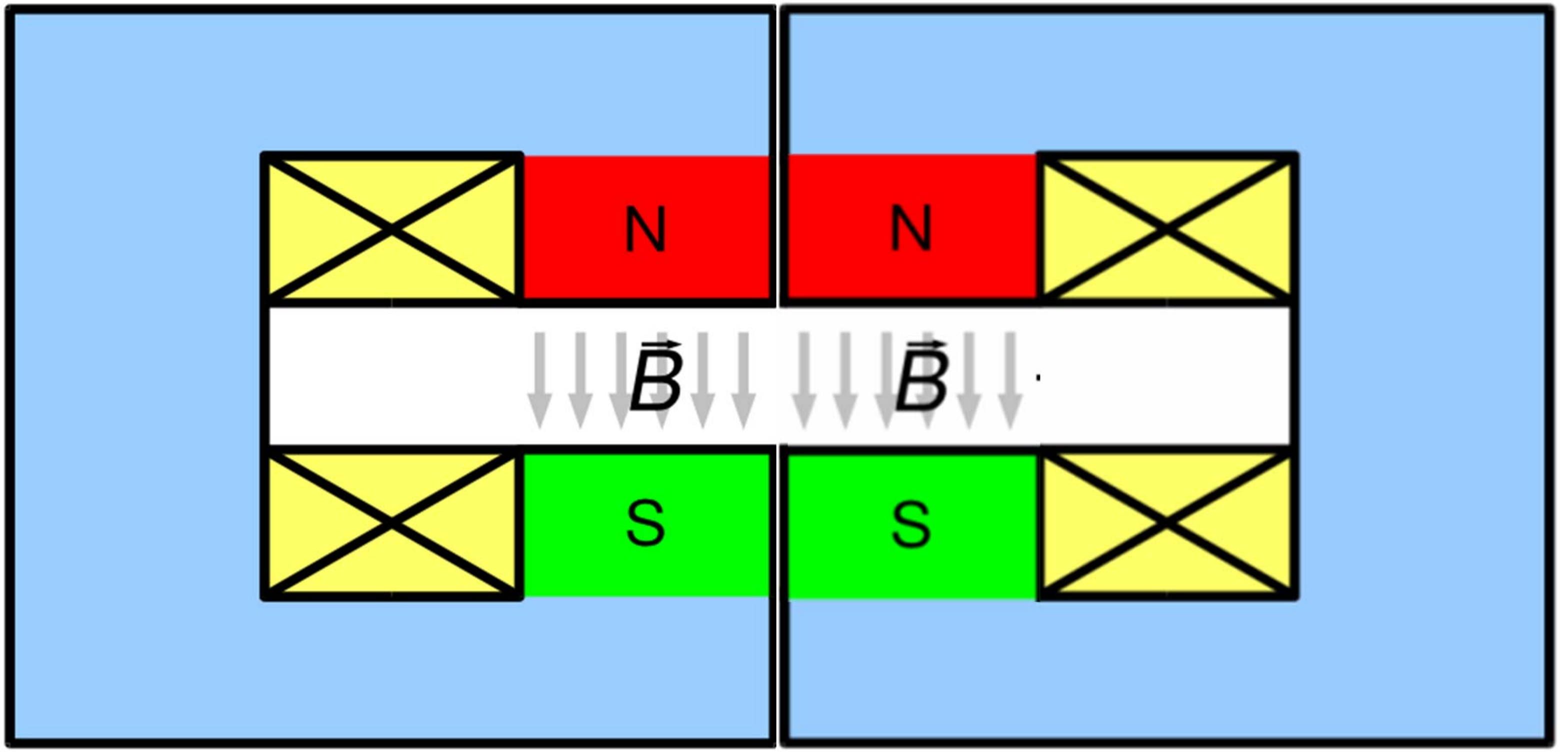
Dipole magnet cross section



Dipole magnet

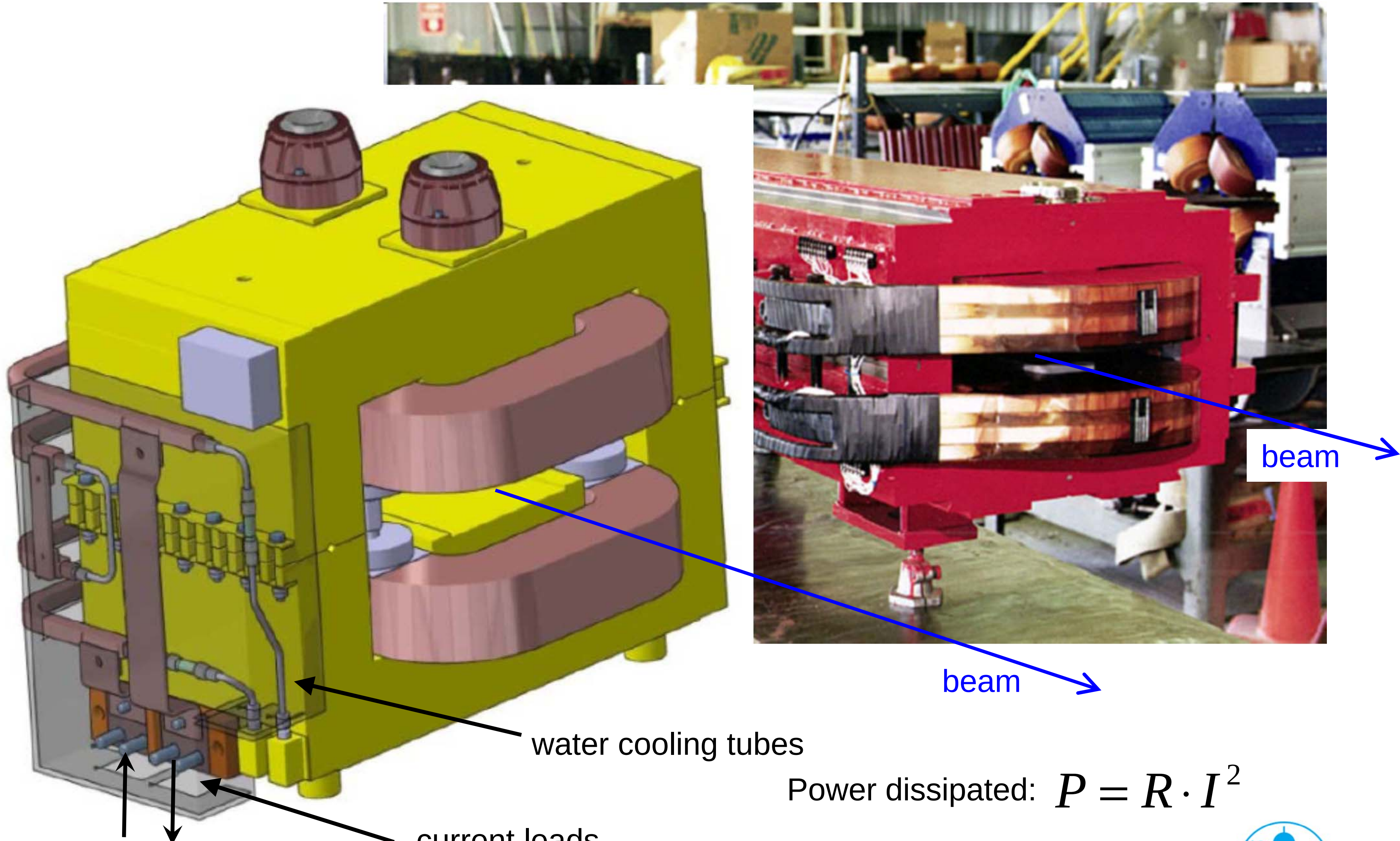


Dipole magnet cross section



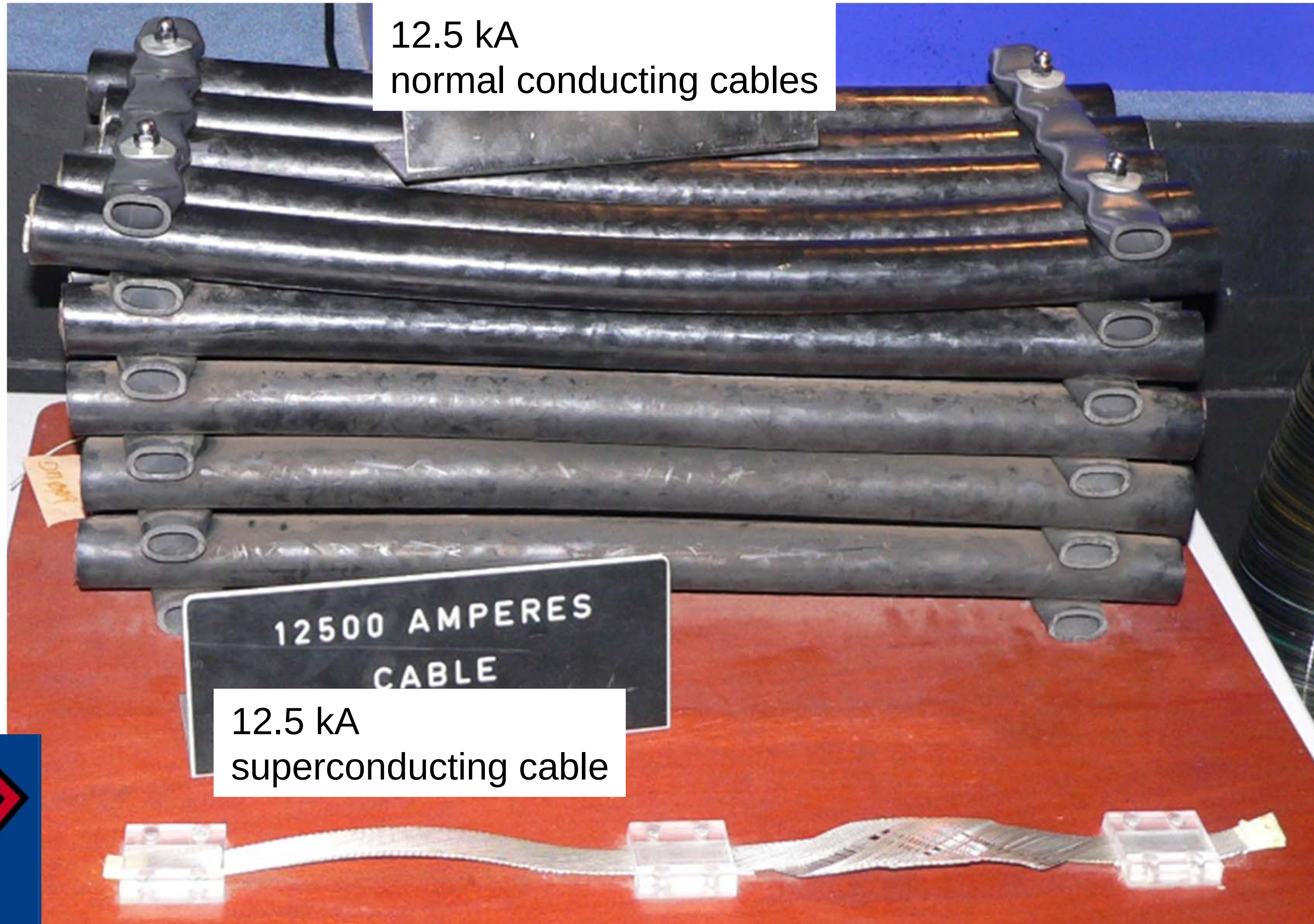
C magnet + C magnet = H magnet

Dipole magnet cross section (another design)



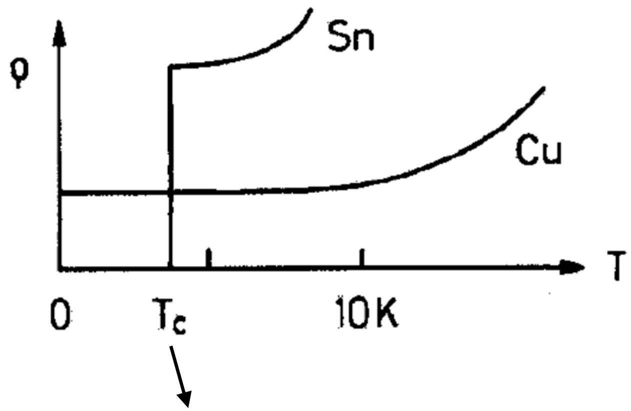
Power dissipated: $P = R \cdot I^2$

Superconductivity



Superconductivity

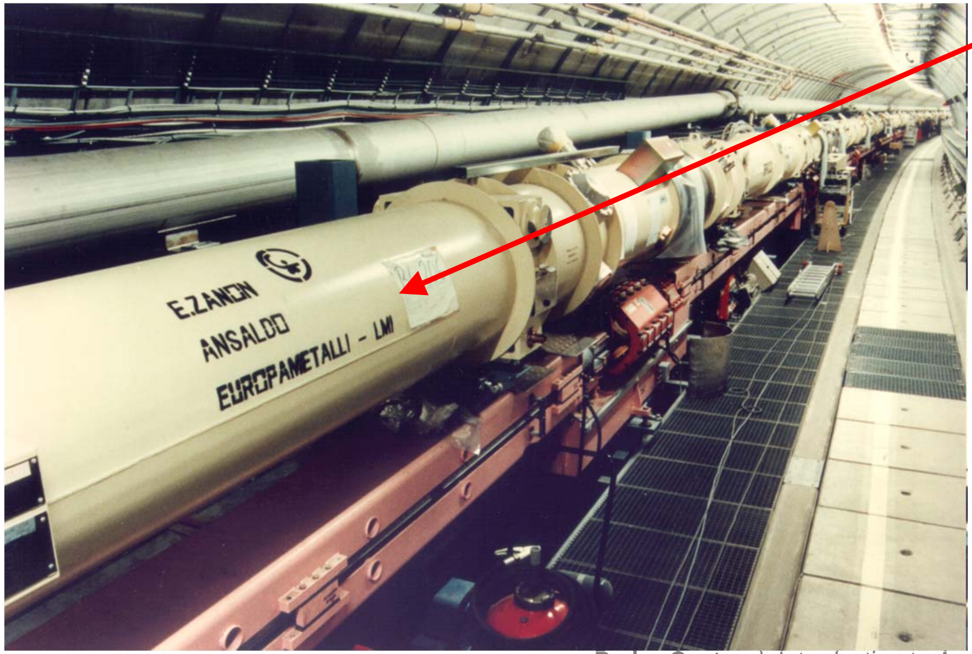
resistance



critical temperature (Tc):

Superconducting dipole magnets

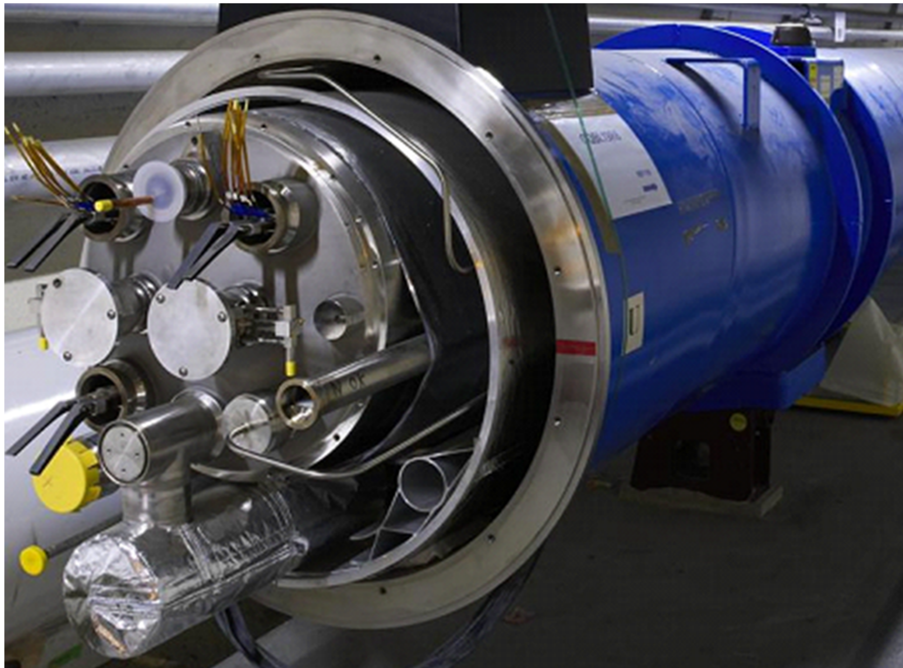
LHC

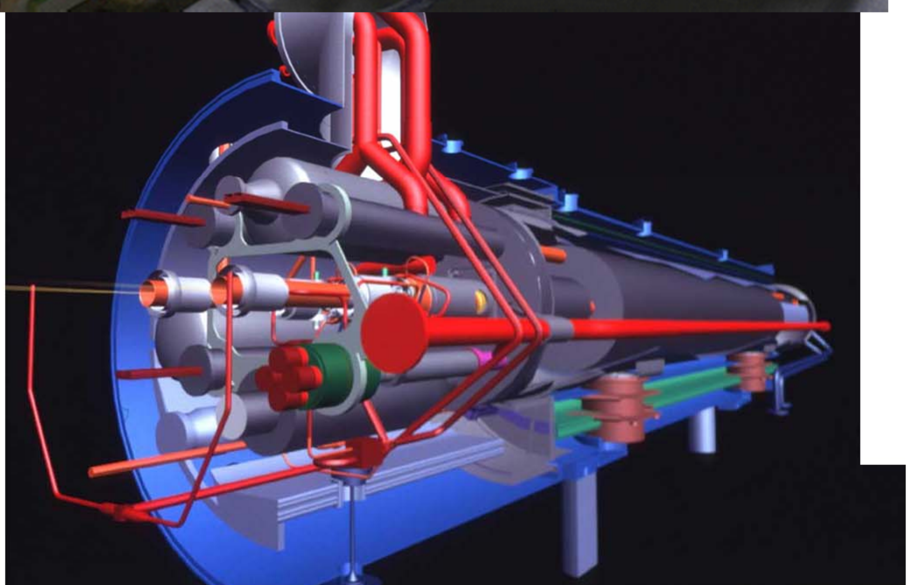


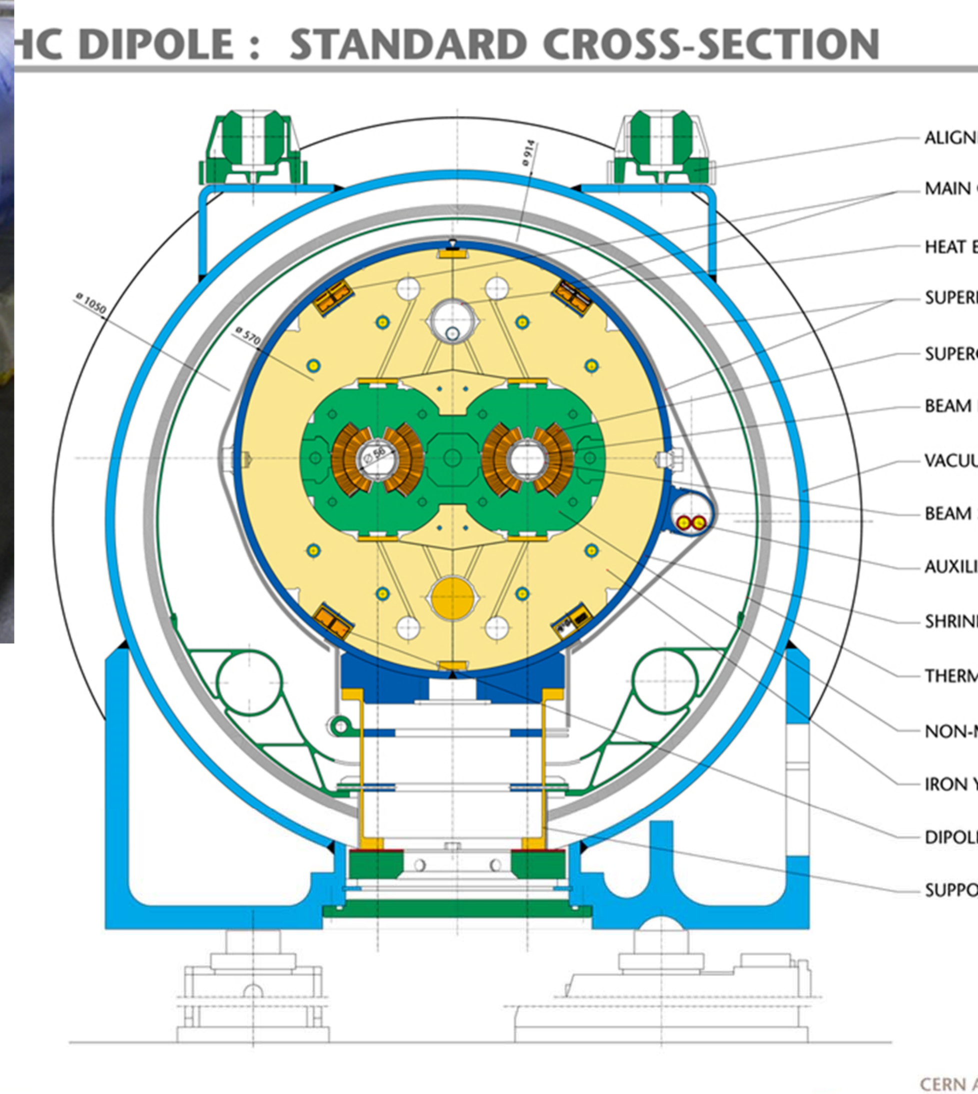
HERA

superconducting dipoles

Superconducting dipole magnets







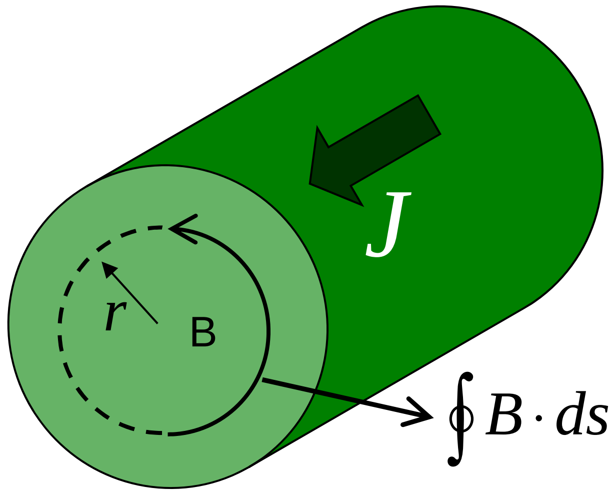
Dipole field from 2 conductors

$J =$ uniform current density

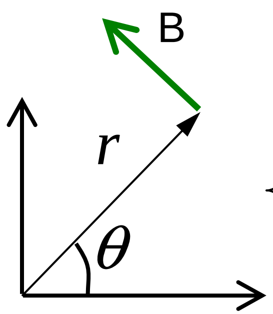
Ampere's law:

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

current through the circle



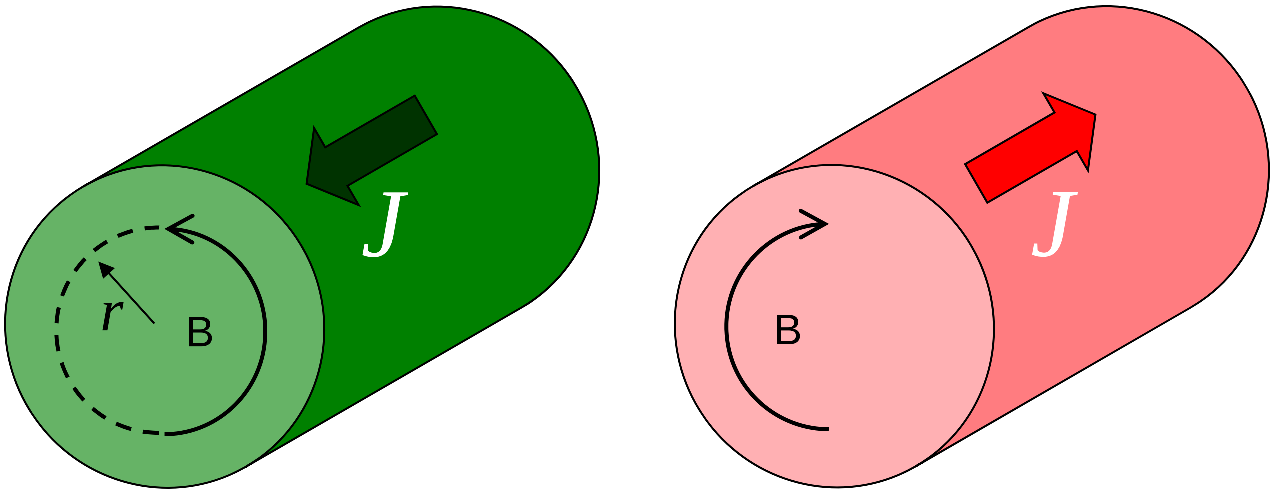
$$\oint B \cdot ds = 2\pi r B = \mu_0 \pi r^2 J \quad \rightarrow \quad B = \frac{\mu_0 J}{2} r$$



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

Dipole field from 2 conductors

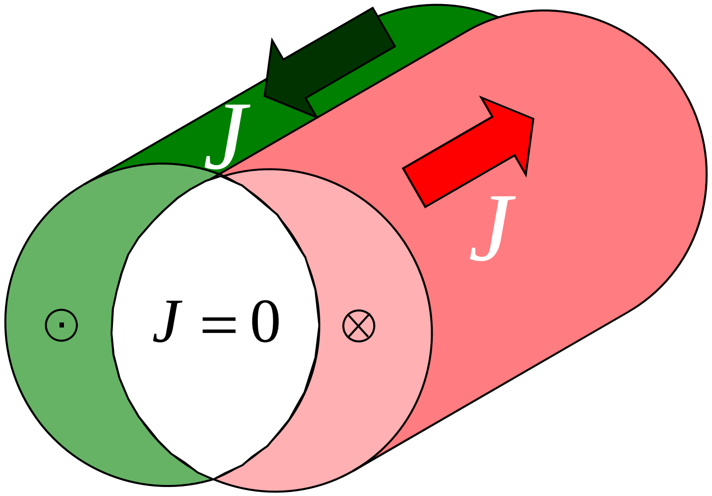
J = uniform current density



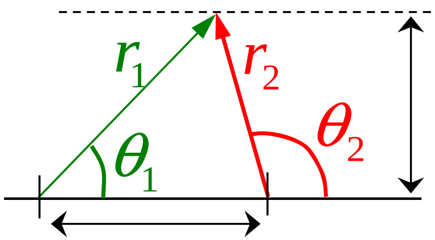
Dipole field from 2 conductors

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

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



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

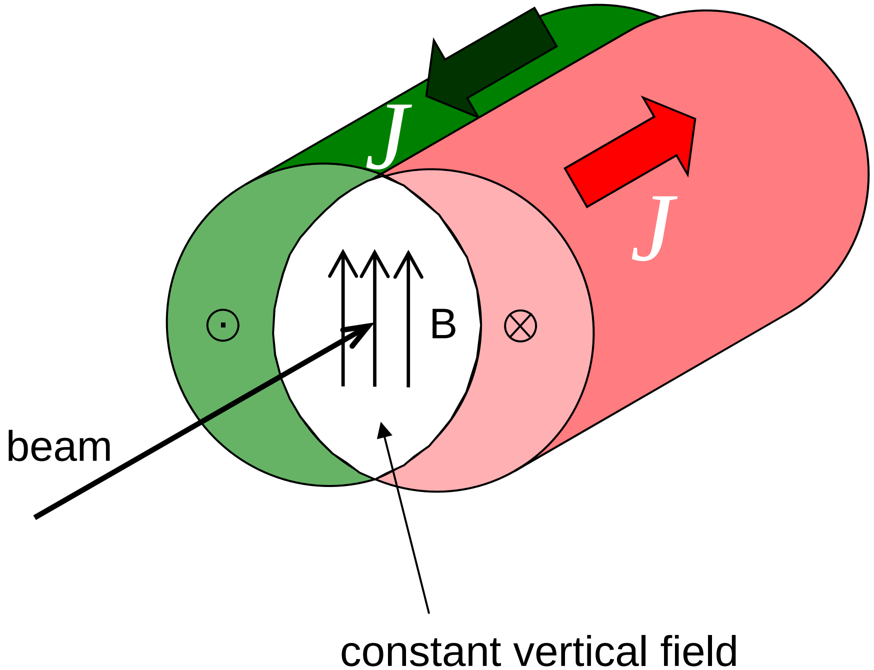


$$h = r_1 \sin\theta_1 = r_2 \sin\theta_2$$

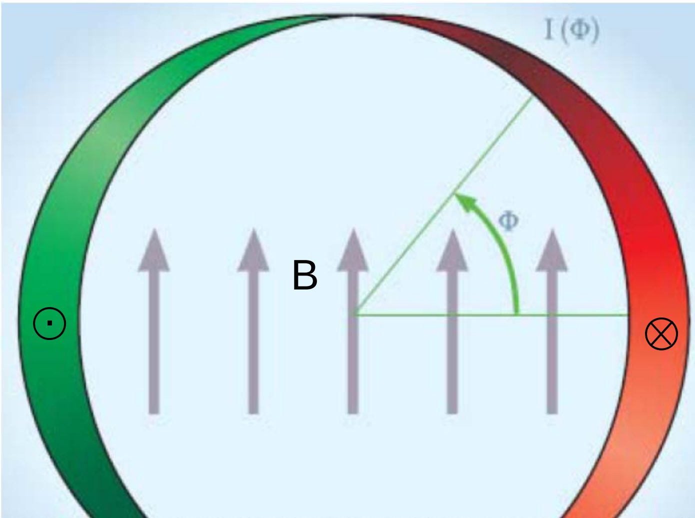
$$B_y = \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2) = \frac{\mu_0 J}{2} d$$

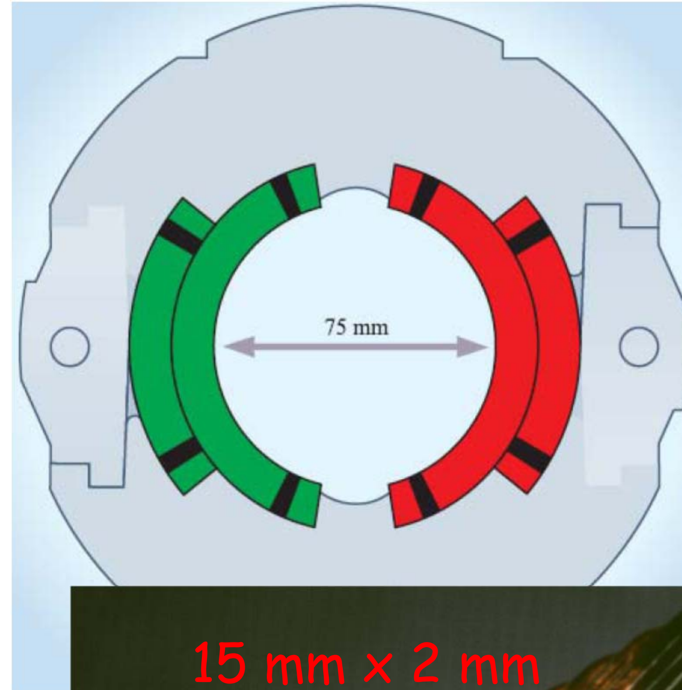
$$d = r_1 \cos\theta_1 + (-r_2 \cos\theta_2)$$

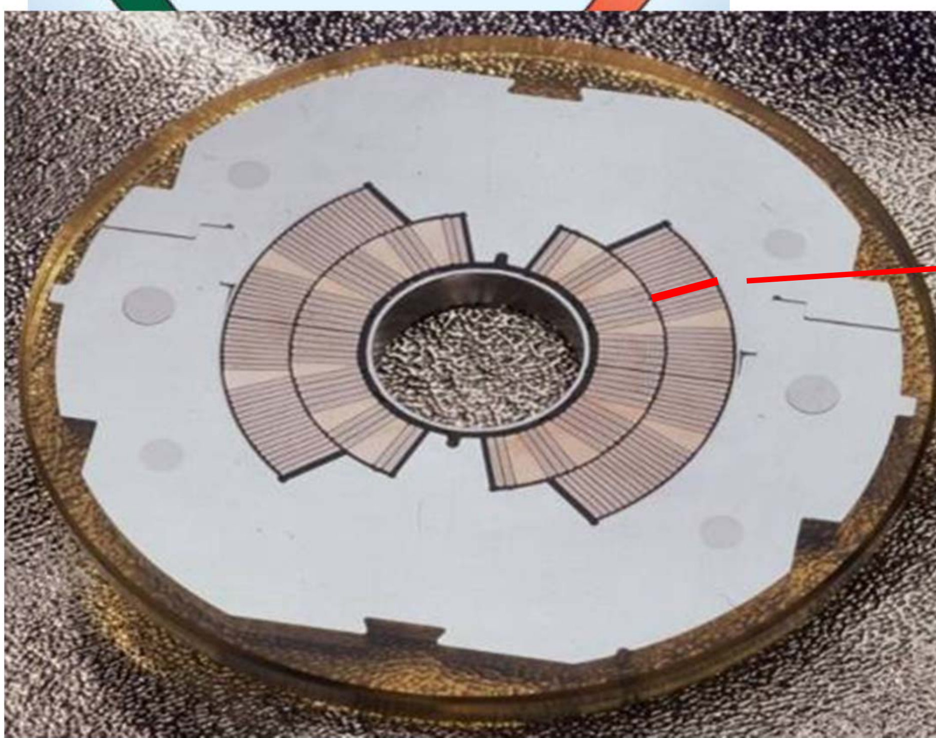
Dipole field from 2 conductors

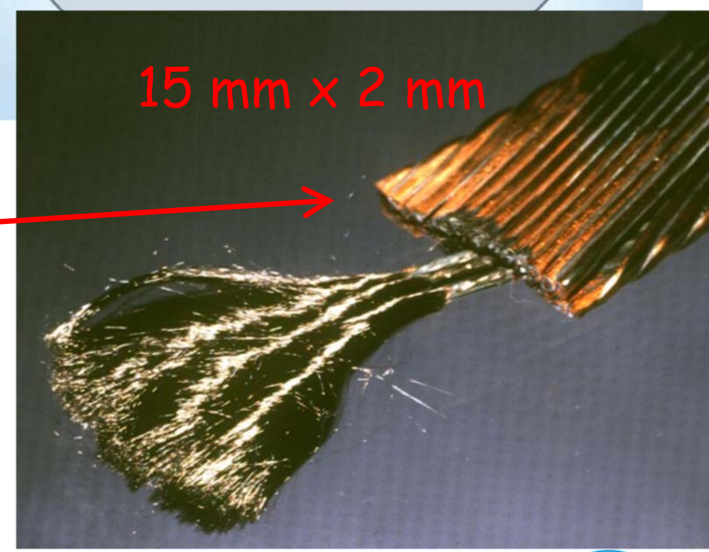


From the principle to the reality…

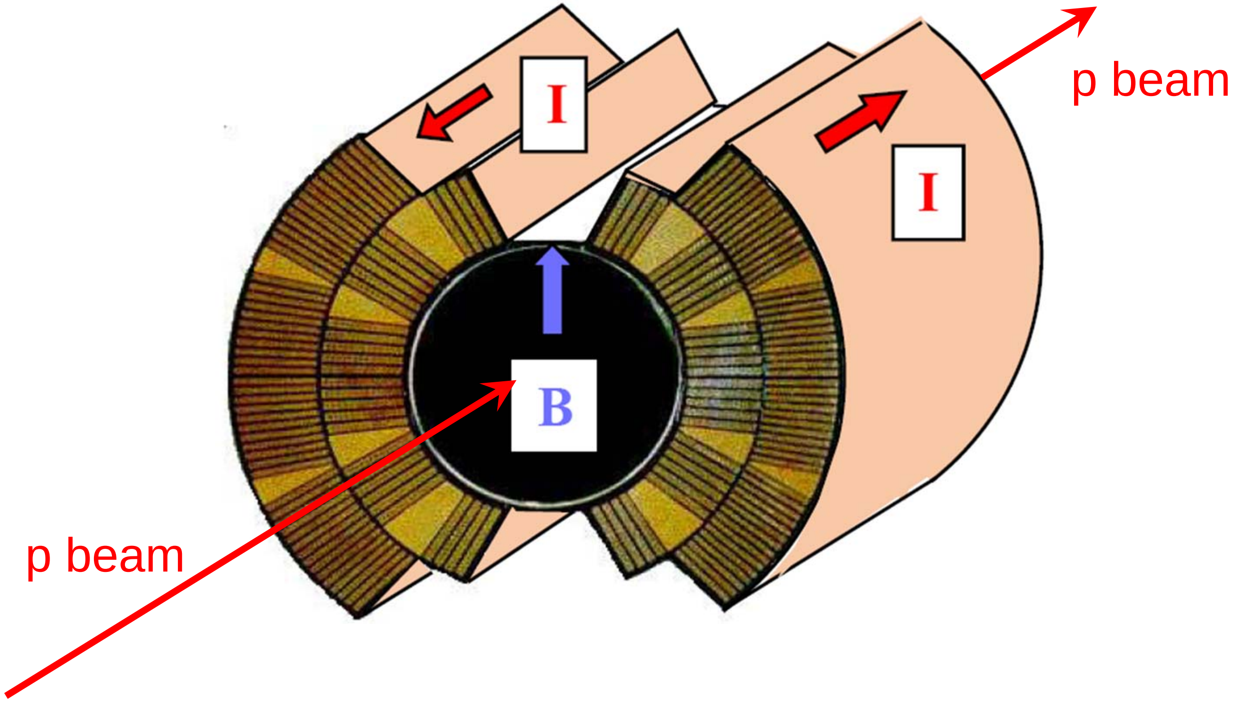




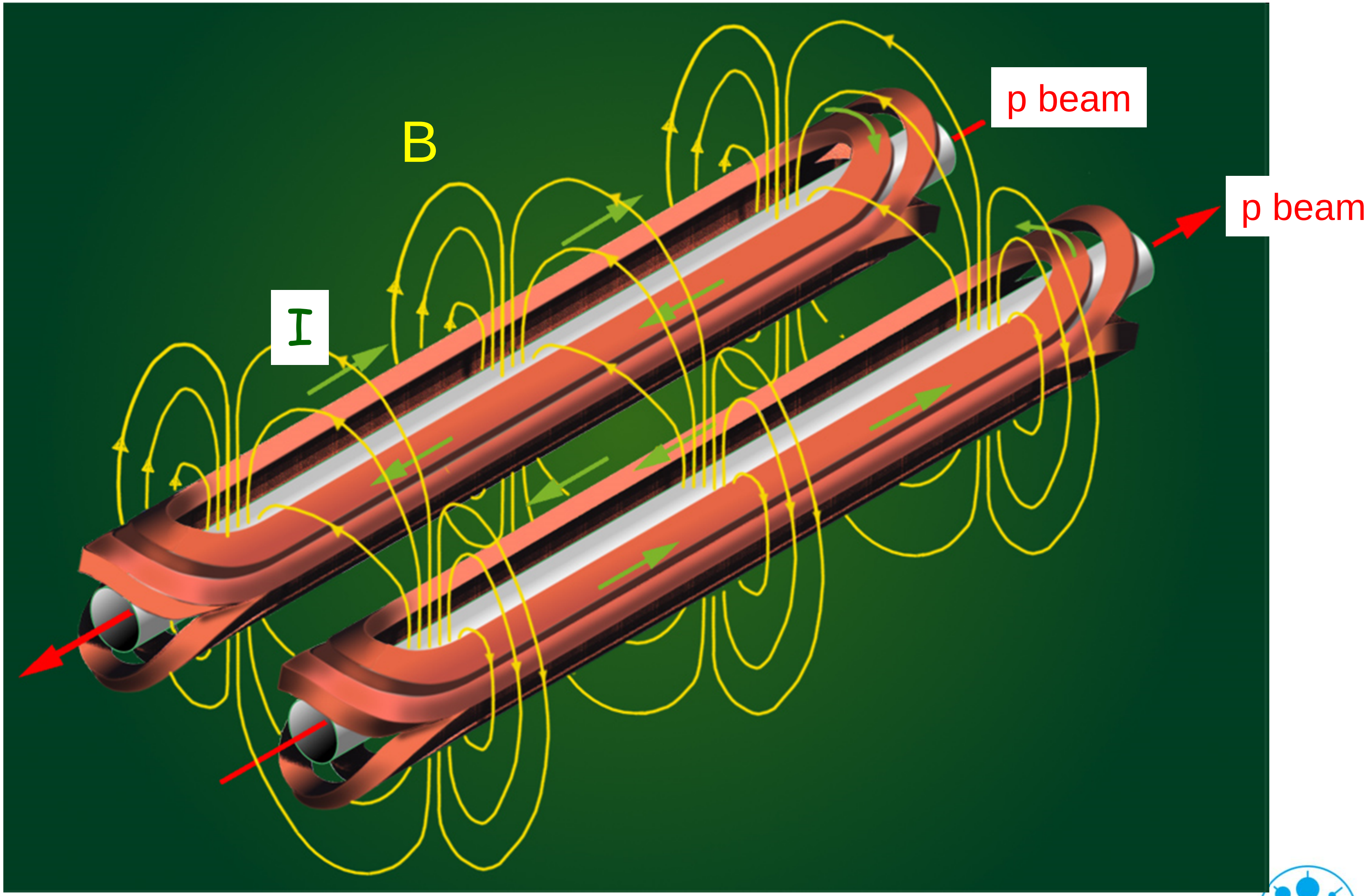




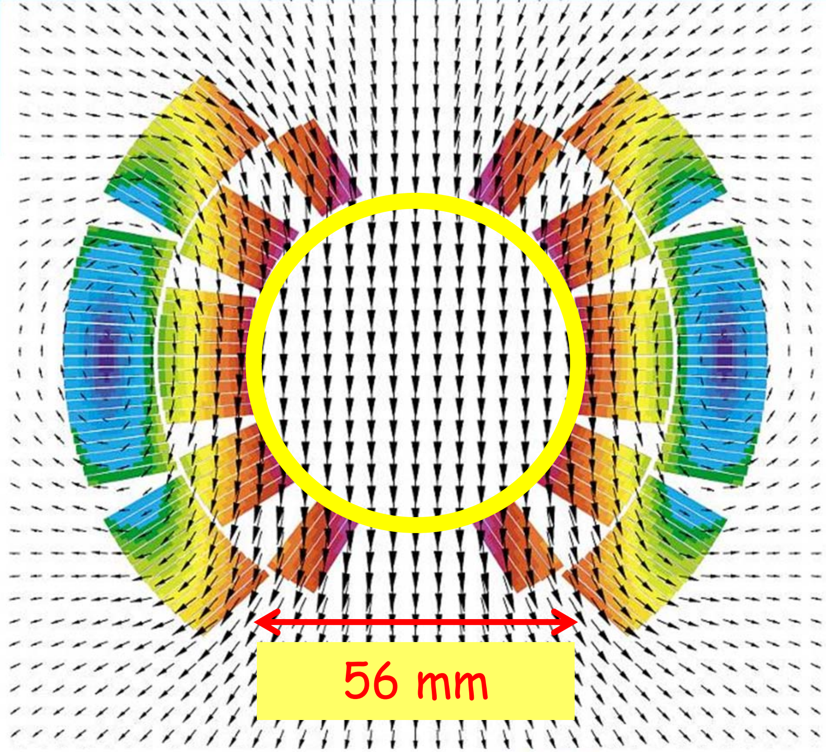
LHC dipole coils in 3D

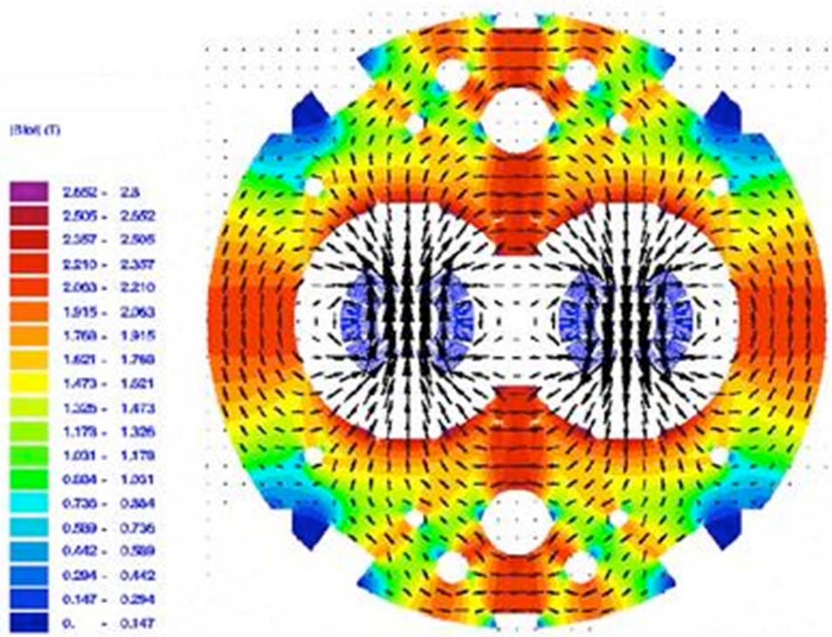


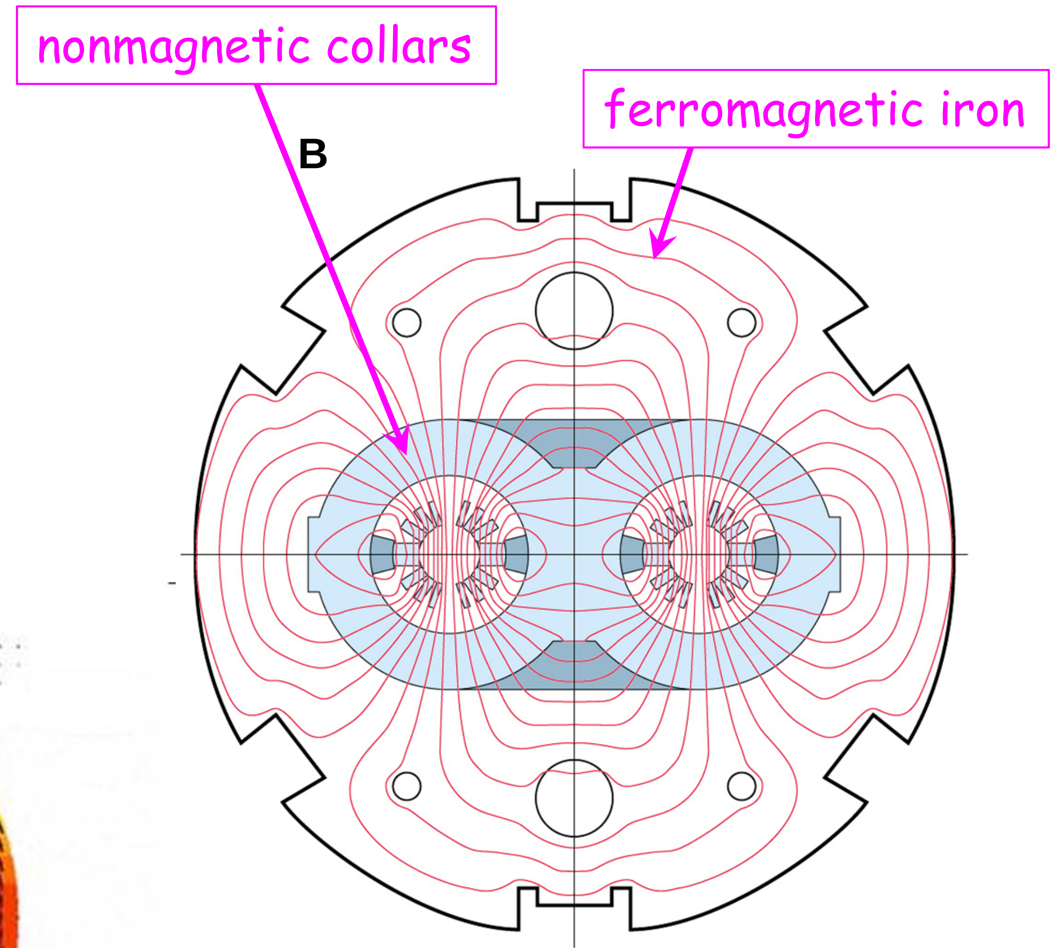
LHC dipole coils in 3D



Computed magnetic field

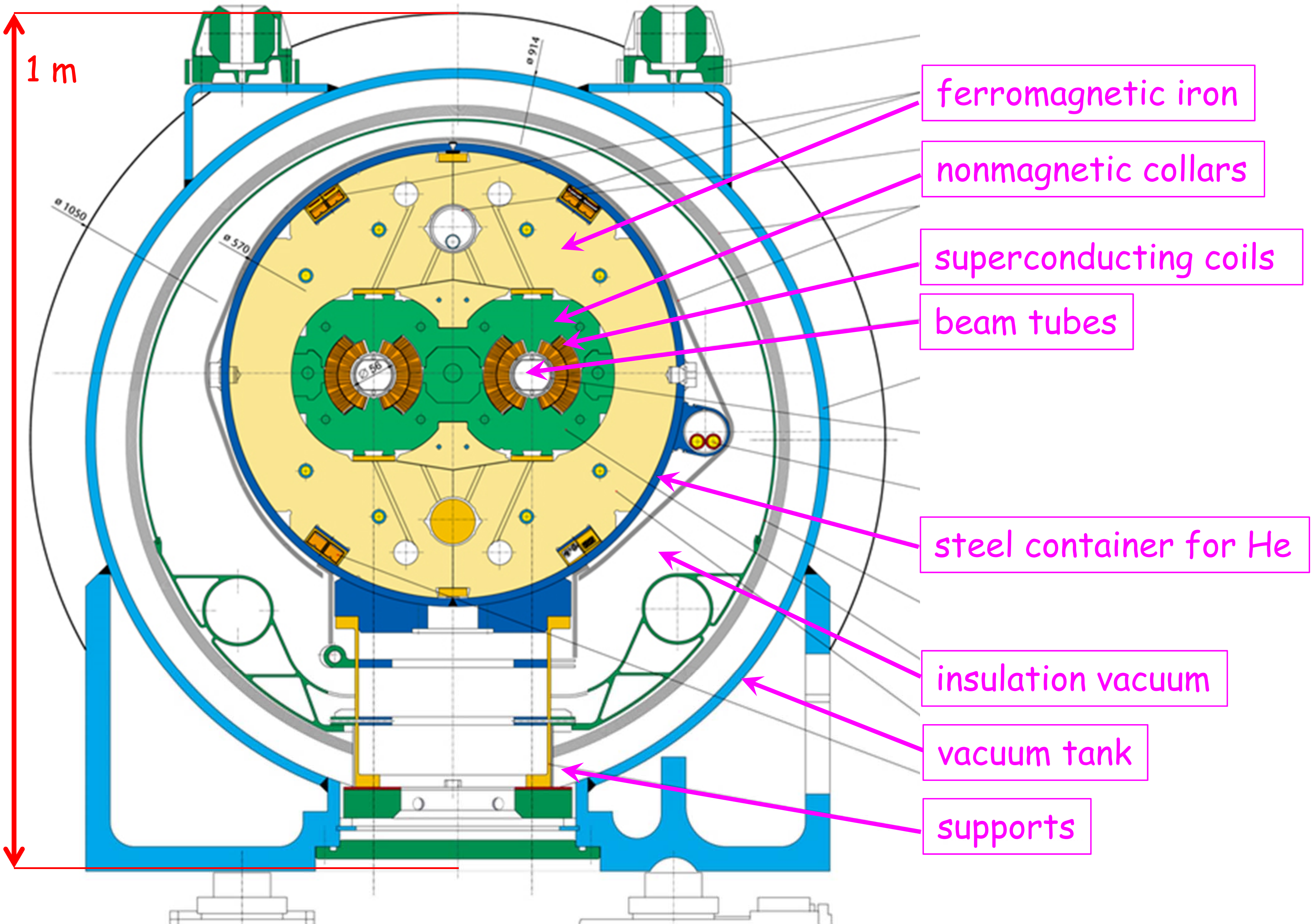






Computed magnetic flux map

LHC DIPOLE : STANDARD CROSS-SECTION

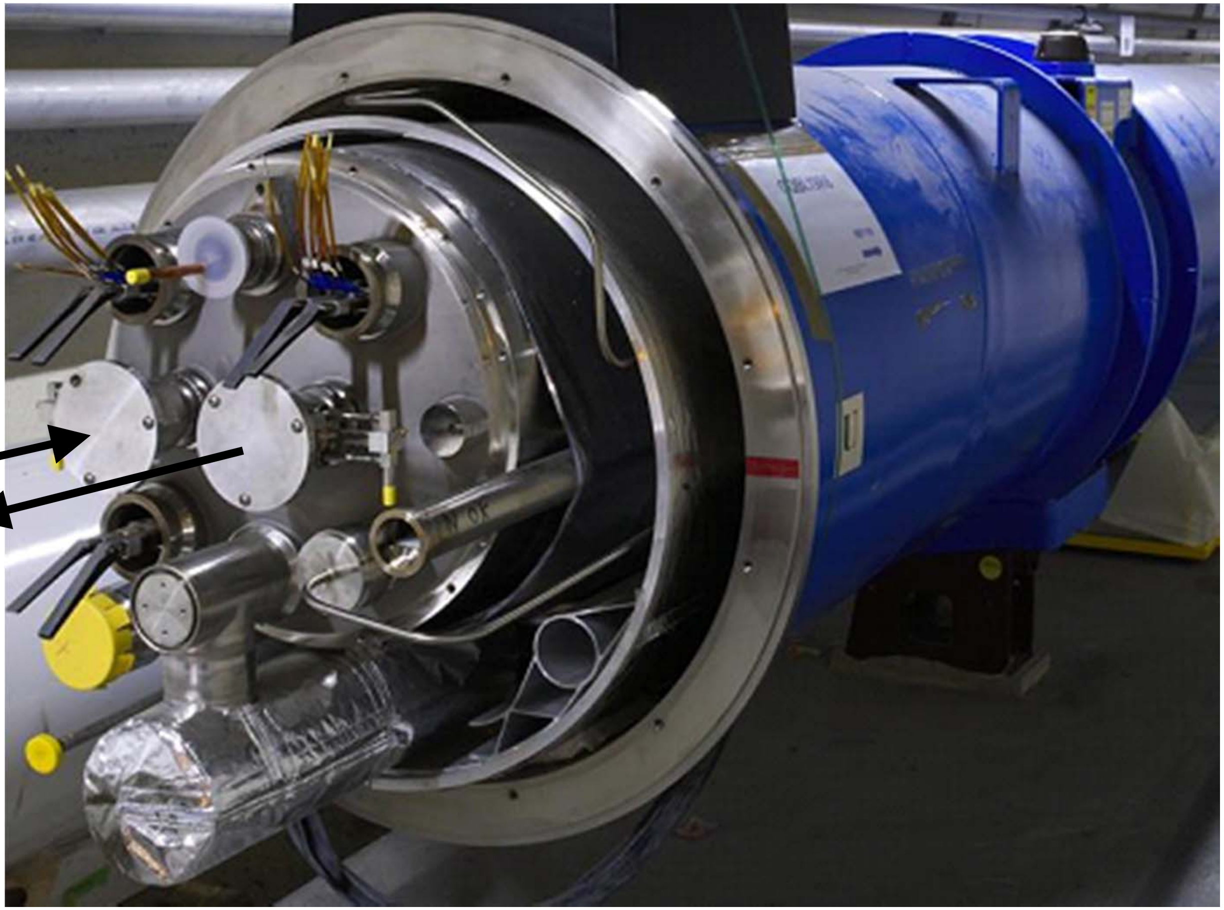


Superconducting dipole magnets

LHC dipole magnet interconnection:

p

p



Summing-up of part 1

Applications:

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

Circular accelerators: the synchrotron

RF cavities:
- pill-box cavity
- superconducting cavities

Dipole magnets:
- normal conducting dipoles
- superconducting dipoles