Introduction to Accelerator Physics

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

Pedro Castro / Accelerator Physics Group (MPY)
Introduction to Accelerator Physics
DESY, 20th July 2011

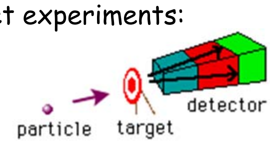
HELMHOLTZ | ASSOCIATION

DESY

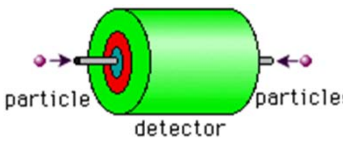
Applications of Accelerators (1)

Particle colliders for High Energy Physics (HEP) experiments

- fix target experiments:



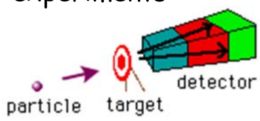
- two beams collision experiments:



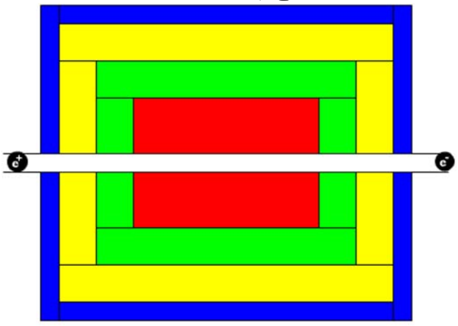
Applications of Accelerators (1)

Particle colliders for High Energy Physics (HEP) experiments

- fix target experiments:



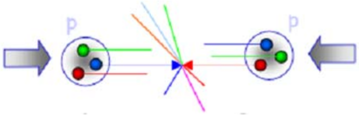
HEP detector

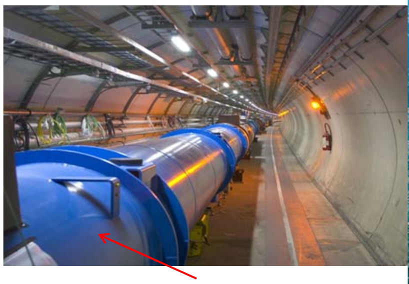


Applications of Accelerators (1)

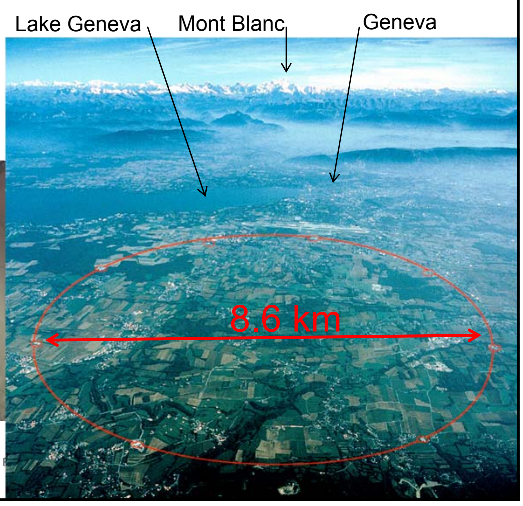
Particle colliders for High Energy Physics experiments

Example: the Large Hadron Collider (LHC) at CERN



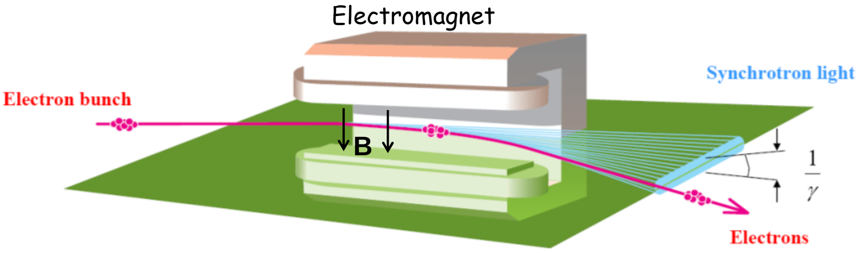


superconducting magnets
(inside a cryostat)



Applications of Accelerators (2)

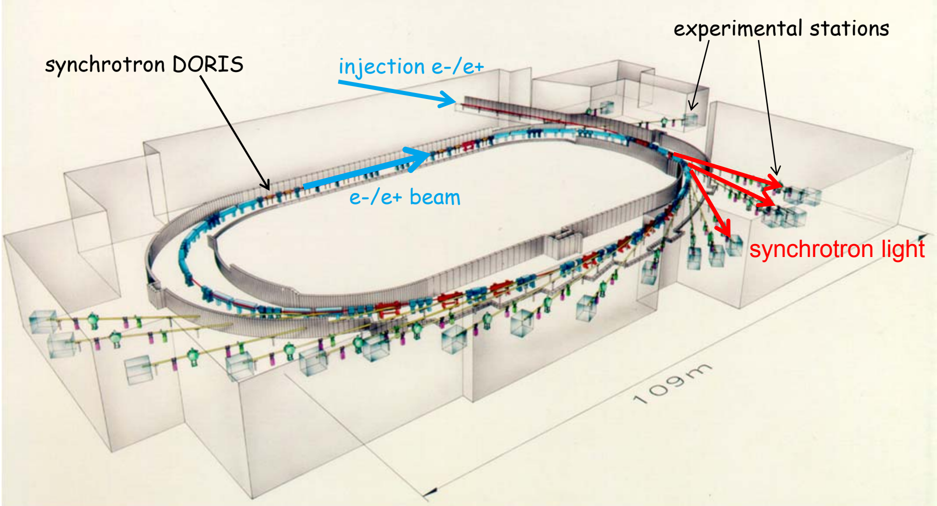
Light sources for biology, physics, chemistry… experiments



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

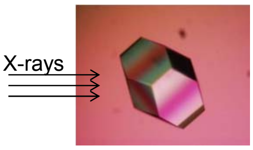
Example: Doppel-Ring-Speicher (DORIS)
'double ring store' at DESY

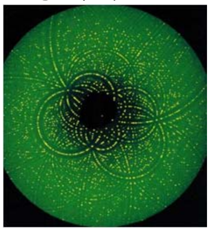
built between 1969 and 1974
HEP exp. until 1983
synchrotron rad. since 1980



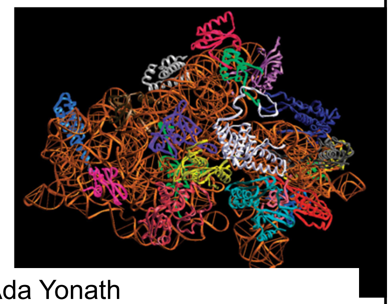
Applications of Accelerators (2)

X-ray crystallography





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

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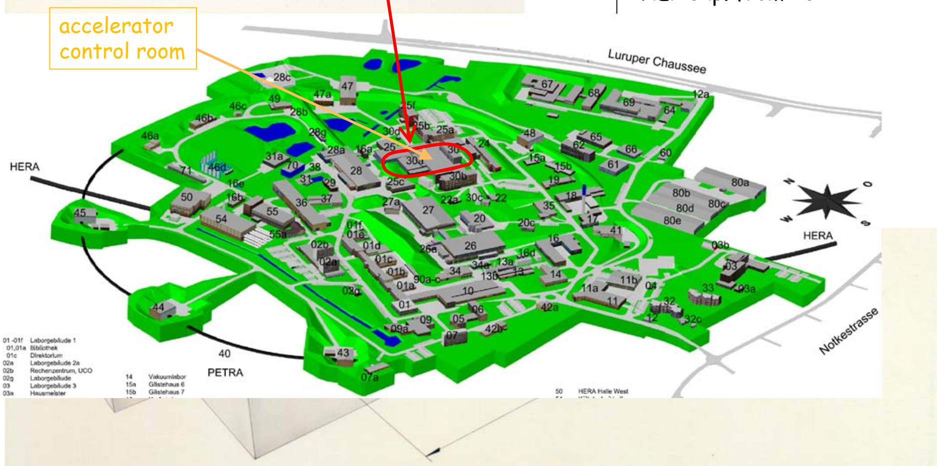
Example: Doppel-Ring-Speicher (DORIS) 'double ring store' at DESY

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"

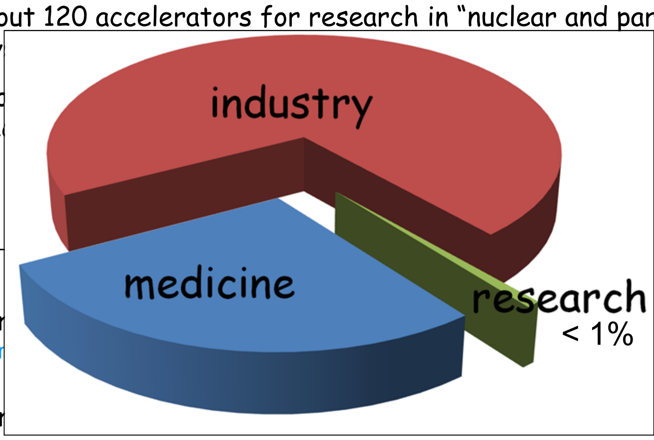
> About 70 electron storage rings and electron linear accelerators used as light sources (so-called 'synchrotron radiation sources')

> 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')



> Mor

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

Applications of Accelerators (3)

Medical applications

For radioisotope production

proton beam + stable isotope —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

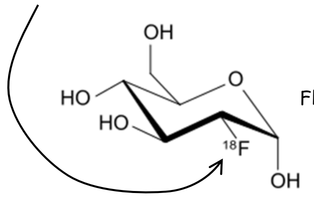
For radioisotope production

For example:

18 MeV proton accelerator —p→ Oxygen-18 (target)

(transmutation)

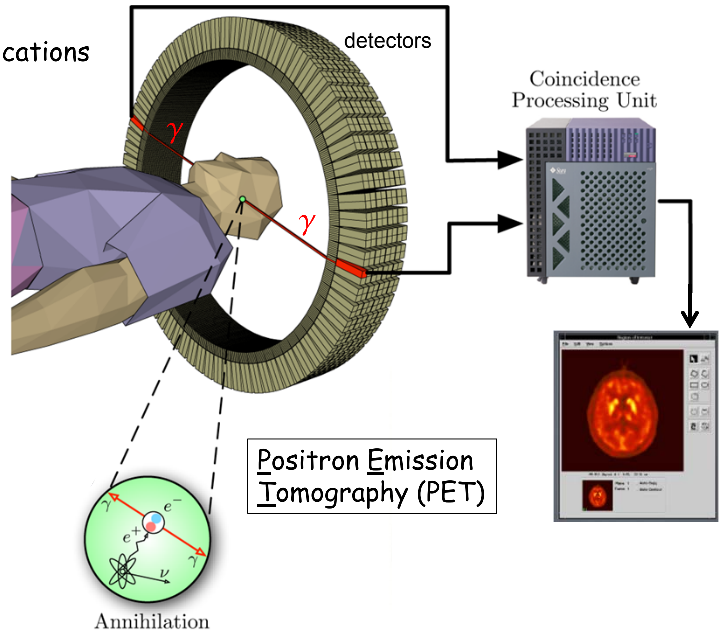
Fluorine-18 (half-life time = 110 min.)



Fludeoxyglucose (^{18}F)

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

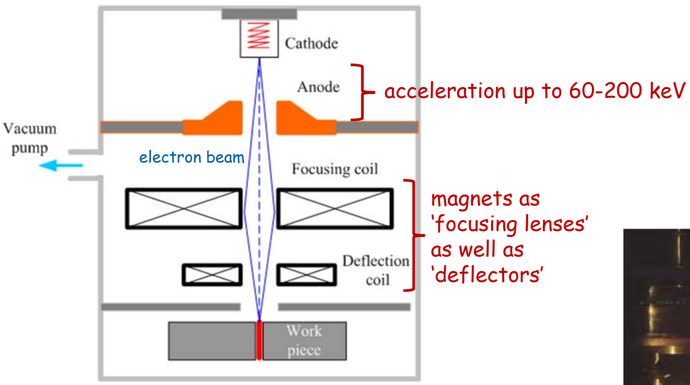
approx. numbers from 2007 (worldwide)

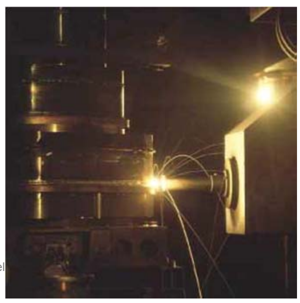
with energies up to 15 MeV

Applications of Accelerators (4)

For industrial applications:

an example: electron beam welding





up to 15 cm

'deep welding effect'

Applications of Accelerators (5)

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

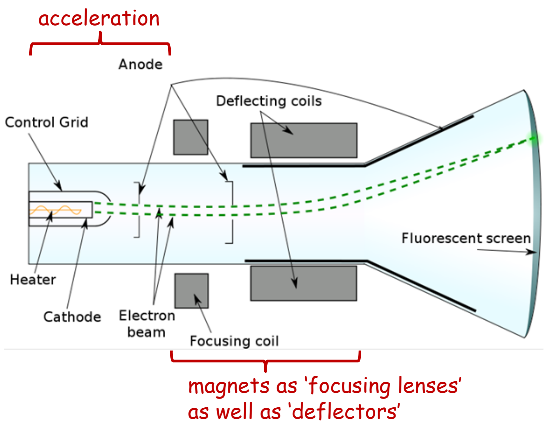
TV

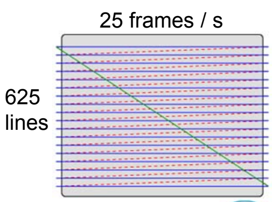
CRT (Cathode Ray Tube)

oscilloscope

Applications of Accelerators (5)

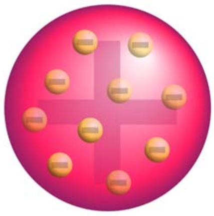
Many millions of television sets, oscilloscopes using CRTs (Cathode Ray Tube)



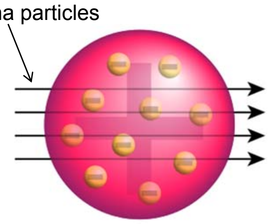


Geiger-Marsden experiment:
the gold foil experiment (1909)

Thomson model of the atom (1904)



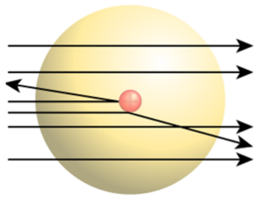
alpha particles



expected result

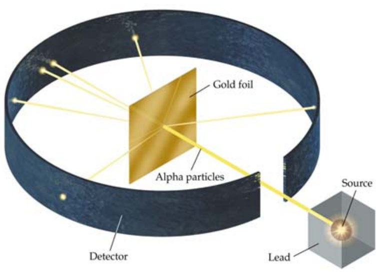
1 in 8000 reflected with θ > 90°

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

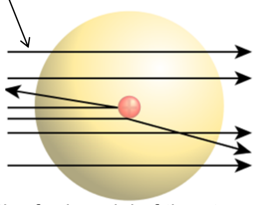


Rutherford model of the atom (1911)

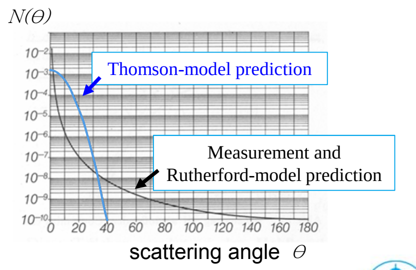
Geiger-Marsden experiment:
the gold foil experiment (1909)



alpha particles



Rutherford model of the atom (1911)



Acceleration with an electrostatic field

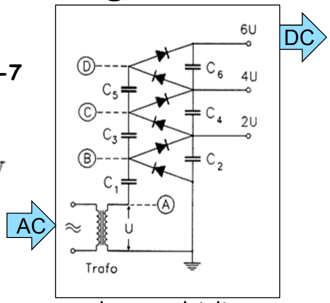
Cockcroft-Walton generator

(1932)

400 keV p → Lithium-7

↓

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



voltage multiplier

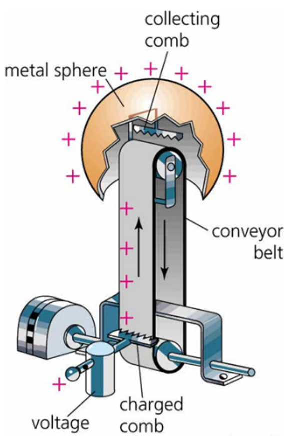
maximum voltage < 1 MV

maximum voltage ~ 25 MV

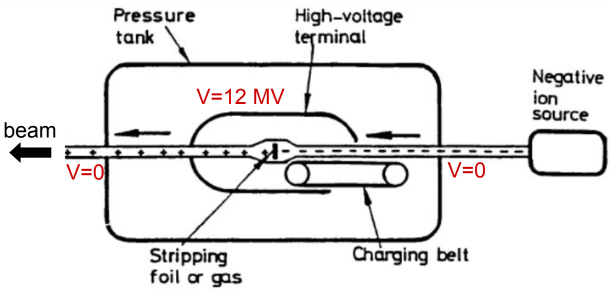
→ **Van de Graaff generator**

Acceleration with an electrostatic field

Van der Graaff generator: invented in 1929

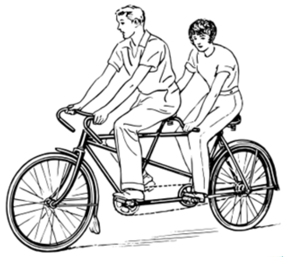


Acceleration with an electrostatic field



Tandem Van der Graaff accelerator

tandem = “two things placed one behind the other”

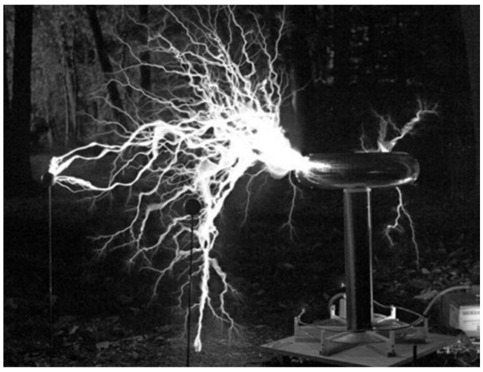


Acceleration with an electrostatic field

20 MV-Tandem
at Daresbury, UK

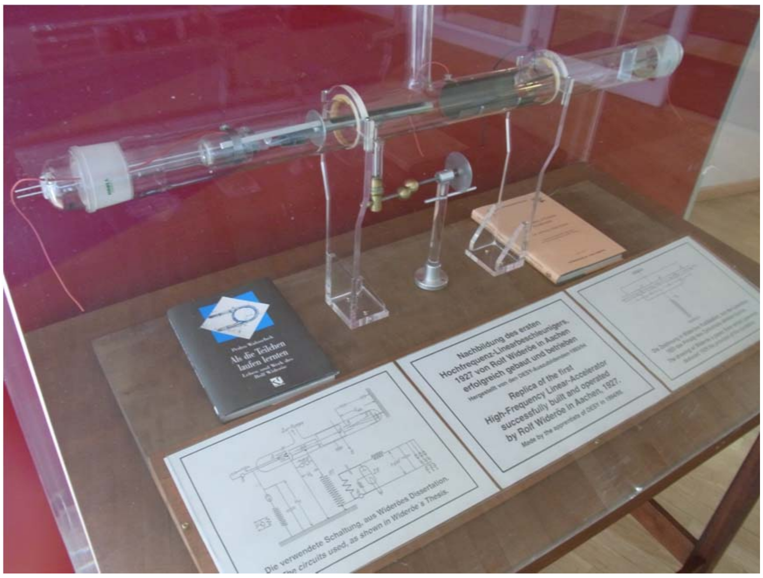
12 MV-Tandem Van de Graaff Accelerator
at MPI Heidelberg, GE

Limitation of electrostatic fields



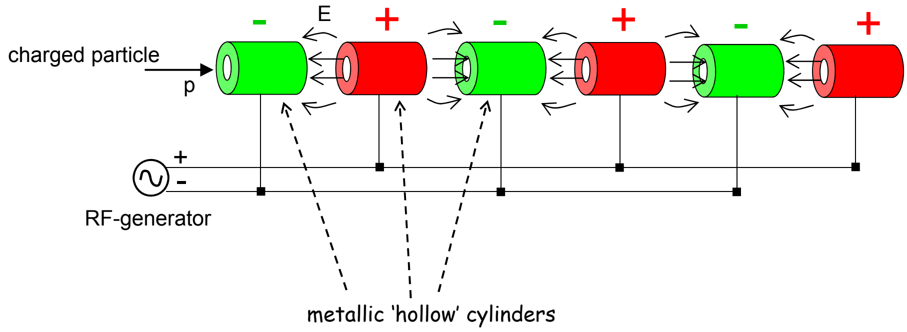
breakdown

Replica of the Widerøe accelerator



Acceleration using Radio-Frequency (RF) generators

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



Acceleration using Radio-Frequency (RF) generators

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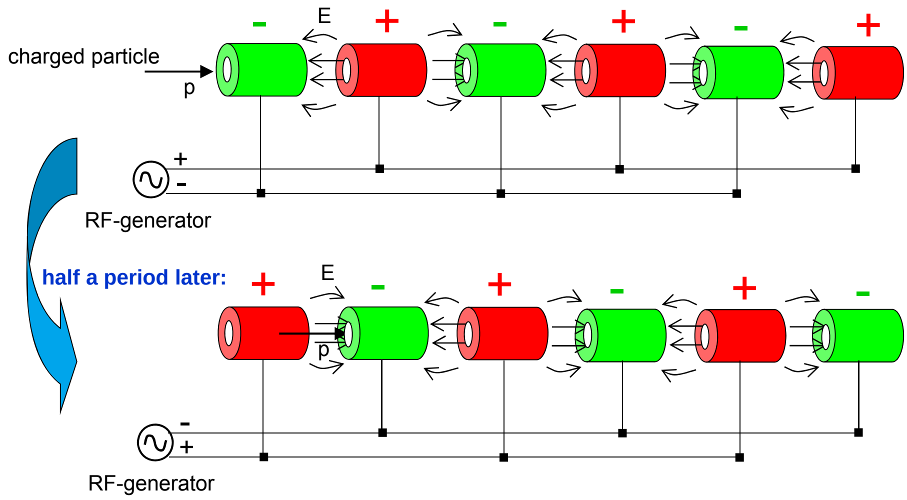
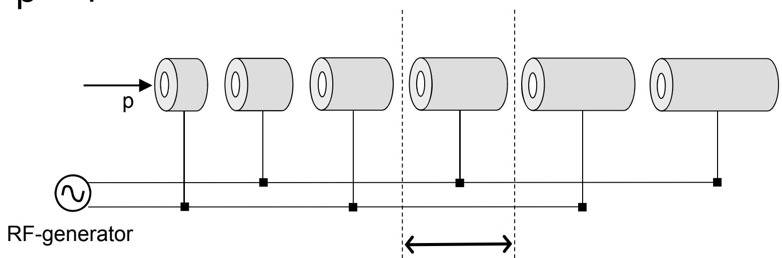


Restrictions of RF

- 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

β < 1



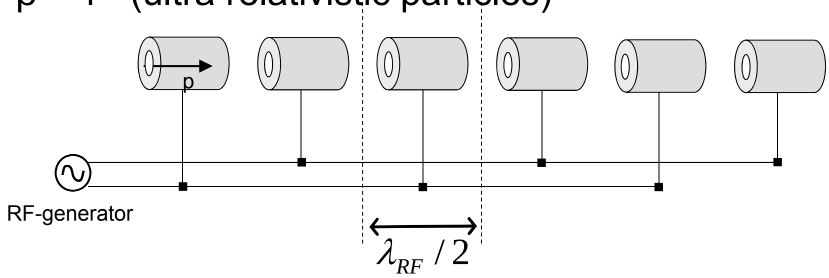
$$v_p \cdot \frac{T_{RF}}{2} = v_p \cdot \frac{\lambda_{RF}}{2c} = \beta_p \cdot \frac{\lambda_{RF}}{2}$$

relativistic β

original Widerøe drift-tube principle

Acceleration using Radio-Frequency (RF) generators

β ≈ 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

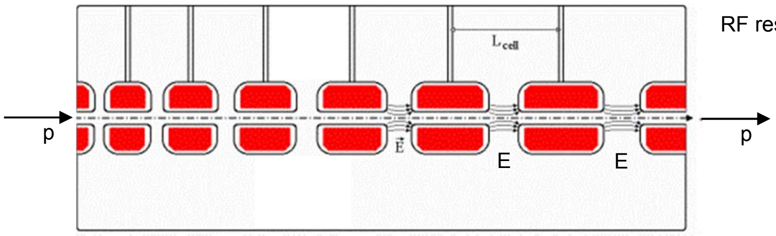
Widerøe drift-tube principle {

Alvarez drift-tube (1946) structure

Cyclotron (1929), E. Lawrence

Resonant cavities

Alvarez drift-tube (1946) structure:

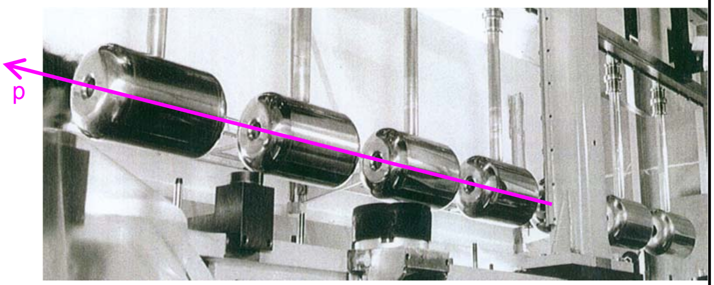


Examples

DESY proton linac (LINAC III)

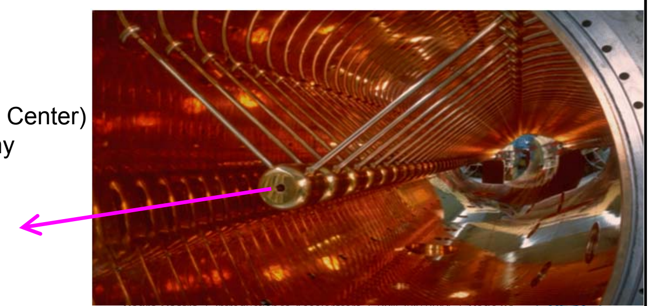
$E_{kin} = 50\,MeV$

$\beta \approx 0.3$

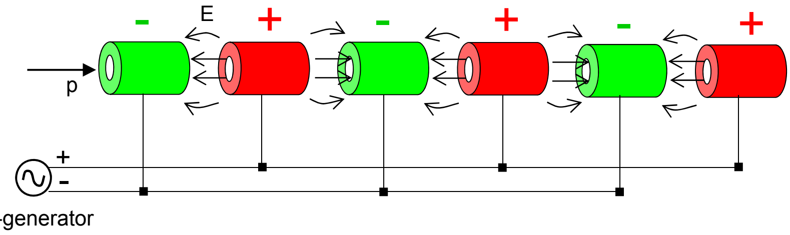


GSI Unilac
(GSI: Heavy Ion Research Center)
Darmstadt, Germany

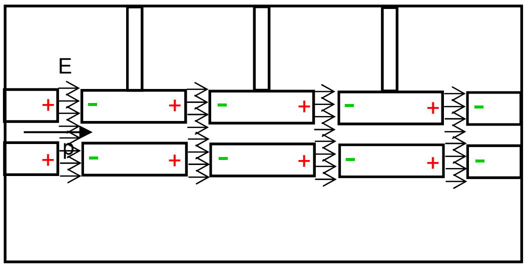
Protons/Ions
E ≈ 20 MeV per nucleon
$\beta \approx 0.04 \ldots 0.2$



Widerøe drift-tube

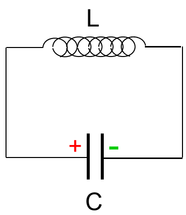


Alvarez drift-tube

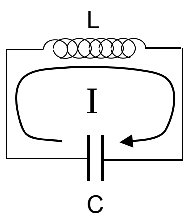


Charges, currents and electromagnetic fields

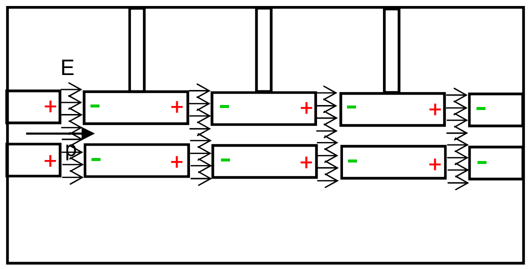
LC circuit (or resonant circuit) analogy:



a quarter of a period later:



Alvarez drift-tube



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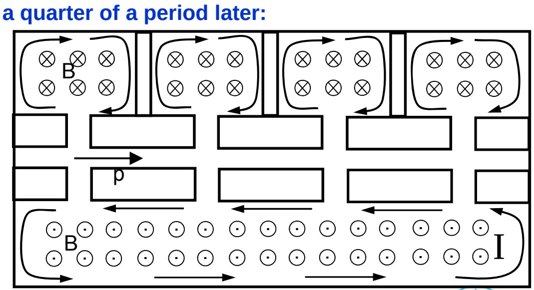
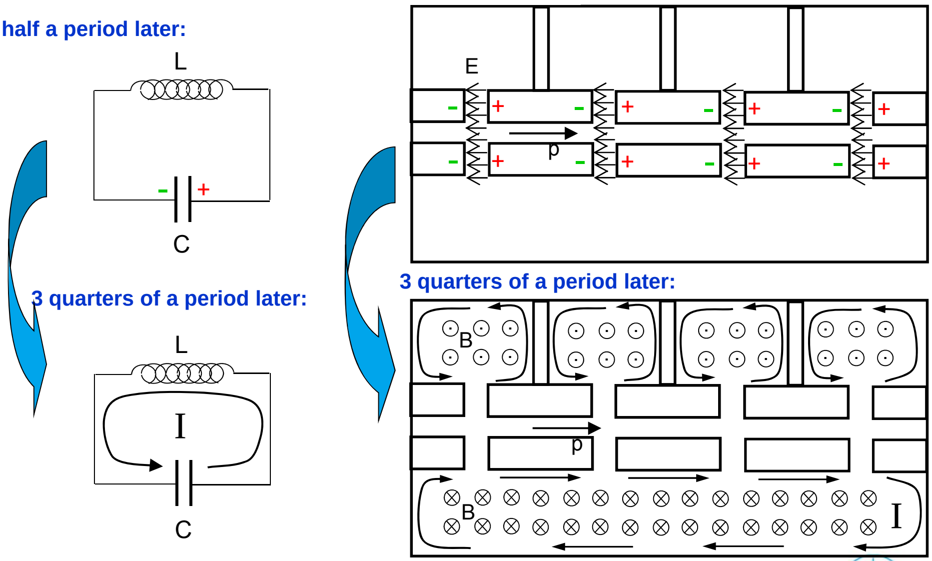
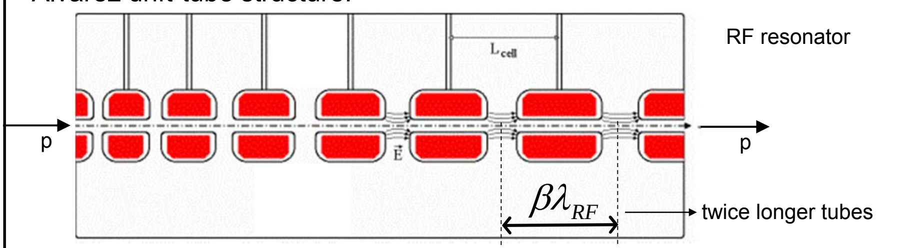


Charges, currents and electromagnetic fields

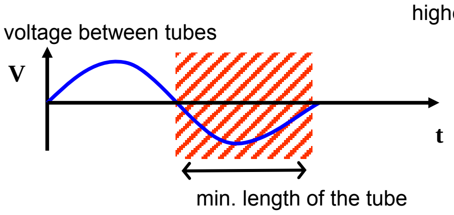


Resonant cavities

Alvarez drift-tube structure:



higher frequencies possible → shorter accelerator



preferred solution
for ions and protons
up to few hundred MeV

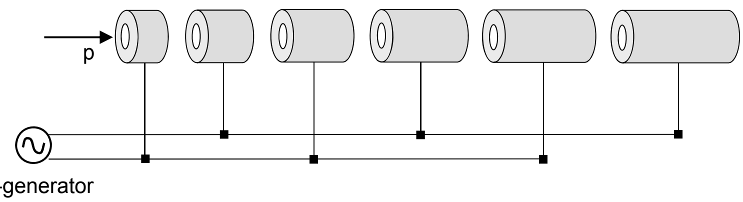
Examples

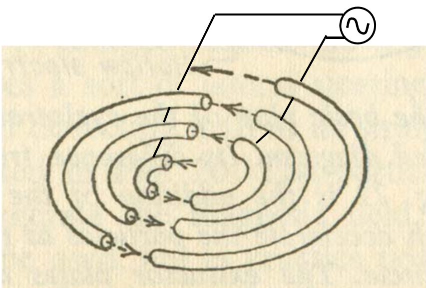
inside a drift tube linac

Linac2 at CERN, 50 MeV

Acceleration using Radio-Frequency (RF) generators

original Widerøe drift-tube principle



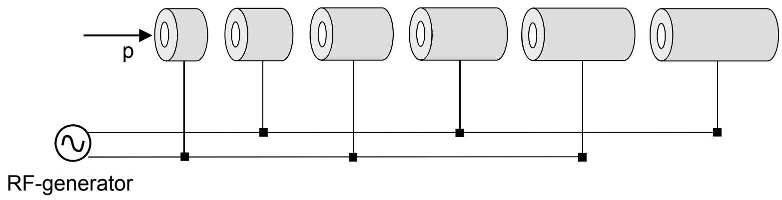


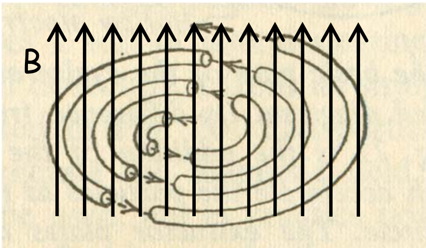
first concept of the 'cyclotron' (1929)
(from E. Lawrence)

drift-tube linac "rolled up"

Acceleration using Radio-Frequency (RF) generators

original Widerøe drift-tube principle





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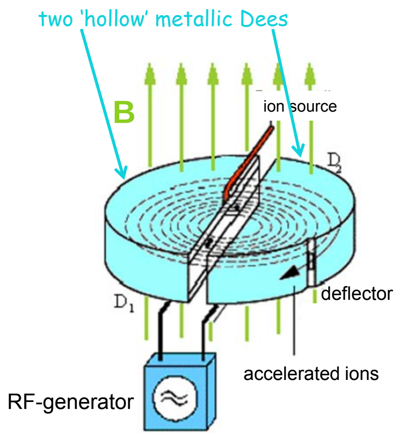
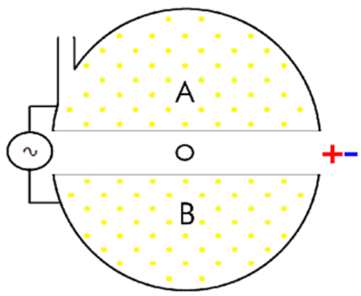
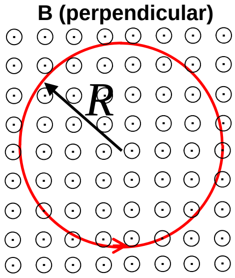
drift-tube linac "rolled up"

Cyclotron





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: $T = \dfrac{2\pi\,R}{v} = 2\pi\dfrac{m}{q\,B} = const.$

Cyclotron

… in a uniform constant magnetic field:

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

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

→ protons up to 15 MeV (β = 0.1)

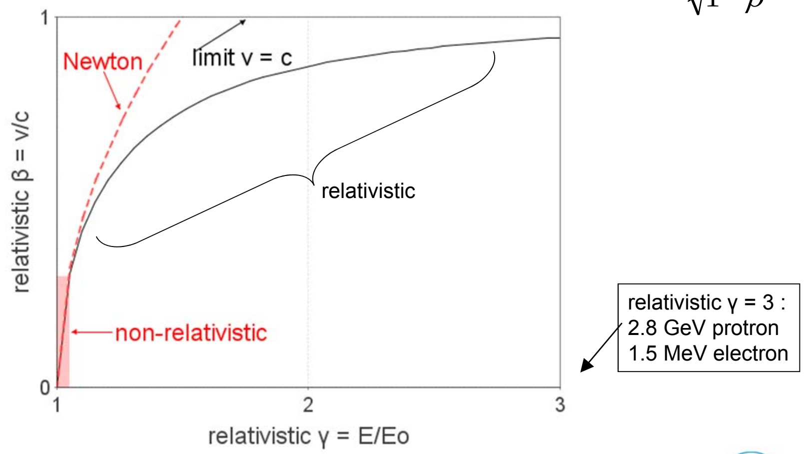
Velocity as function of energy → β as function of γ

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

Einstein:

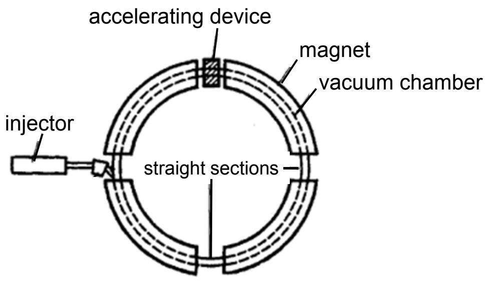
$$E = E_o + E_{kin} = \gamma m c^2 = \frac{mc^2}{\sqrt{1-\beta^2}}$$

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



Cyclotron at Fermilab, Chicago IL, USA

Circular accelerators

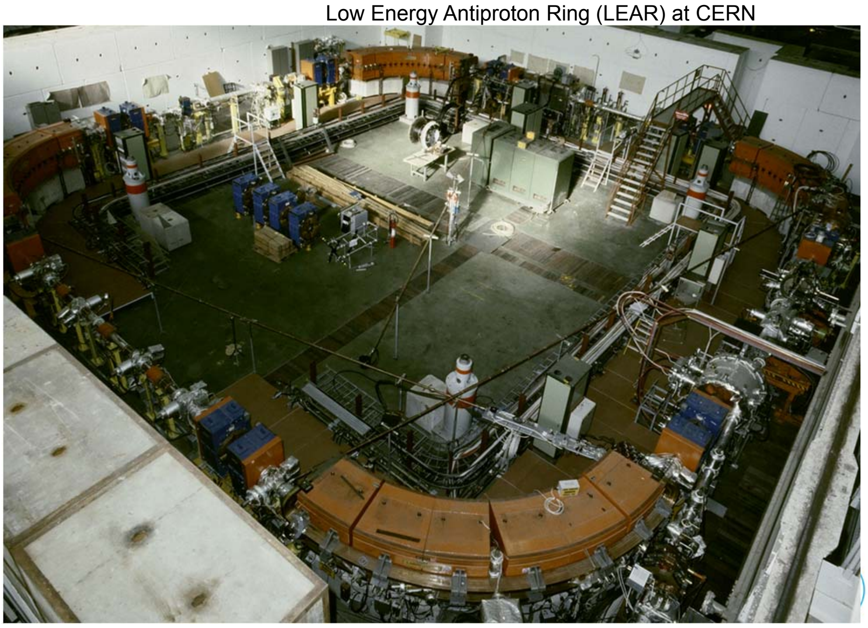


$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = q\,v\,B = m\frac{v^2}{R} \quad \Rightarrow \quad R = \frac{m\,v}{q\,B}$$

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

Circular accelerators

Low Energy Antiproton Ring (LEAR) at CERN



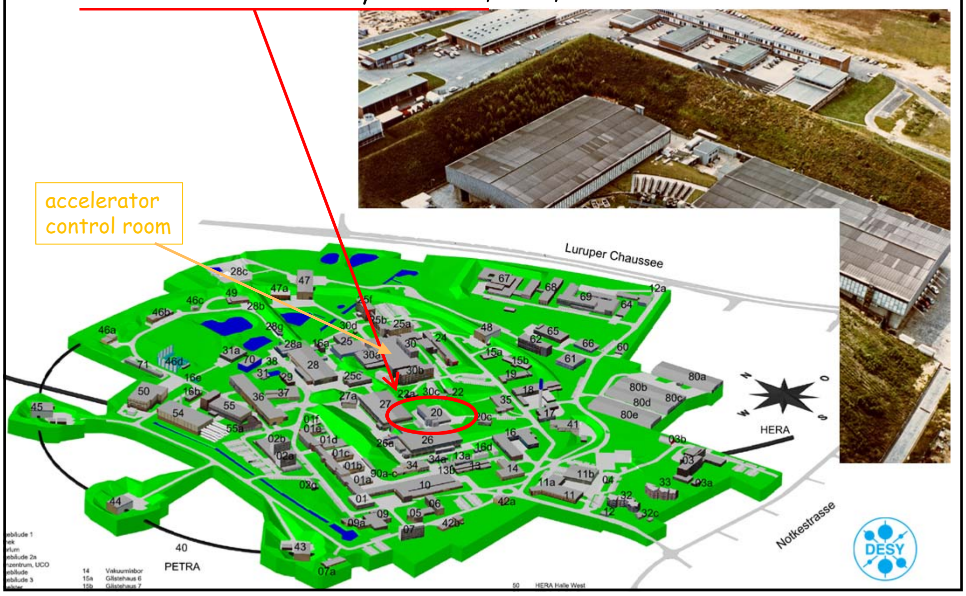
DESY (Deutsches Elektronen Synchrotron)

DESY: German electron synchrotron, 1964, 7.4 GeV

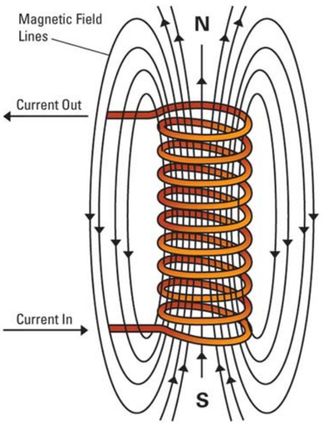
DESY (Deutsches Elektronen Synchrotron)

DESY: German electron synchrotron, 1964, 7.4 GeV

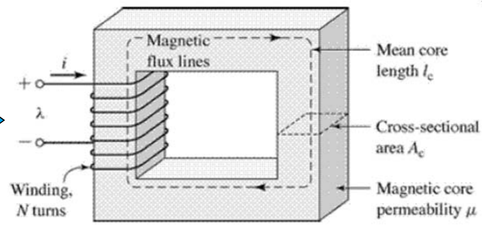
accelerator control room



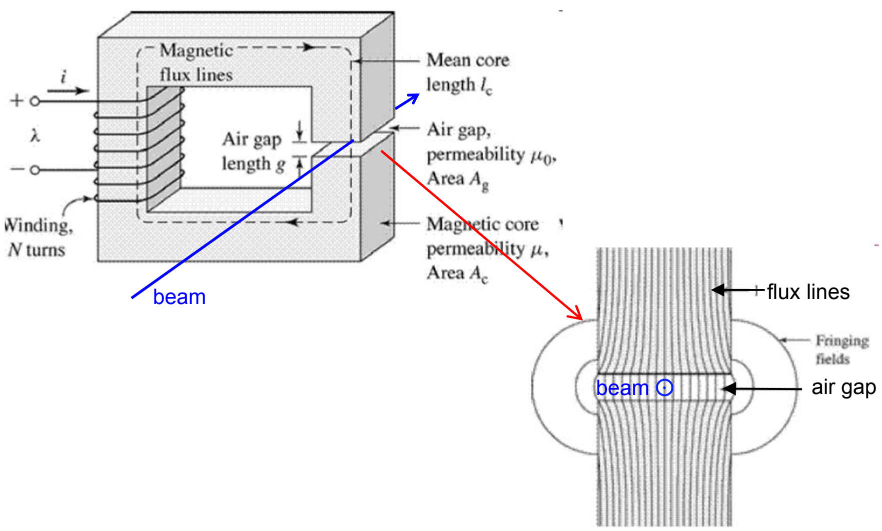
Electromagnet



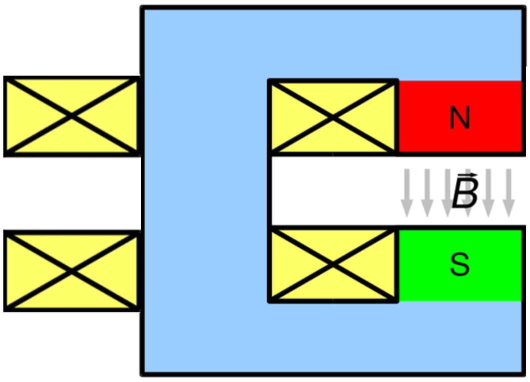
permeability of iron = 300…10000 larger than air



Dipole magnet



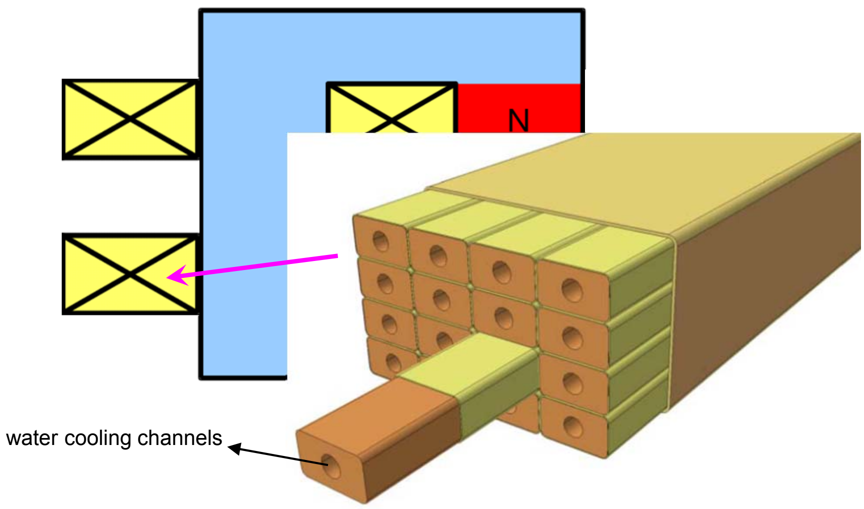
Dipole magnet cross section



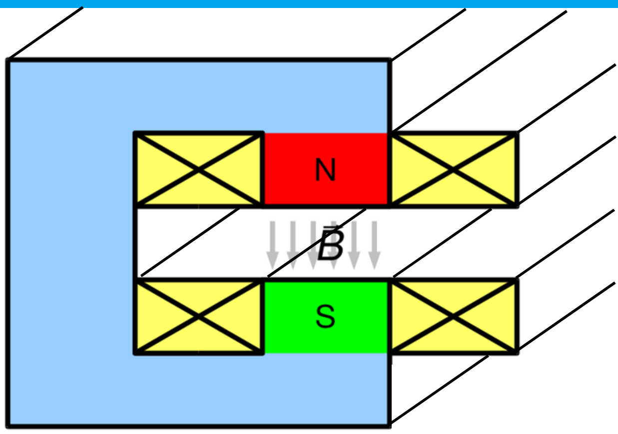
Max. B ➔ max. current ➔ large conductor cables

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

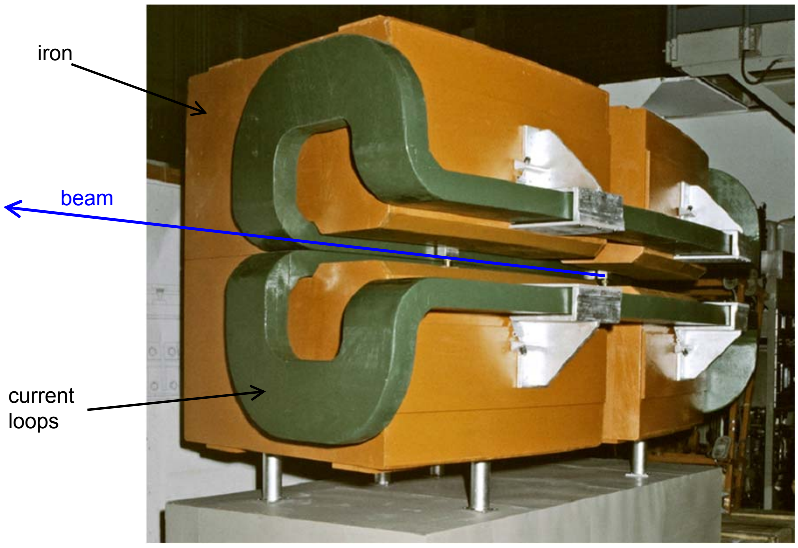
Dipole magnet cross section



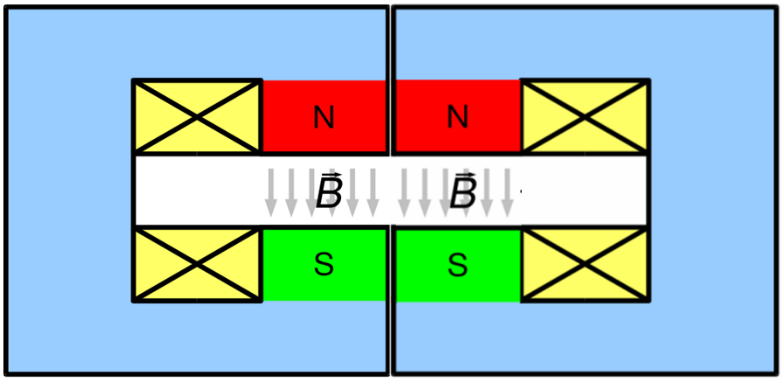
Dipole magnet cross section



Dipole magnet

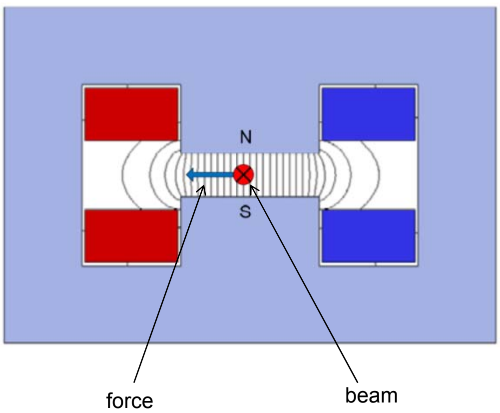


Dipole magnet cross section

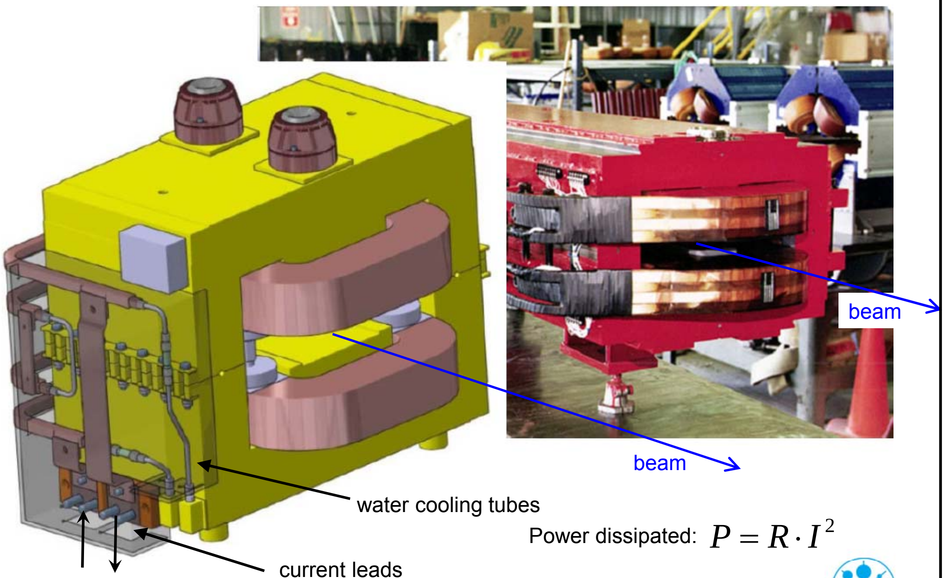


C magnet + C magnet = H magnet

Dipole magnet cross section (another design)

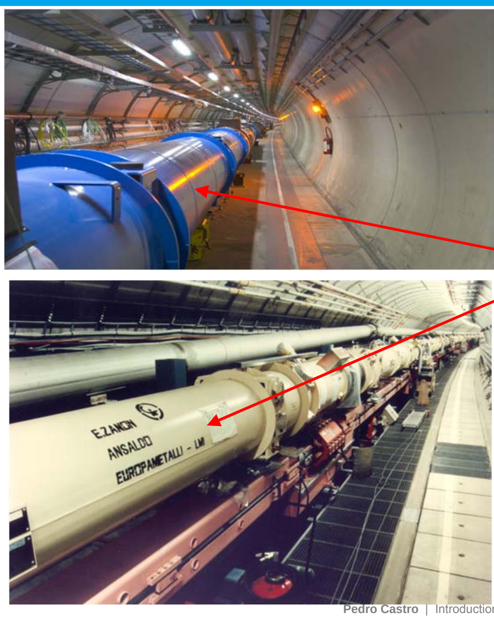


Dipole magnet cross section (another design)

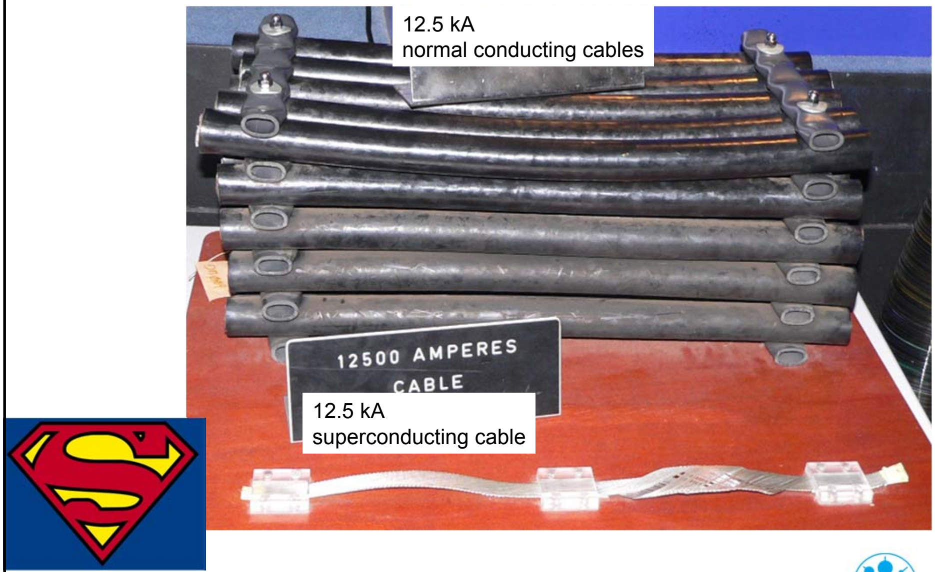


Power dissipated: $P = R \cdot I^2$

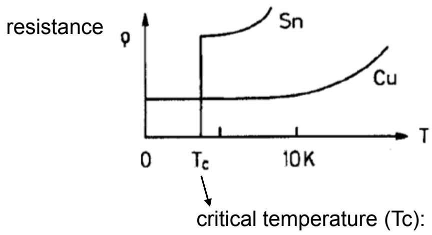
Superconducting dipole magnets



Superconductivity

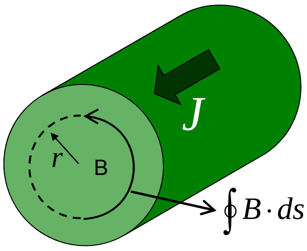


Superconductivity



Dipole field from 2 conductors

J = uniform current density

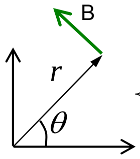


Ampere's law:

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

current through the circle

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

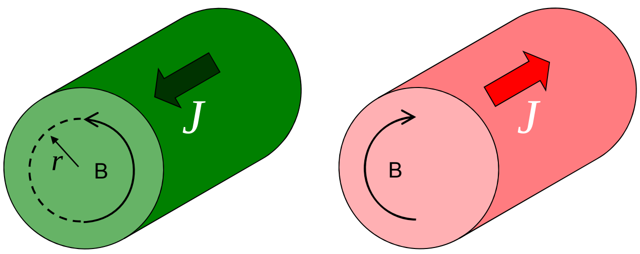


$$B_x = -\frac{\mu_0 J}{2} r \sin\theta$$

$$B_y = \frac{\mu_0 J}{2} r \cos\theta$$

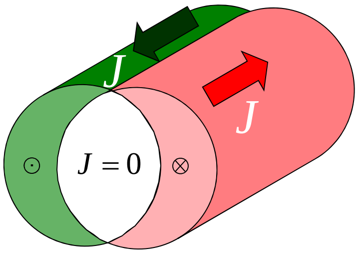
Dipole field from 2 conductors

J = uniform current density



Dipole field from 2 conductors

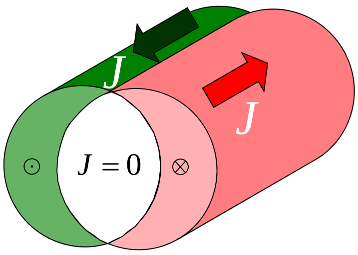
J = uniform current density



Dipole field from 2 conductors

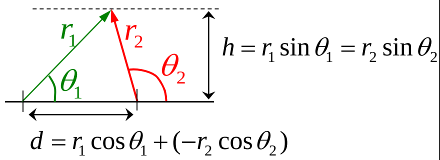
J = uniform current density

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

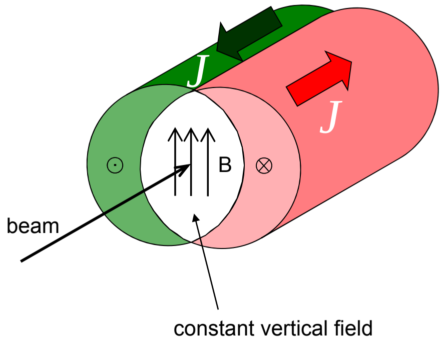


$$B_x = \frac{\mu_0 J}{2}(-r_1 \sin\theta_1 + r_2 \sin\theta_2) = 0$$

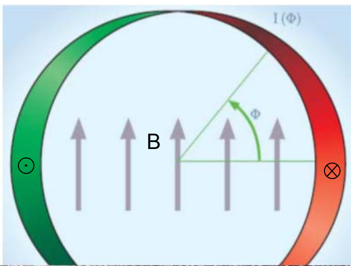
$$B_y = \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2) = \frac{\mu_0 J}{2} d$$

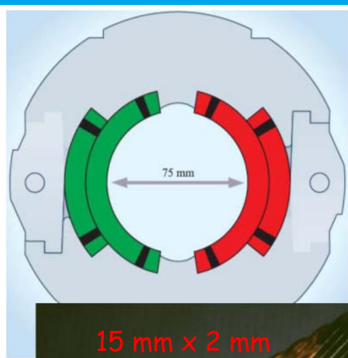


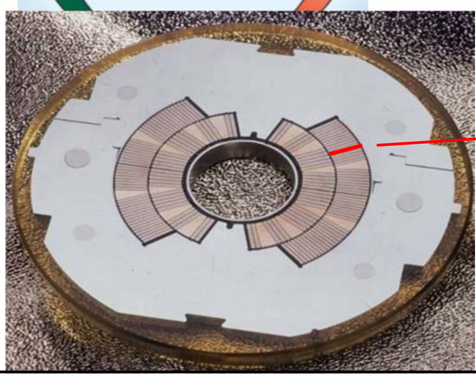
Dipole field from 2 conductors

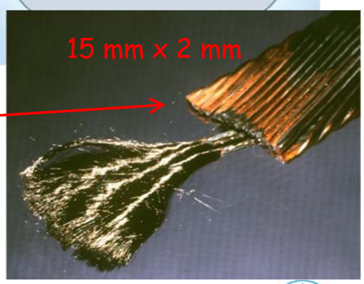


From the principle to the reality…



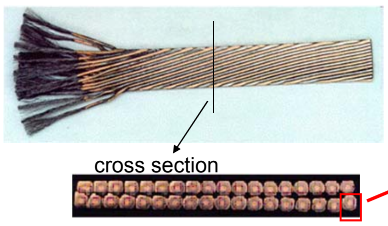




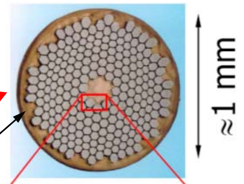


LHC cables

1 cable houses 36 strands



1 strand = 0.825 mm diameter
houses 6300 filaments

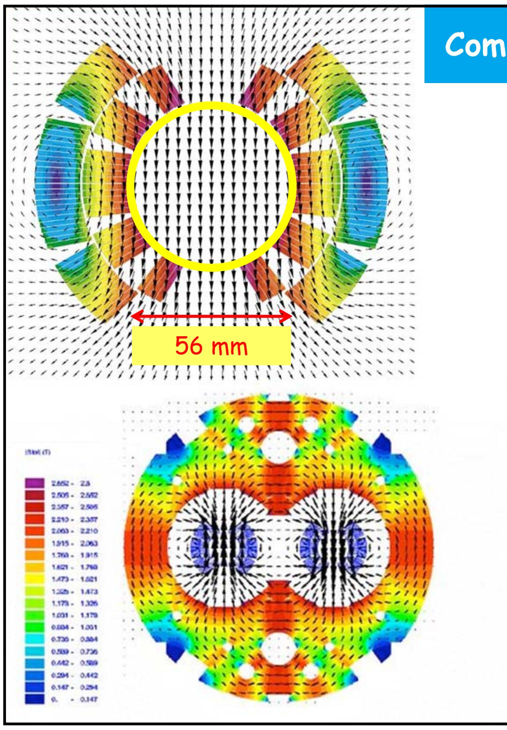


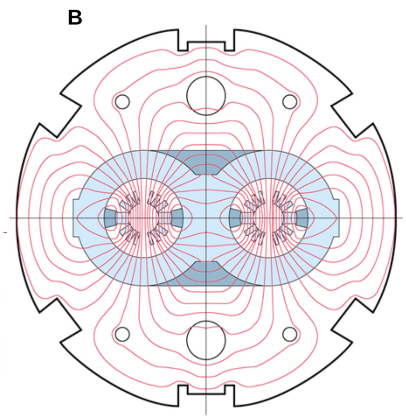
Copper is the insulation material between two filaments

(around each filament: 0.5 μm Cu)

1 filament = 6 μm

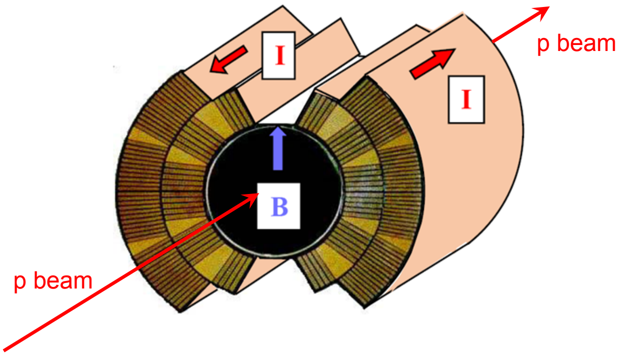
Computed magnetic field



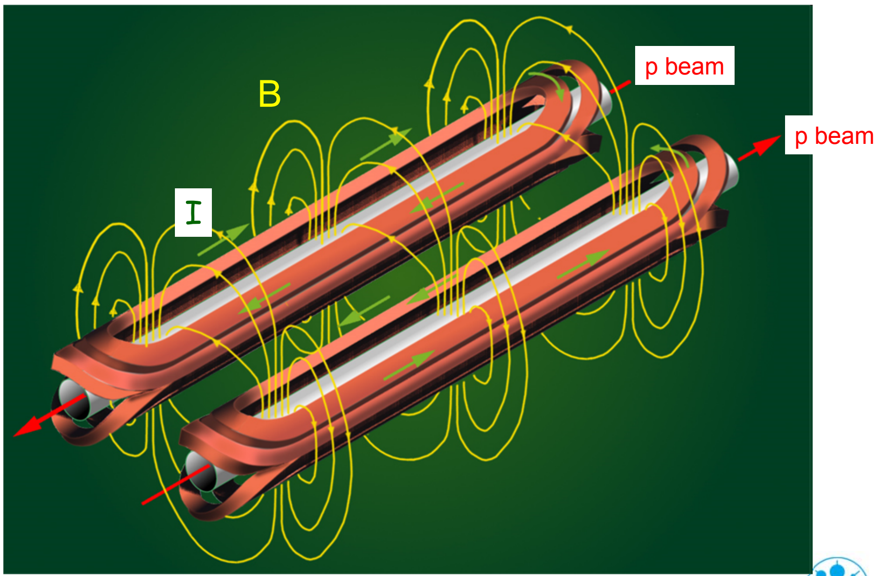


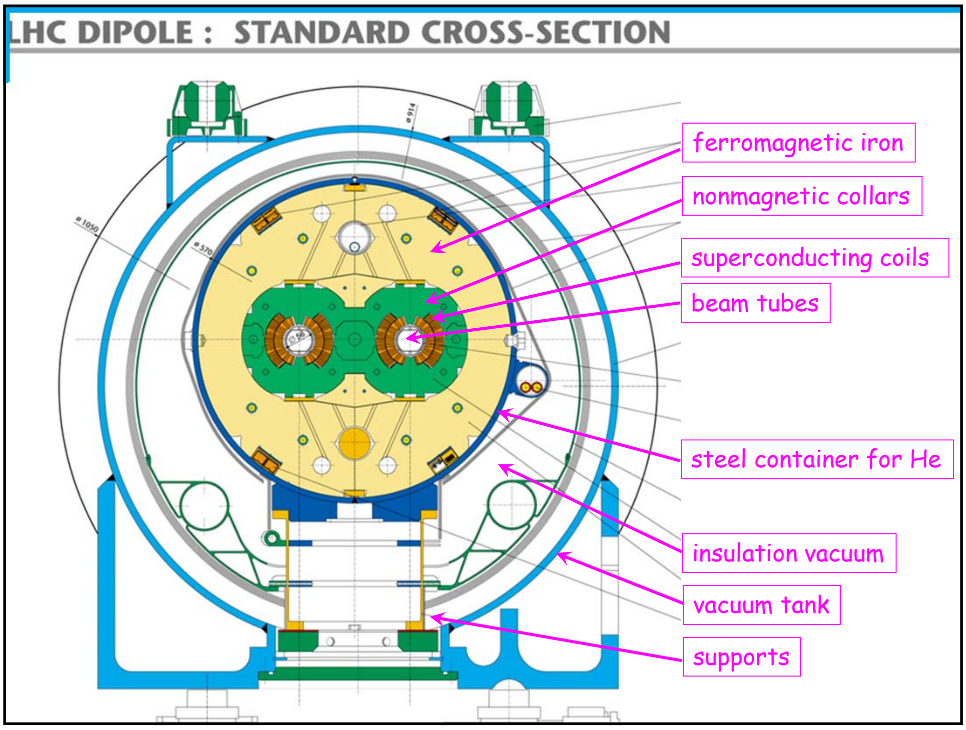
Computed magnetic flux map

LHC dipole coils in 3D



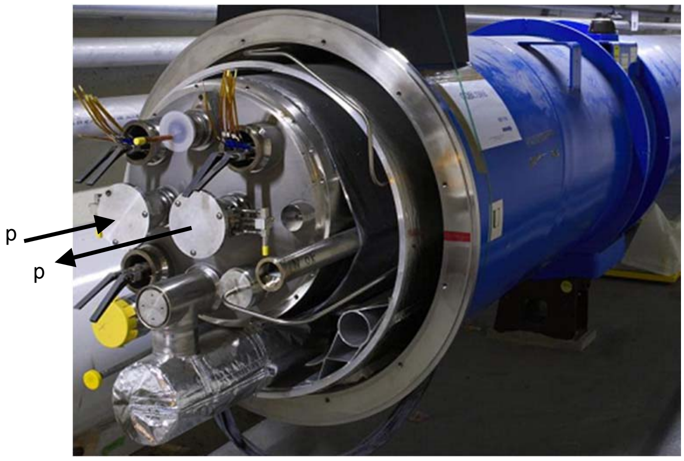
LHC dipole coils in 3D



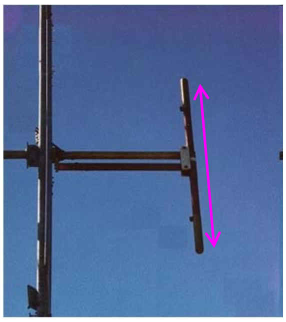


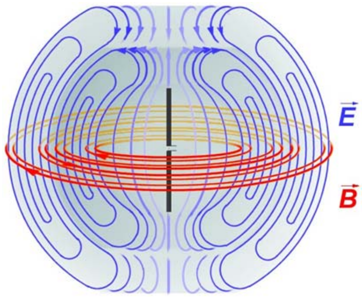
Superconducting dipole magnets

LHC dipole magnet interconnection:

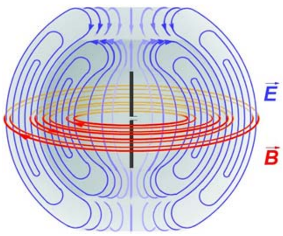


Dipole antenna

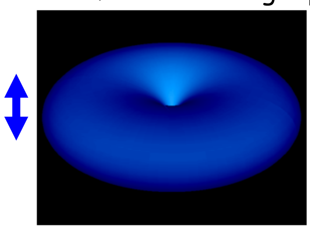


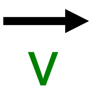


Radiation of a dipole antenna

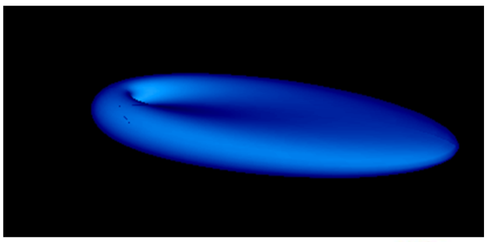


Radiation of an oscillating dipole



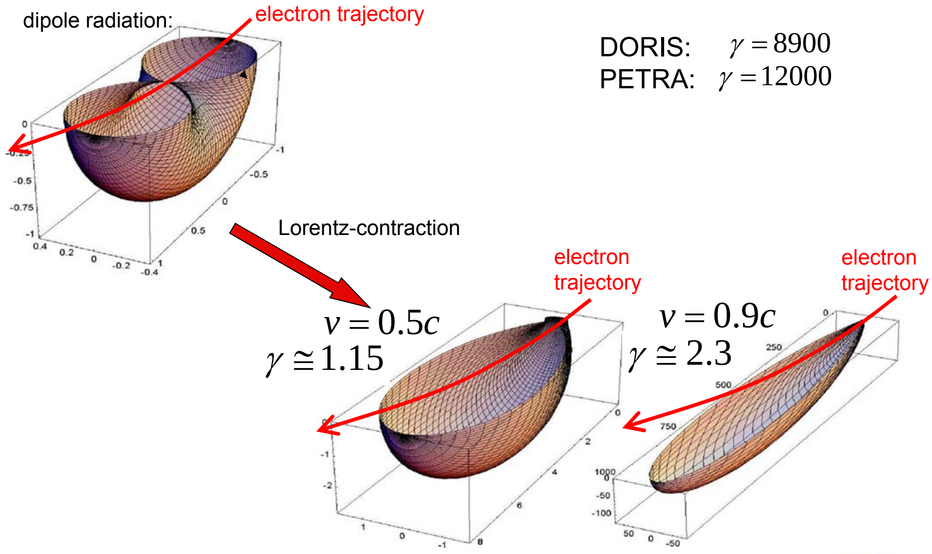


Radiation of a moving oscillating dipole



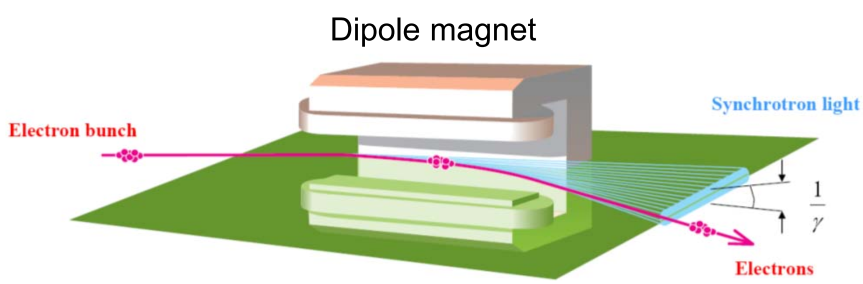
Lorentz-contraction

Radiation of a oscillating dipole under relativistic conditions



DORIS: $\gamma = 8900$
PETRA: $\gamma = 12000$

Synchrotron radiation



Power radiated by one electron in a dipole field:

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

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

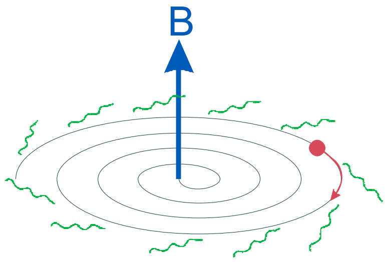
$$\frac{1}{r} = \frac{q\,B}{p}$$

vacuum permitivity

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \Rightarrow \Delta E_{\text{turn}}[\text{GeV}] = 6.032\times10^{-18}\,\frac{\gamma^4}{r[\text{m}]}$$



Synchrotron radiation

Total energy loss after one full turn:

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HERA electron ring:

$r = 580\text{ m}$ ←same→

$E = 27.5\text{ GeV}$

$\gamma = 54000$

$\Delta E_{turn} = 87\text{ MeV } (0.3\%)$

HERA proton ring:

$r = 580\text{ m}$

$E = 920\text{ GeV}$

$\gamma = 980$

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

need acceleration = 87 MV per turn

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032\times 10^{-18}\,\frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:

$r = 580\ \text{m}$ ← same → HERA proton ring: $r = 580\ \text{m}$

HERA electron ring	HERA proton ring
$r = 580\ \text{m}$	$r = 580\ \text{m}$
$E = 27.5\ \text{GeV}$	$E = 920\ \text{GeV}$
$\gamma = 54000$	$\gamma = 980$
$\Delta E_{turn} = 87\ \text{MeV}\ (0.3\%)$	the limit is the max. dipole field = 5.5 Tesla

need acceleration = 87 MV per turn

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

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032\times 10^{-18}\,\frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:	x5 →	LEP collider:
$r = 580\ \text{m}$		$r = 2800\ \text{m}$
$E = 27.5\ \text{GeV}$		$E = 105\ \text{GeV}$
$\gamma = 54000$		$\gamma = 205000$
$\Delta E_{turn} = 87\ \text{MeV}\ (0.3\%)$		$\Delta E_{turn} \cong 4\ \text{GeV}\ (4\%)$

need acceleration = 87 MV per turn

need 4 GV per turn !!

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032\times 10^{-18}\,\frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:

$r = 580\ \text{m}$

$E = 27.5\ \text{GeV}$

$\gamma = 54000$

$\Delta E_{turn} = 87\ \text{MeV}\ (0.3\%)$

need acceleration = 87 MV per turn

x5

LEP collider:

$r = 28$...

...000

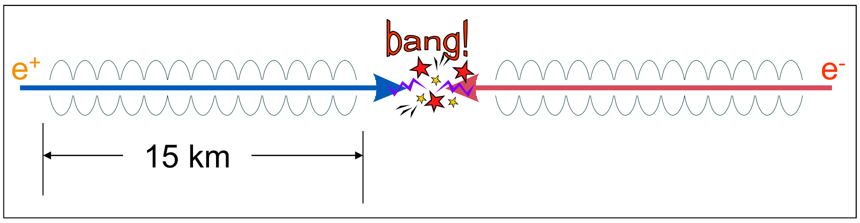
$\Delta E_{turn} \cong 4\ \text{GeV}\ (4\%)$

need 4 GV per turn !!

LEP = Last Electron-Positron Collider ?

Project for a future e-e+ collider: ILC

The International Linear Collider



Colliding beams with E = 500 GeV

e+e-LC lecture on Monday, by J. Timmermans

more: http://www.linearcollider.org/

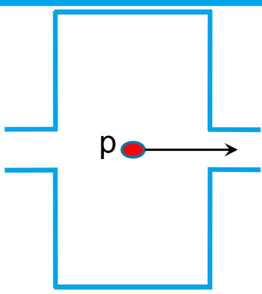
Superconducting cavities for acceleration

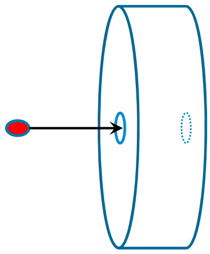
- International L... ...er (ILC) ...re project)
- European X-ray Free-Electron Laser (...) (in construction)
- Free-electron LASer in Hamburg (FLASH) (in operation)

e+e-LC lecture on Monday, by J. Timmermans

FELs lecture on Friday, by M. Dohlus

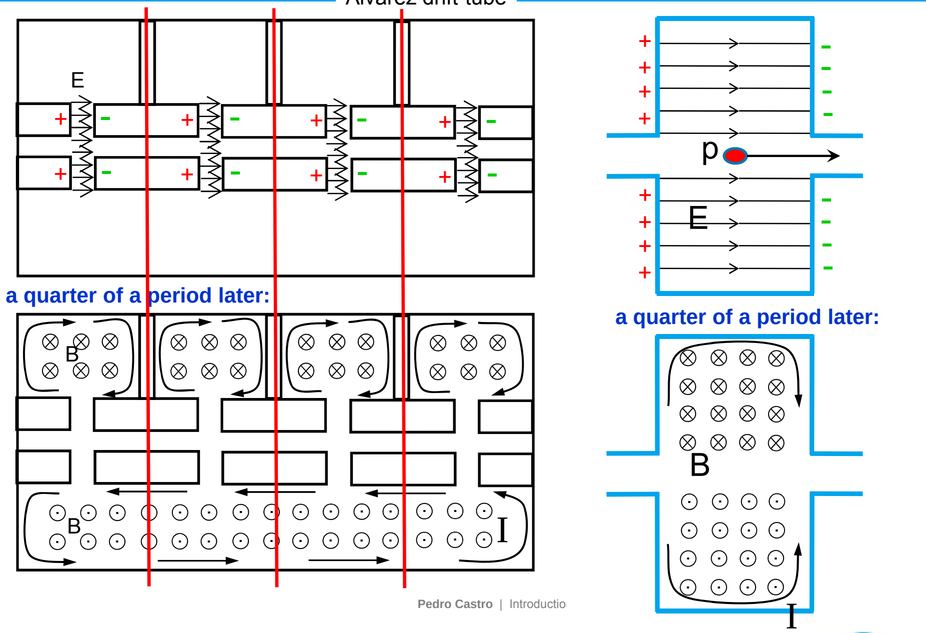
RF cavity basics: the pill box cavity



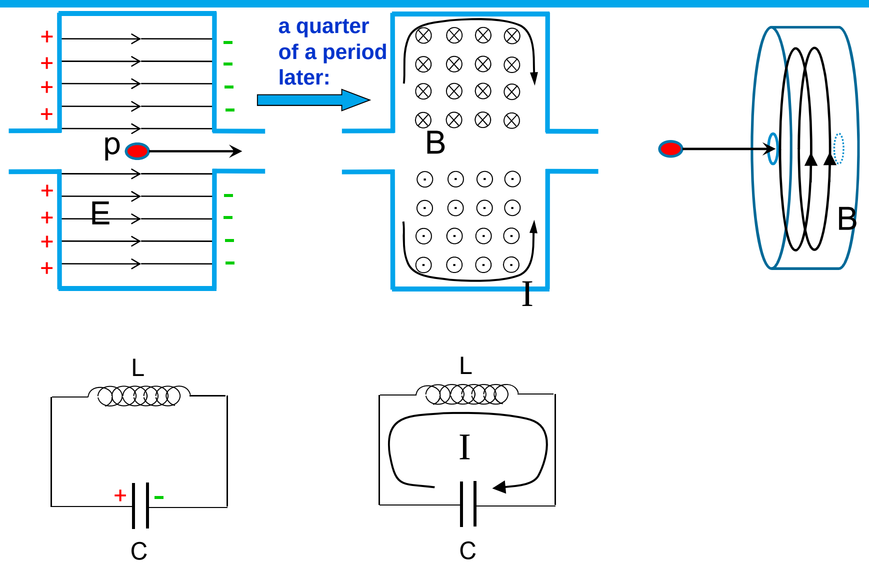


pill boxes

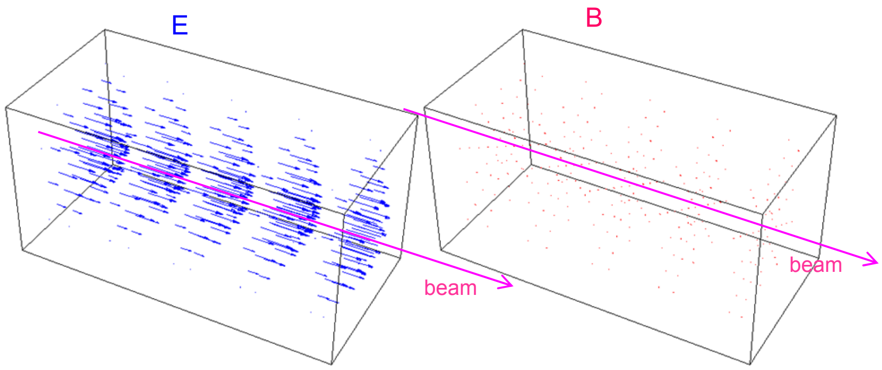
Alvarez drift-tube



RF cavity basics: the pill box cavity

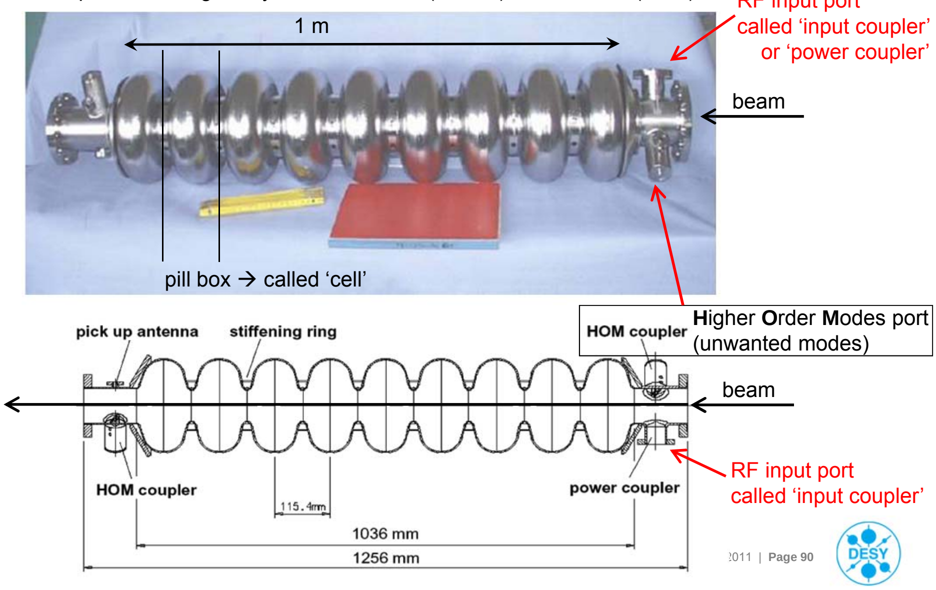


Pill box cavity: 3D visualisation of E and B



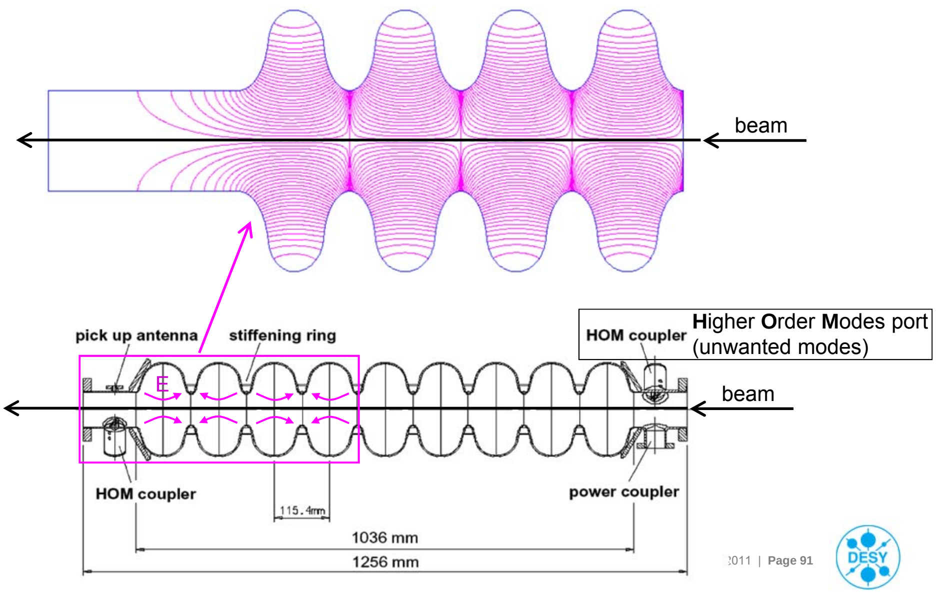
Superconducting cavity used in FLASH and in XFEL

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

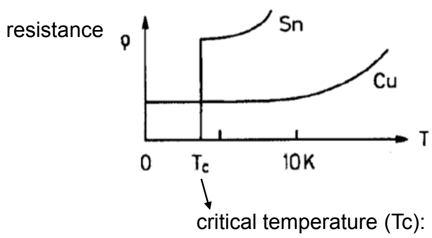


Accelerating field map

Simulation of the fundamental mode: electric field lines



Advantages of RF superconductivity



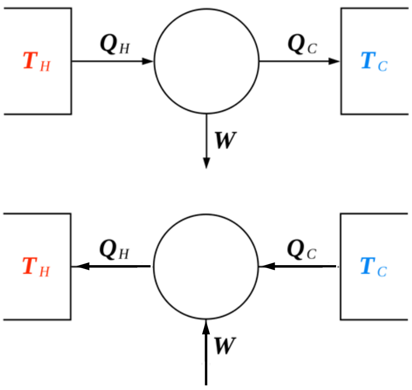
for DC currents !

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

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

2^{nd} law of Thermodynamics

"Heat cannot spontaneously flow from a colder location to a hotter location"



	max. efficiency	most common applications
heat engine	$\eta_c = \frac{T_H - T_C}{T_H}$	thermal power stations, cars, …
refrigerator	$\eta_c = \frac{T_C}{T_H - T_C}$	air conditioners, refrigerators, …

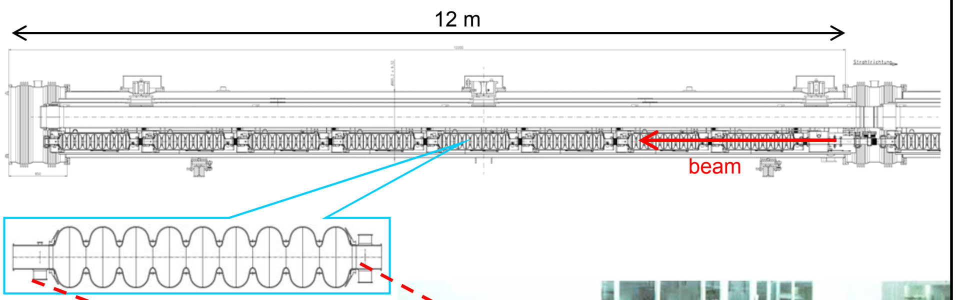
Carnot efficiency:

Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

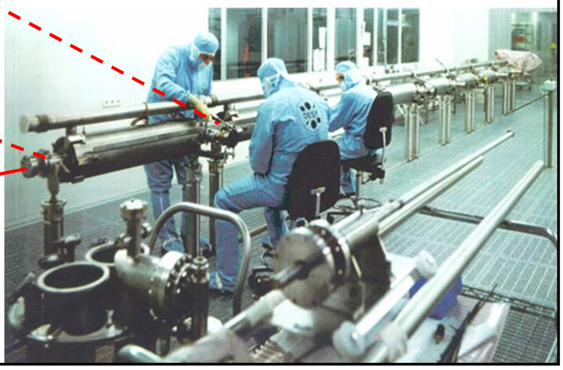
	superconducting cavity	normal conducting cavity	
for E = 1 MV/m	1.5 W / m at 2 K	56 kW / m	dissipated at the cavity walls
Carnot efficiency: $\eta_c = \frac{T}{300-T} = 0.007$	x		cryogenics efficiency 20-30%
for E = 1 MV/m	1 kW / m	56 kW / m	
for E = 1 MV/m	1 kW / m	112 kW / m	including RF generation efficiency (50%)

>100 (electrical) power reduction factor



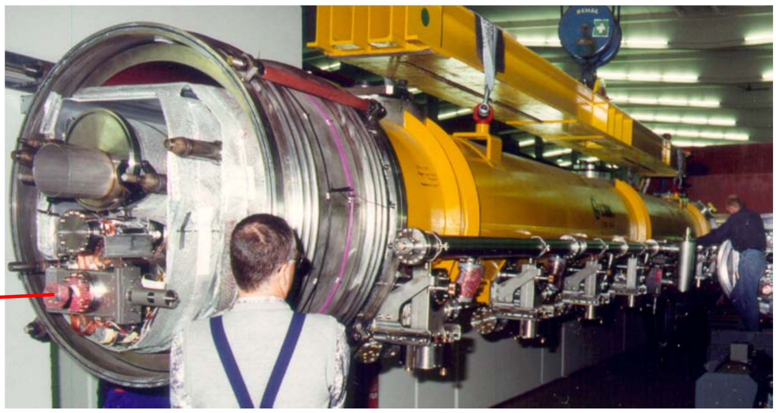
Number of cavities	8
Cavity length	1.038 m
Operating frequency	1.3 GHz
Operating temperature	2 K
Accelerating Gradient	23..35 MV/m

beam



Cavities inside of a cryostat

beam

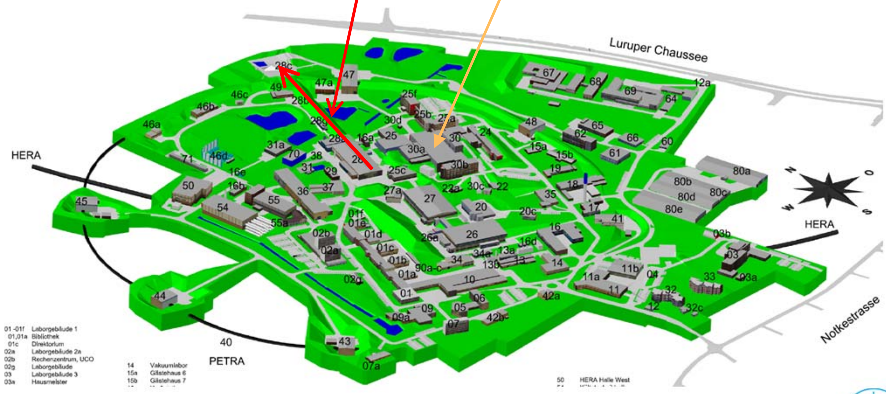


module installation in FLASH (2004)

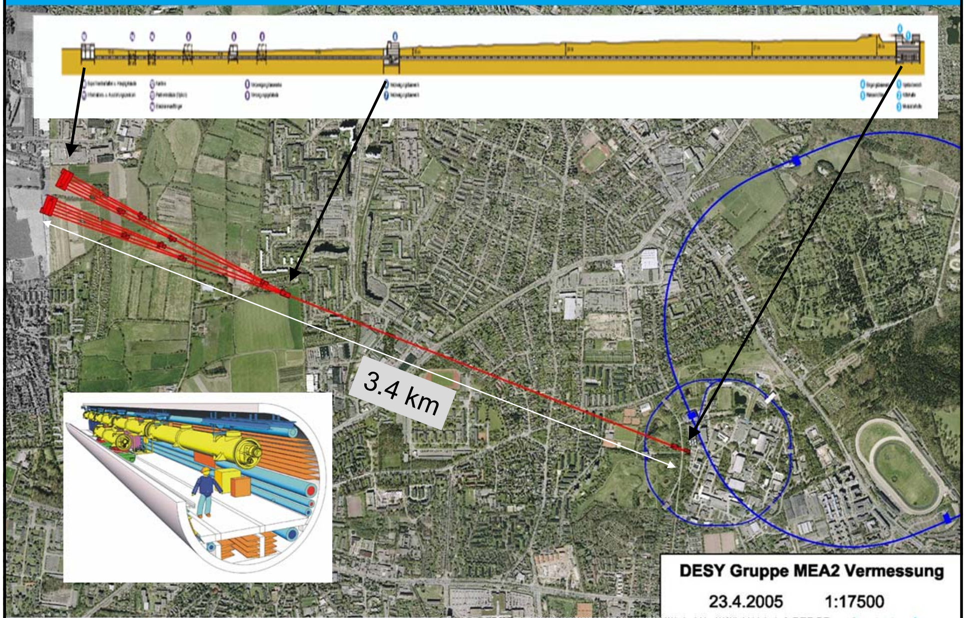
~300 m

Free-electron LASer in Hamburg (FLASH)

accelerator control room



European X-Ray Free Electron Laser (XFEL)



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

Second summing-up

Linear accelerators:

- Alvarez drift-tube structure

Circular accelerators:

- Cyclotron, E. Lawrence
- Synchrotron

Dipole magnets:
- normal conducting dipoles
- superconducting dipoles

Third summing-up

Circular colliders (synchrotons with R=const.):

	limitation
• proton synchrotrons	dipole magnet
• electron synchrotrons	synchrotron radiation

Linear accelerators:

- International Linear Collider (ILC)
- European X-ray Free-Electron Laser (XFEL)
- Free-electron LASer in Hamburg (FLASH)

} based on S.C. cavities

Thank you for your attention

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