Experimental methods in particle physics

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Webpage of lecture:
http://atomfizika.elte.hu/rfkm/rfkm2019.html

Accelerators

- Historical Van de Graaf, Cockcroft-Walton accelerators
- Radio frequency acceleration
- Circular accelerators
- Magnets
- Limits on accelerator energy
- Beam optics, beam parameters
- The LHC
- Future accelerators

Accelerators: References

- http://www.desy.de/f/students/lectures2010/castro.pdf
- http://www.slideshare.net/kumar_vic/lhc-construction-operation
- http://www.lhc-closer.es/taking_a_closer_look_at_lhc/1.home

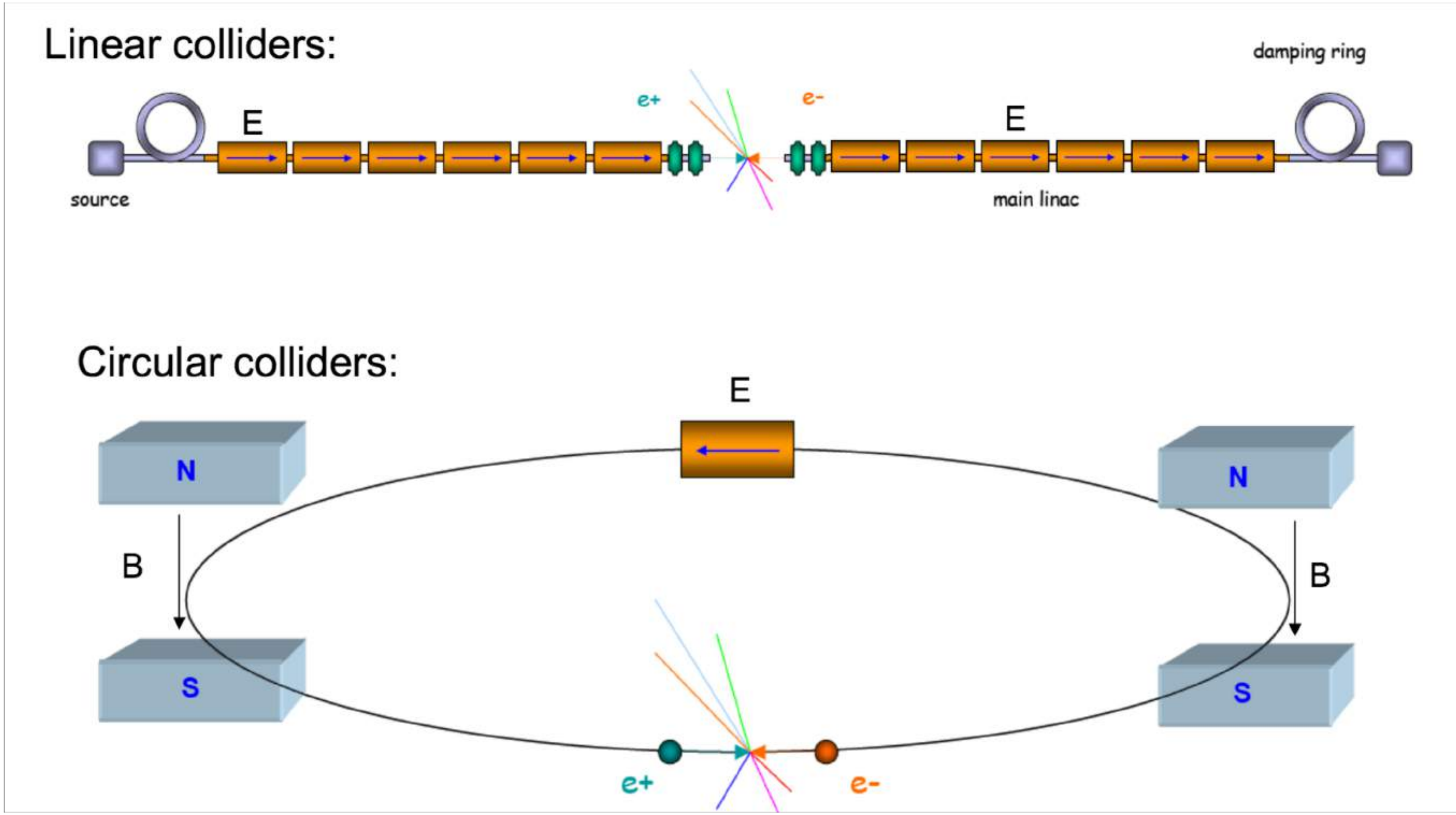
Further reading:

- http://www.ncp.edu.pk/docs/iss/talks/Plannary_Sessions/P_D3_F_Gerigk.pdf
- https://www.classe.cornell.edu/~liepe/webpage/docs/P4456L1.pdf

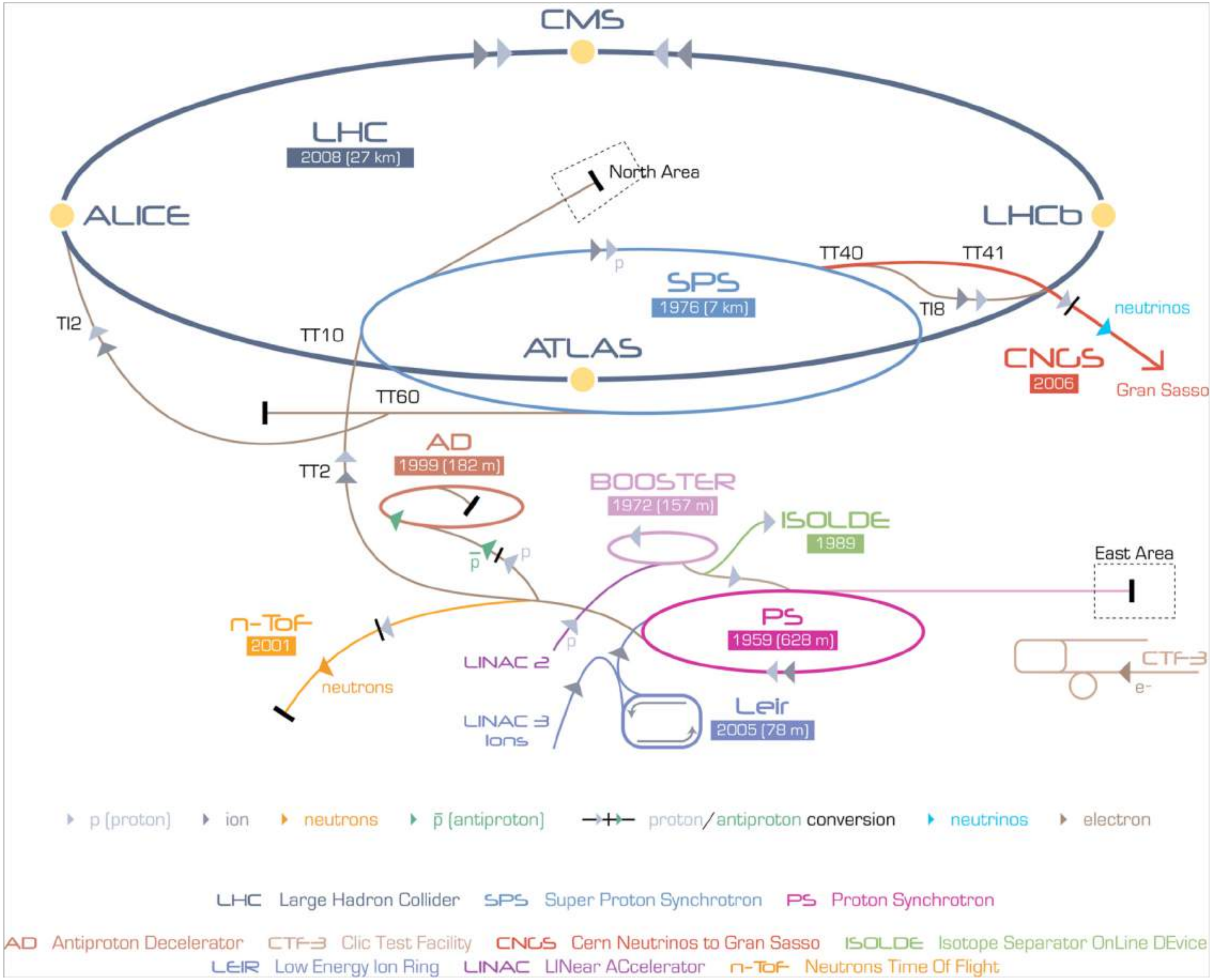
Accelerator parameters:

- http://pdg.lbl.gov/2016/reviews/rpp2016-rev-hep-collider-params.pdf

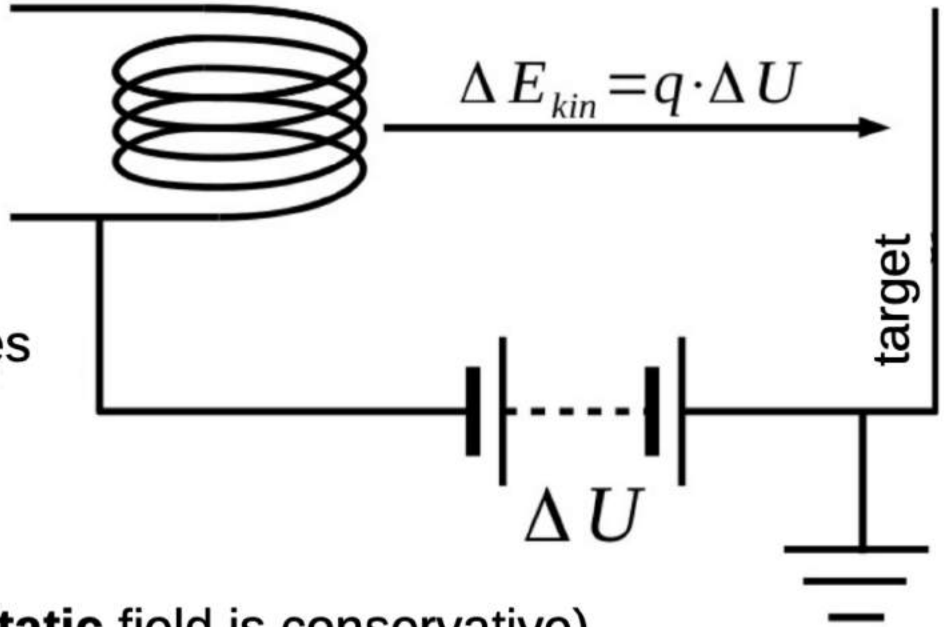
Accelerator types



CERN, lord of the rings



Electrostatic acceleration



- Target or source is at high voltage (MV), (except in the Tadems), the other on earth.

- Single-pass (we cannot drive the particles through the accelerating section over and over, since we cannot gain energy following a closed orbit:

$$\oint E \, \mathrm{d}s = 0$$

(the electro**static** field is conservative)

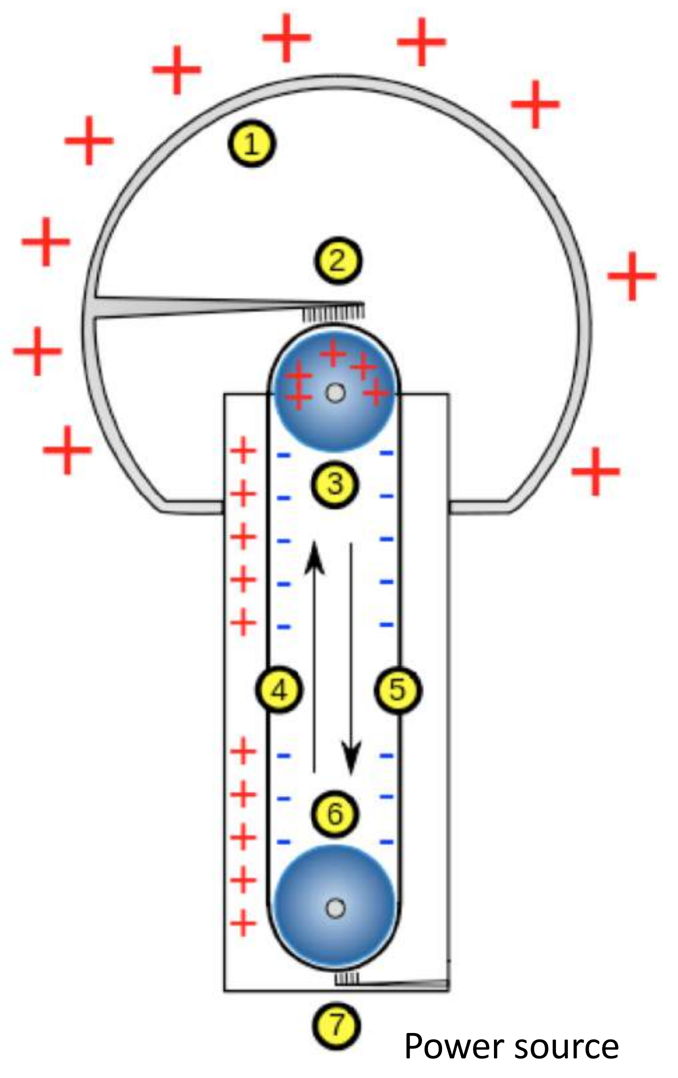
- HV generator types:
  - Cockroft-Walton (~MeV)
  - Van de Graaff (~10 MeV)

- Limit: electric breakdown, discharge, insulation.

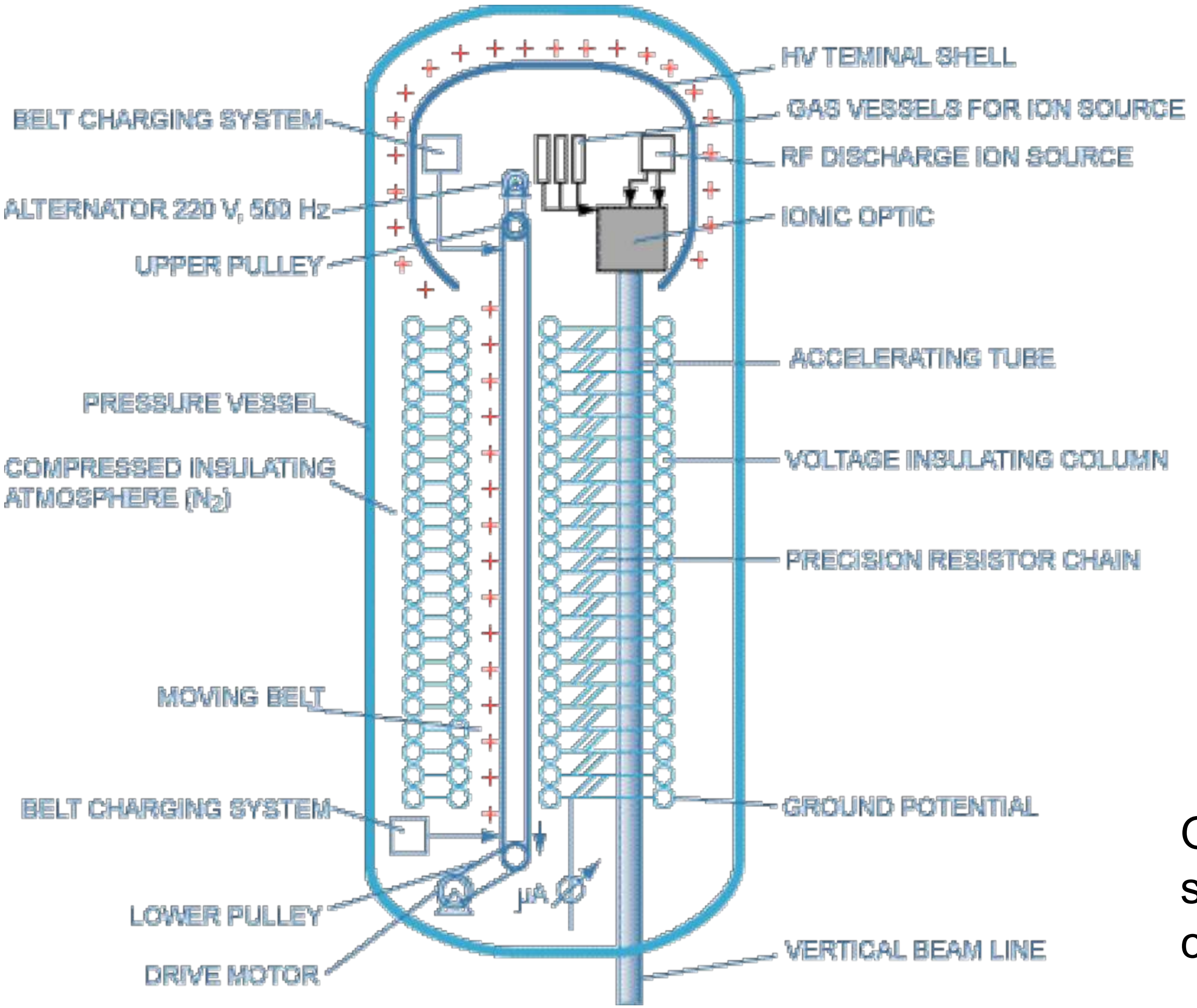
creenshot

Van de Graaf generator

- Large metal sphere (1) on the top of an insulating column
- An electric motor (6) drives a belt (4,5) that is made of conductive material inside the insulating column by means of two rotating disks (3,6)
- There are metal combs at the extremities of the belt (2, 7). The bottom one (7) is connected to a power source to ensure continuous charging. The belt (4) takes the charges to the upper metal comb (2) which passes them to the large metal sphere electrode (1)
- The accumulated charge creates a potential difference between the electrode (1) and ground
- The Van de Graf accelerator is a huge Van de Graf generator with an internal accelerator tube
- 1929: first model (canned box, small engine, silk tape)
  1931: 100 USD 1.5 MV
- 1937: 5 MV, nuclear research for civil use



Van de Graaf accelerator

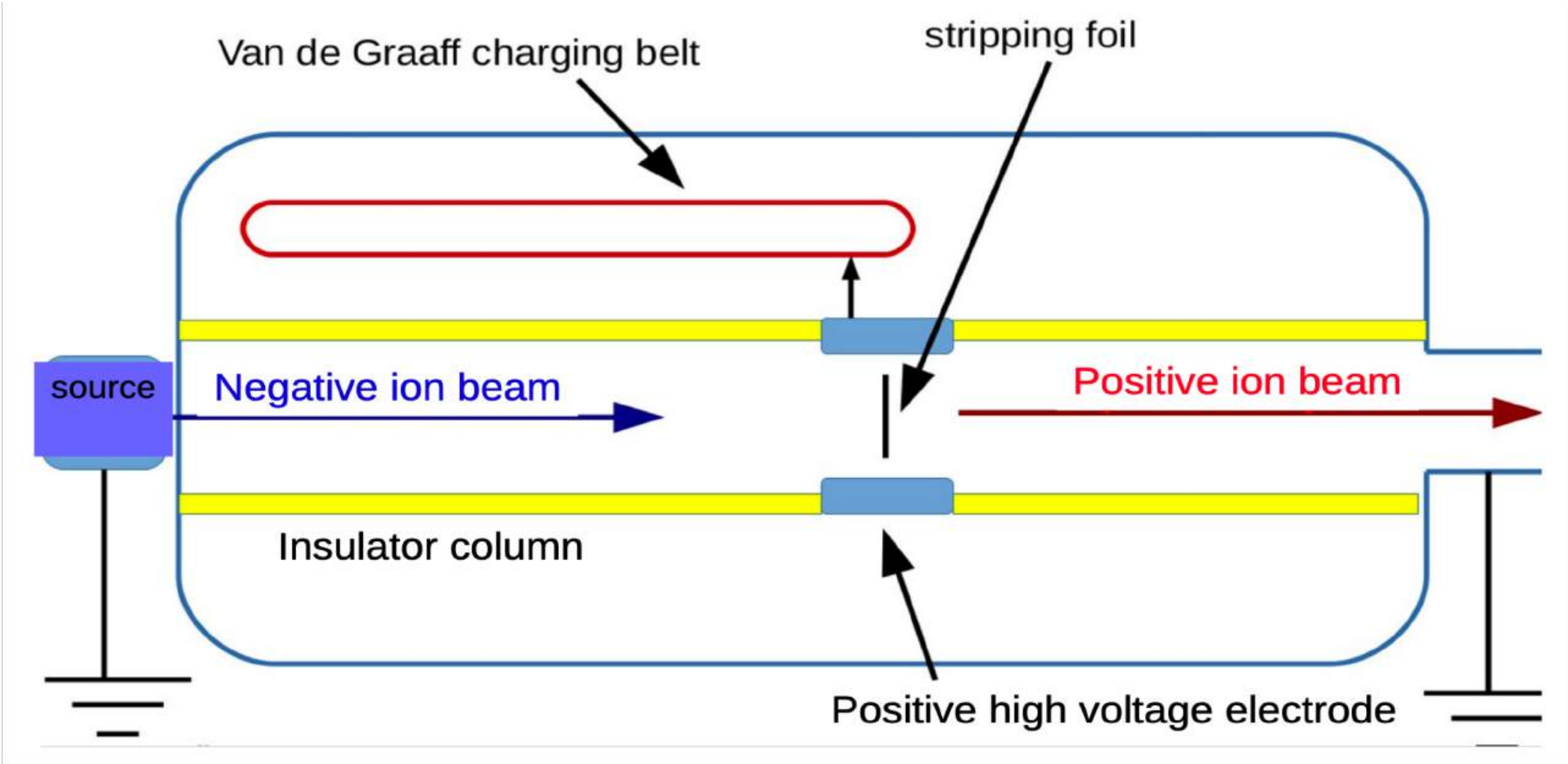


Often arranged vertically, so that the long insulator column is not stressed

Just a few steps away…

First Hungarian
linear accelerator's
Van de Graaf generator
1951: 700 kV
1952: 1000 kV

Tandem van de Graaf generator



Advantages:

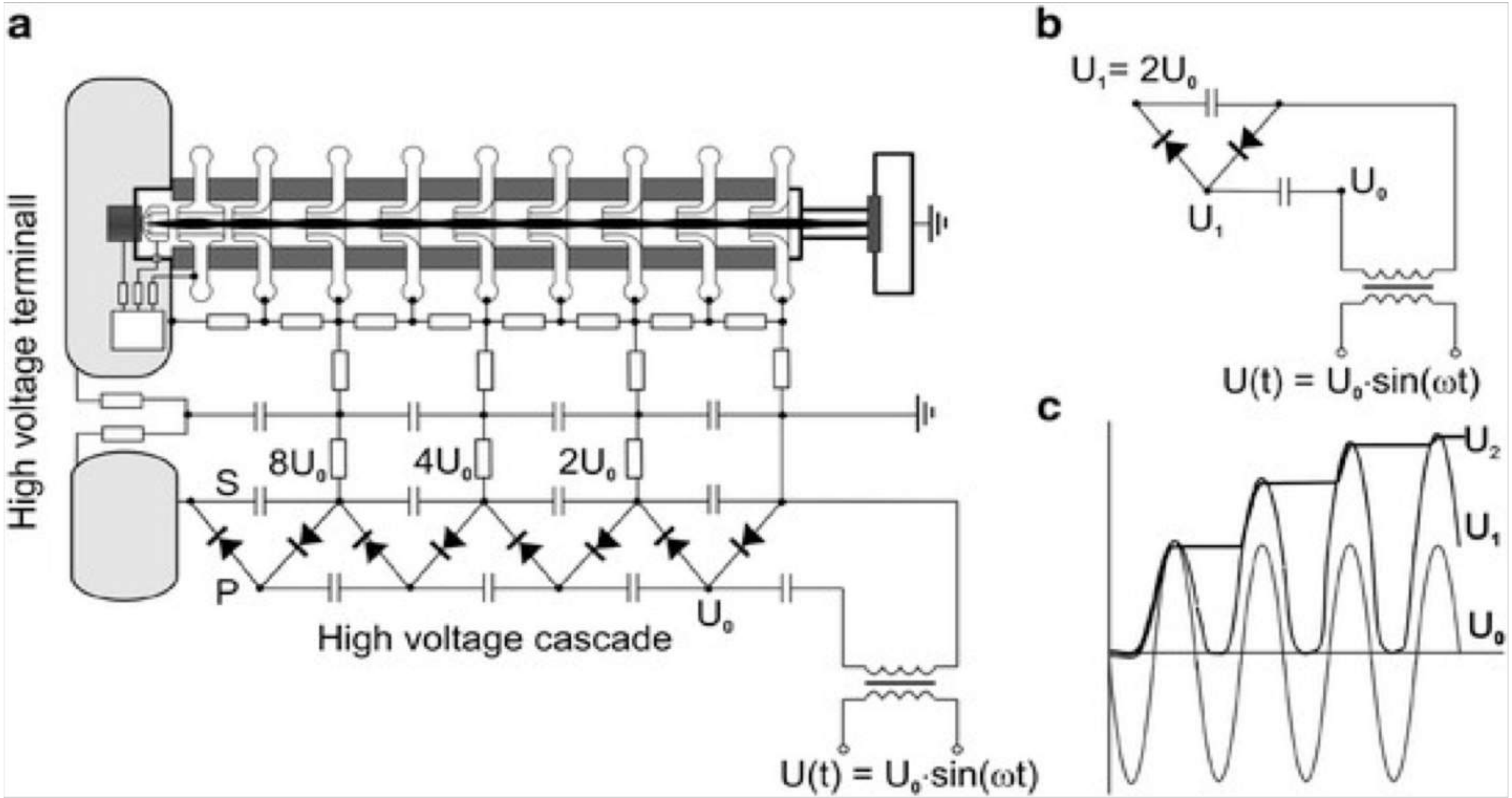
- Double energy, high voltage can be used two times
- Source and target can be on ground potential as well!

Limitations:

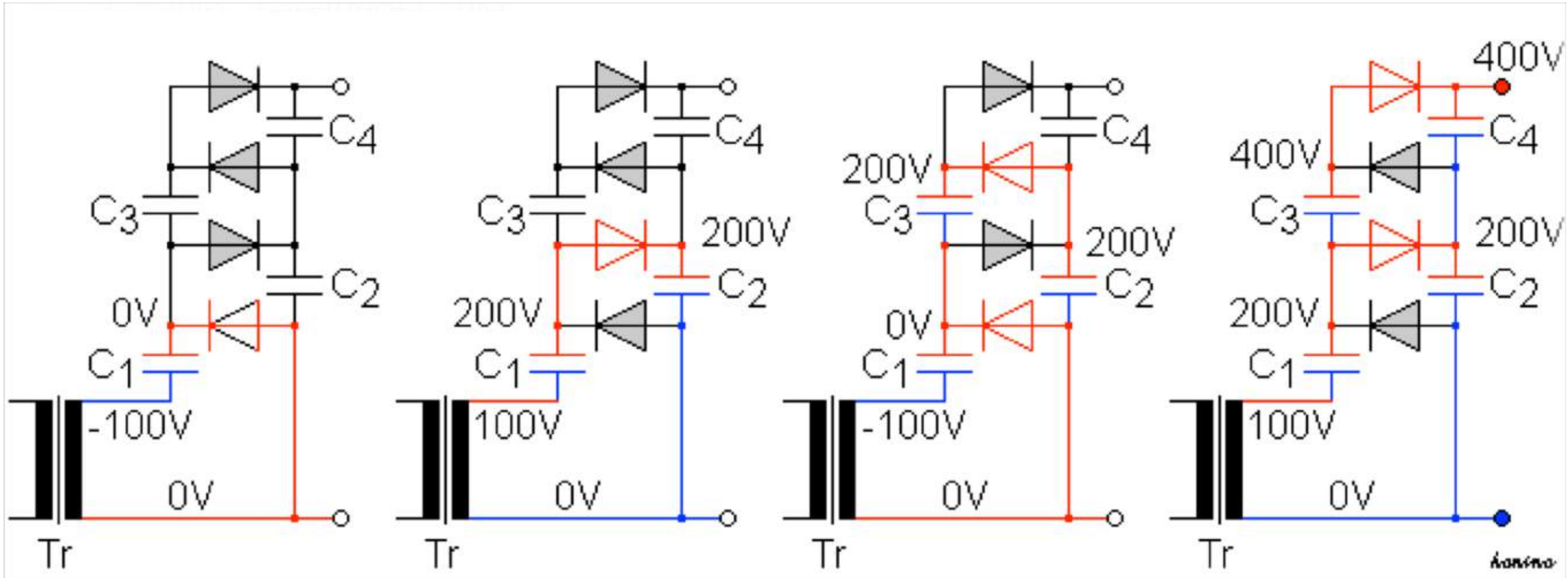
- size of potential difference that can be kept
- need negative ions (for some elements difficult to produce, do not exist)
- generally only ions with one extra electron

Cockcroft-Walton accelerator

Based on a complex electrical circuit, a voltage amplification cascade
High direct-current voltage from alternating current voltage
Diodes used as switches



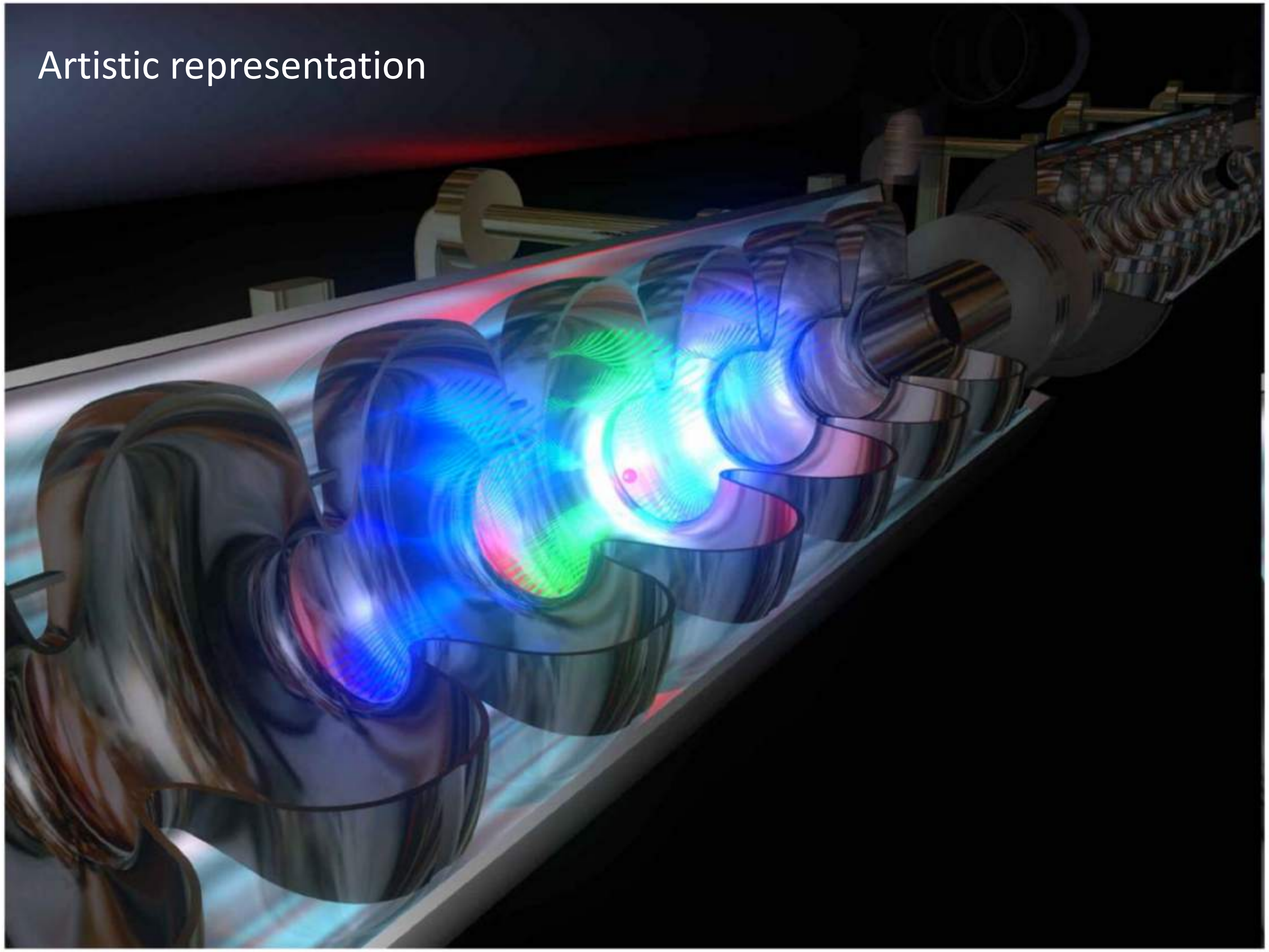
Cascade voltage generator



1) negative voltage (-U): The capacitor C1 is charged over the diode D1 to voltage U
2) positive voltage (+ U): The voltage on C1 capacitor adds to the source so that the capacitor C2 is charged through the diode D2 to 2U voltage
3) negative voltage (-U): At C1 the voltage is 0, so C3 is charged via D3 to 2U voltage
4) positive voltage (+ U): On capacitor C2, the voltage rises to 2U, so C4 is charged to 2U. The output voltage (the sum of the voltage on the C2 and C4 capacitors) rises to 4U.
In reality, multiplied output voltages is reached in more cycles

Radio frequency particle acceleration

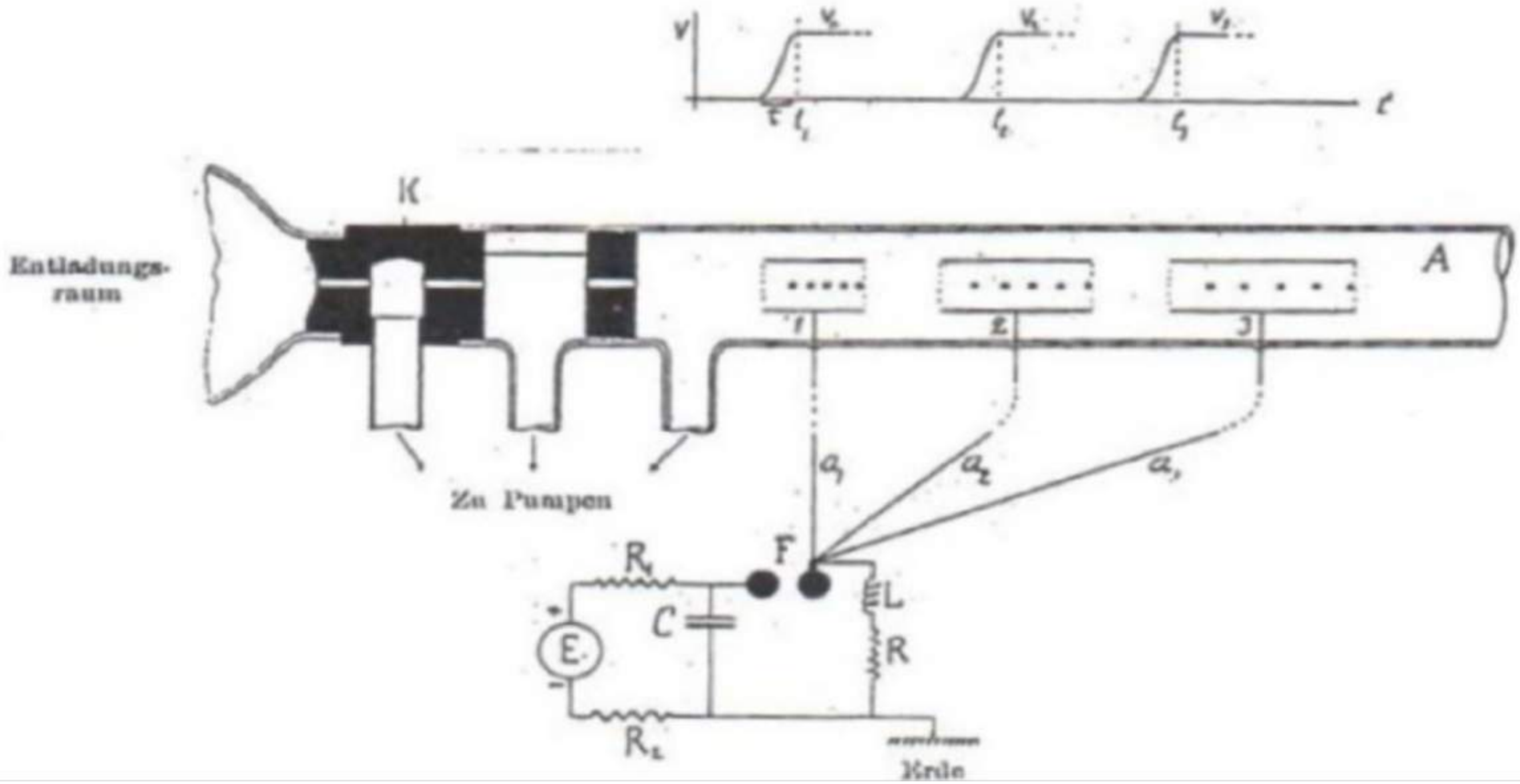
"Electromagnetic fields accelerate the electrons in a superconducting resonator "



Pulsed drift tube linac

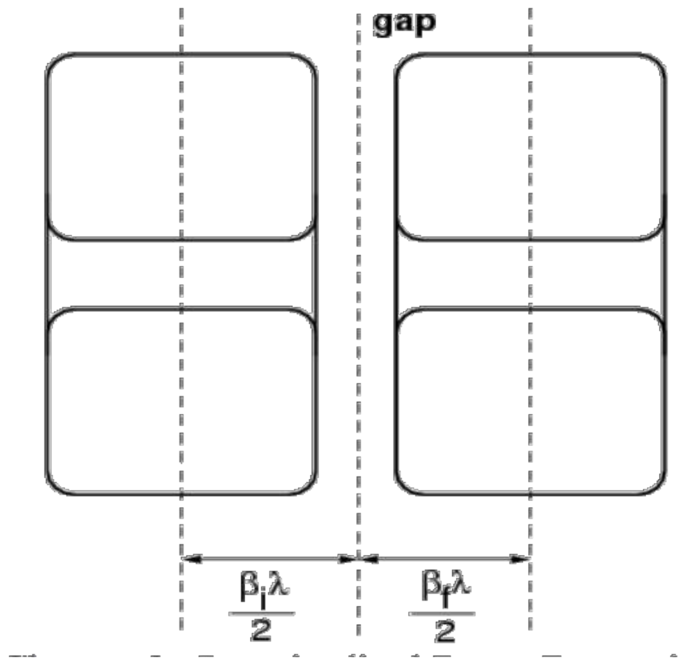
Ising, 1924 – concept

- Not necessary for the complete accelerating field to be available at the same time (risk of discharge). It is sufficient at the location of the particle.
  The electric field accelerates, not the potential.
- Instead of a single section, several smaller sections
- Using well-timed pulses (as long as the particle is inside the tube)
- Gap between the tubes accelerates, the length of the tubes increases with speed



The Linac Drift Tube

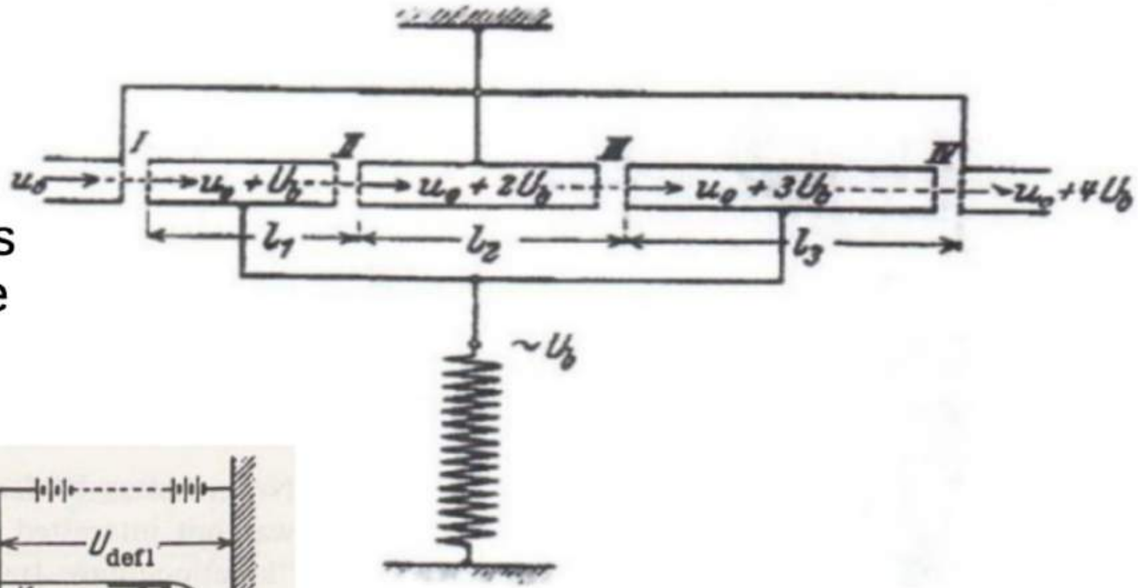
- A linear accelerator (linac) is comprised of a succession of drift tubes with holes at their ends so that the particles can enter and exit
- When particles are inside the drift tube (= a Faraday Cage) the potential of the drift tube may vary without changing the energy of the particle
  - Acceleration takes place when a charged particle is subjected to a field The field inside the Faraday cage is not affected by the potential outside
- The drift tubes are arranged in a sequence with a passage through their middle for the particles to pass
- The field in the gap between the drift tubes accelerates the particles

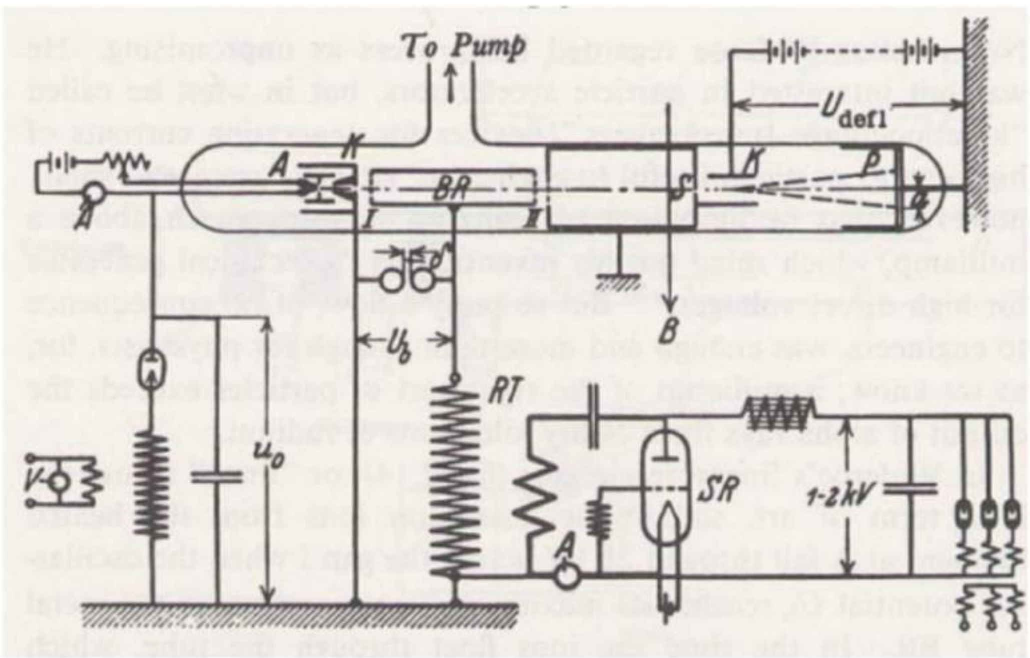


Wideröe linac

- Wideröe (1928):

- Instead of well timed pulses, radio frequency. The RF changes by 180 degrees while the particle passes from one gap to another

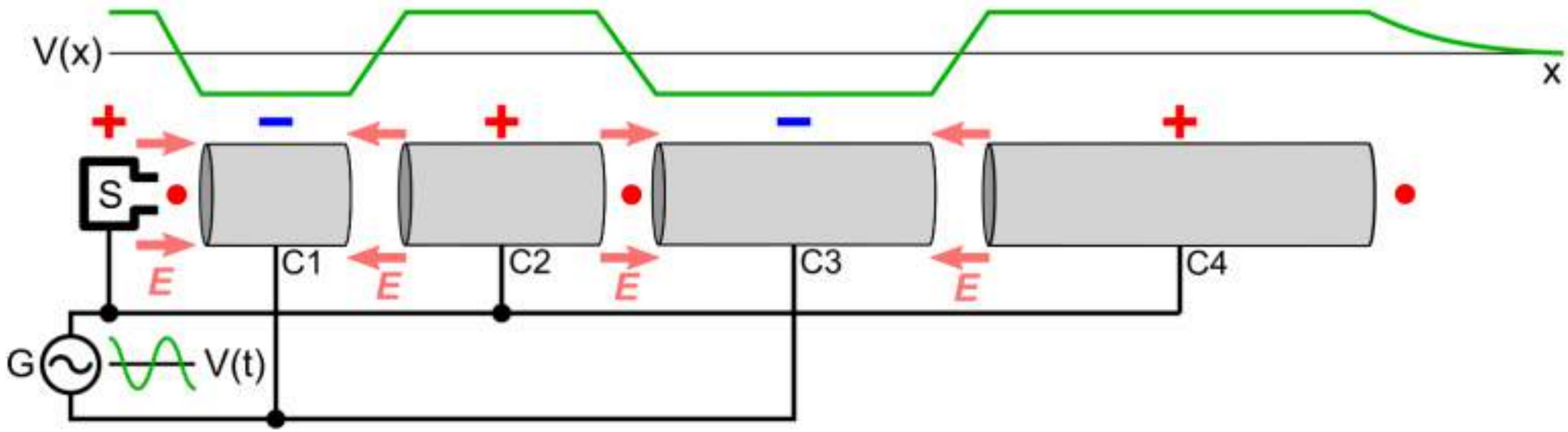




First accelerator with a single tube with RF signal of 25 kV amplitude @ 1 MHz between two grounded electrodes Single-charged Potassium ions gained in the 2 accelerating gaps 2x25=50 kV

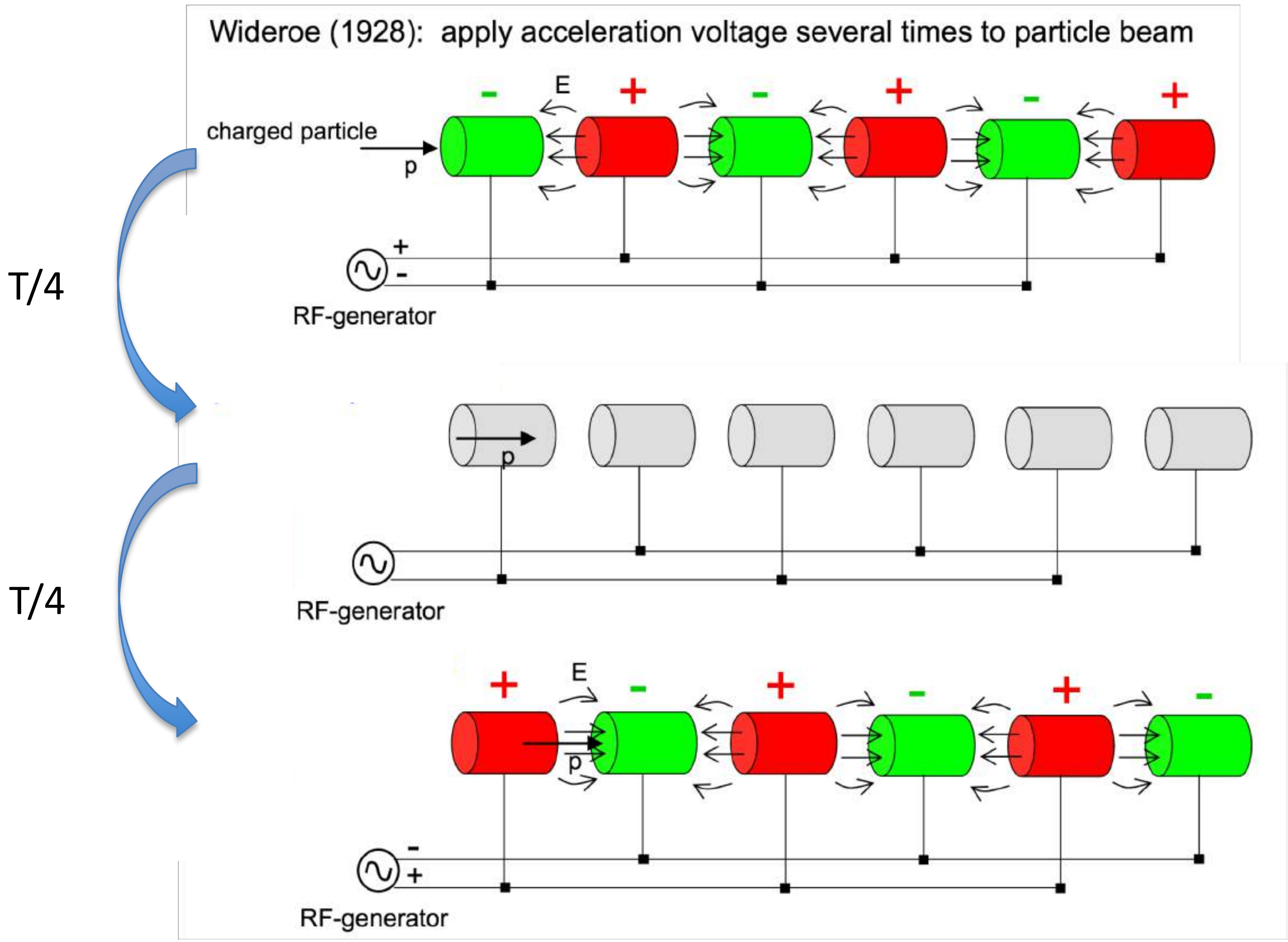
- Limitations:
  - Before WWII only low RF frequencies → the length of the tubes is too large
  - At high frequencies (WWII developments) the tubes radiate as antennas

RF linac



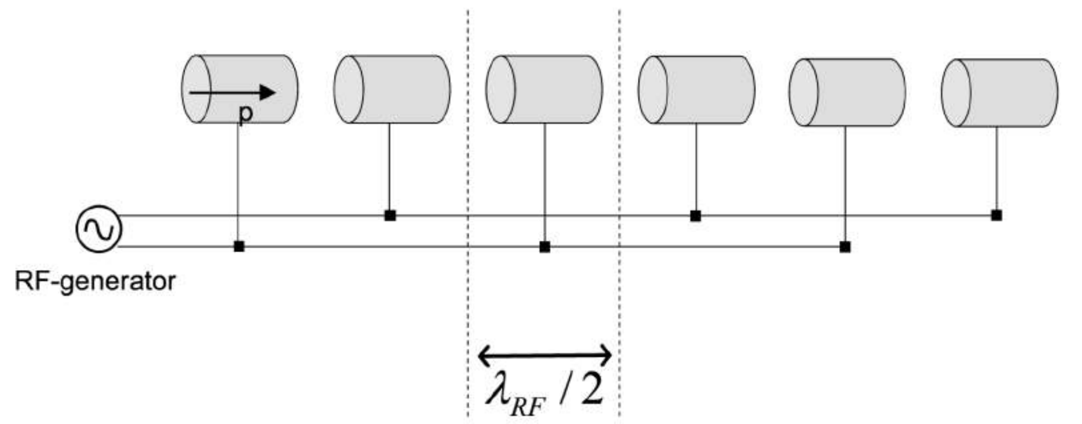
A linear accelerator at work. The particles accelerated (red dots) are assumed to have a positive charge. In actual linacs a large number of particles are injected and accelerated each cycle. The graph *V*(x) shows the electrical potential along the axis of the accelerator at each point in time. The polarity of the RF voltage reverses as the particle passes through each electrode, so when the particle crosses each gap the electric field *(E, arrows)* has the correct direction to accelerate it. The action is shown slowed down enormously.

Radio frequency particle acceleration



Radio frequency particle acceleration

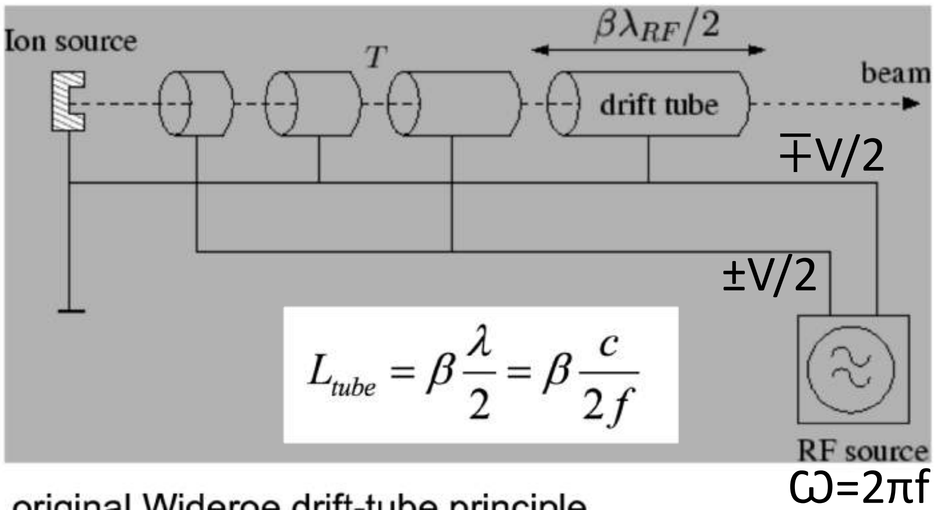
β = 1 (ultra relativistic particles)



Synchron condition: L=v·T/2 = βc/2f = βλ/2

- The particles must travel in packets
- The packets travel in sync with the RF periods
- With increasing energy (momentum), the RF frequency should be tuned: Δp → Δf

β < 1 v speed increases → pipe length increases



original Wideroe drift-tube principle

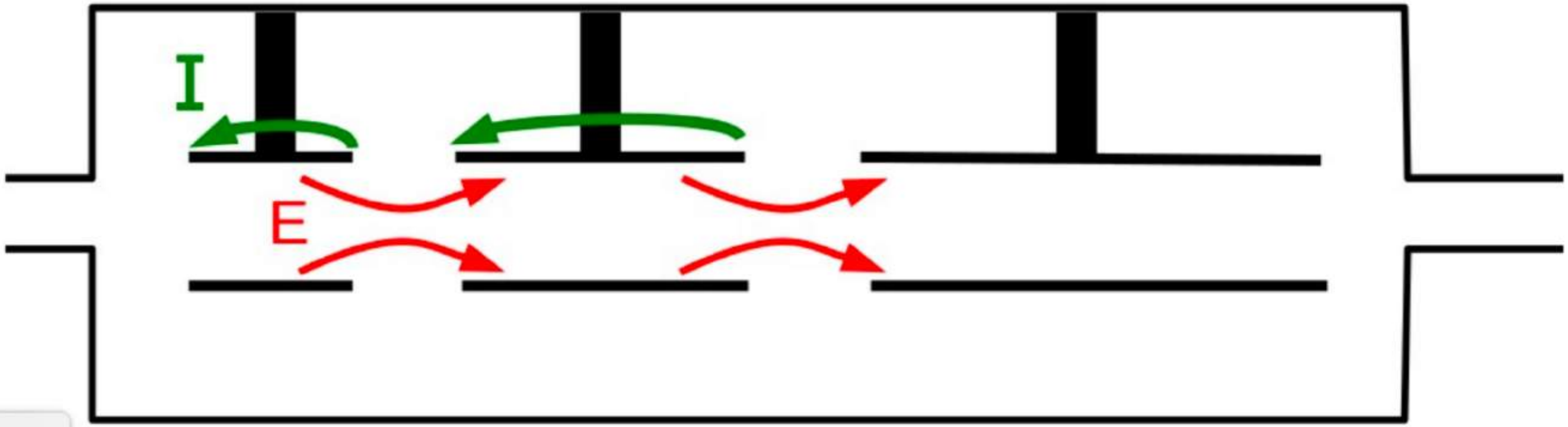
Drift Tube Accelerators:

- Oldest, simplest
- Basis of cyclotrons
- Can be used only at low frequencies (<10 MHz)
- At max frequency: for f = 10 MHz and β = 1: L = 30 m
- Not practical for ultrarelativistic particles → suitable for low β

Alvarez linac

- Alvarez (1946)
  - The earthed electrodes of Wideröe can be connected to the other RF electrode
  - The accelerator structure can be transformed into a single RF resonator
  - Electromagnetic standing wave locked into a box
  - Resonator – there are no radiative losses

They can be standalone accelerators or injectors of larger accelerators
Examples: CERN Linac 2 (50 MeV protons) and new CERN Linac 4

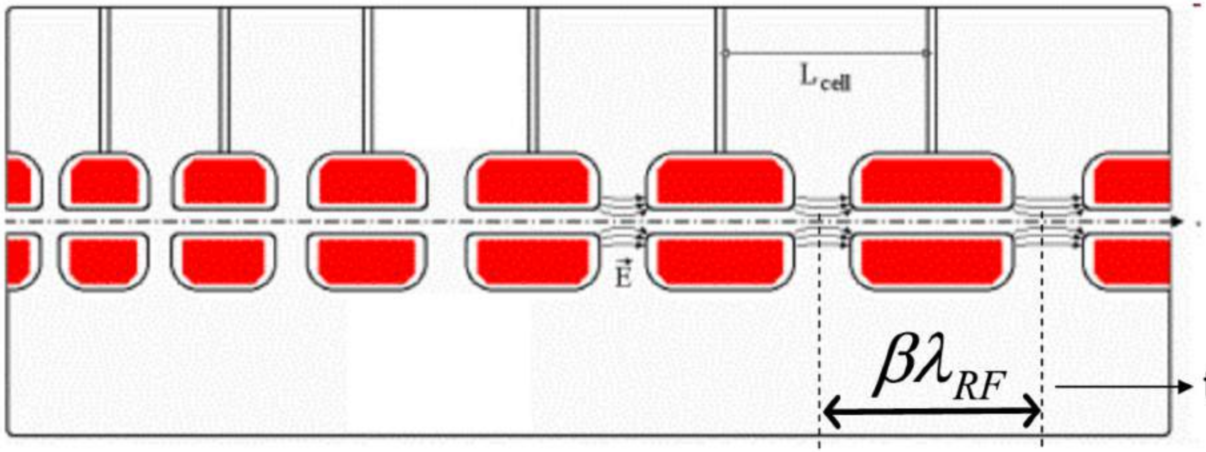


Screenshot

RF cavities

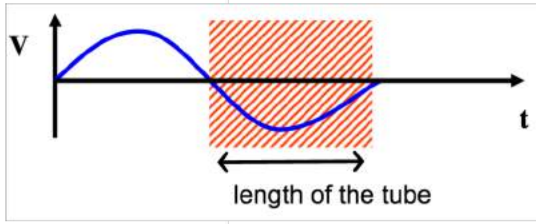
The RF space is enclosed in a box
While the space is in the "wrong" direction,
the particle is shielded by a tube
E field || z axis of cavity
All cavities are in phase

Alvarez drift-tube structure:

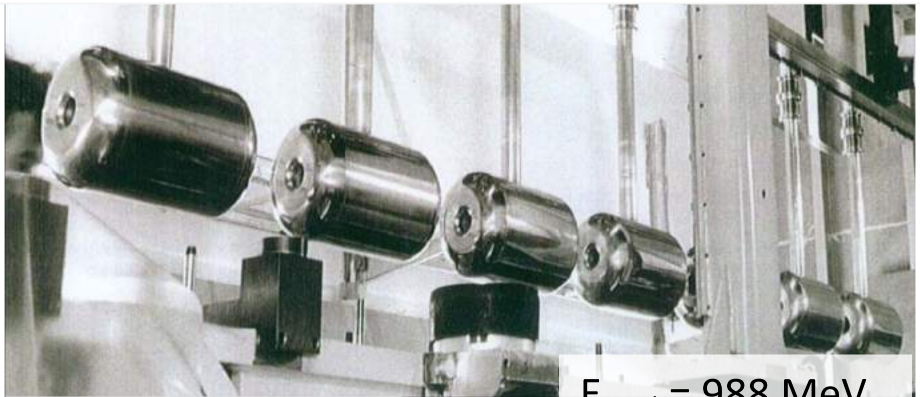


→ twice longer tubes

RF resonator

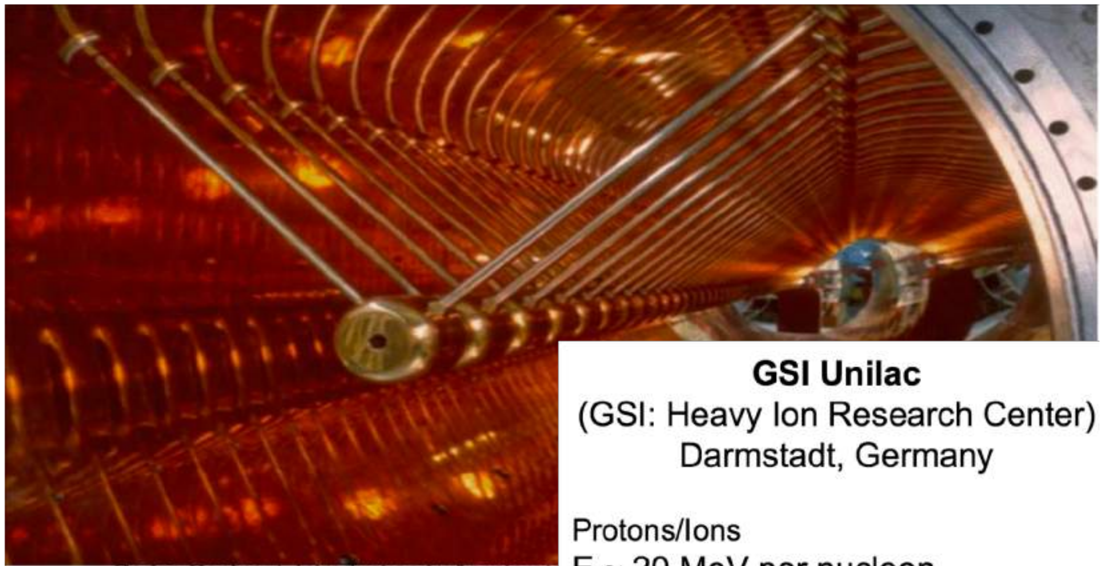


higher frequencies possible → shorter accelerator



DESY proton linac (LINAC III)

E_{total} = 988 MeV
m_p = 938 MeV/c^2
p = 310 MeV/c
β ≈ 0.3



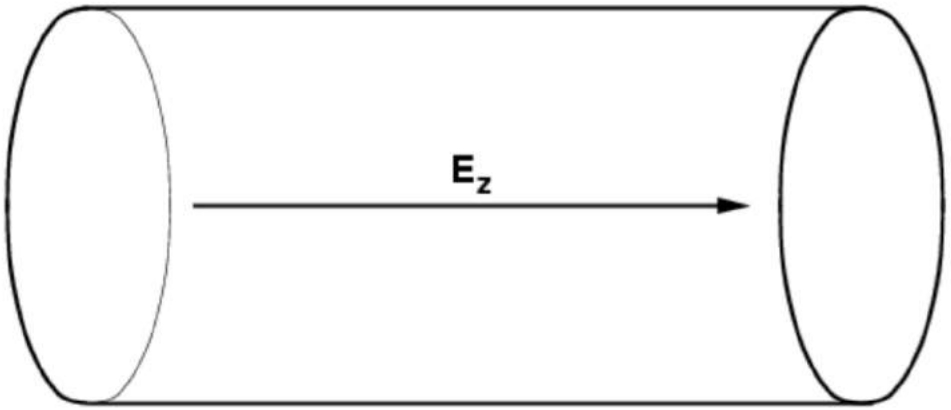
GSI Unilac
(GSI: Heavy Ion Research Center)
Darmstadt, Germany

Protons/Ions
E ≈ 20 MeV per nucleon
β ≈ 0.04 … 0.6

An Alternate Way of Considering the Alvarez Structure.

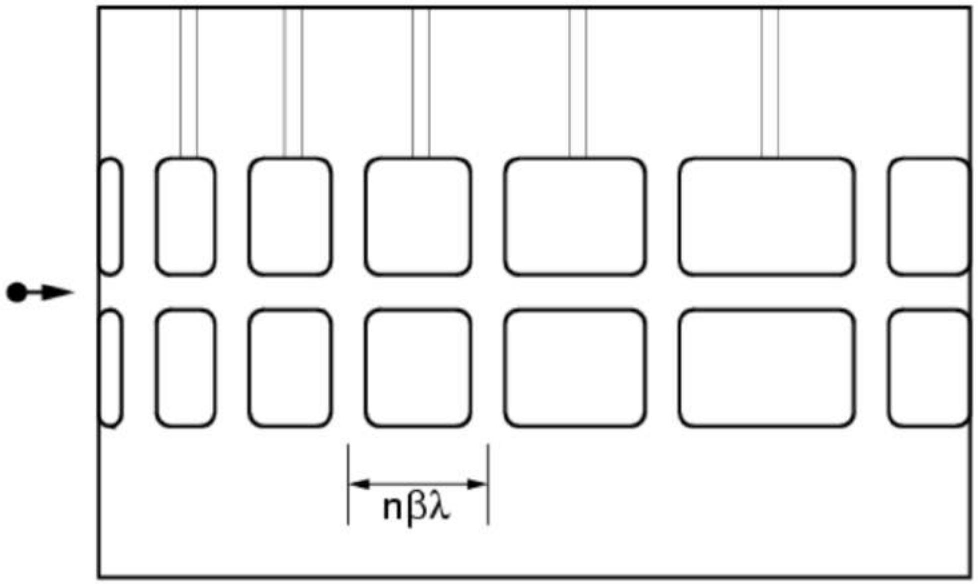
Start off with a long pillbox cavity with the electric field along the axis.

An ion in this field will just oscillate along z, but not be accelerated.



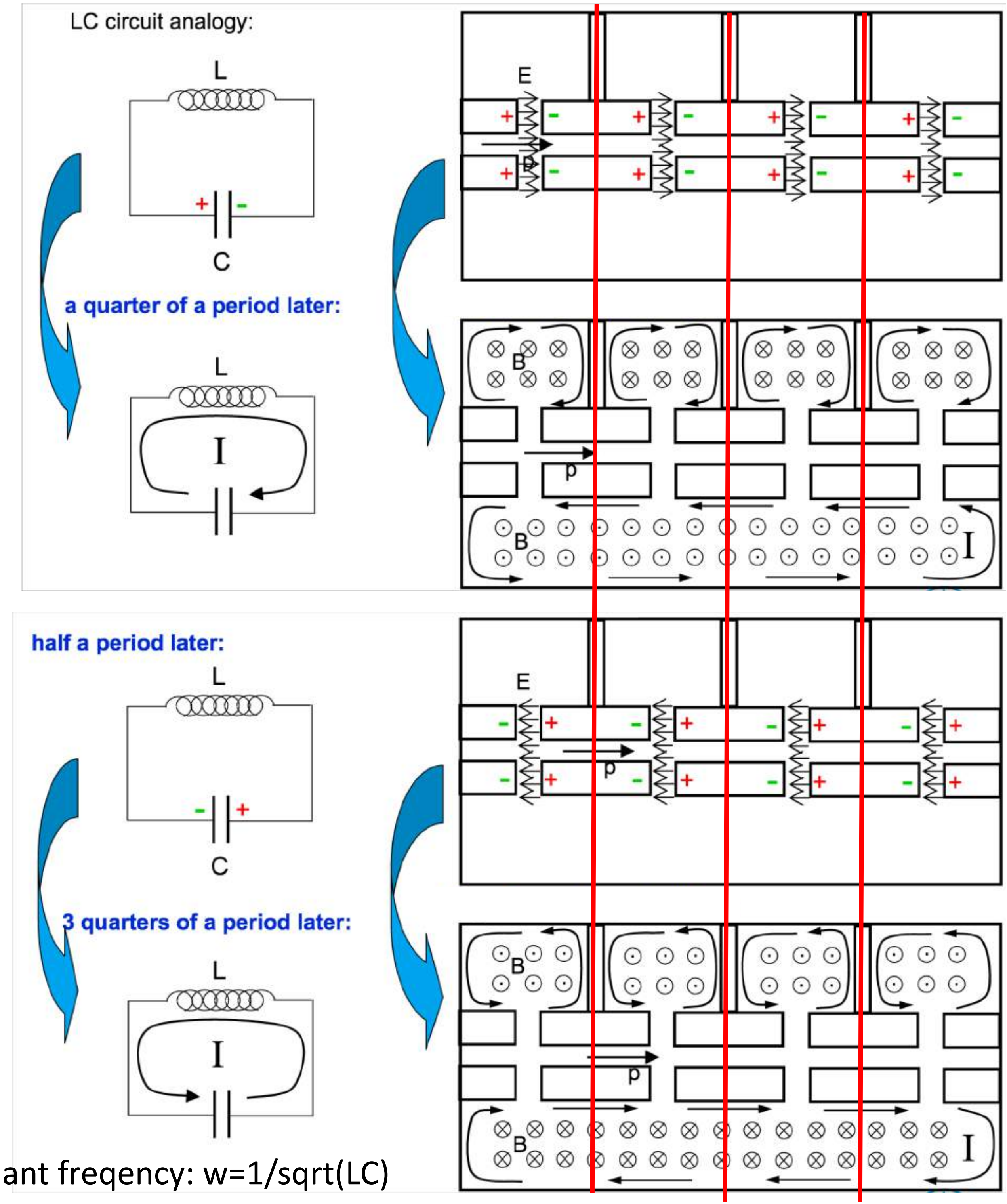
If drift tubes are introduced into the cavity with the right spacing, the ion will be inside a **Faraday Cage**. When the field reverses the ion is shielded from the field and is not decelerated. The ion comes to the accelerating gap at the time when the field will accelerate the beam.

Note the half drift tubes at the ends.



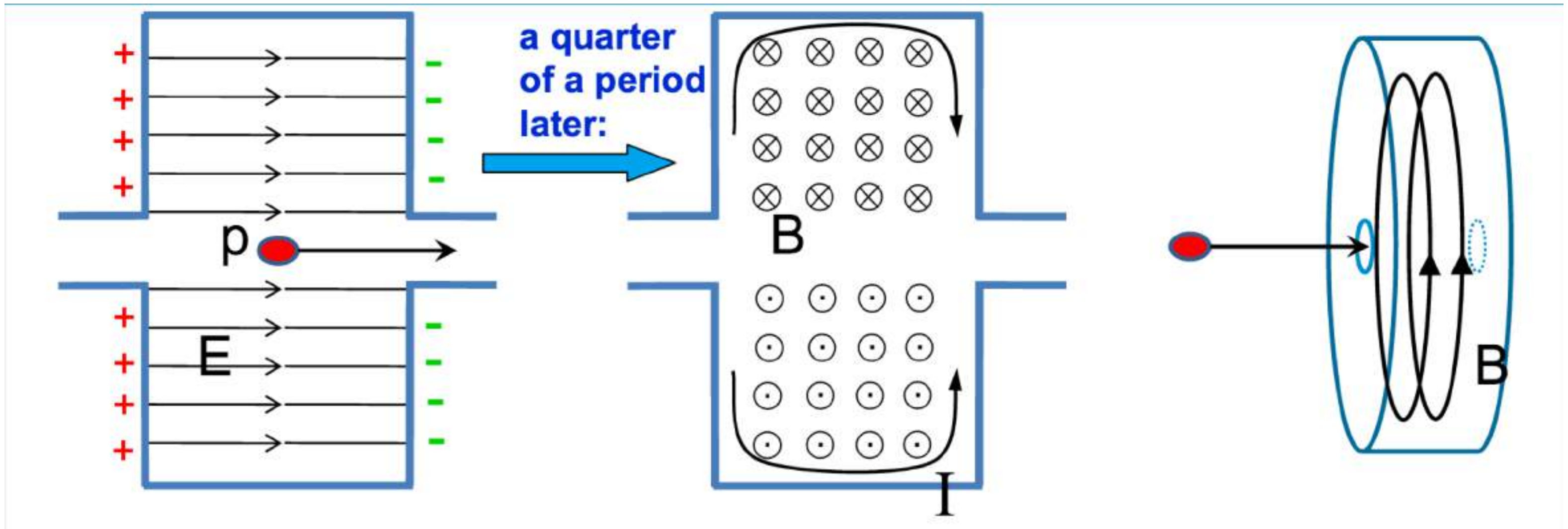
RF cavities

Alvarez drift tube



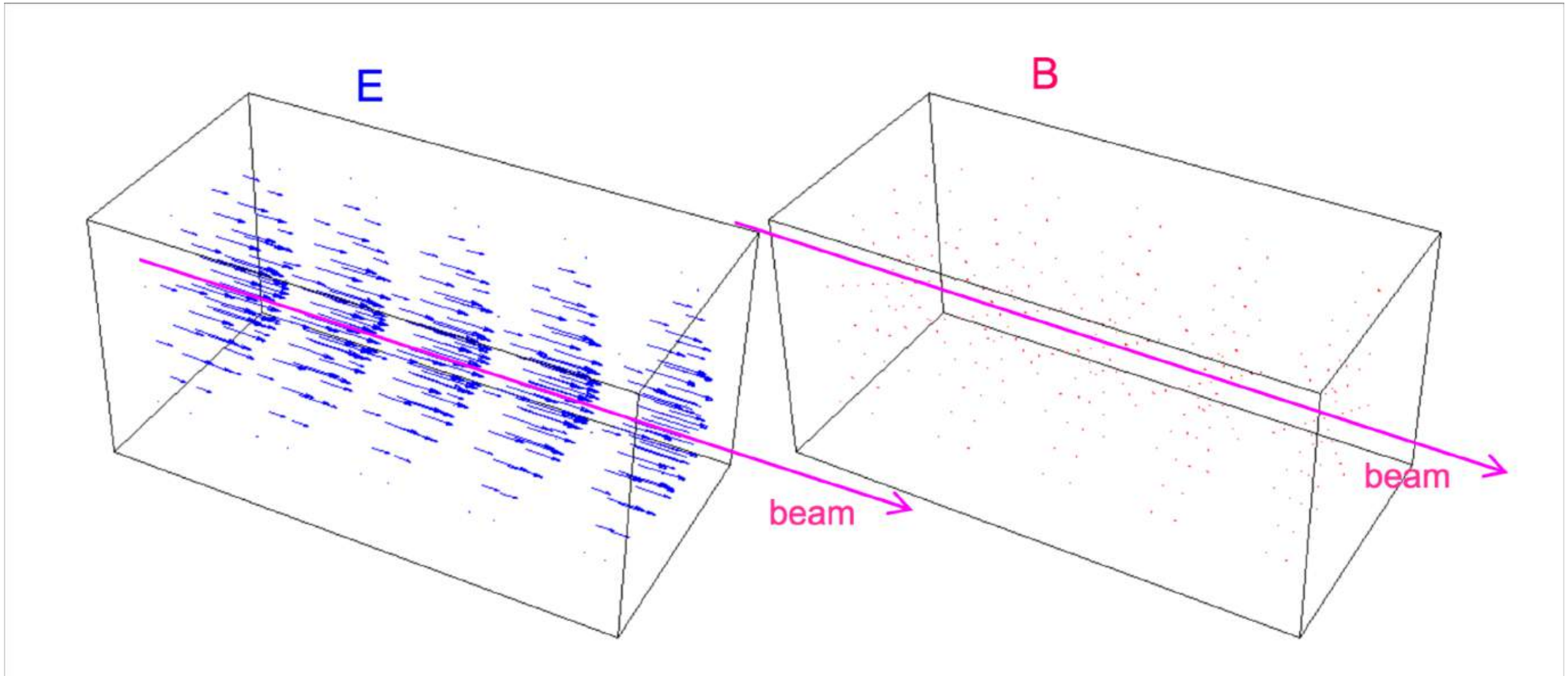
Resonant freqency: w=1/sqrt(LC)

RF pillbox cavity



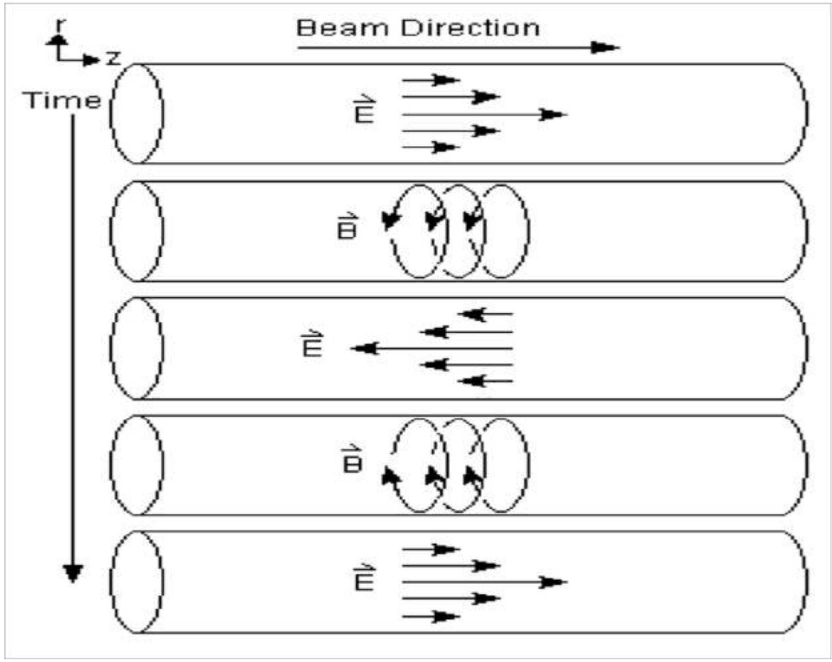
RF cavities

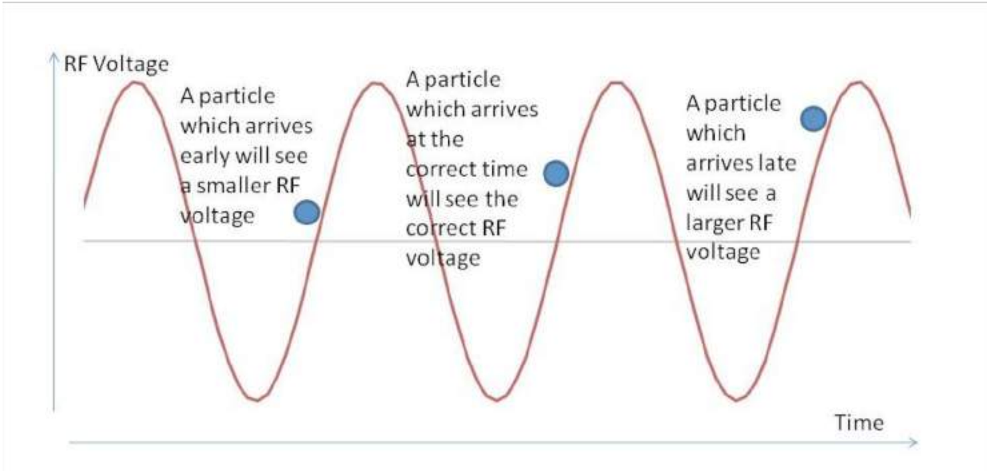
3D demonstration of electric and magnetic fields in a pillbox (cylindrical) cavity resonator

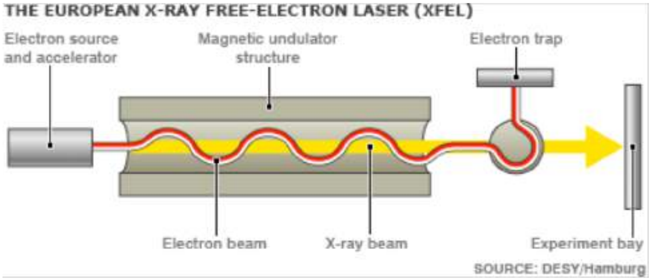


RF particle acceleration

- Within the RF cavities, the RF space can be imagined as a sinusoidal oscillating voltage (electrical field)
- When the charged particle feels this voltage, it accelerates
- As the voltage oscillates, the particle must pass through the cavity at the right time
- Small deviations can be tolerated, these only cause oscillations of the particles within the packets



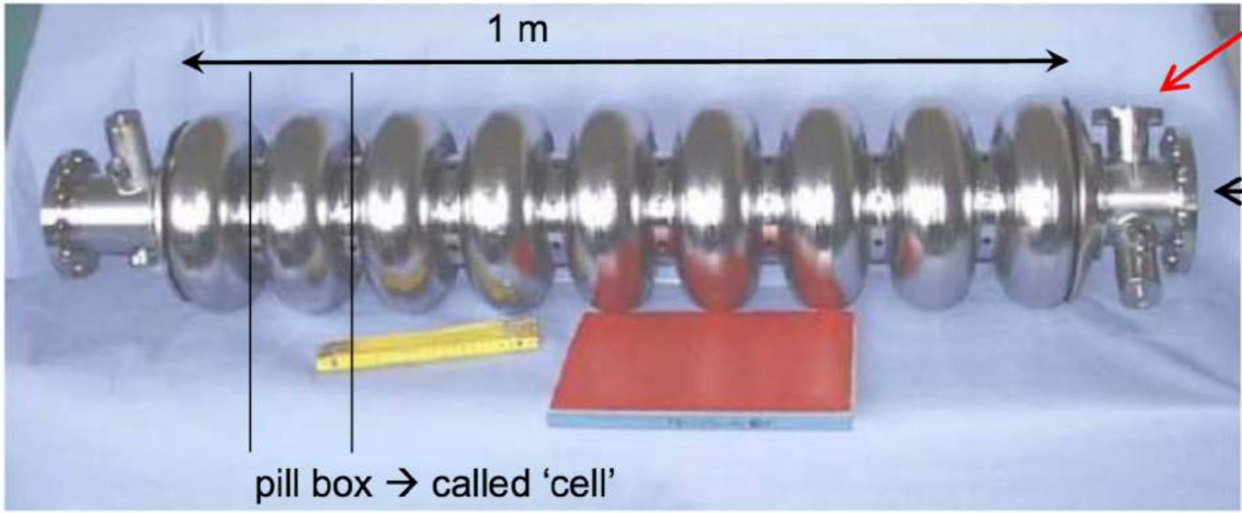


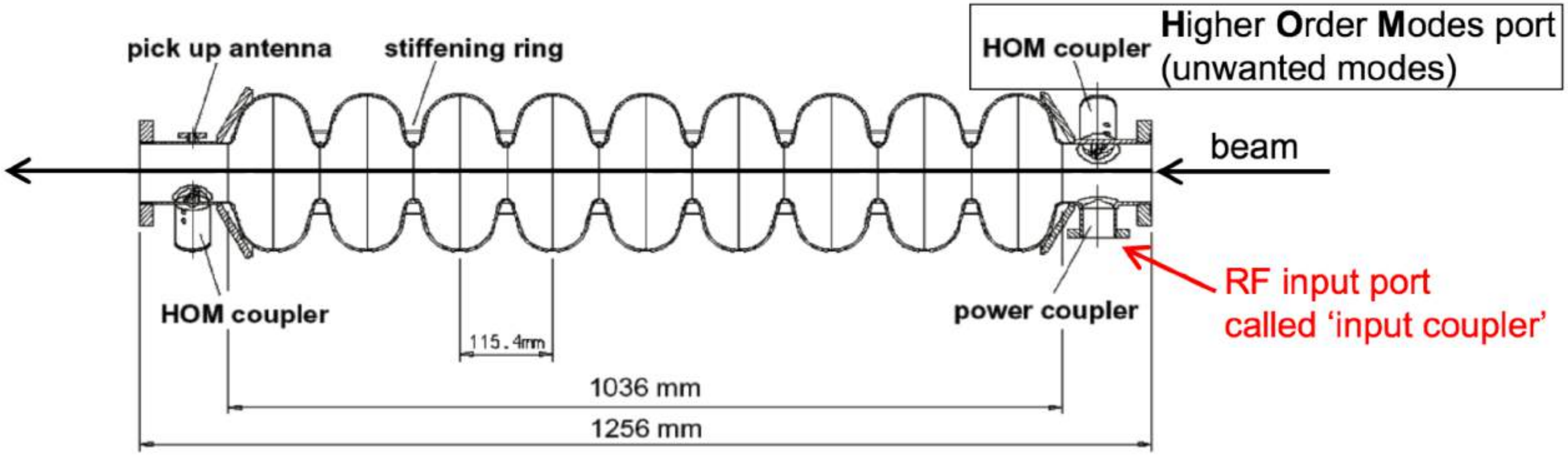


In real life

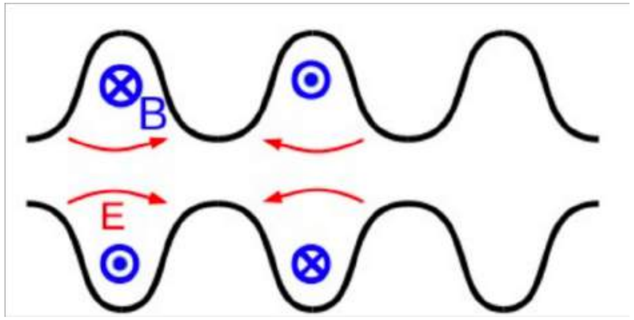
Free-electron lasers at DESY:
FLASH (2005),
XFEL (2017)

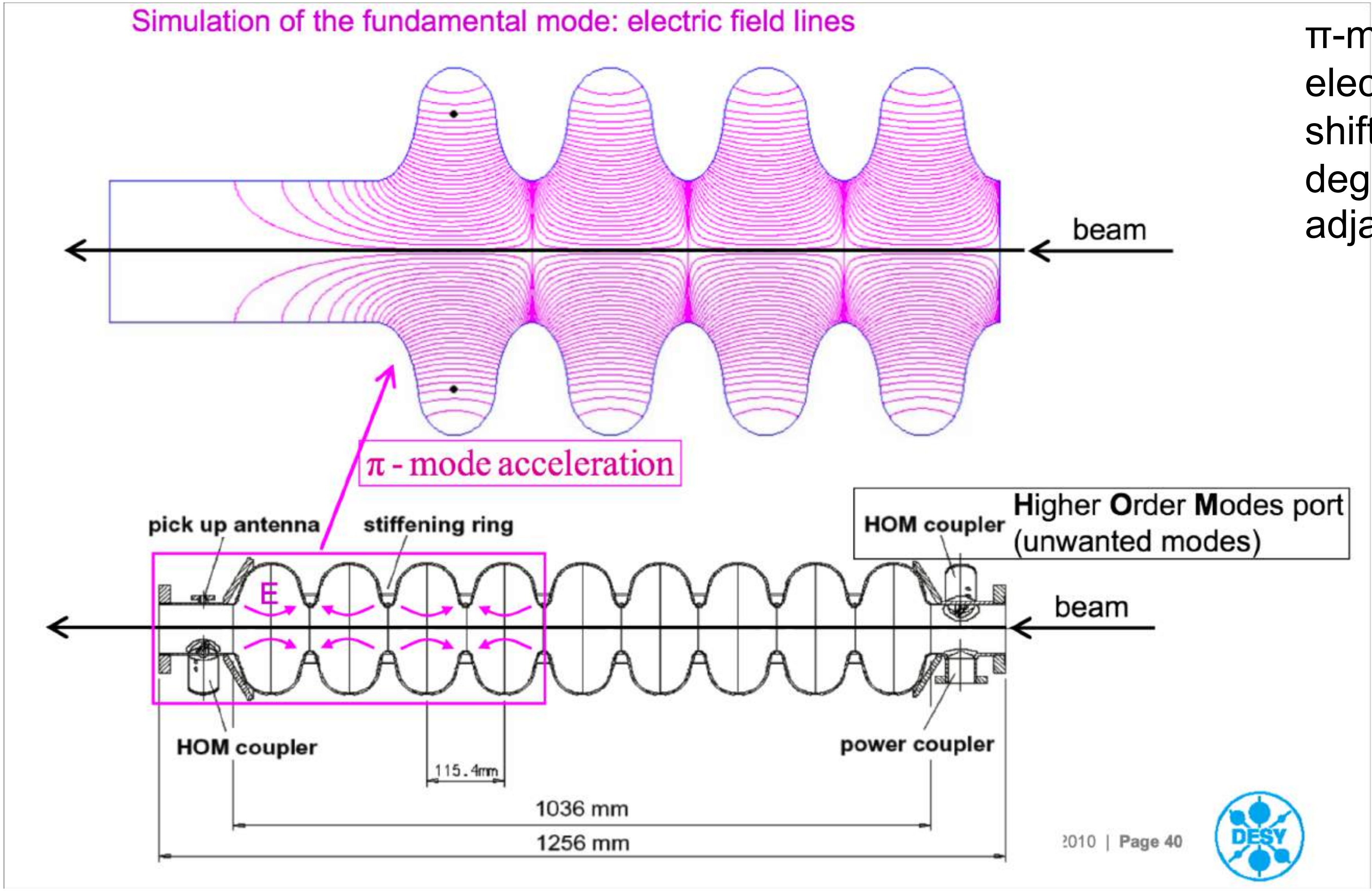
Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)





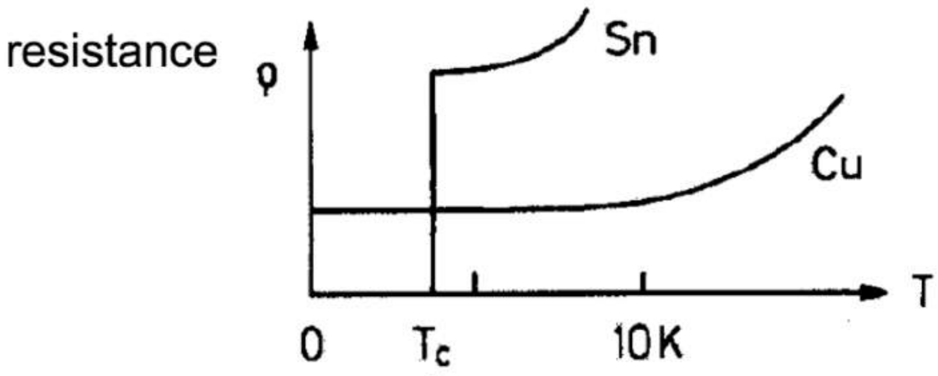
In real life





π-mode:
electric field
shifted by 180
degrees in
adjacent cells

Superconducting RF cavities



critical temperature (Tc):

for DC currents !

at radio-frequencies, there is a "microwave surface resistance"

which typically is <u>5 orders of magnitude</u> lower than R of copper

Superconducting RF cavities

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

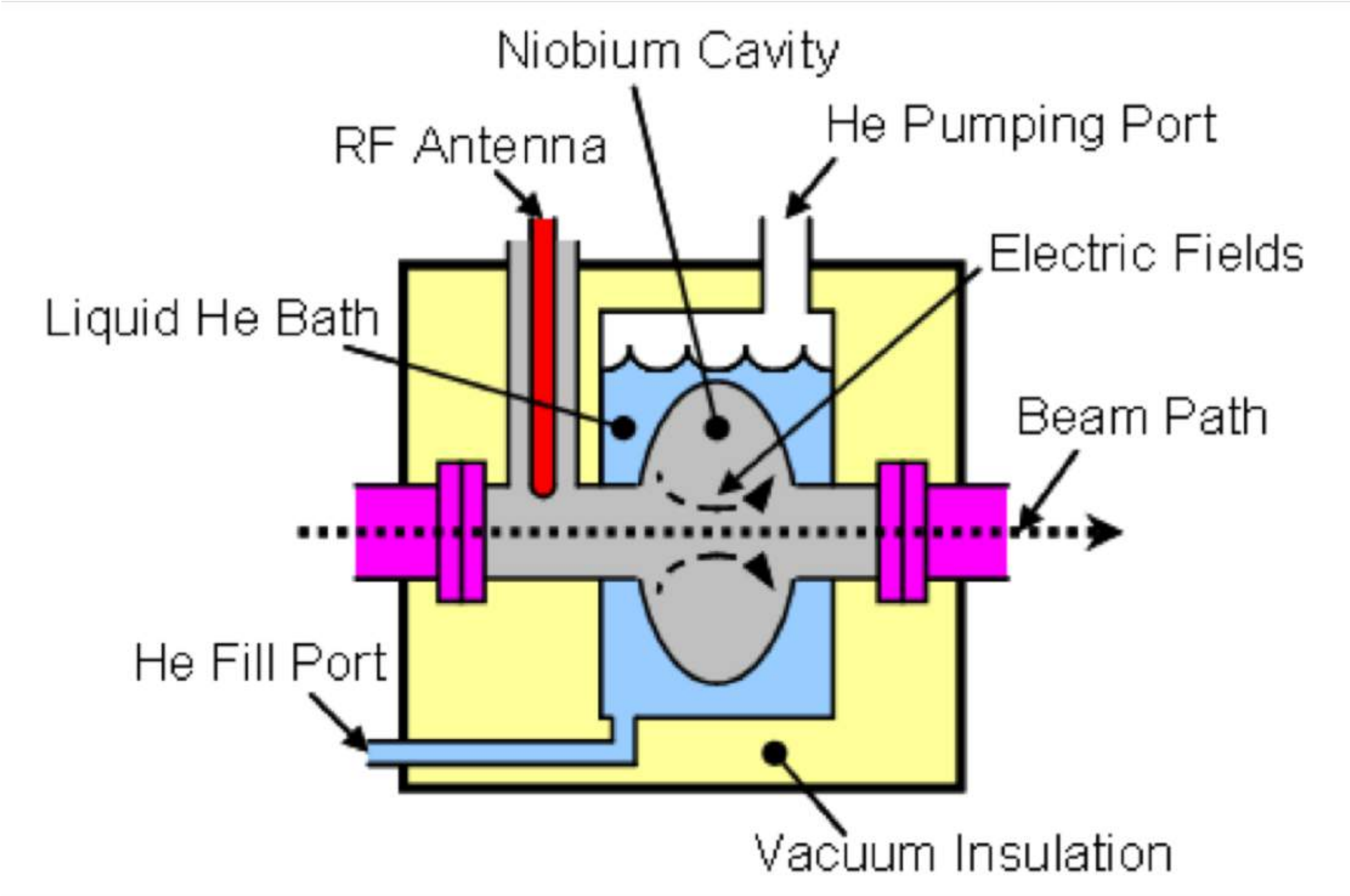
Thermic efficiency:

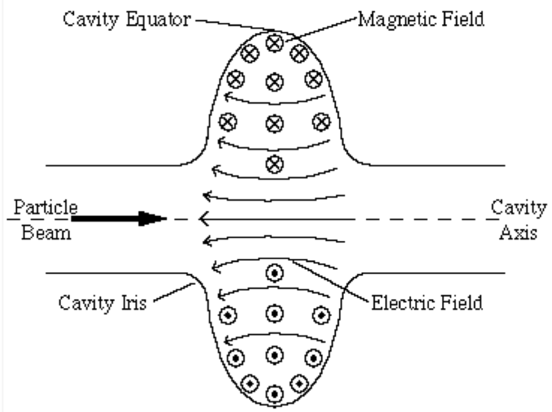
Carnot efficiency: $\eta_c = \dfrac{T}{300 - T} = 0.007$ x cryogenics efficiency 20-30%

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

>100 power reduction factor

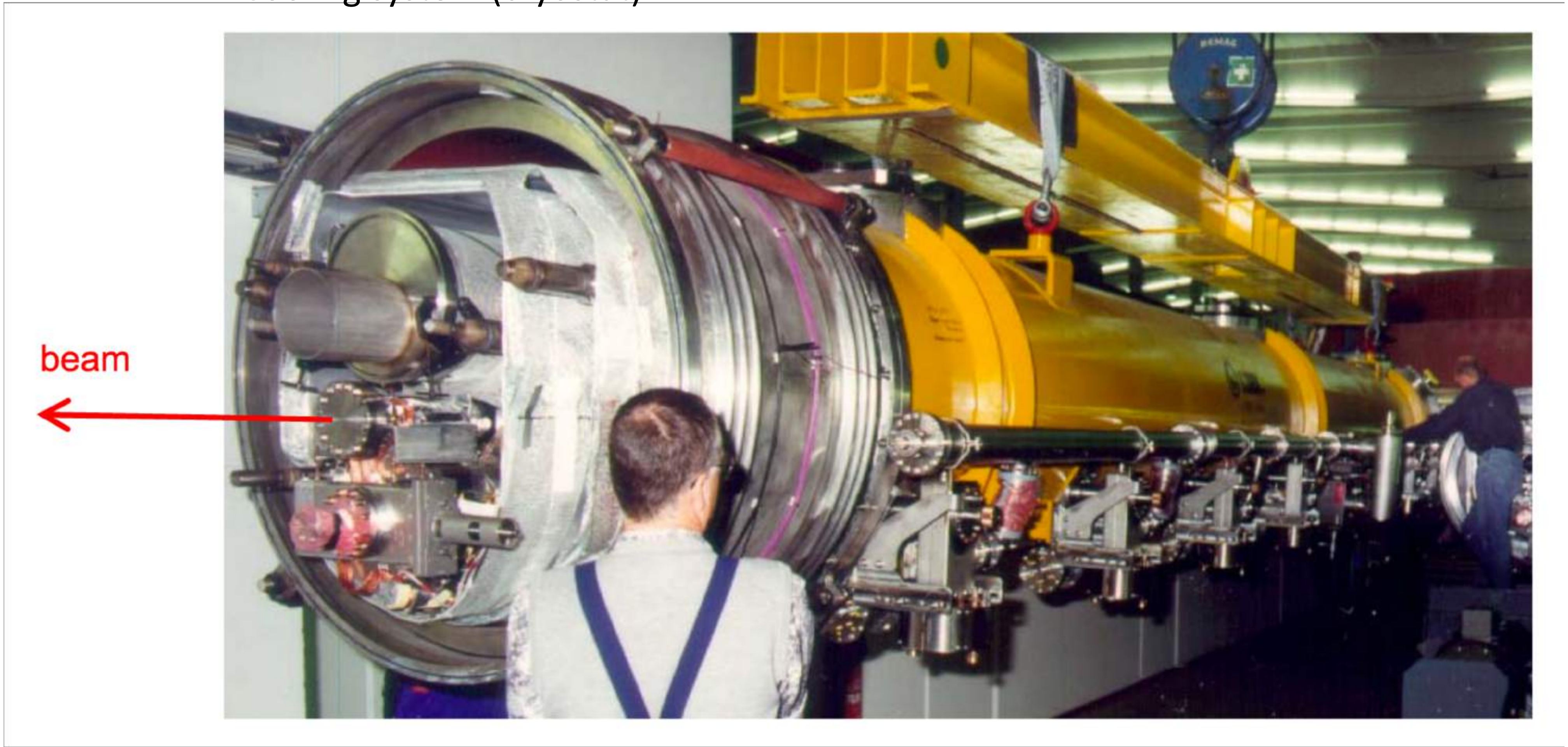
Superconducting RF cavities





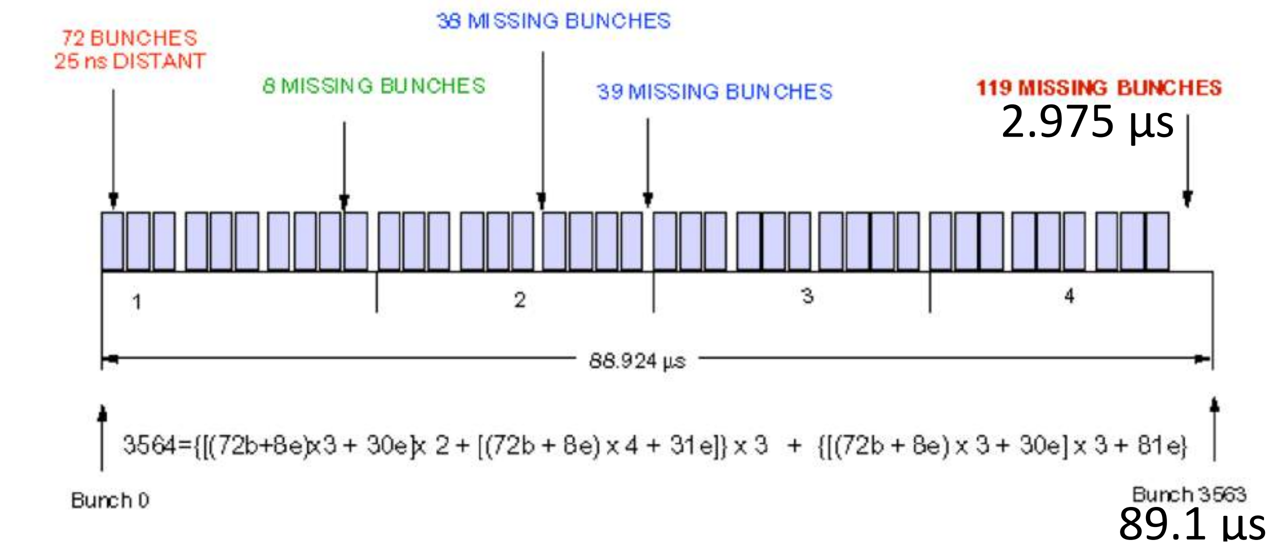
XFEL RF cavities with their cooling system

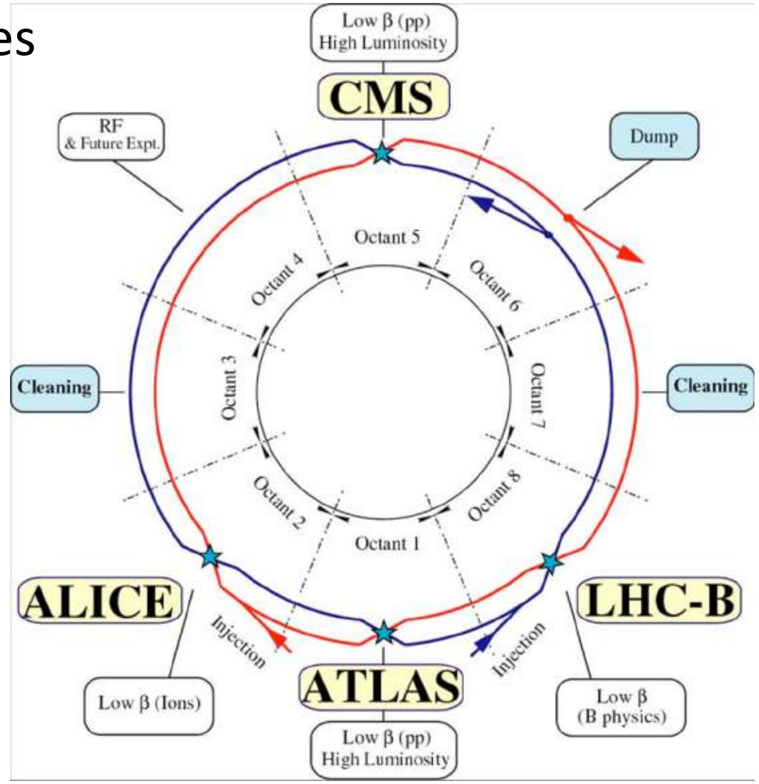
Cooling system (cryostat)



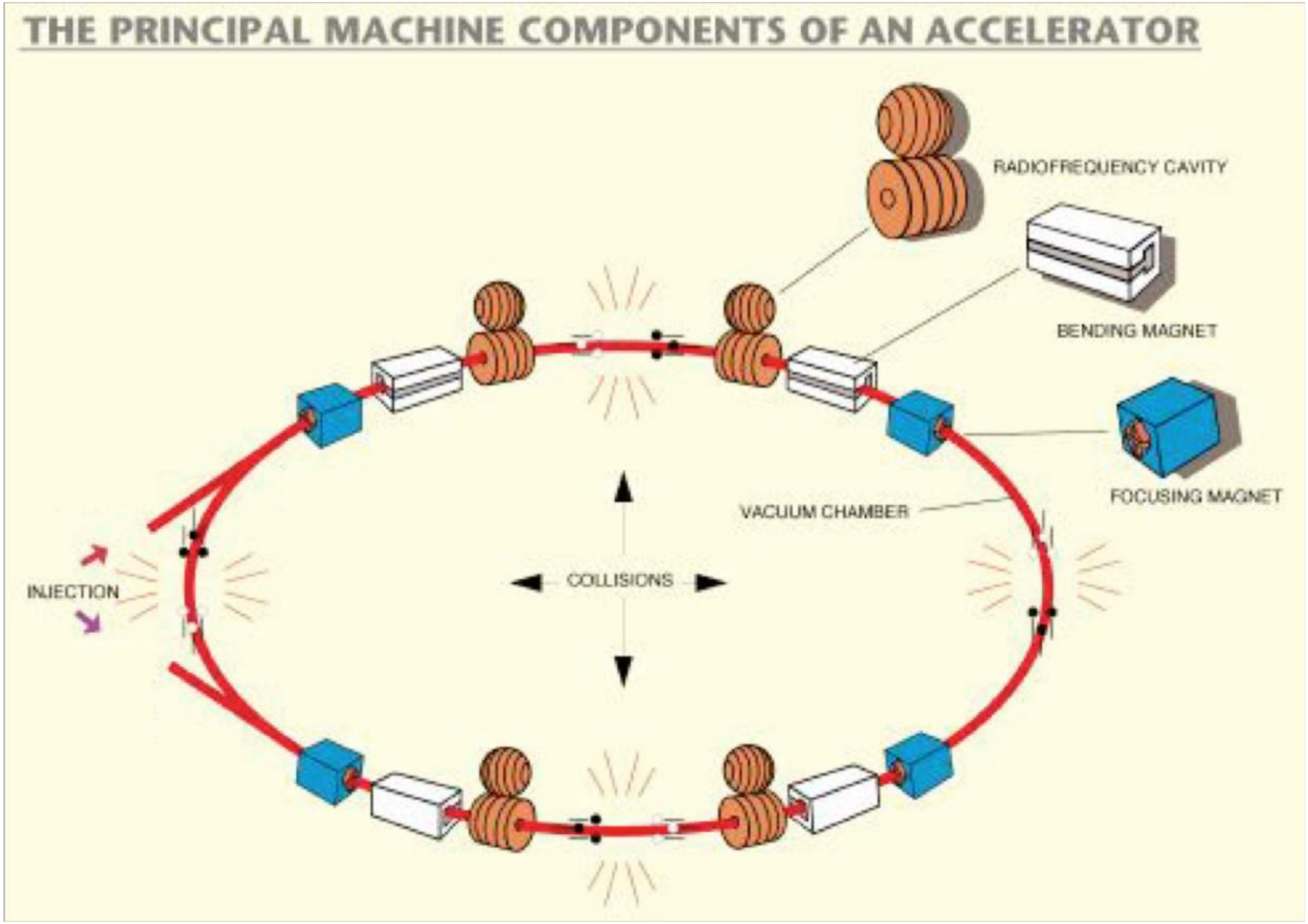
LHC

- LHC not a perfect circle: eight 2.45-km-long arcs + eight 545-m-long straight sections (insertions)
- 16 superconducting RF cavities (2x4/beam) operating at 400 MHz housed in a straight section
- Maximum voltage: 2 MV/cavity (16 MV/beam)
- Injection energy: 450 GeV
- Nominal energy 7 TeV (currently 6.5 TeV)
- Time to accelerate to collision energy: ~20 minutes (homework: calculate it!)
- Beam lifetime: ~10 h (reach initial luminosity / e)



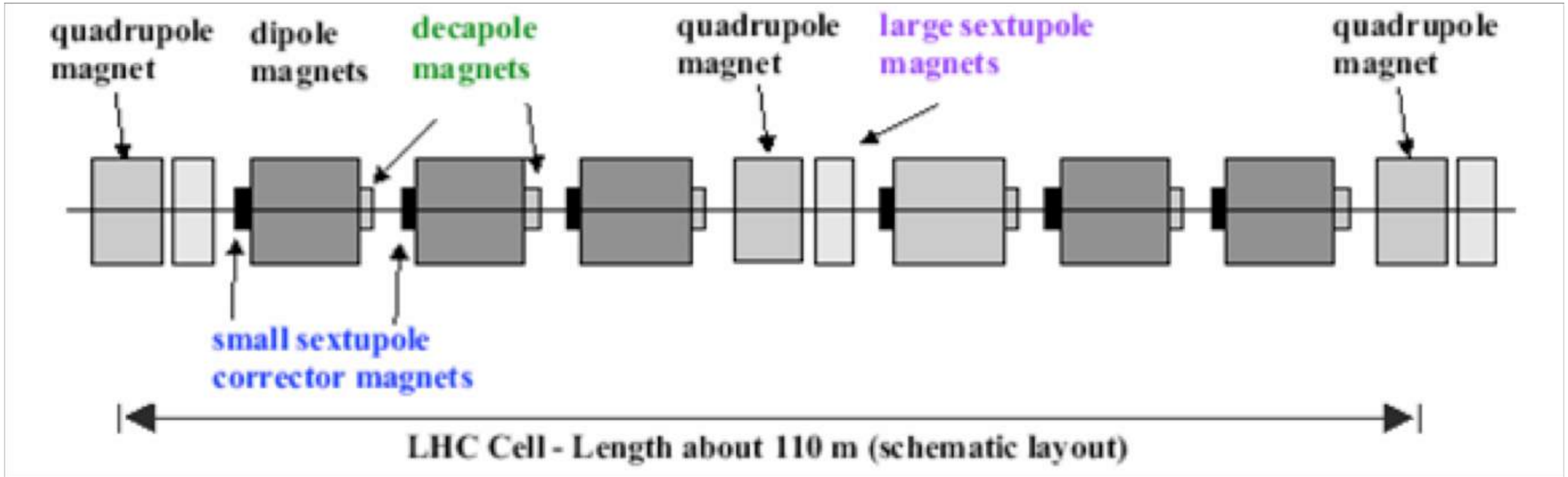


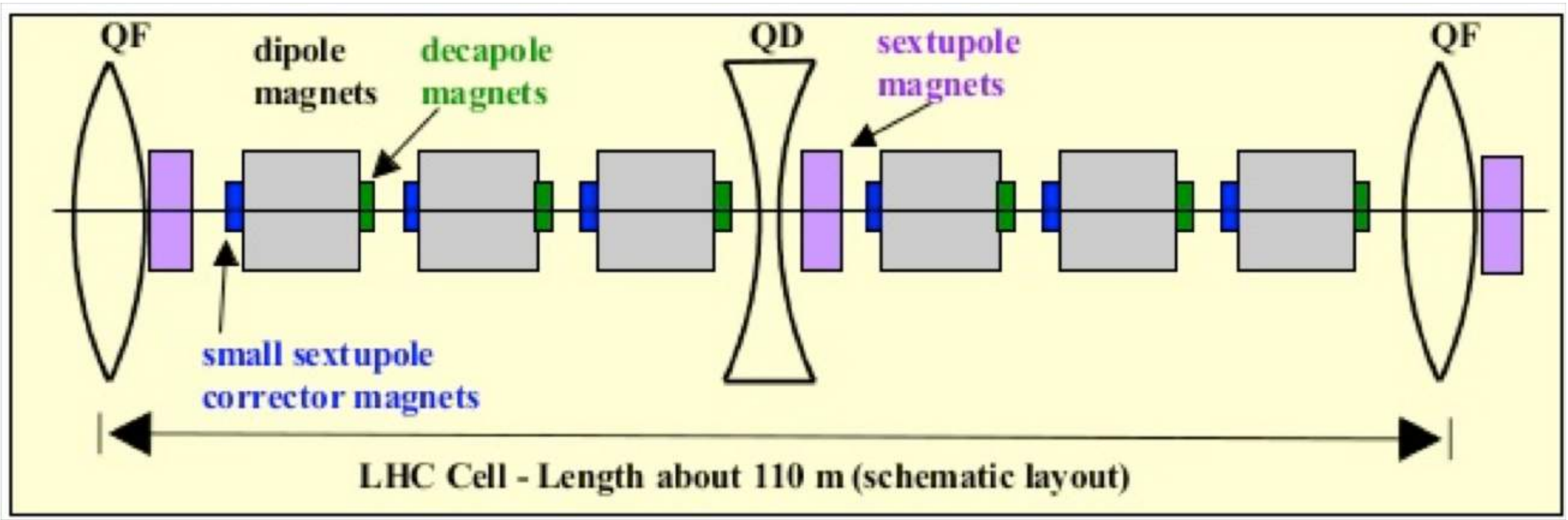
Main components of accelerators



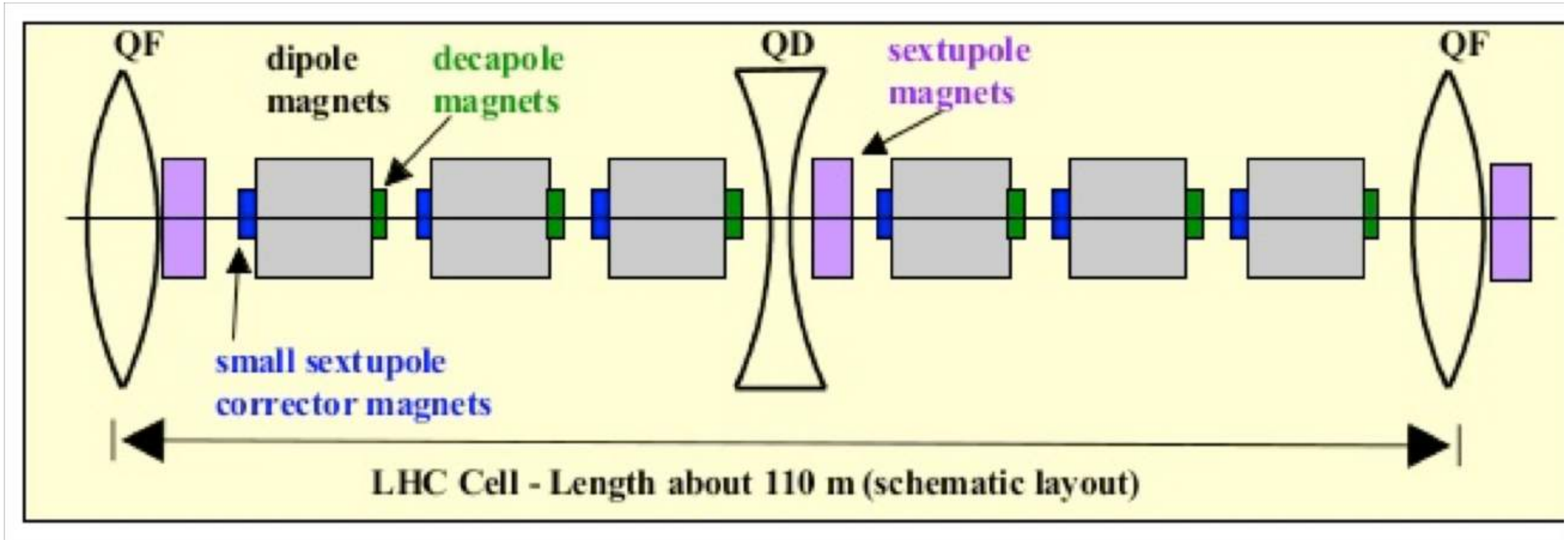
Magnets

LHC magnet system

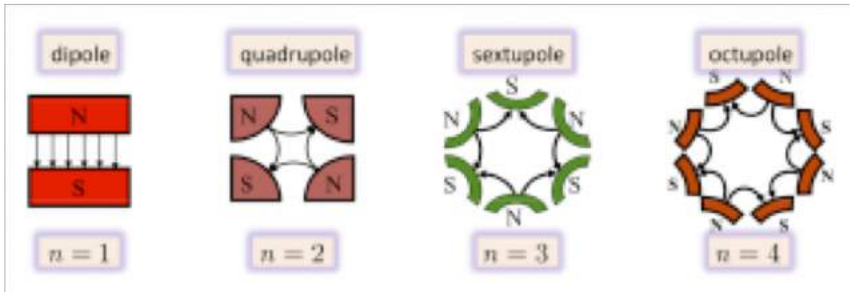




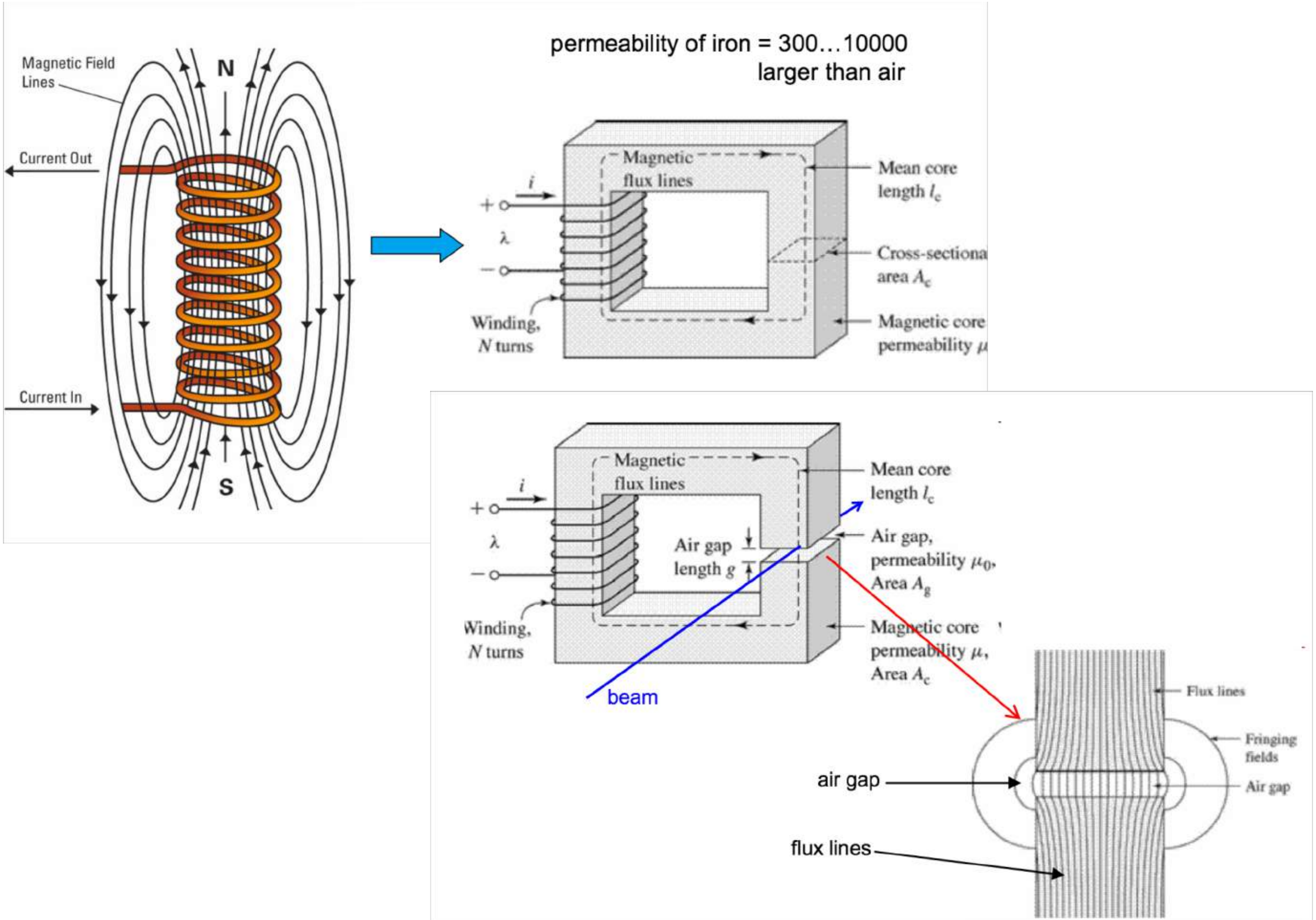
LHC magnet system



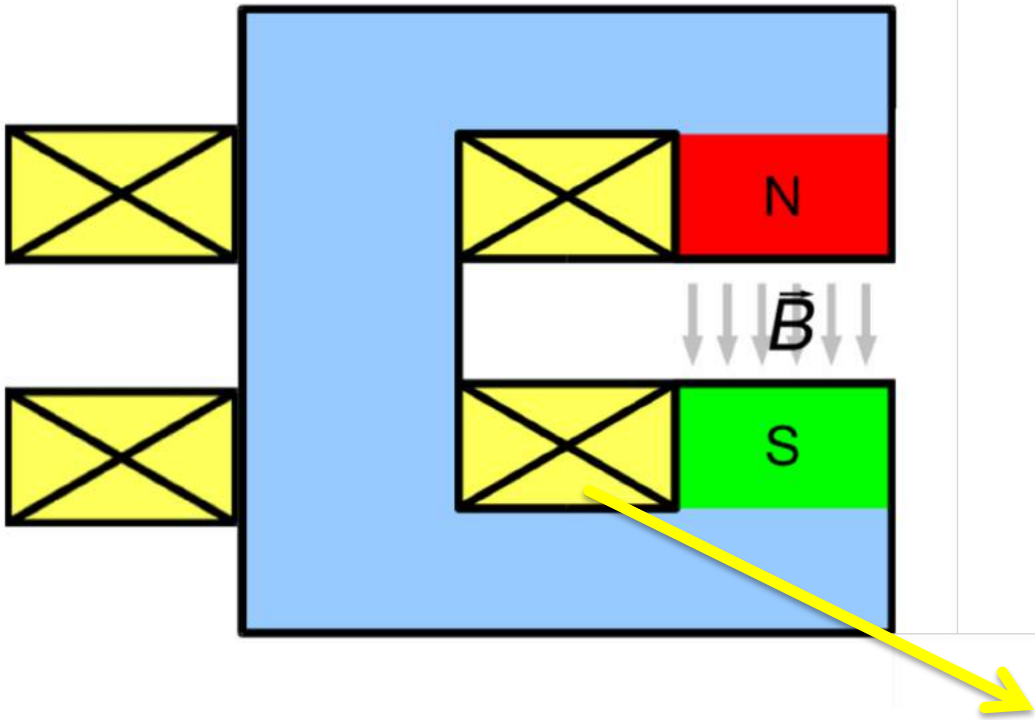
- Dipole magnets: keep the particle beam on a circular path
- Quadrupole magnets: focus the beam
- Sextupole magnets: Correct path of particles with non-nominal momentum (chromatic errors)
- Multipole magnets: Sextupole, octupole és decapole corrector magnets improve the dipole field at the end of the dipoles
  Stabilize the the path of particles with large amplitude
  Very important to keep the beam lifetime high



Dipole magnets

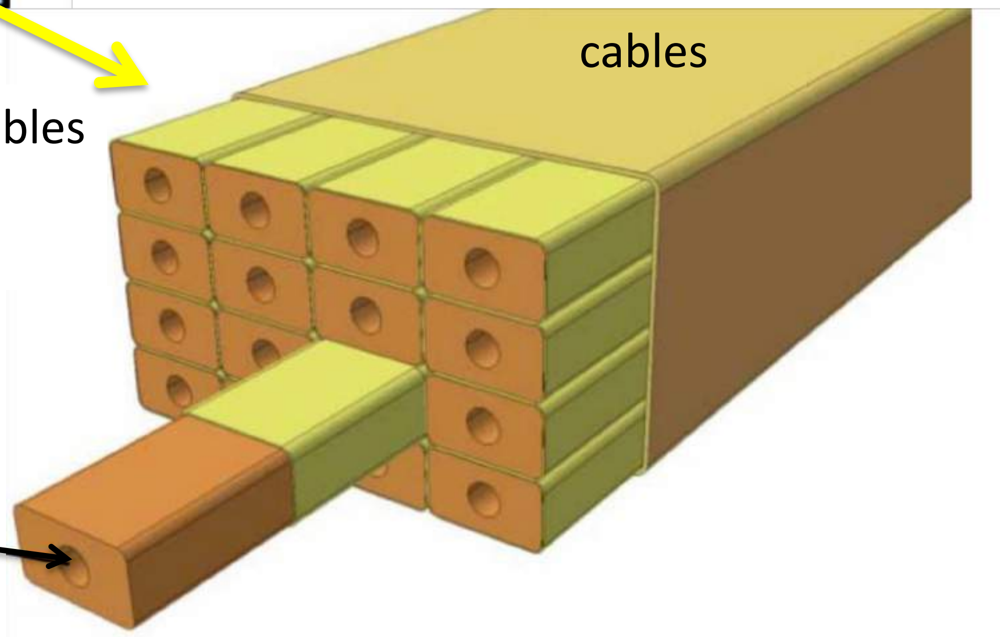


Dipole magnets

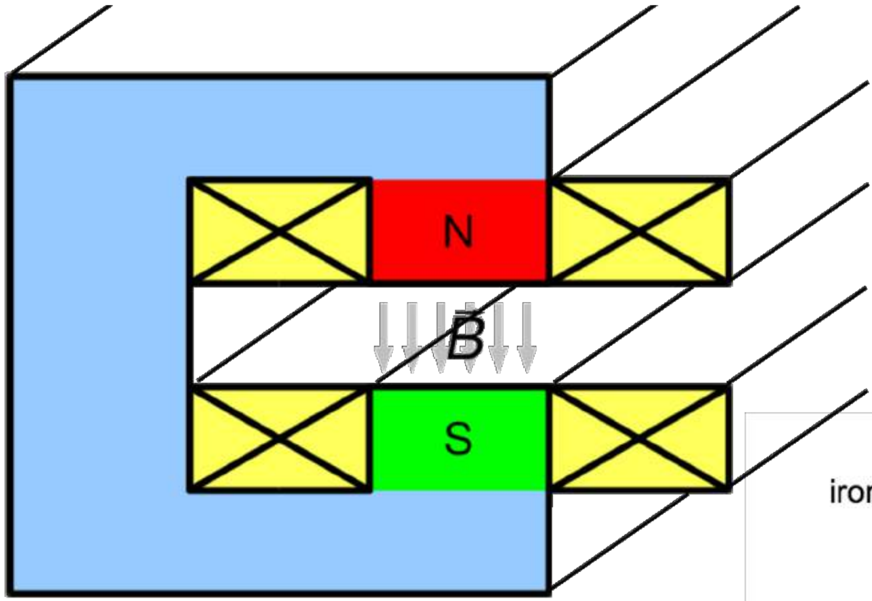


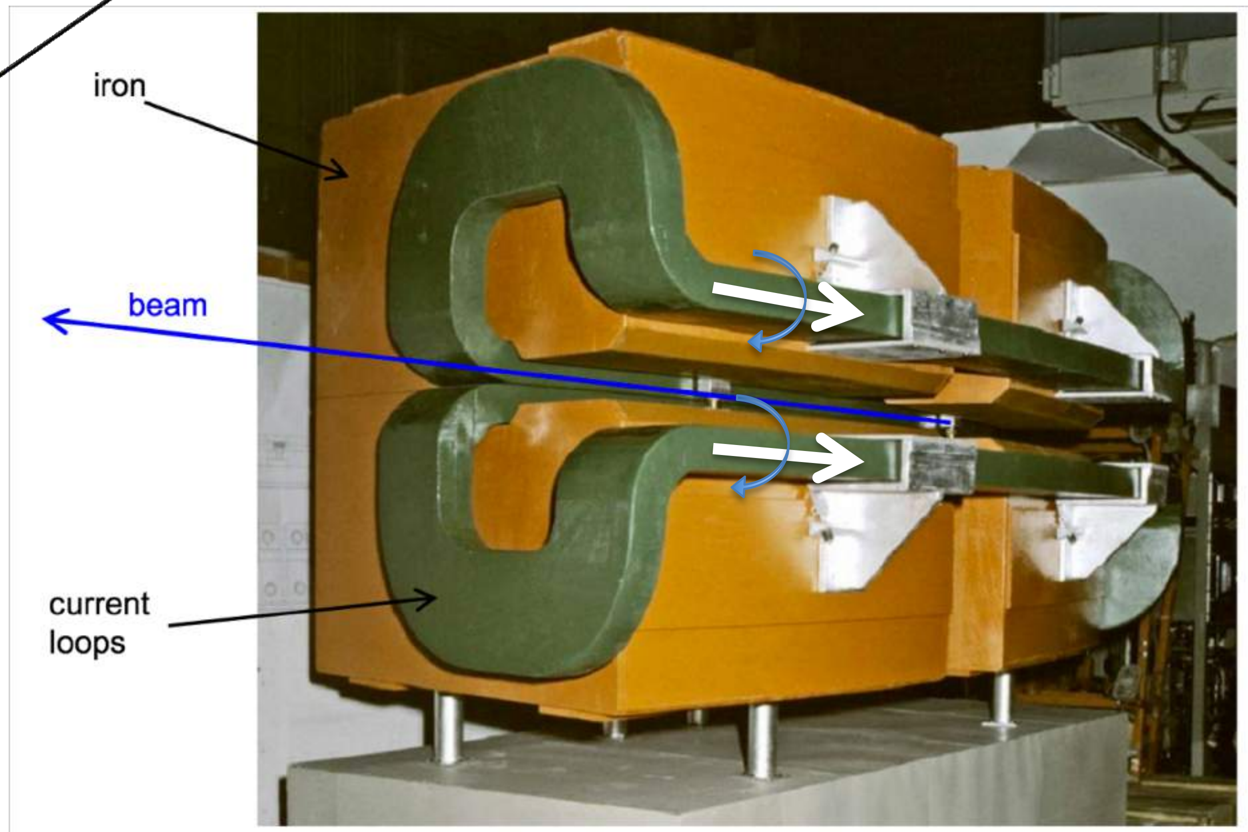
Max. B field ← max. current ← need thick cables

Dissipated power: $P = R \cdot I^2$

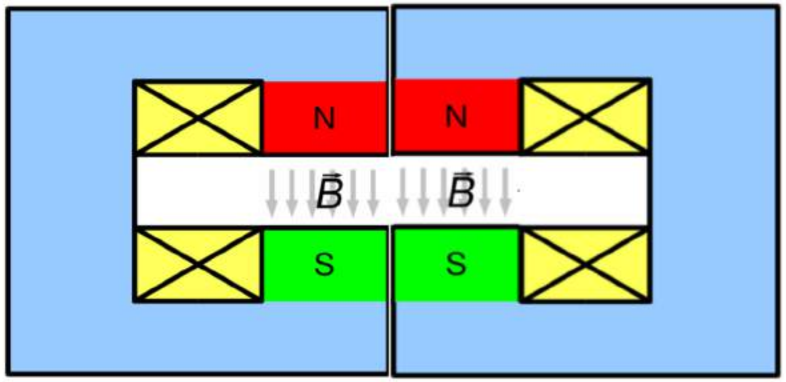


Dipole magnets

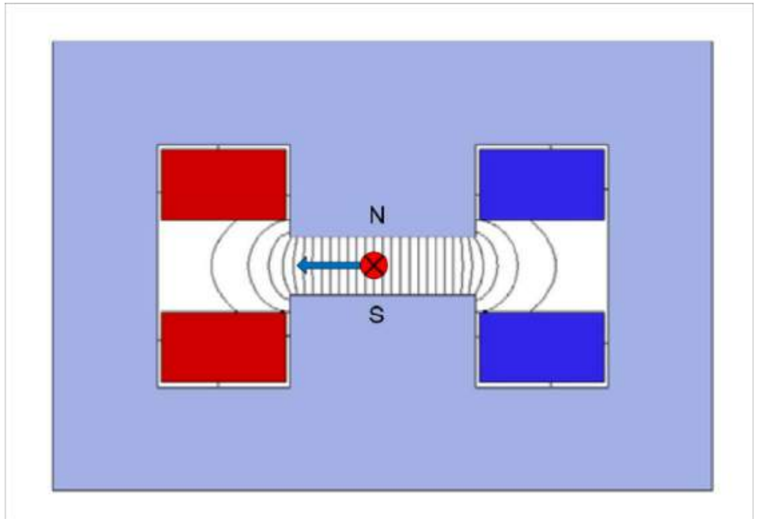


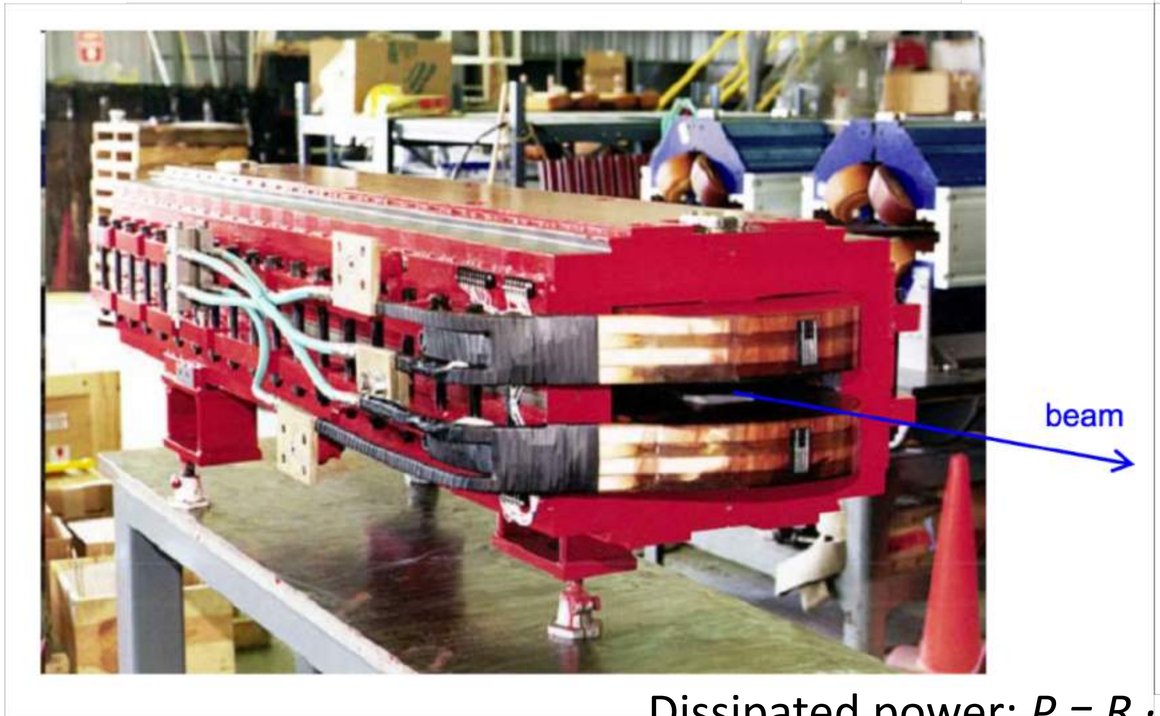


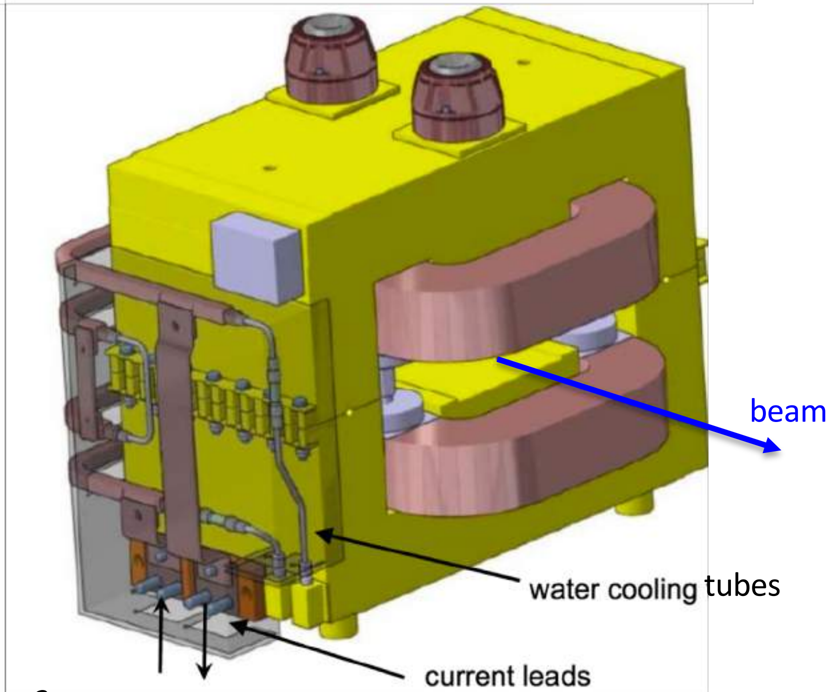
Dipole magnets



C magnet + C magnet = H magnet

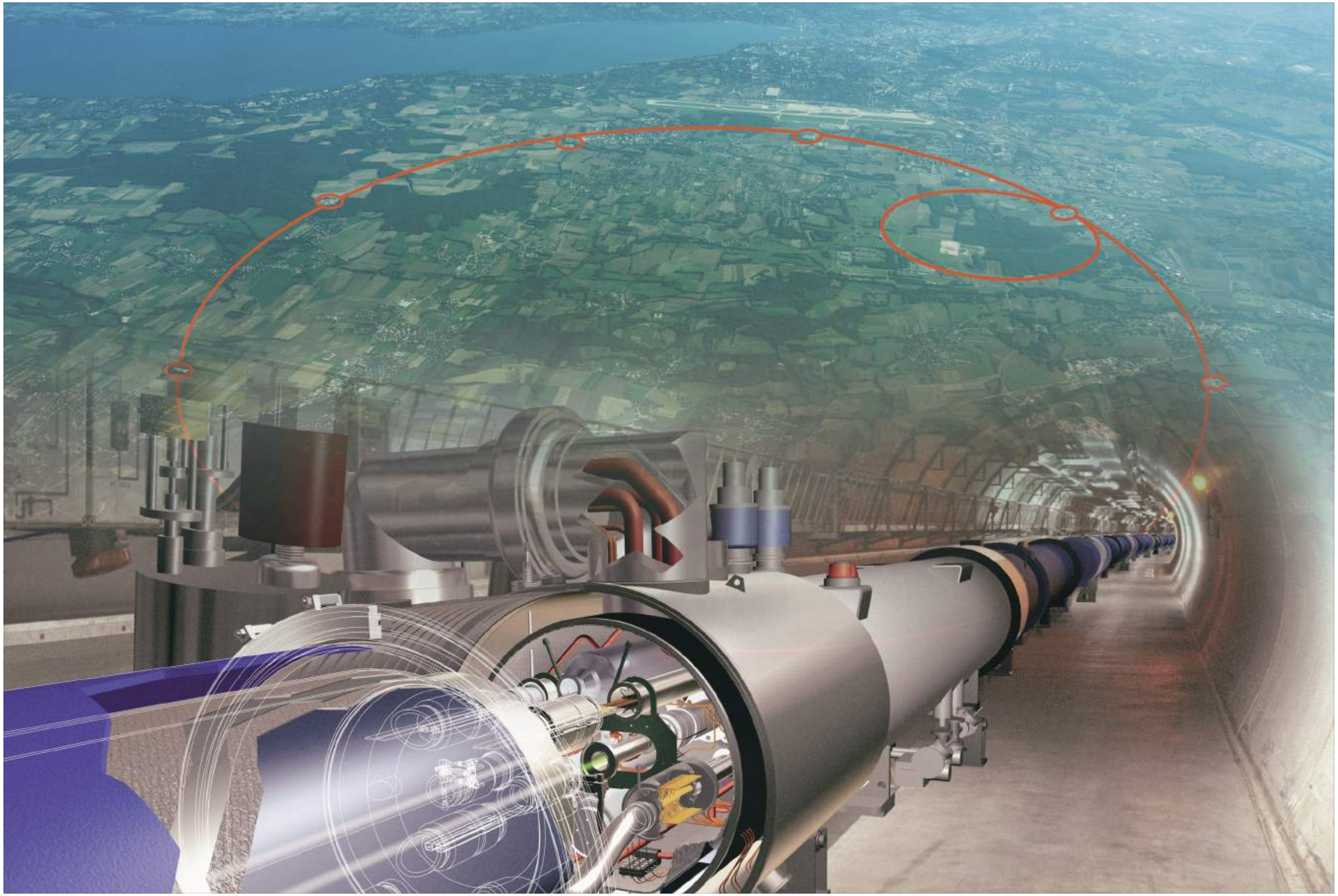






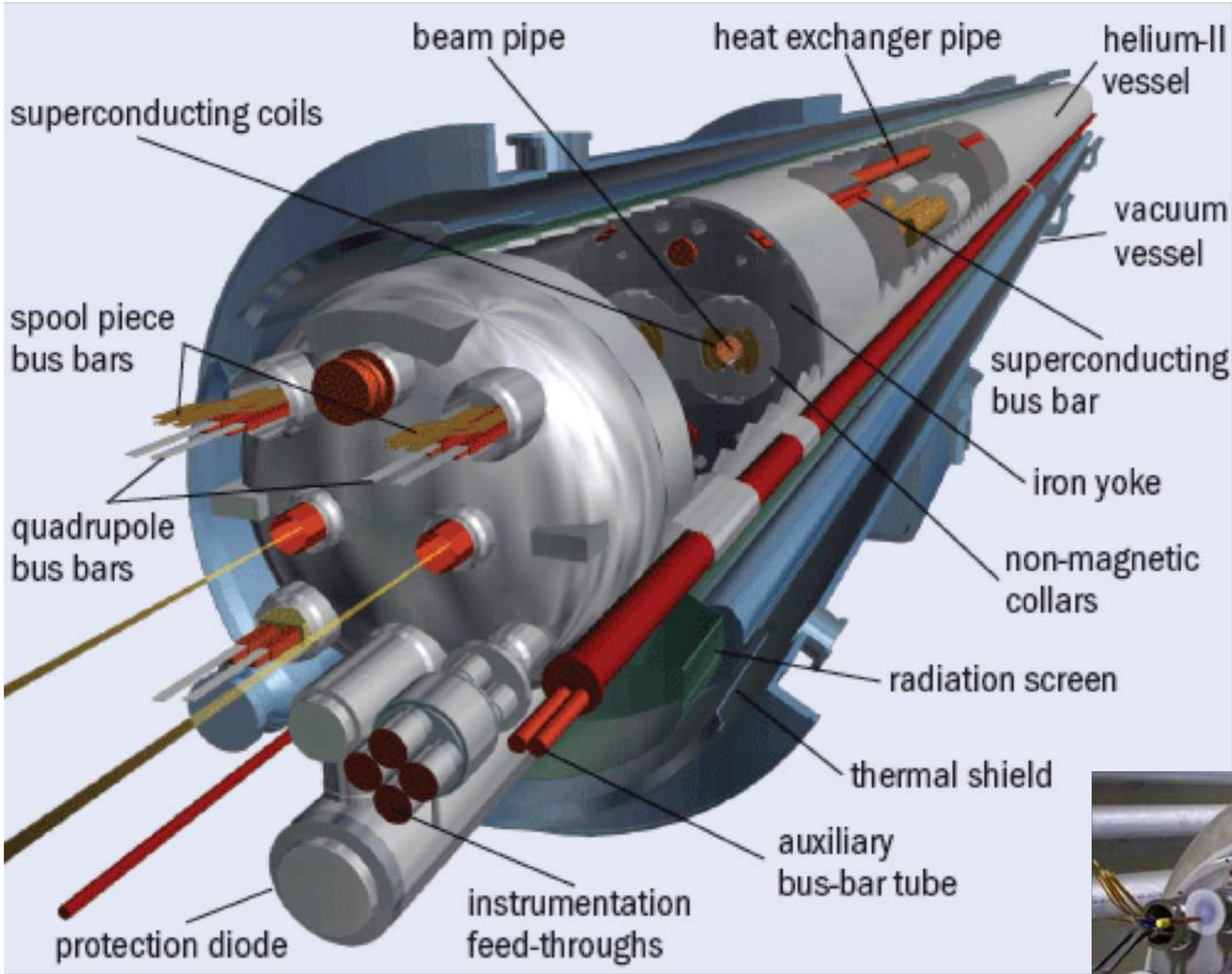
Dissipated power: $P = R \cdot I^2$

Superconducting magnets

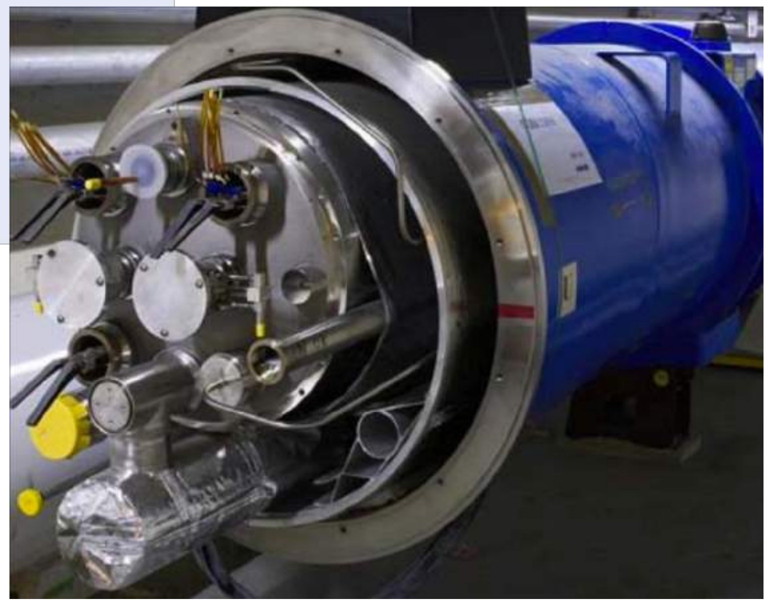


LHC cryo-dipoles

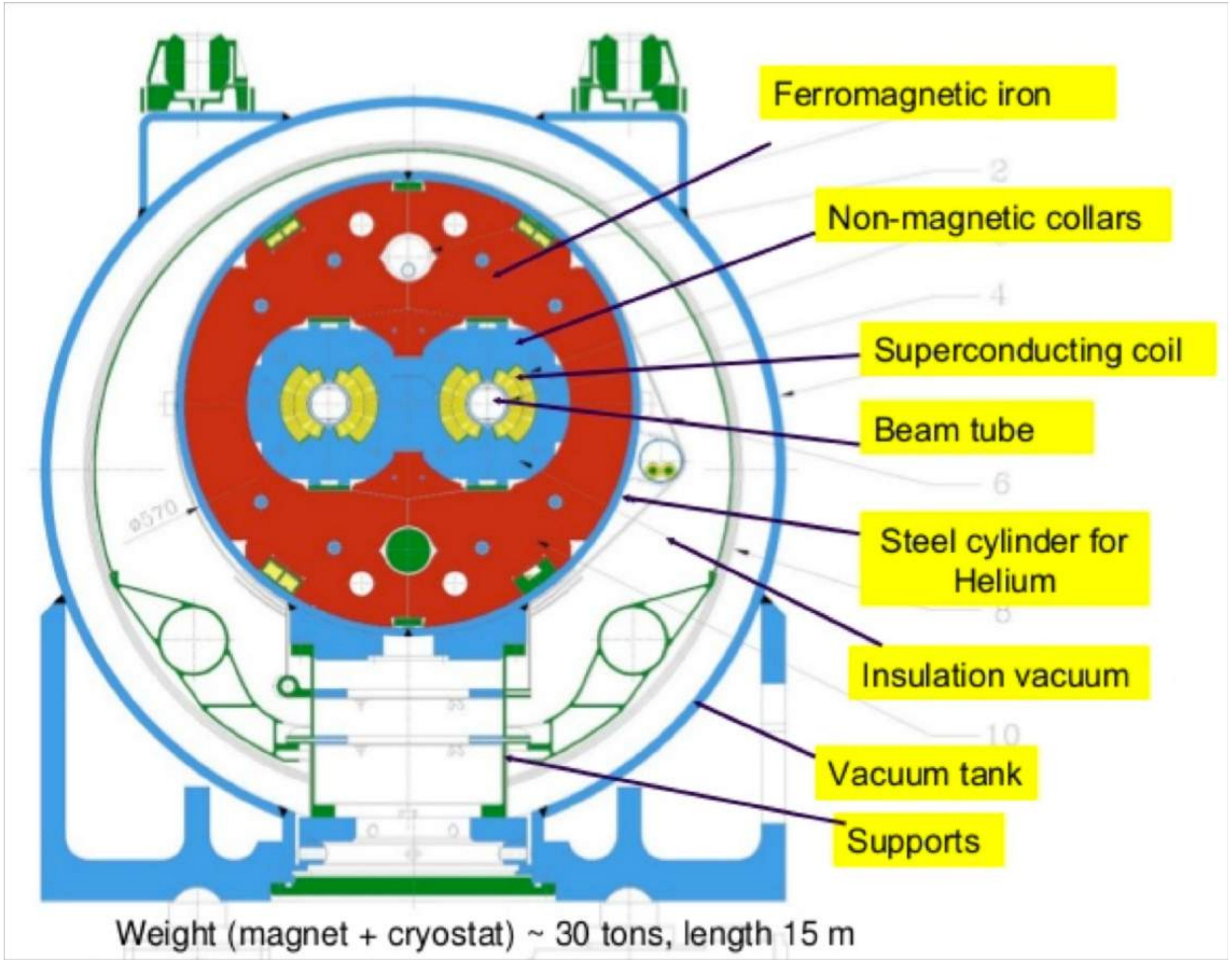
15 m long



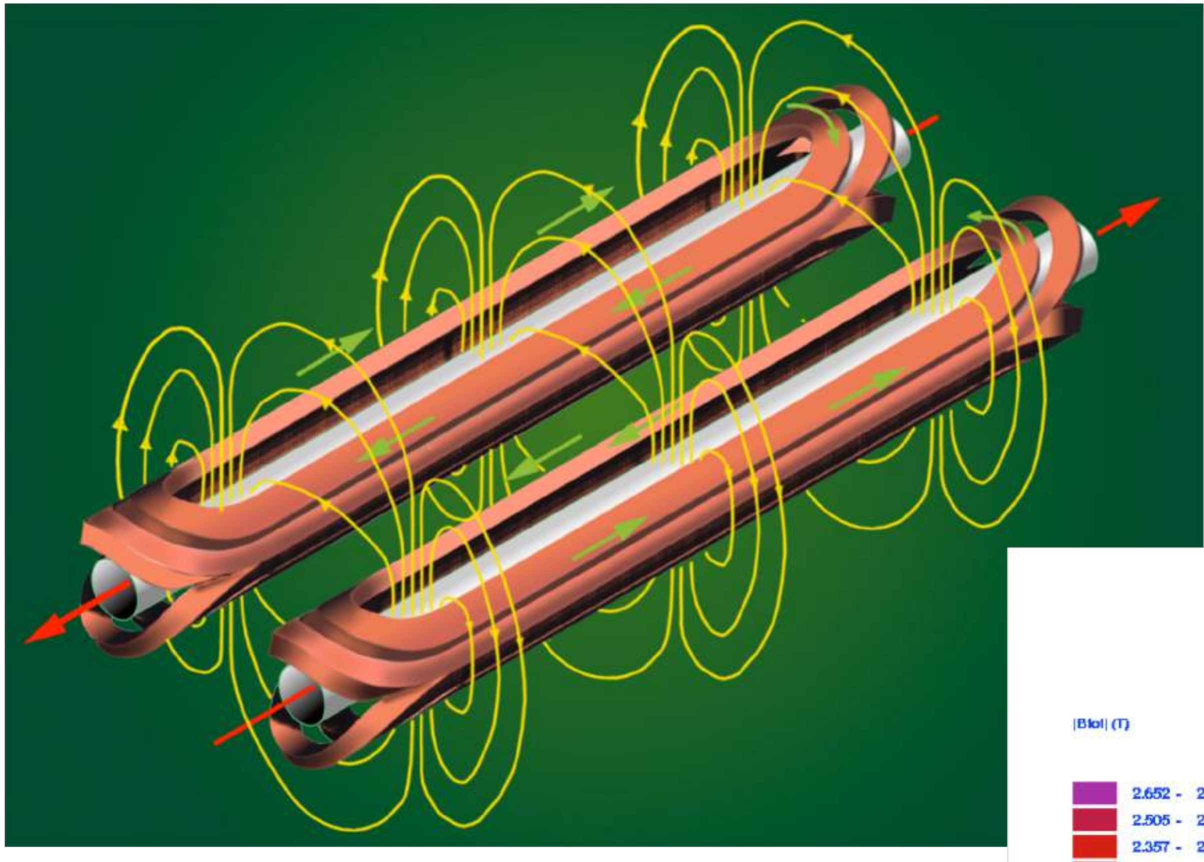
End of quadrupole magnet



LHC dipole magnets



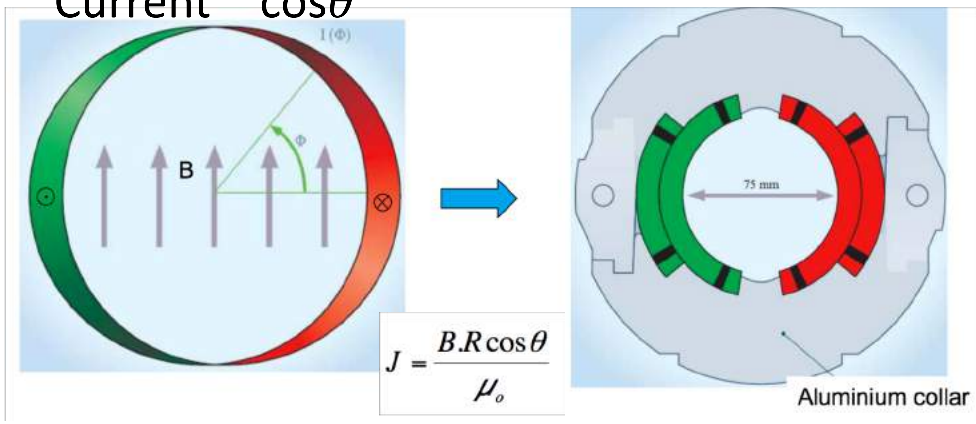
LHC “cosθ” dipole magnets

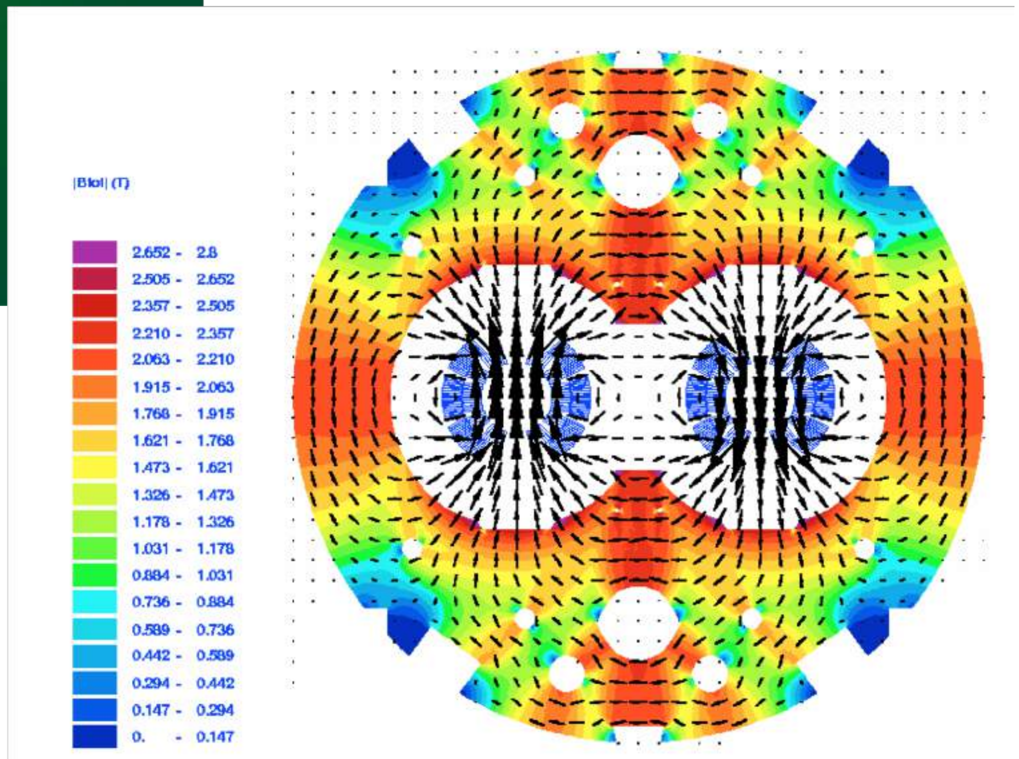


11800 A @ 8.3 T

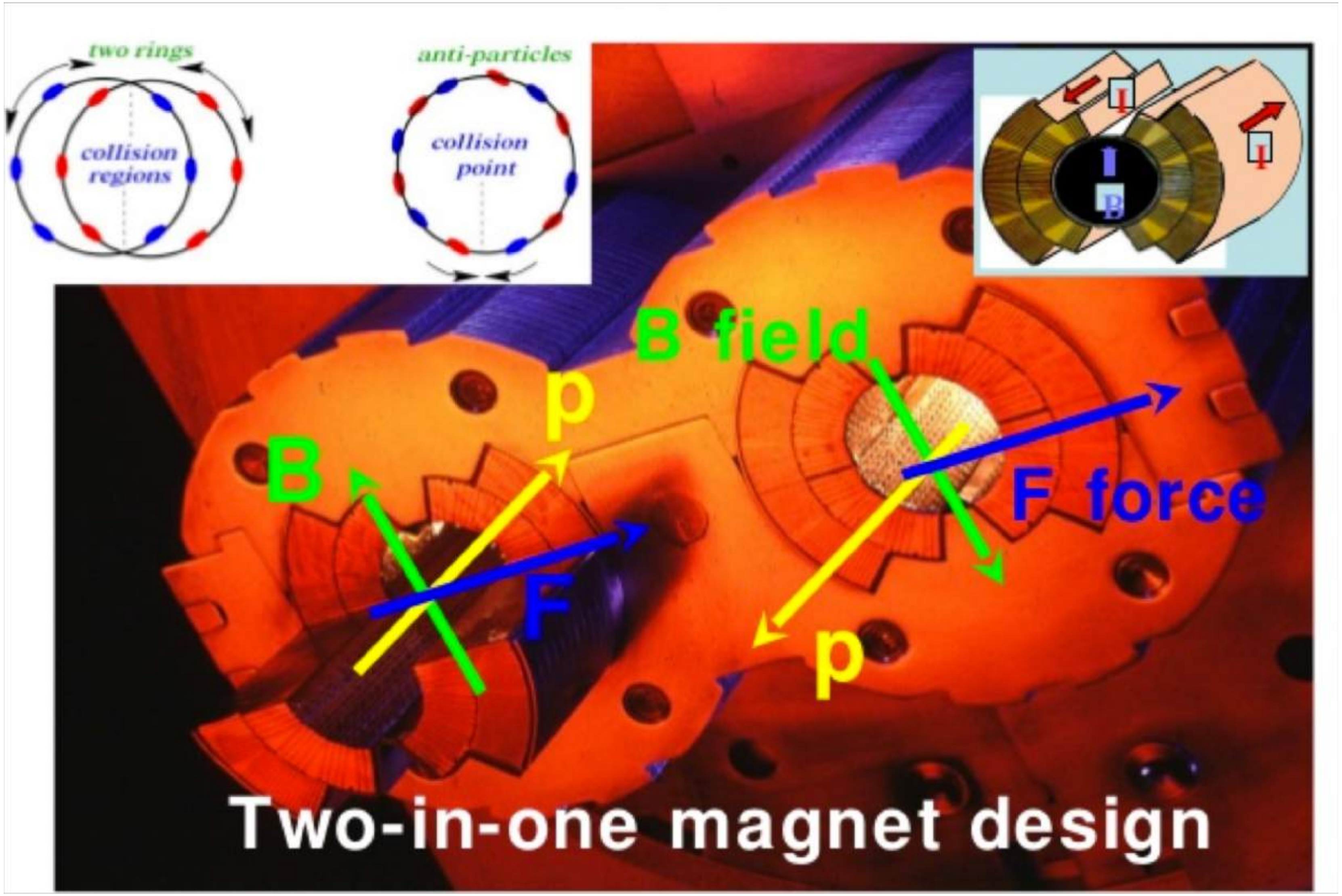
The position of the coils must be very precise to have high quality magnetic field

Current ~ cosθ

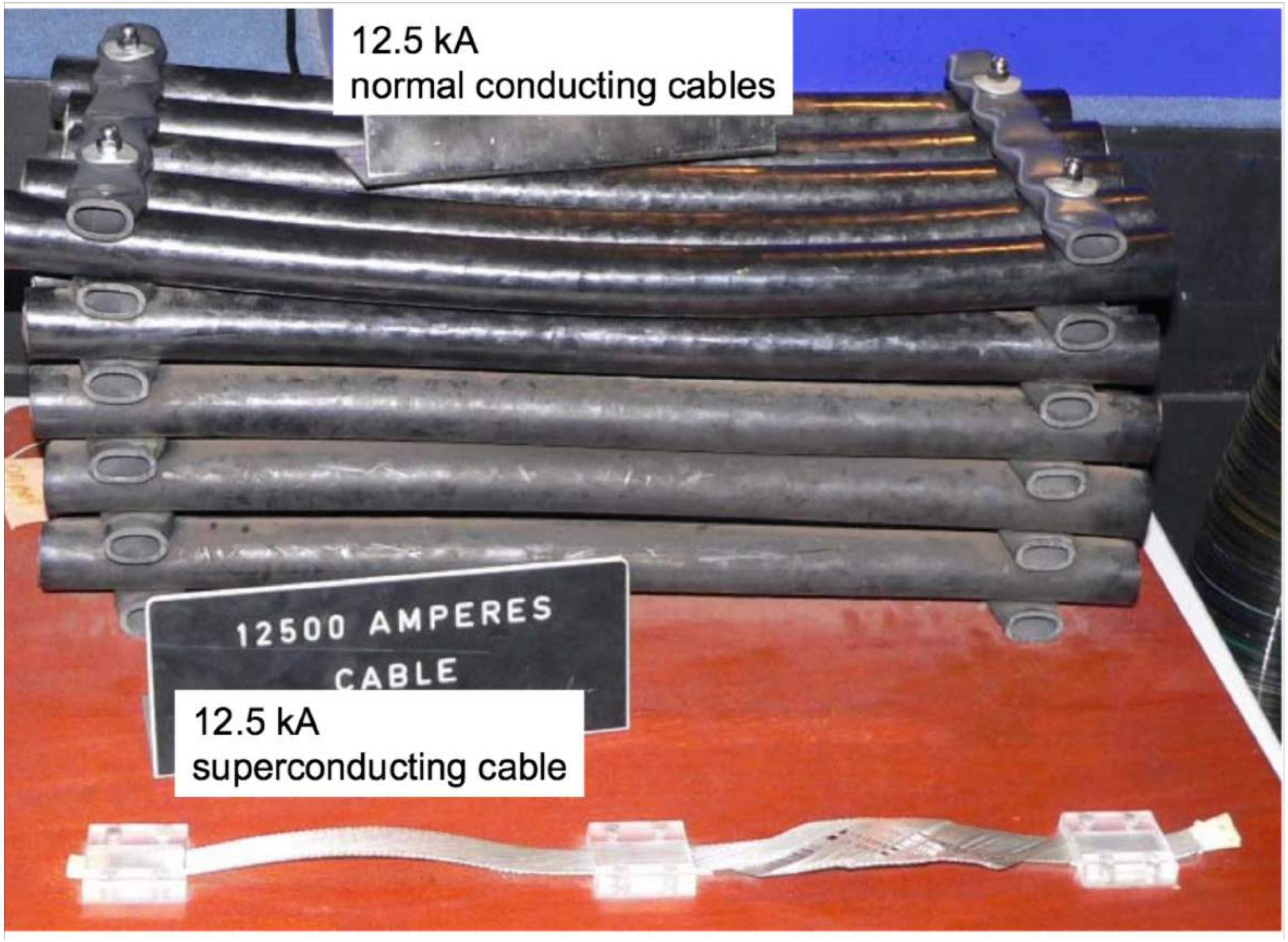




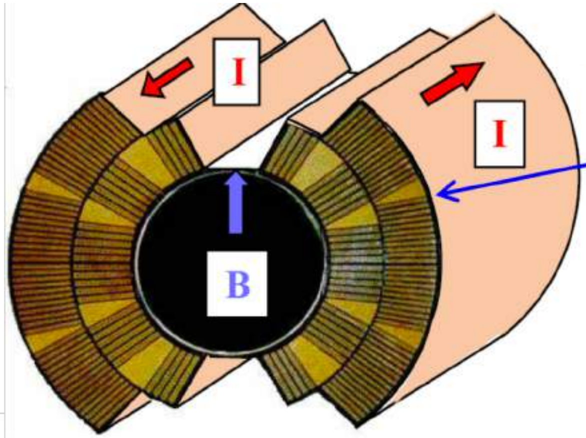
LHC dipole magnets

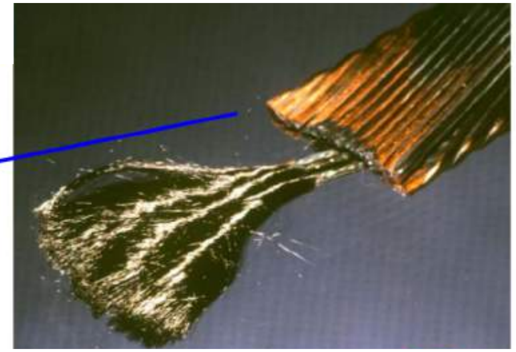


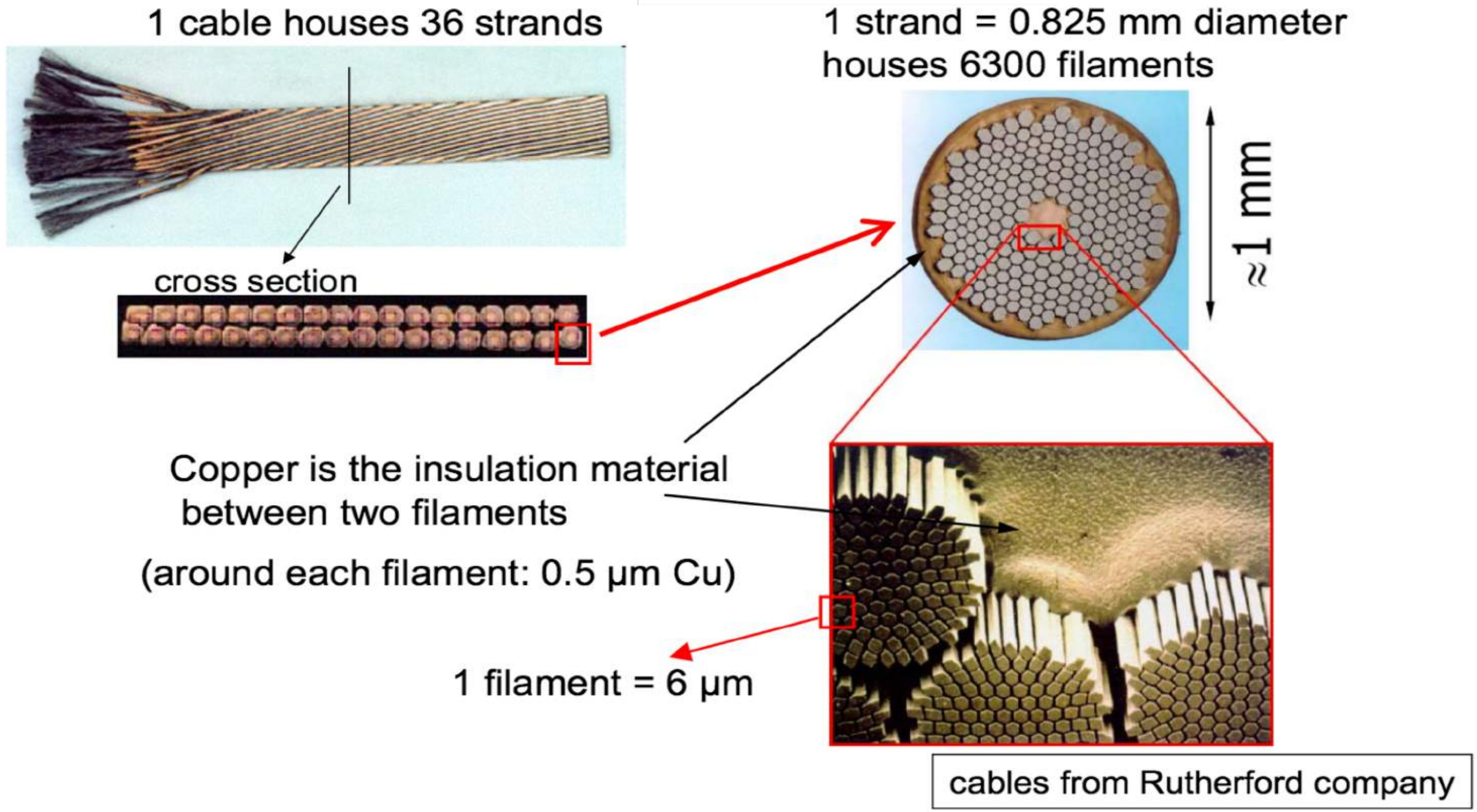
Superconducting cabels



Superconducting cabels







LHC History

1982 : First studies for the LHC project

1983 : Z0/W discovered at SPS proton antiproton collider (Spp

1989 : Start of LEP operation (Z/W boson-factory)

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

2000 : Last year of LEP operation above 100 GeV

2002 : LEP equipment removed

2003 : Start of LHC installation

2005 : Start of LHC hardware commissioning

2008 : Start of (short) beam commissioning

Powering incident on 19th Sept.

2009 : Repair, re-commissioning and beam commissioning

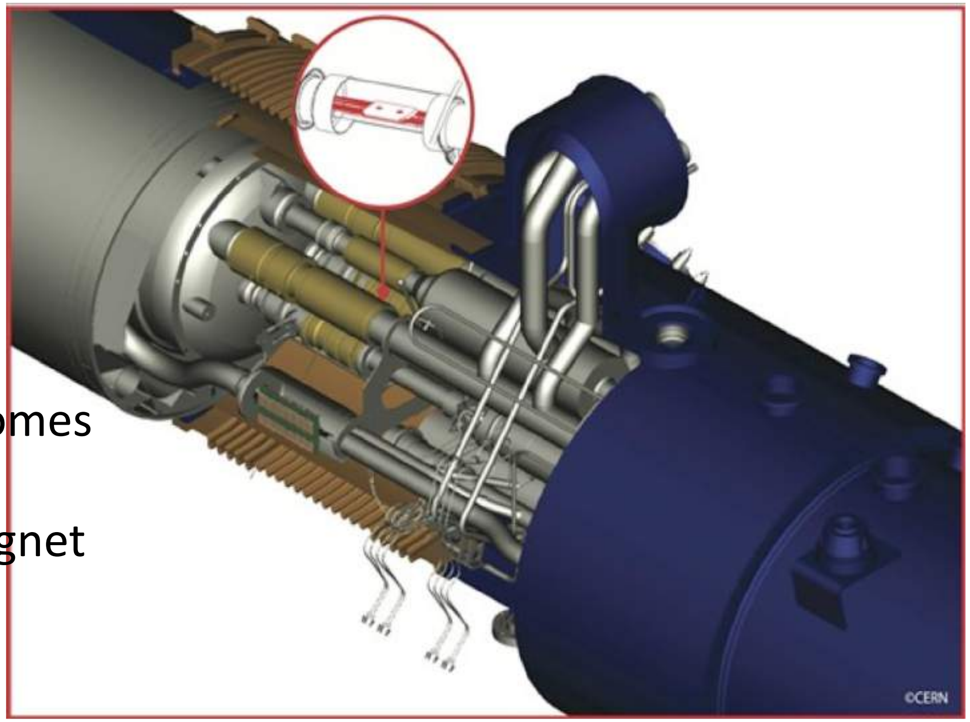
2010 : Start of a 2 year run at 3.5 TeV/beam

12 év

16 év

LHC accident

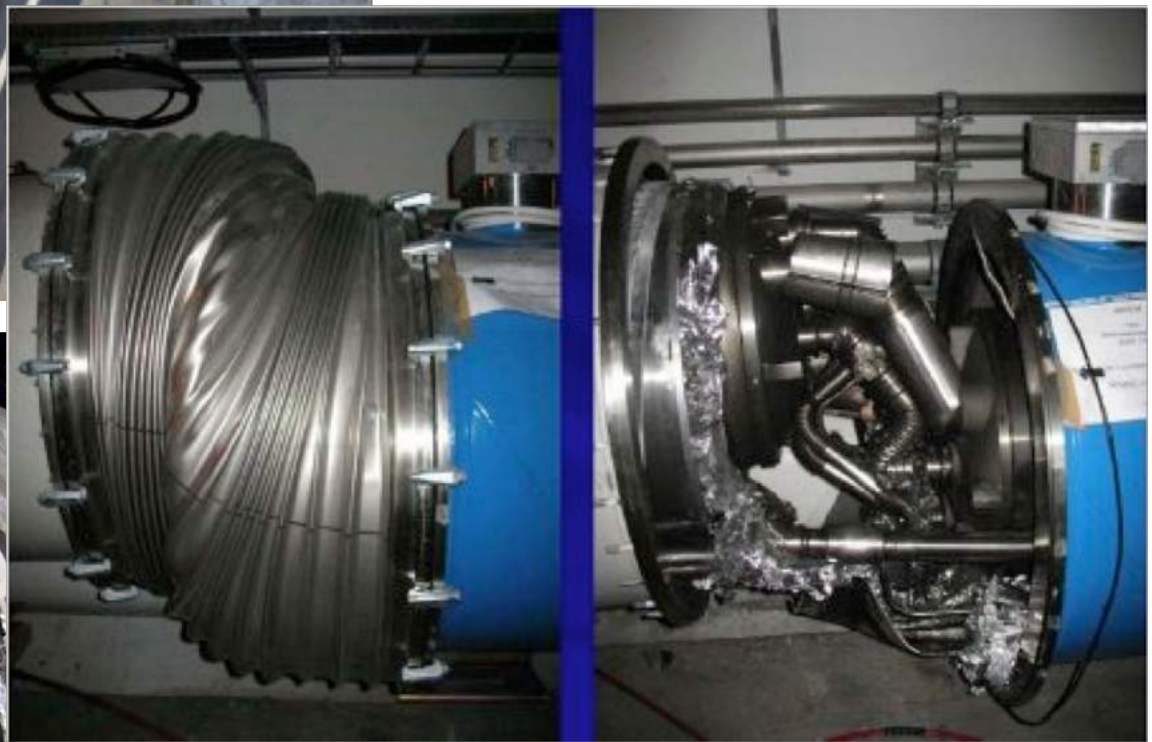
- When raising the dipole current with the nominal 10 A/s, due to a faulty electrical connection between a dipole and a quadrupole accelerator magnet, a resistive area developed in less than 1 s: 1V voltage appeared at 9 kA current
- The built-in protection systems (including the quench protection system) have been activated: the power supply has been switched off and to rapidly discharge / drain the energy resistors have been added to the system
- An electric spark was generated and punctured by a He tank, so He flowed to the insulating vacuum of the cryostat within 1 second
- Within a few seconds, the vacuum of the beam deteriorated as well as the insulating vacuum between the adjacent sectors
- When the pressure exceeded the atmospheric pressure, the spring protection windows opened and He reached the tunnel
- Even with these protections, the pressure exceeded the nominal 0.15 MPa in the vacuum vessel of the central sector, causing large forces between the the sector boundaries, causing mechanical injuries ("explosion")

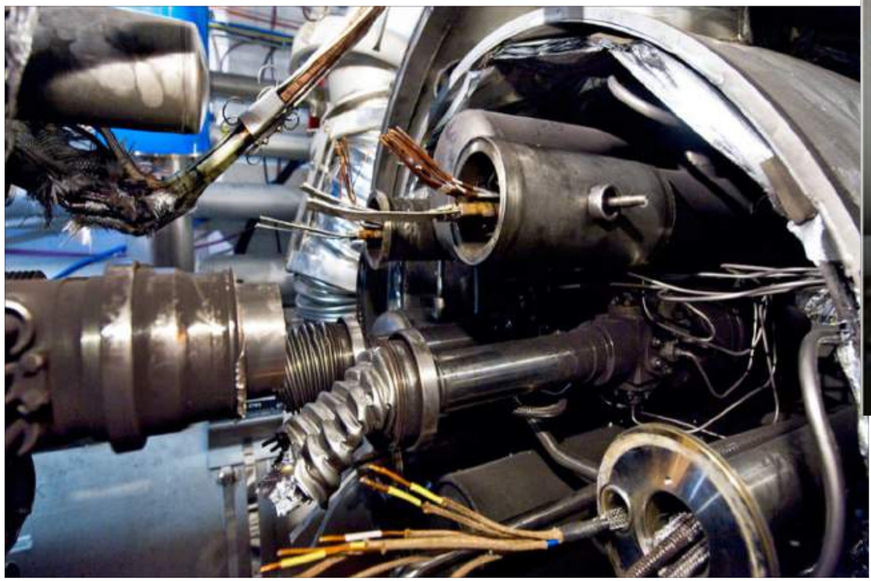


Magnet "quench": abnormal termination of the magnet operation, when some of the magnet becomes a normal conductor (loss of superconductivity)

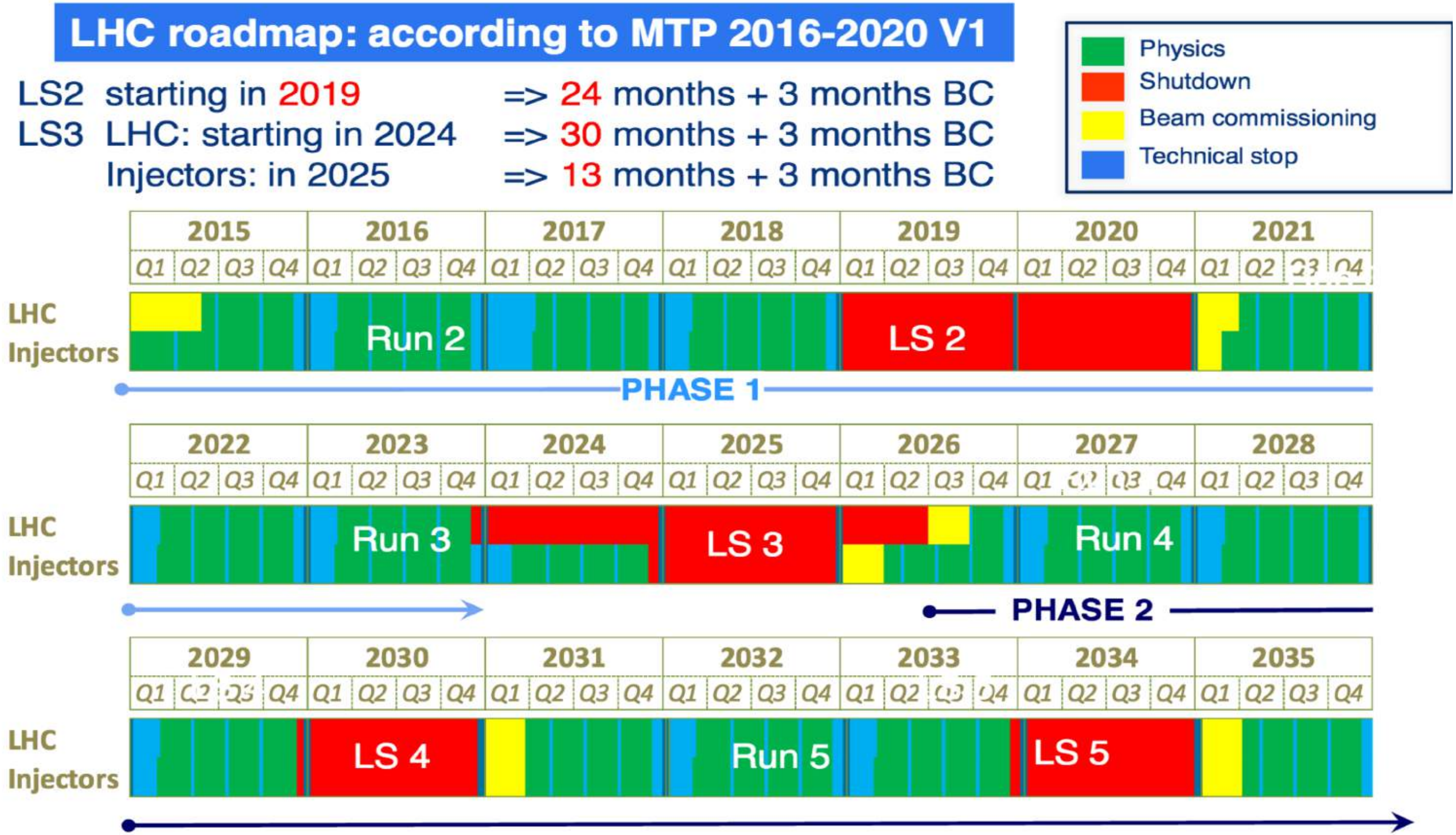
Magnet "training": the gradual increase of the magnet currents in operation to get the magnet “trained” (crystal errors otherwise could cause catastrophic quenches)

LHC accident





LHC plans



Project lifetime from start: > 50 years, data collection: > 25 years, continuous development, many upgrades of accelerator and detectors

Electron and hadron colliders

HERA (Hadron Electron Ring Accelerator) tunnel:

proton accelerator

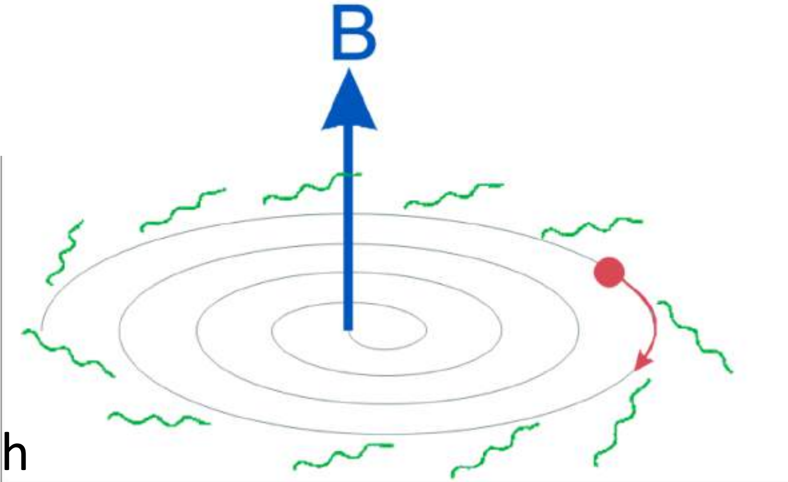
920 GeV

electron accelerator

27.5 GeV

Why are the beam energies so different?

Synchrotron radiation



- When charged particles are accelerated,
  they emit radiation perpendicular to their path
- Energy loss per round:

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

↑ pályasugár

- HERA electron beam: proton beam:

HERA electron beam	proton beam
$r = 580\ \mathrm{m}$	$r = 580\ \mathrm{m}$
$E = 27.5\ \mathrm{GeV}$	$E = 920\ \mathrm{GeV}$
$\Delta E \cong 80\ \mathrm{MeV}\ (0.3\%)$	$\Delta E \cong 10\ \mathrm{eV}\ (10^{-9}\%)$

- The electron beam needed 80 MV acceleration per round
- The maximum energy of a proton beam is given by the max strength of the solenoidal magnetic field: p = qBr
  → B = 5.5 T

Large Electron Positron collider

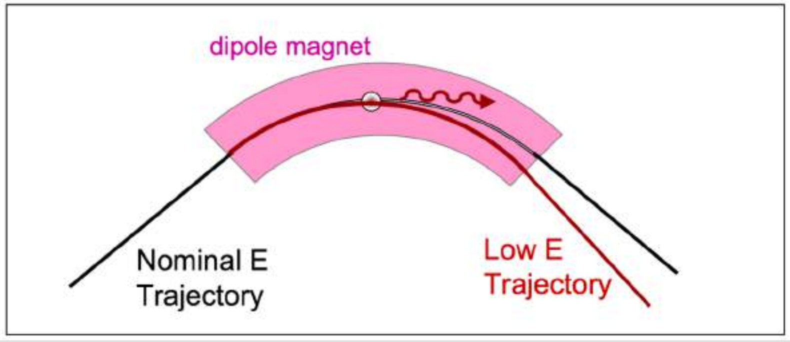
- From HERA elektron beam to LEP:

$$r = 580\ \text{m} \xrightarrow{\text{x5}} r = 2800\ \text{m}$$

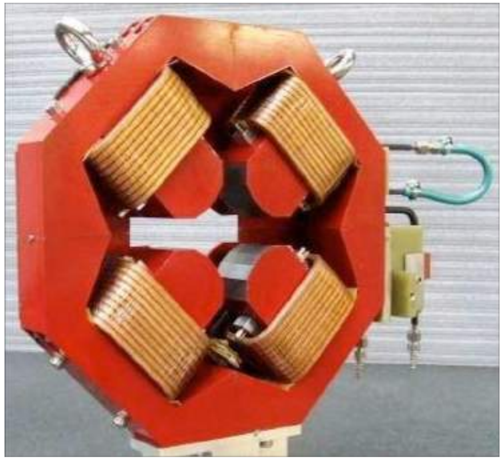
$$E = 27.5\ \text{GeV} \qquad E = 105\ \text{GeV}$$

$$\Delta E \cong 80\ \text{MeV}\ (0.3\%) \qquad \Delta E \cong 3\ \text{GeV}\ (3\%)$$

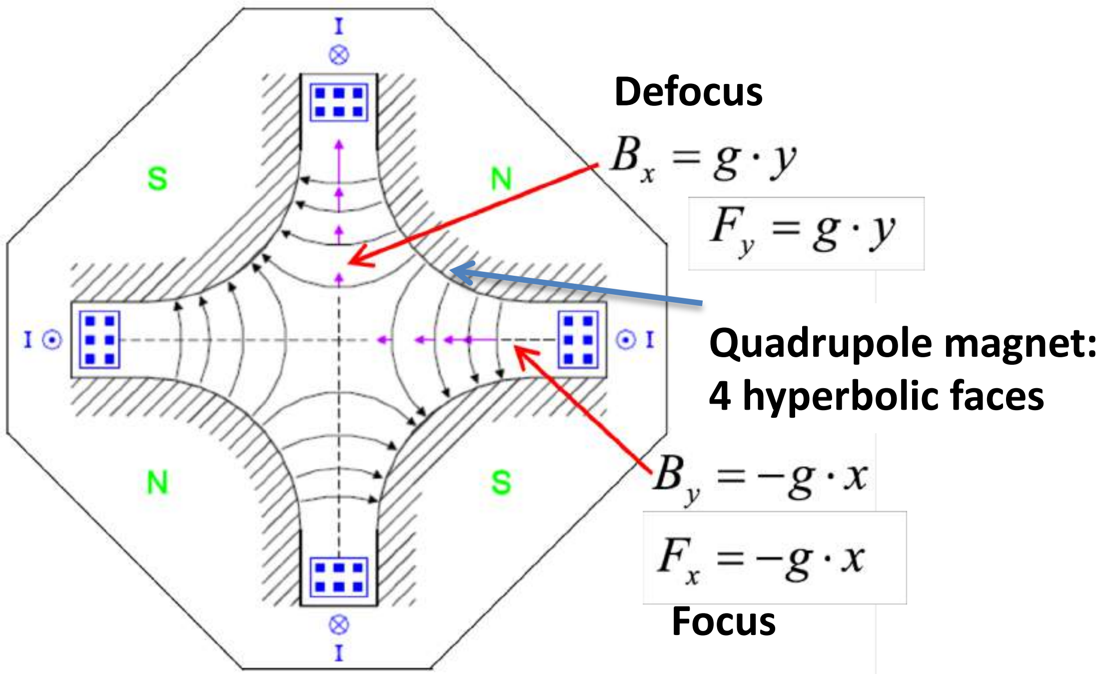
- LEP beams needed 3 GeV acceleration per cycle!
- Cost of electricity for LEP was several MCHF / year, the biggest item in the operating cost
- LEP = Last (circular) Electron Positron collider?

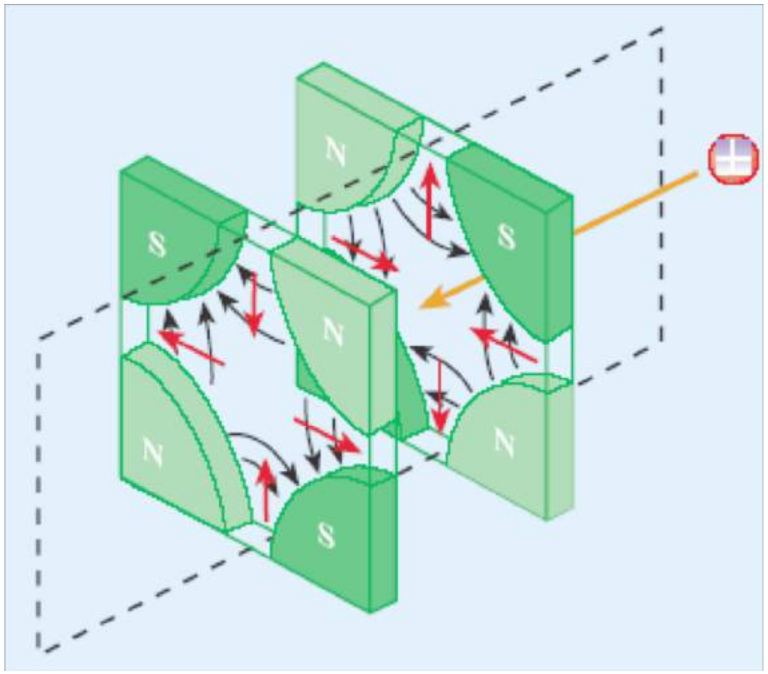


Beam focusing

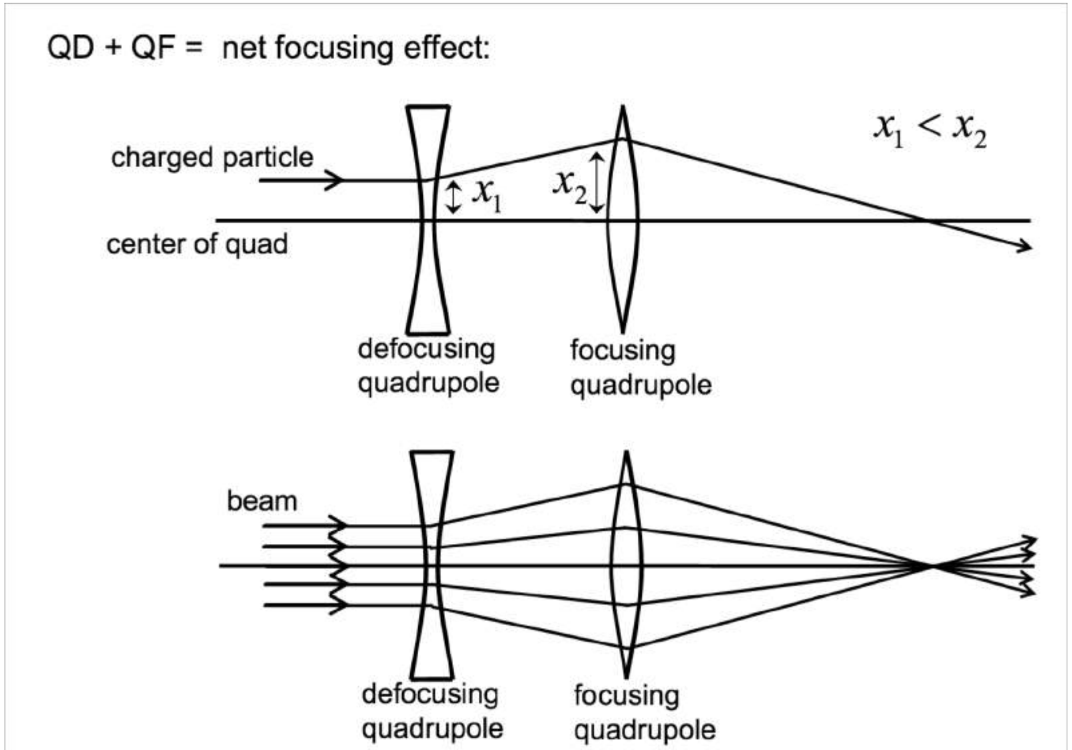


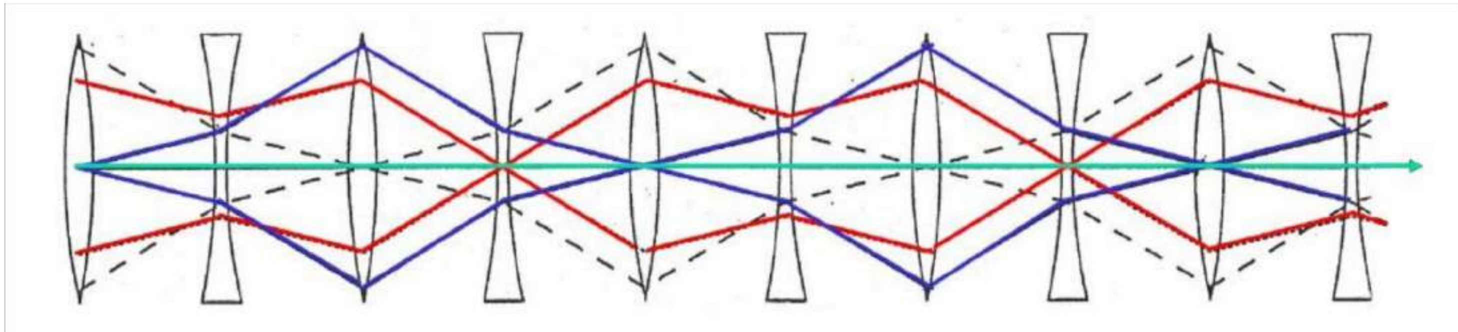
- Accelerating particles radiate energy in discreet quanta
- Statistical process, energy distribution according to the laws of statistics
- Radiation increases beam emittance (beam size)
- Need to focus the beam!





Beam focusing





Homework #2

- Estimate the energy stored in the LHC beams using the accelerator parameters given in http://pdg.lbl.gov/2018/reviews/rpp2018-rev-hep-collider-params.pdf
  - How heavy should be a high-speed train that travels with 200 km/h to have the same energy?
  - How much water could be boiled at room temperature with the same energy?
- Discuss what could happen to a hamster that stands (without movement) in front of the beamline of the LHC for 10 seconds. ☺
- One of the main challenges for linear colliders is to reach sufficient accelerating gradient, $g \equiv \Delta E/L$ (energy increase per meter). There are currently two on-going design efforts for such a linear collider: ILC and CLIC. ILC has a target gradient of g_{ILC}= 31.5 MeV/m while CLIC has g_{CLIC} = 100 MeV/m. Assume that the cavity fill factor is 70% and that the final focusing and beam collimation requires a 3 km long section before the collision point. Calculate the required machine length for ILC and CLIC to reach 1 TeV collision energy.
- Estimate how much power would be needed to operate the accelerating cavities at ILC and CLIC if they are built using traditional or superconducting cavities.