II. Experimental methods

- Before 1950s, cosmic rays were the source of high energy particles, and cloud chambers and photoemulsions were the means to detect them.
- The quest for heavier particles and more precise measurements lead to the increasing importance of *accelerators* to produce particles and more complicated *detectors* to observe them.

Figure 18: Large Hadron Collider at CERN

Accelerators

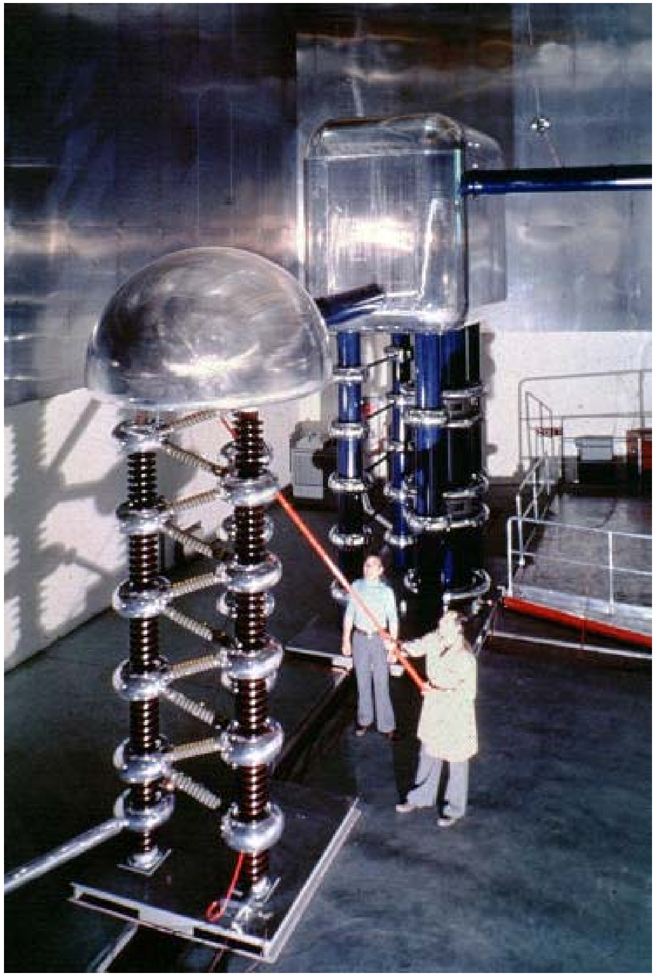


Figure 19: The Cockroft-Walton "generator" at CERN: accelerates particles by an electrostatic field

❖ Basic idea of all accelerators: apply voltage to accelerate particles

Main varieties of accelerators are:

– Linear accelerators (*"linacs"*)

– Cyclic accelerators (*"cyclotrons"*, *"synchrotrons"*)

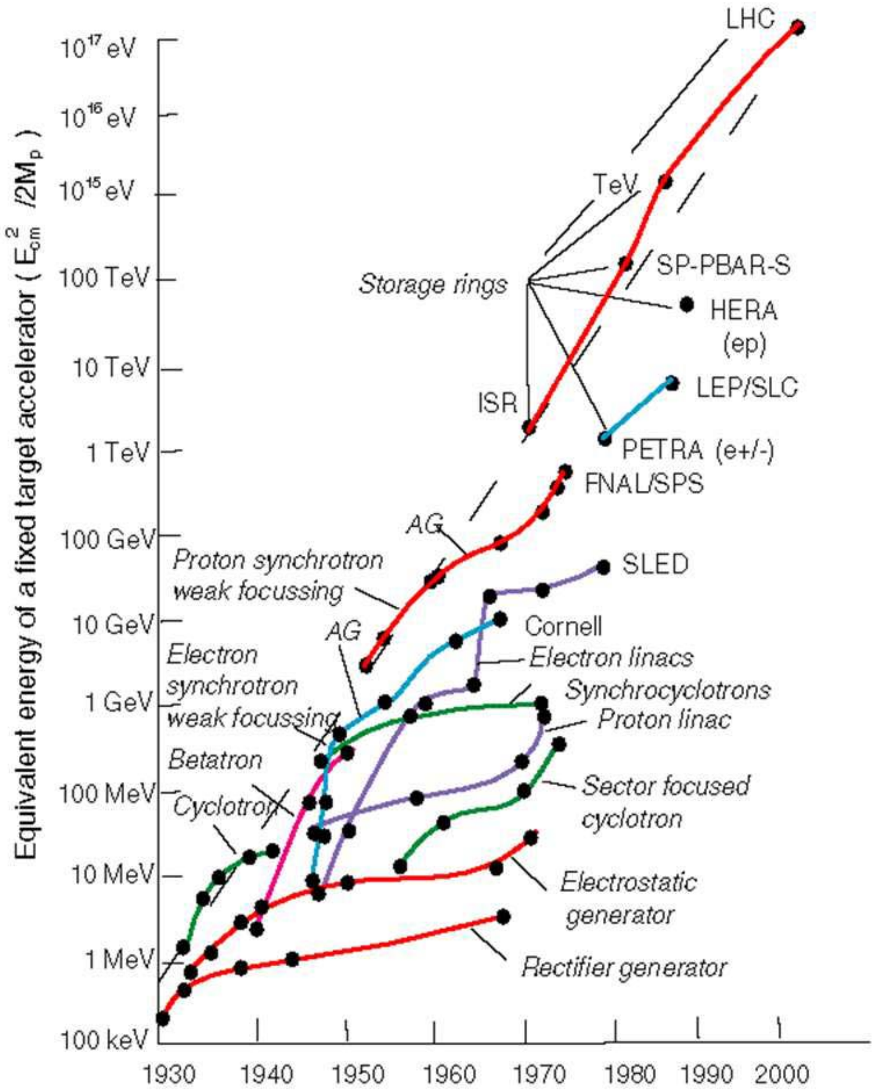


Figure 20: The history of accelerators (by E.Wilson); colors indicate different accelerator types

Why do we need accelerators

- Optic microscopes use photons to resolve "microscopic" structures; electron microscopes "see" yet smaller structures; accelerators can do even better
  - recall deBroglie's relation: $\lambda = h/p \Rightarrow$ better resolution requires a "probe" of higher momentum
  - accelerators produce particle beams of very high energy $\Rightarrow$ allow us to study structure of other particles, e.g. protons or neutrons
- We are made of quite light particles, but elsewhere it the Universe heavier particles are being produced
  - recall Einstein's $E=mc^2 \Rightarrow$ if we want to create ourselves heavy particles, we have to reach very high energies
  - accelerators allow us to create and study special particles that are not normally available on Earth

Linear accelerators

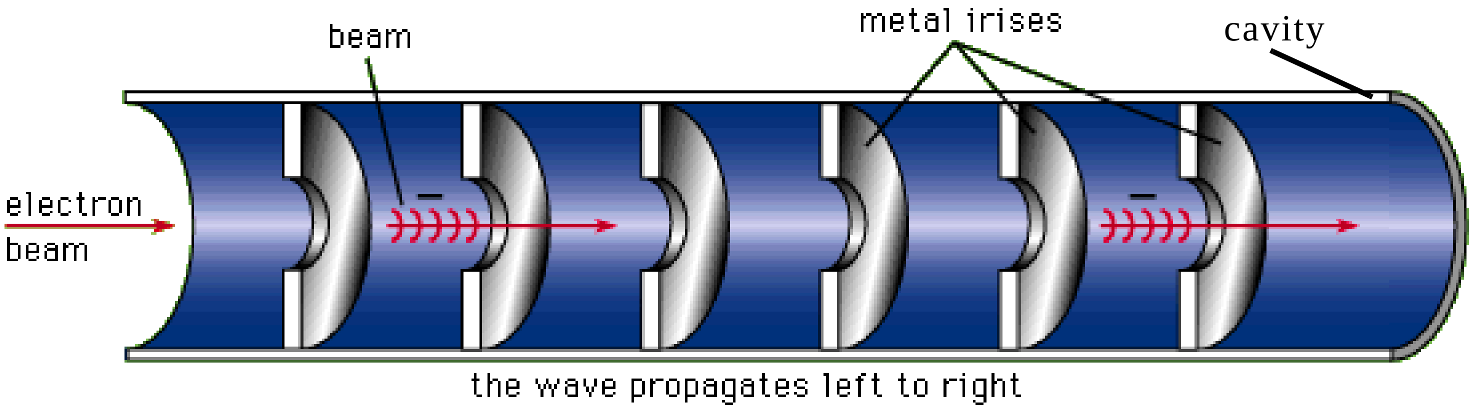


Figure 21: A traveling-wave linear accelerator schematics

- Linacs are used mostly to accelerate electrons
  - Electrons are accelerated along a sequence of cylindrical vacuum cavities
  - Inside cavities, an electromagnetic field is created with a frequency near 3,000 MHz (radio-frequency), the electric field along the beam axis ($\bar{F}=q\bar{E}$)
  - Electrons arrive into each cavity at the same phase as the electric wave

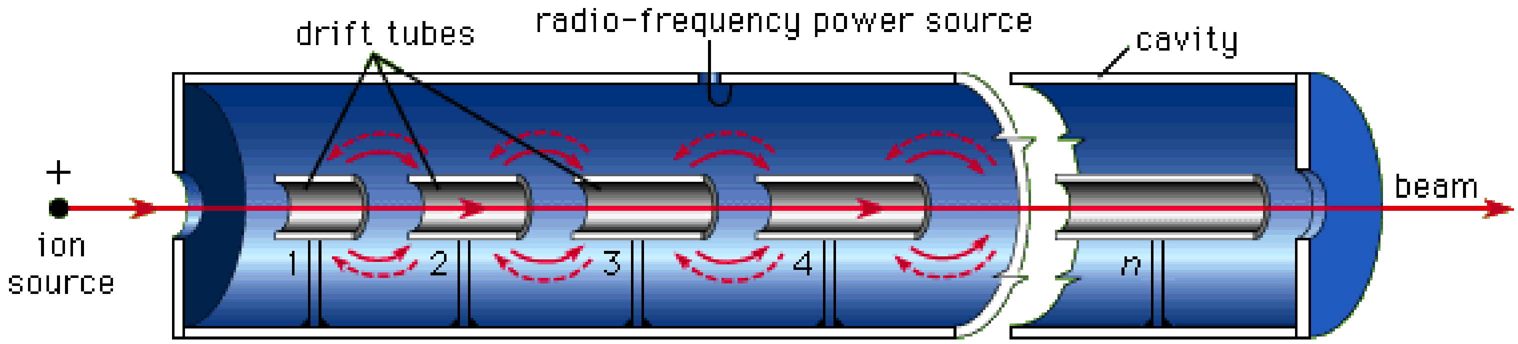


Figure 22: Standing-wave linac

- Standing-wave linacs are used to accelerate heavier particles, like protons
  - Typical frequency of the field is about 200 MHz
  - Drift tubes screen particles from the electromagnetic field for the periods when the field has decelerating effect
  - Lengths of drift tubes are proportional to particles' speed

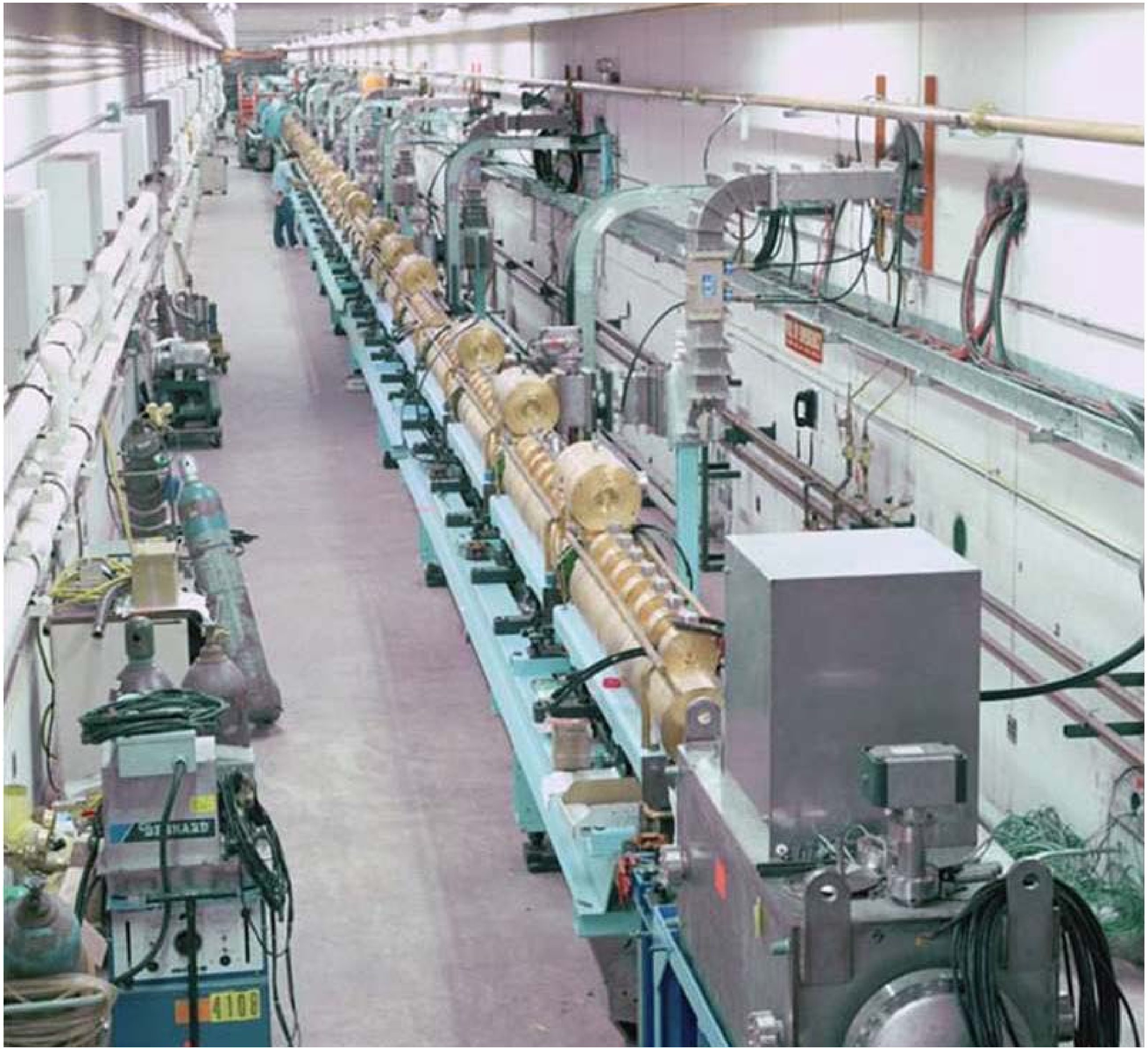
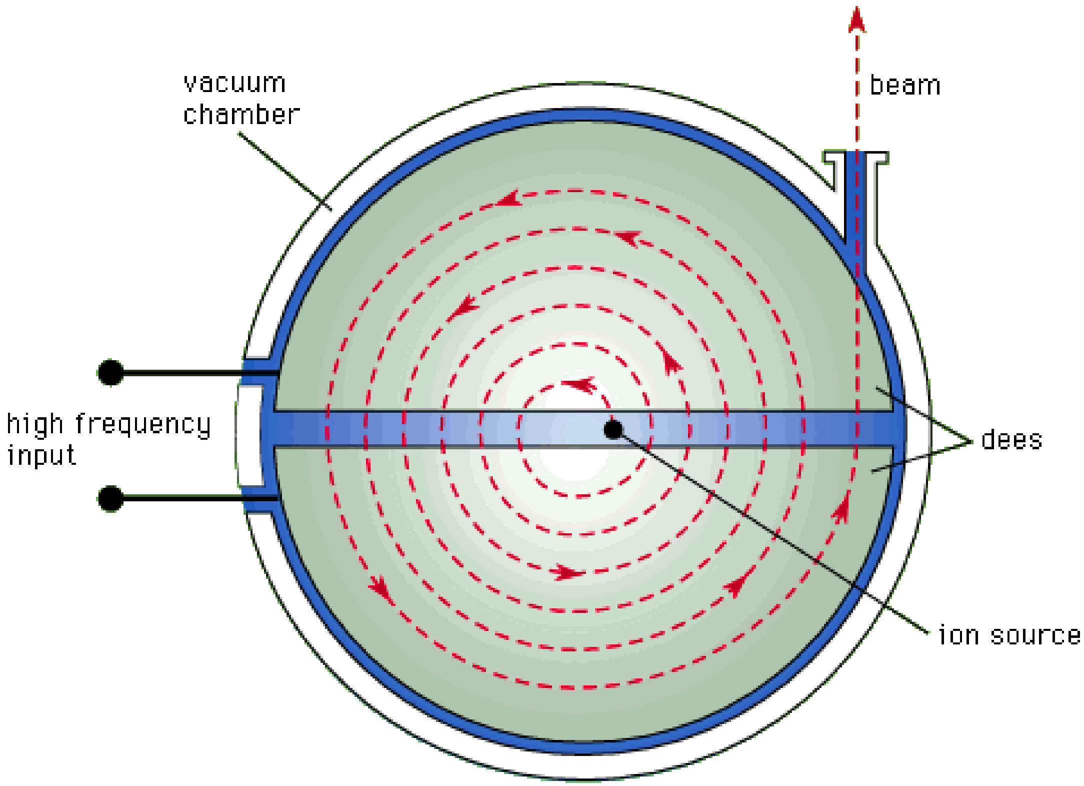


Figure 23: LINAC a Fermilab (400 MeV) - side-coupled (left) and drift-tube (right)

Cyclic accelerators.



- $\overline{F}=q(\overline{E}+\overline{v}\times\overline{B})$
- Particle is accelerated by the high frequency field $\overline{E}$ between the dees ($\overline{F}=q\overline{E}$)

Figure 24: Cyclotron, the first resonance accelerator. Maximum energy for protons: 25 MeV.

– The vacuum chamber is placed inside a magnetic field $\overline{B}$, perpendicular to the rotation plane

– Dees ("D") are empty "boxes" working as electrodes; inside the dees $\overline{E}=0$ ($\overline{F}=q\,\overline{v}\times\overline{B}$)

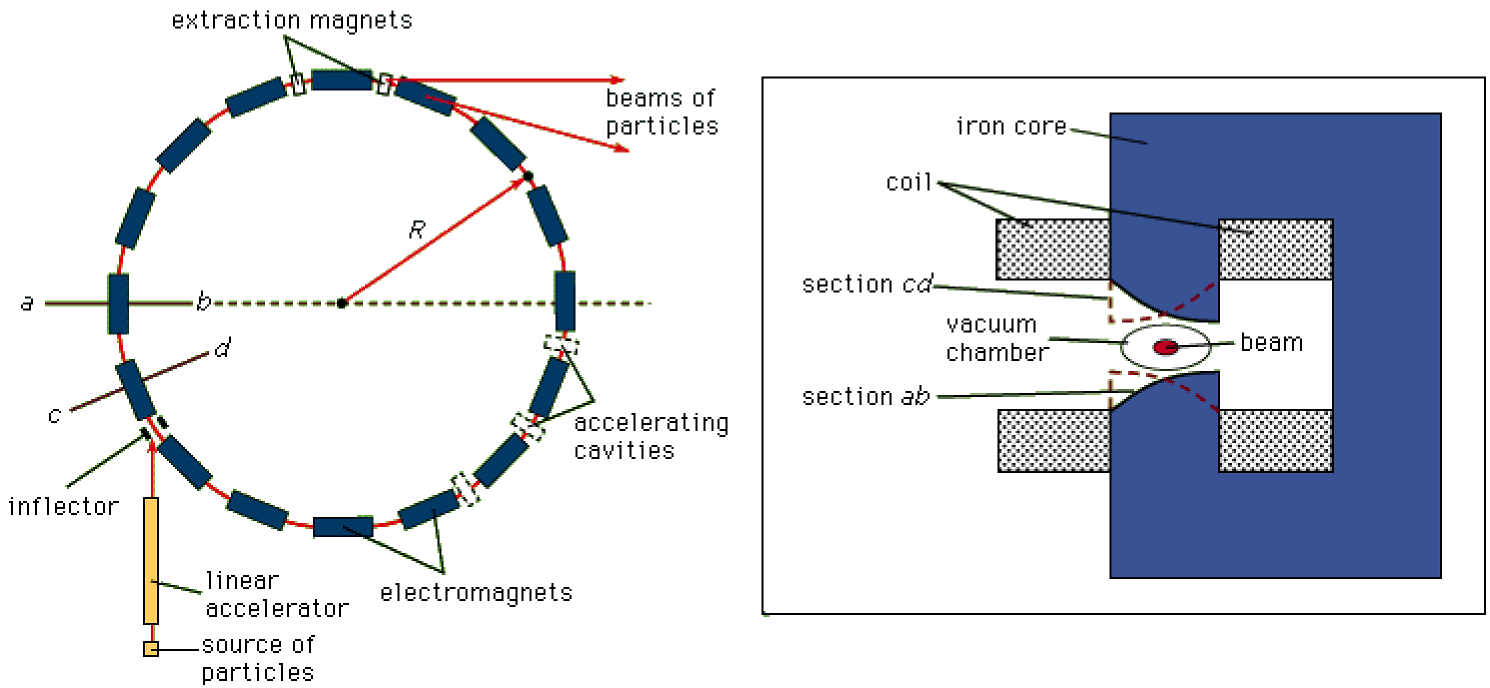


Figure 25: Schematic layout of a synchrotron

❖ Synchrotrons are the most widely used circular accelerators

– Particle beam is constrained in a circular path by bending dipole magnets ($\bar{F}=q\,\bar{v}\times\bar{B}$)

– Accelerating cavities are placed along the ring ($\bar{F}=q\bar{E}$)

Figure 26: Large Hadron Collider at CERN accelerates protons

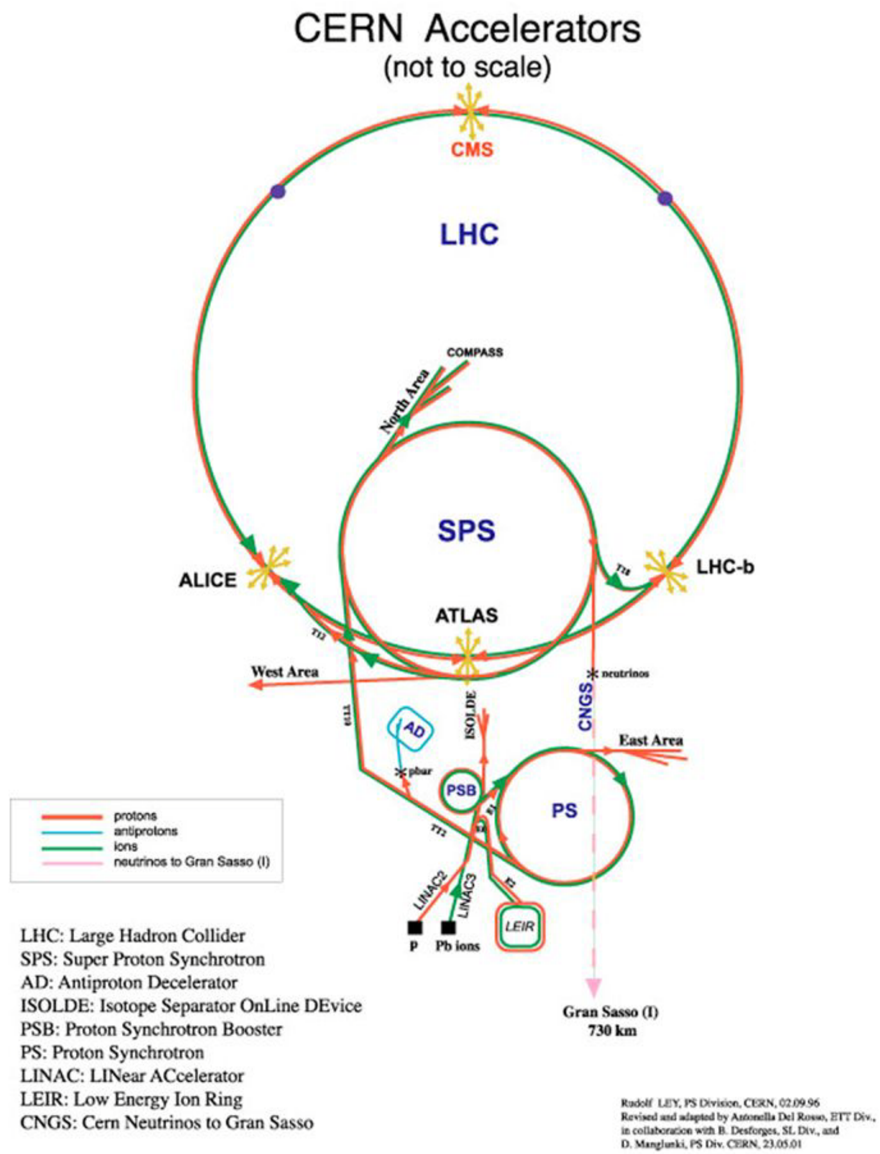


Figure 27: Scheme of the accelerator complex at CERN

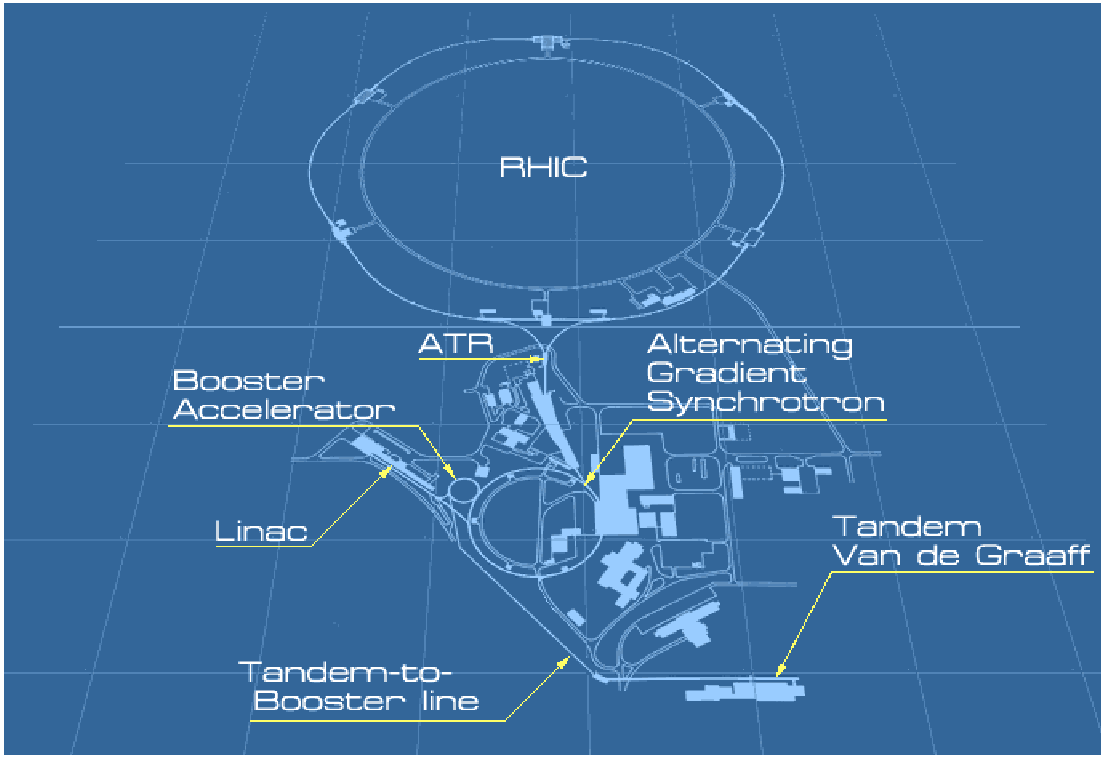


Figure 28: Scheme of the Relativistic Heavy Ion Collider (RHIC) accelerator complex at Brookhaven National Laboratory (left) and its RF cavity system (right). RHIC accelerates ions, from protons to gold

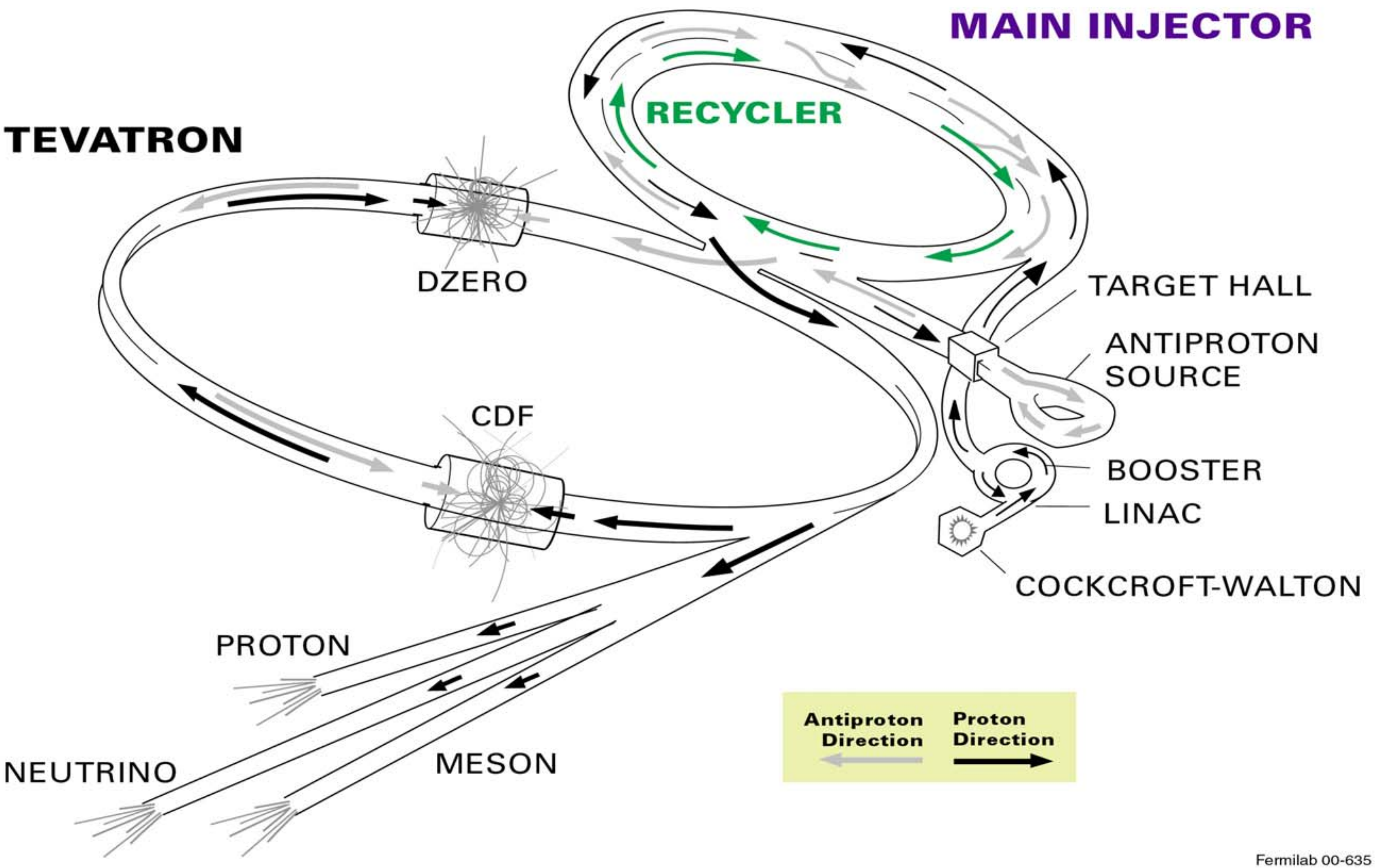


Figure 29: Tevatron accelerator chain at Fermilab.
Tevatron accelerates protons and antiprotons (key technology: stochastic cooling)

- Charged particles which travel in a circular orbit with relativistic speeds emit *synchrotron radiation*

Amount of energy radiated per turn is:

$$\Delta E = \frac{q^2\beta^3\gamma^4}{3\varepsilon_0\rho} \qquad (27)$$

Here q is electric charge of a particle, velocity $\beta \equiv v/c$, Lorentz factor $\gamma \equiv (1-\beta^2)^{-1/2}$, and ρ is the radius of the orbit.

- For relativistic particles $\gamma = E/mc^2 \Rightarrow$ energy loss increases as E^4/m^4, becoming very significant for high-energy light particles (electrons)
- Radio-frequency power is limited $\Rightarrow$ electron synchrotrons would become extremely large (large ρ) to compensate for the synchrotron radiation.

From the standard expression for the centrifugal force, momentum of the particle with the unit charge ($q=1$) in a synchrotron is

$$p = 0.3B\rho \qquad ([B]=Tesla, [\rho]=meters, [p]=GeV/c)$$

If the requirement is that ρ must be constant, the magnetic field B has to increase in order to achieve higher momentum.

- Maximal momentum is therefore limited by both the maximal available magnetic field and the size of the ring
  - For LHC, bend radius is ~2.8 km, and magnetic field of ~8.3 T is needed to achieve the planned beam energy of 7 TeV
- To keep particles well contained inside the beam pipe and to achieve the stable orbit, particles are accelerated in *bunches*, synchronized with the radio-frequency field

Analogously to linacs, all particles in a bunch have to move in phase with the radio-frequency field.

Requirement of precise synchronisation, however, is not very tight: particles behind the radio-frequency phase will receive lower momentum increase, and other way around.

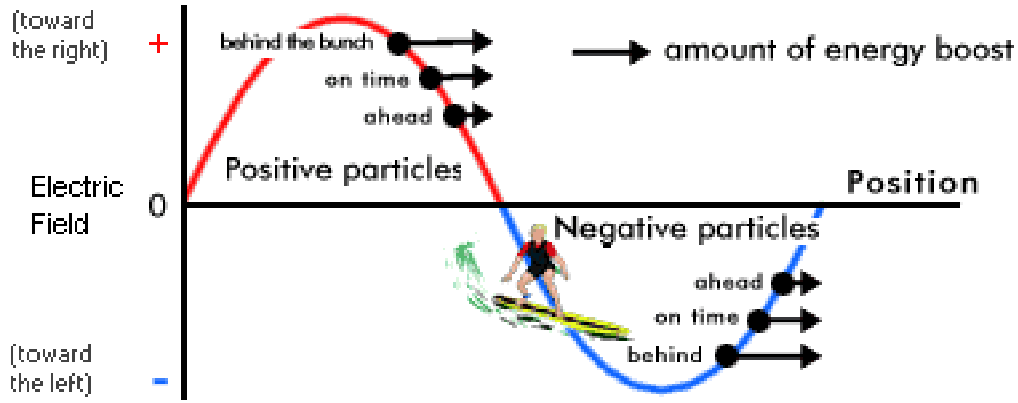


Figure 30: Effect of the electric field onto particles in accelerator cavities (*phase stability*)

- Therefore all particles in a bunch stay basically on the same orbit, slightly oscillating

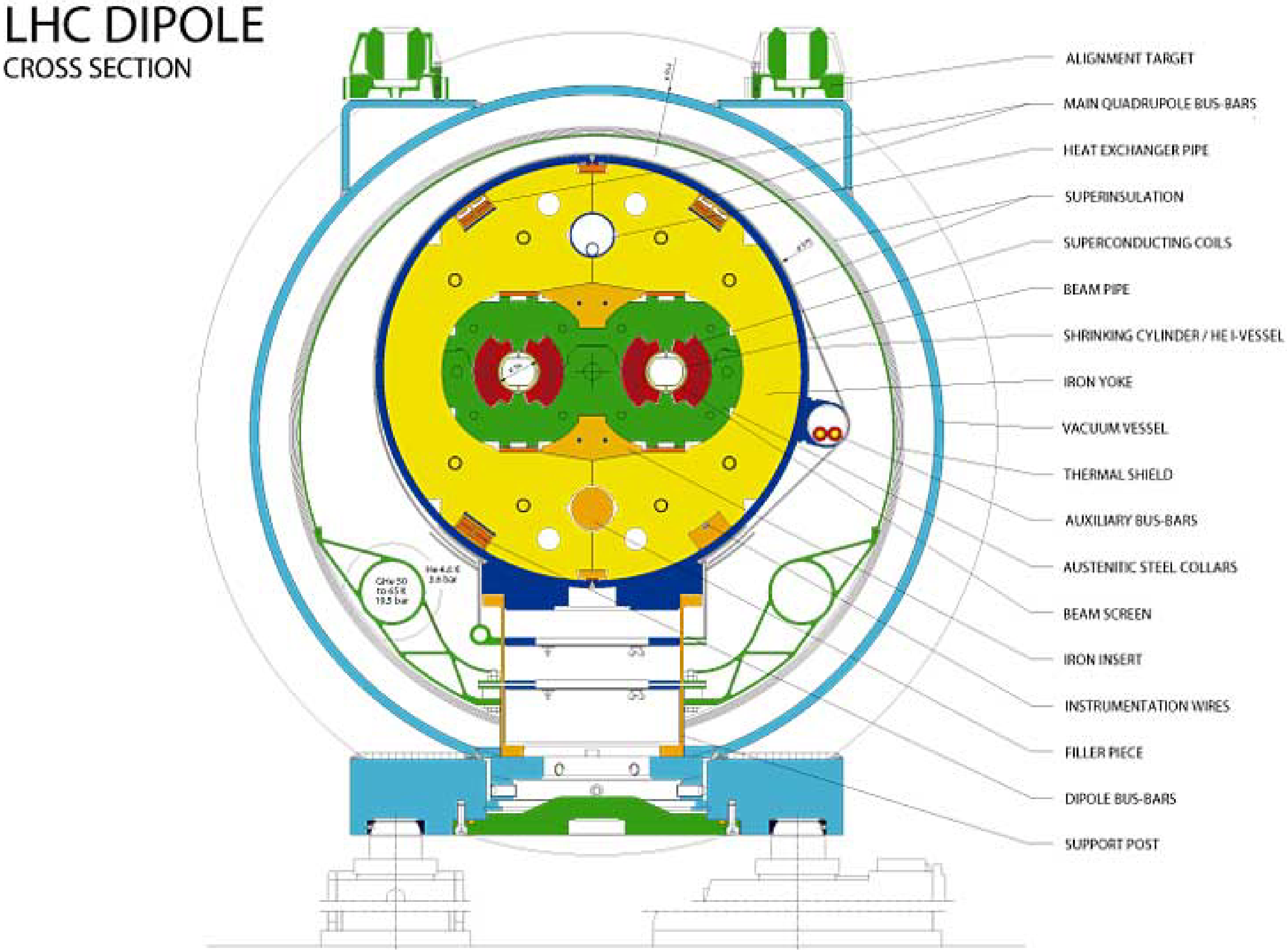


Figure 31: LHC dipole cross-section (note two pipes for proton beams)

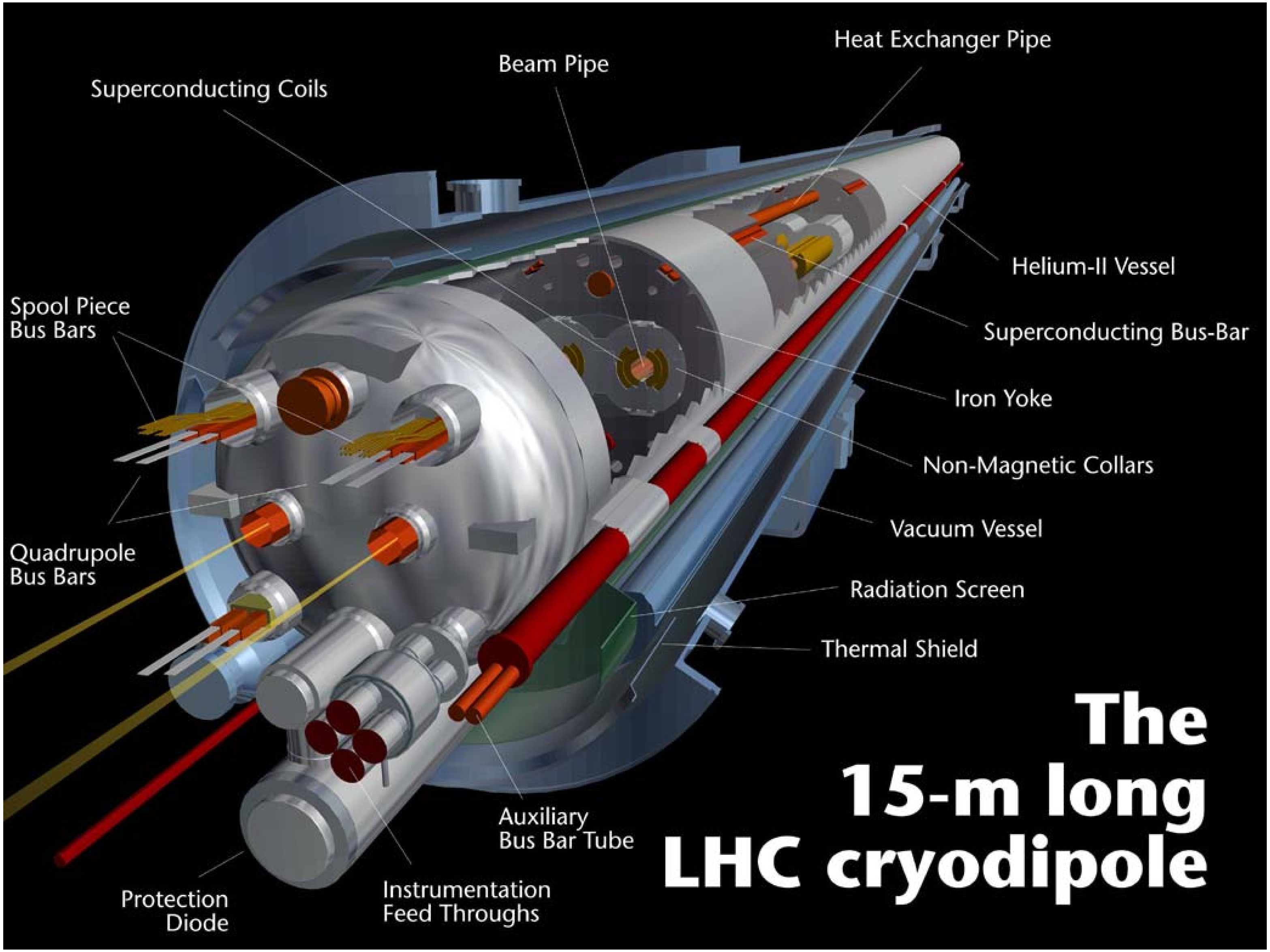


Figure 32: LHC dipole weighs 30 tons

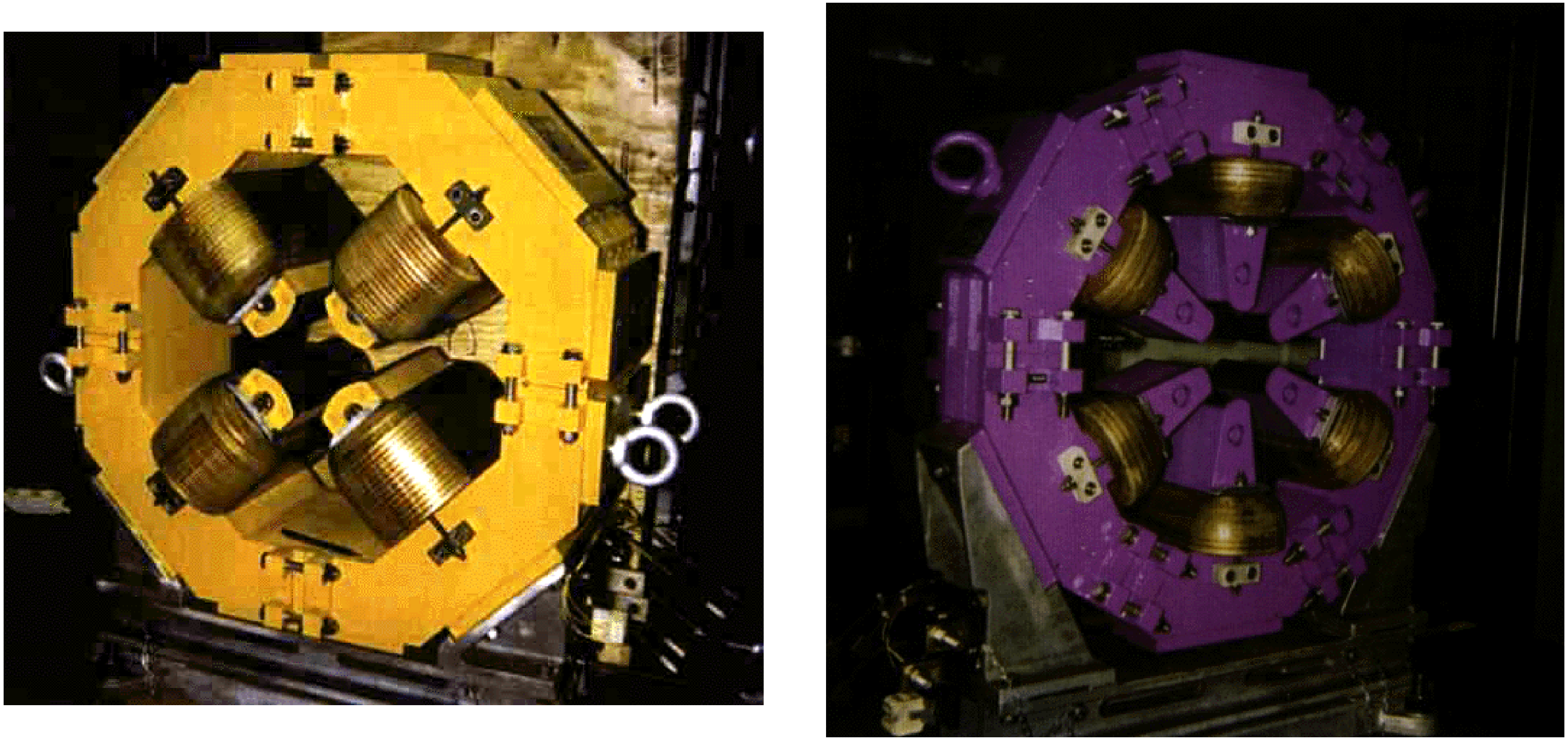


Figure 33: Quadrupole (left) and sextupole (right) magnets (not LHC)

To keep particle beams focused, quadrupole and sextupole magnets are placed along the ring and act like optical lenses

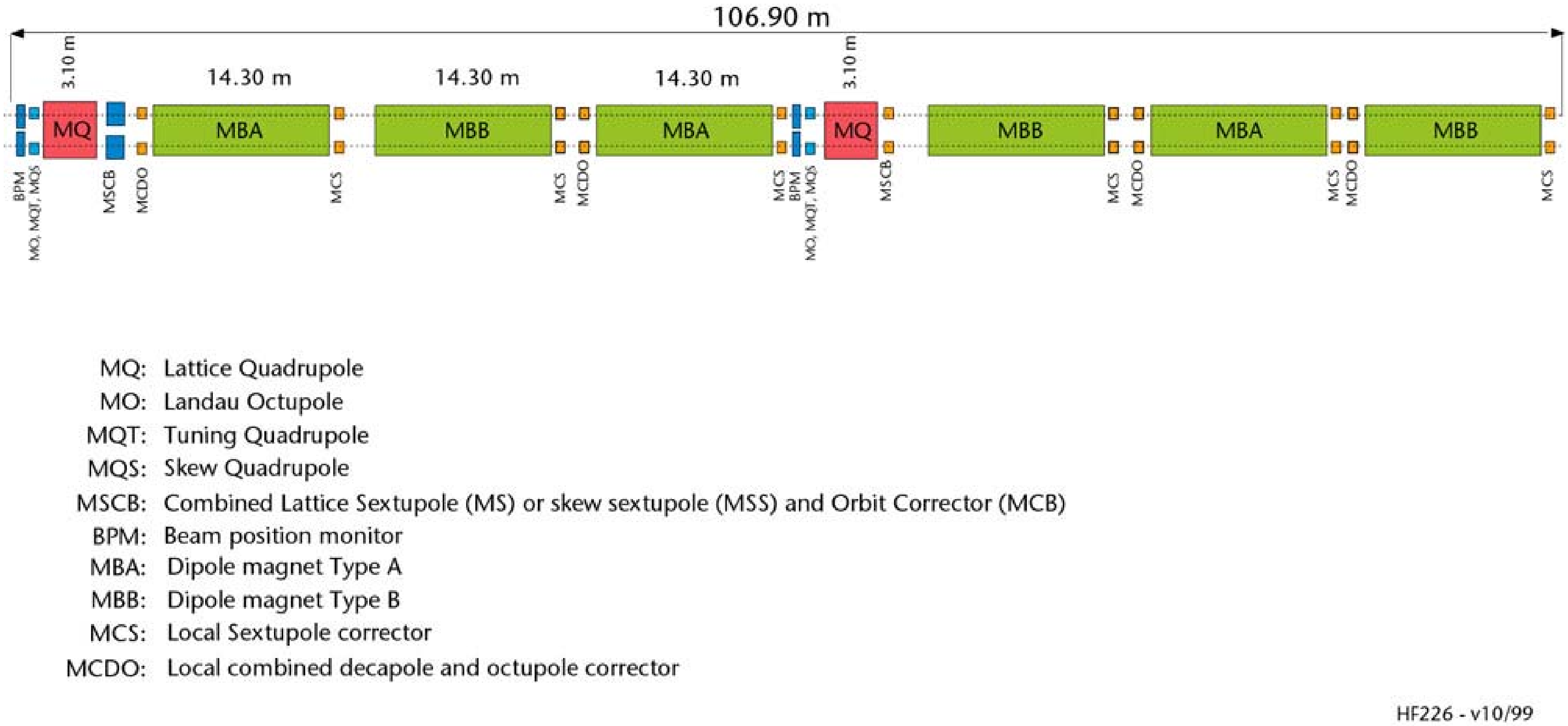


Figure 34: LHC cell (23 periods per arc)

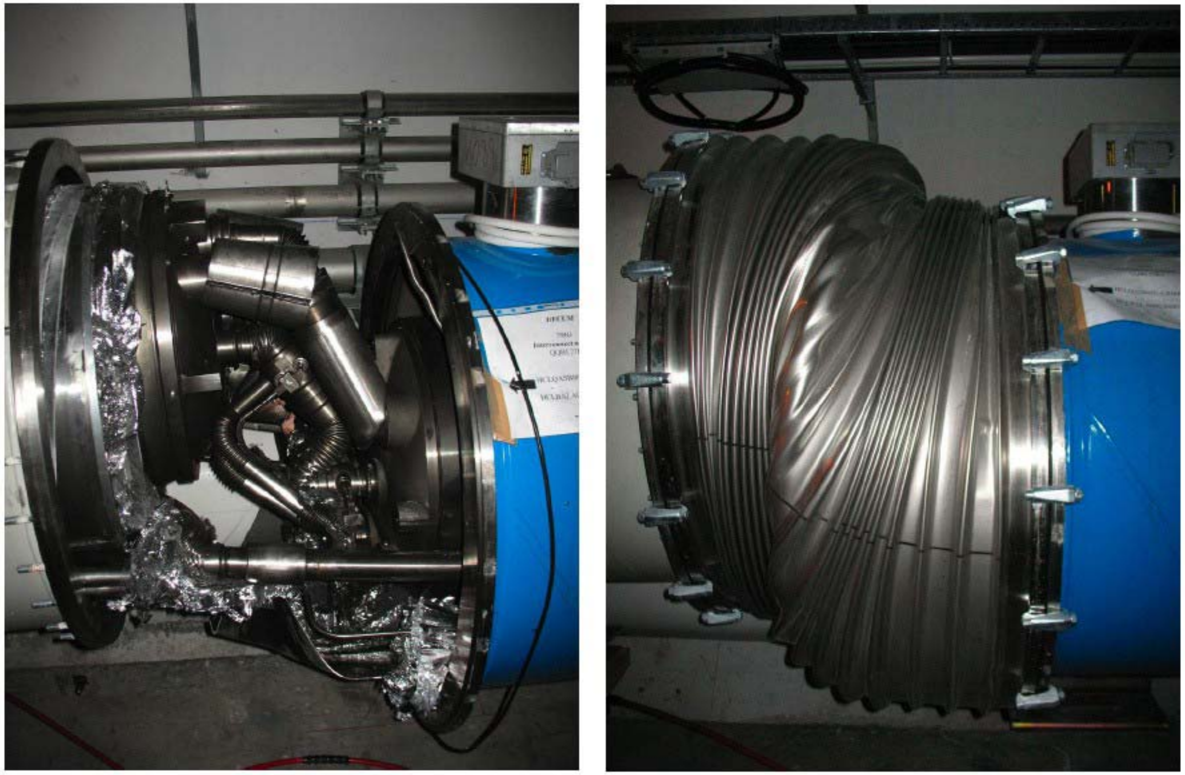


Figure 35: Damage of the LHC magnets in sector 3-4 of the LHC, caused by the incident of 19 September 2008

Colliders vs fixed target machines

Depending on whether the beam is shooting into a stationary ("fixed") target, or is colliding with another beam, both linear and cyclic accelerators are divided into two types:

- *"fixed-target"* machines
- *"colliders"* (*"storage rings"* in case of cyclic machines)

Figure 36: Scheme of a beam colliding with a fixed target; m_b is the beam particle mass and m_t is the target material mass, E_L is the beam energy

Centre-of-mass energy, i.e., energy available for particle production during collisions of a beam of energy E_L with a target, is :

$$E_{CM} = \sqrt{m_b^2 c^4 + m_t^2 c^4 + 2 m_t c^2 E_L} \quad (28)$$

- Fixed-target E_{CM} increases only as square-root of E_L! (Here m_b and m_t are masses of the beam and target particles respectively)

Some fixed target accelerators:

Machine	Type	Particles	E_{beam} (GeV)
Tevatron II (Fermilab, Illinois, USA)	synchrotron	p	1000
SPS (CERN, Geneva, Switzerland)	synchrotron	p	450
SLAC (Stanford, California, USA)	linac	e^-	25

Much higher energies are achieved for protons compared to electrons, due to smaller losses caused by synchrotron radiation.

- Fixed-target machines can be used to produce secondary beams of neutral or unstable particles.

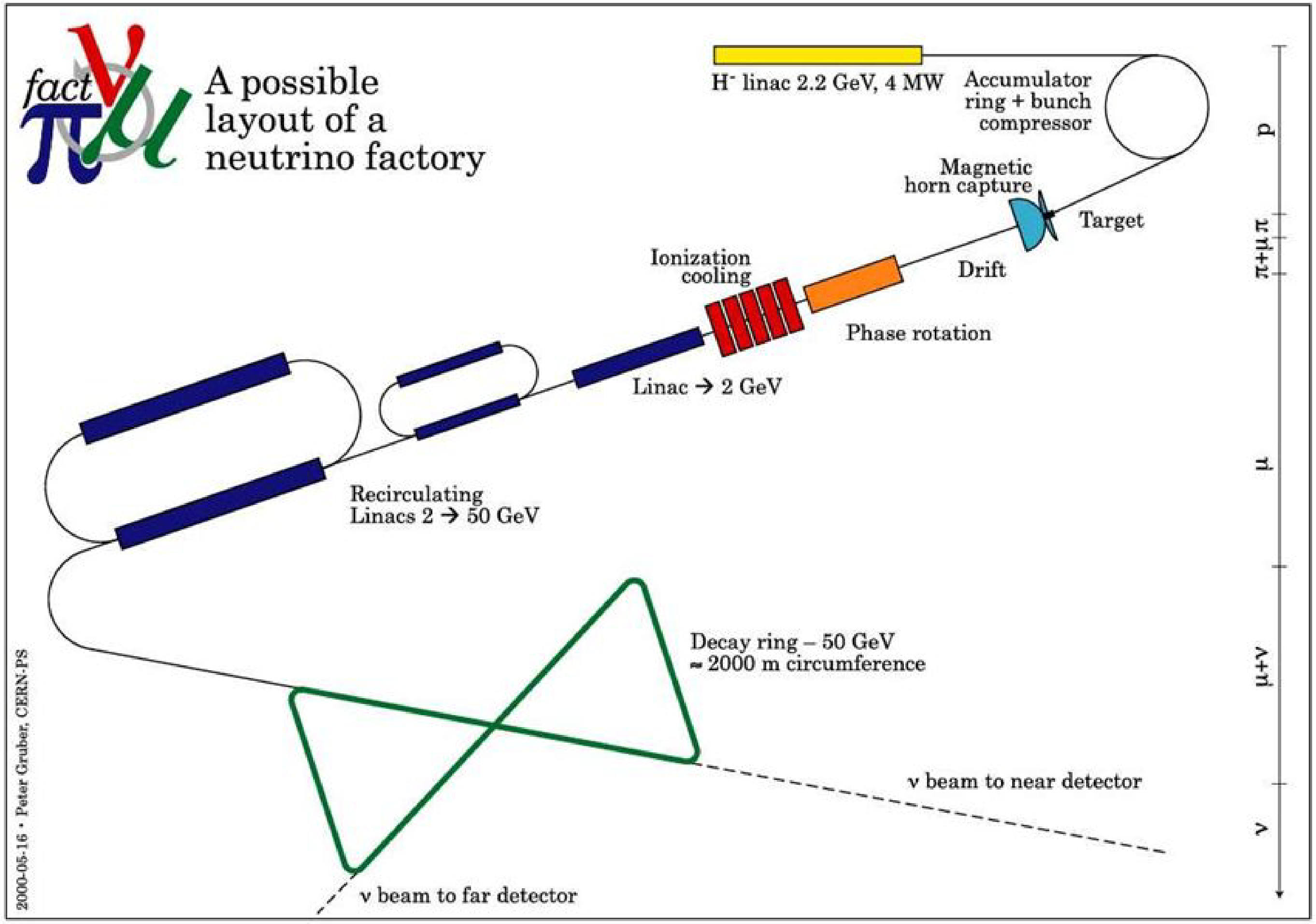


Figure 37: A possible neutrino factory

- Higher centre-of-mass energies can be achieved by colliding two beams of energies E_A and E_B (at an optional crossing angle θ), so that

$$E_{CM}^2 = 2E_AE_B(1 + \cos\theta) \tag{29}$$

Problem: smaller probability for particles to collide

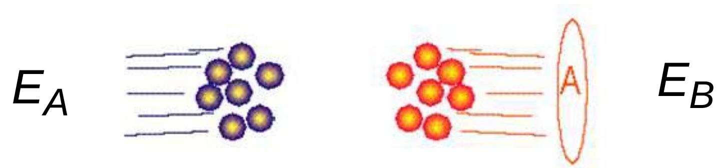


Figure 38: Scheme of colliding beams; E_A and E_B are respective beam energies

- Goal: achieve as high as possible *Luminosity*:

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma^2}F(\theta) \approx 10^{29}\ldots10^{34}cm^{-2}s^{-1} \tag{30}$$

– N : number of particles per bunch

– f : frequency of bunch collisions

– σ : beam transverse size

– $F(\theta)$: reduction factor due to crossing angle

- Luminosity depends only on intensities and geometrical characteristics of the colliding beams, but not on the nature of the reaction
- LHC goal: $\mathcal{L}$ of 10^{34} $cm^{-2}s^{-1}$ at 7 TeV

Some colliders:

Machine	In operation	Particles	E_{beam} (GeV)
KEKB (KEK, Tokyo, Japan)	1999-	e^-, e^+	8, 3.5
PEP-II (SLAC, California, USA)	1999-	e^-, e^+	9, 3.1
LEP (CERN, Geneva, Switzerland)	1989-2000	e^-, e^+	105
HERA (Hamburg, Germany)	1992-2007	e^-, p	30, 920
Tevatron II (Fermilab, Illinois, USA)	1987-2011	p, $\bar{p}$	1000
LHC (CERN, Geneva, Switzerland)	2008-	p, p	7000

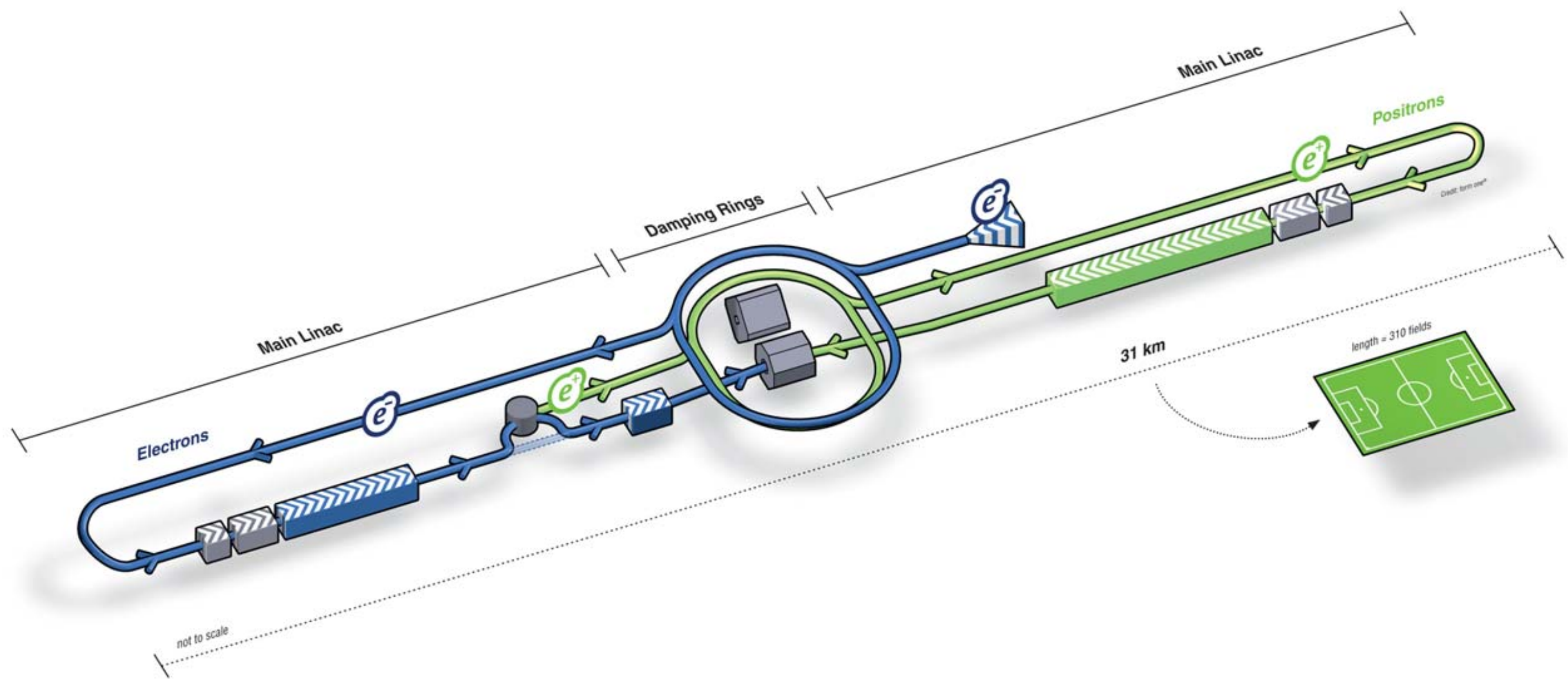
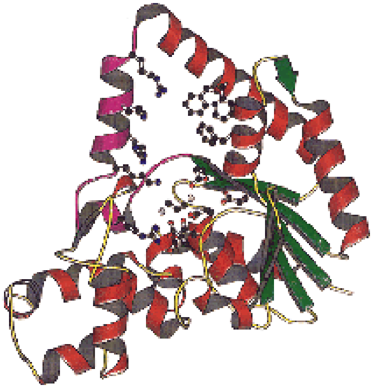
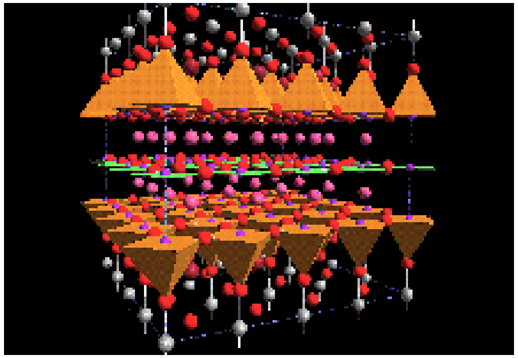


Figure 39: Future International Linear Collider (ILC)

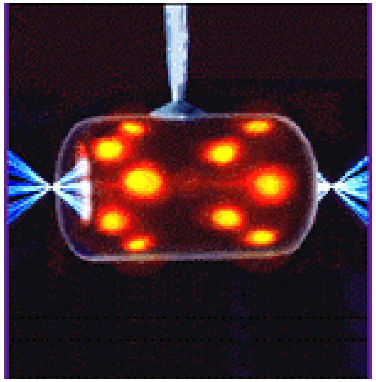
- Future research accelerators will be dedicated to precision measurements: have to provide electron-positron collisions at very high energies, up to 1 TeV



Synchrotron light radiation (ESRF)
5' exonuclease from bacteriofage T5

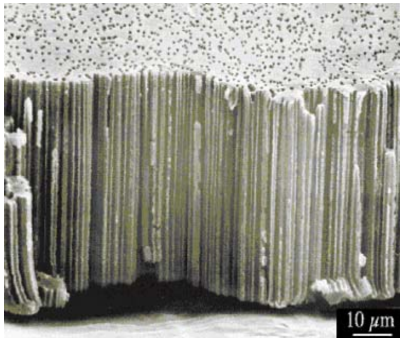


Spallation Neutron diffraction (ISIS)
Structure of HighTC semiconductor



Heavy ion fusion
Laser beam simulation

Proton therapy (PSI)
Gantry



Ion beams (GSI)
Etched ion tracks in polymer foil

Surface treatment
Sterilisation
Polymerisation etc etc

Figure 40: Application of accelerators outside HEP (by E.Wilson)