# III. 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 24: Large Hadron Collider at CERN

# Accelerators

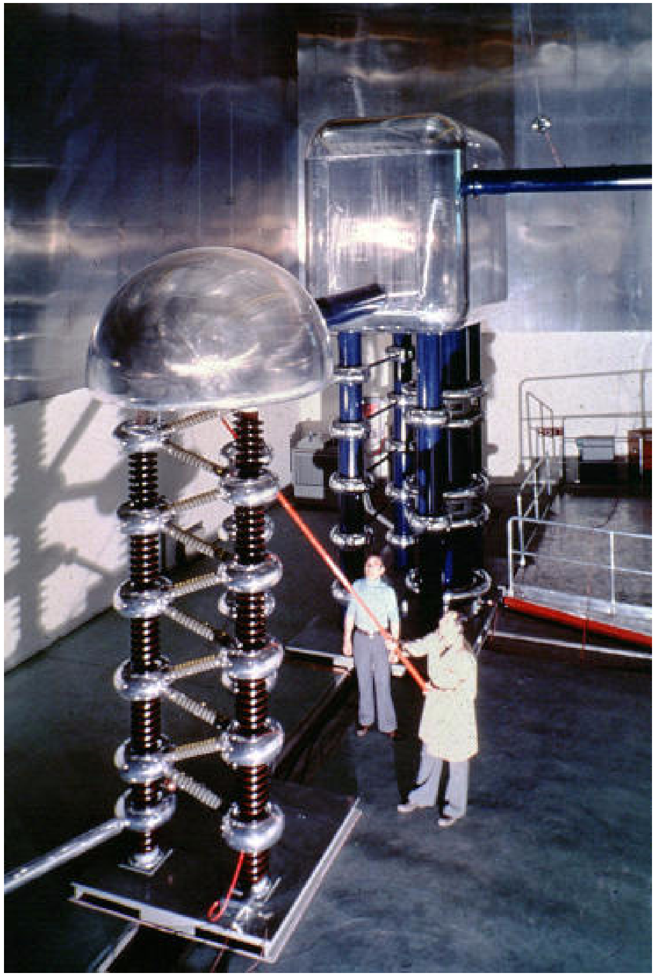


Figure 25: The Cockroft-Walton "generator" at CERN: accelerates particles by an electrostatic field

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

Main varieties of accelerators are:

– Linear accelerators ( *"linacs"* )

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

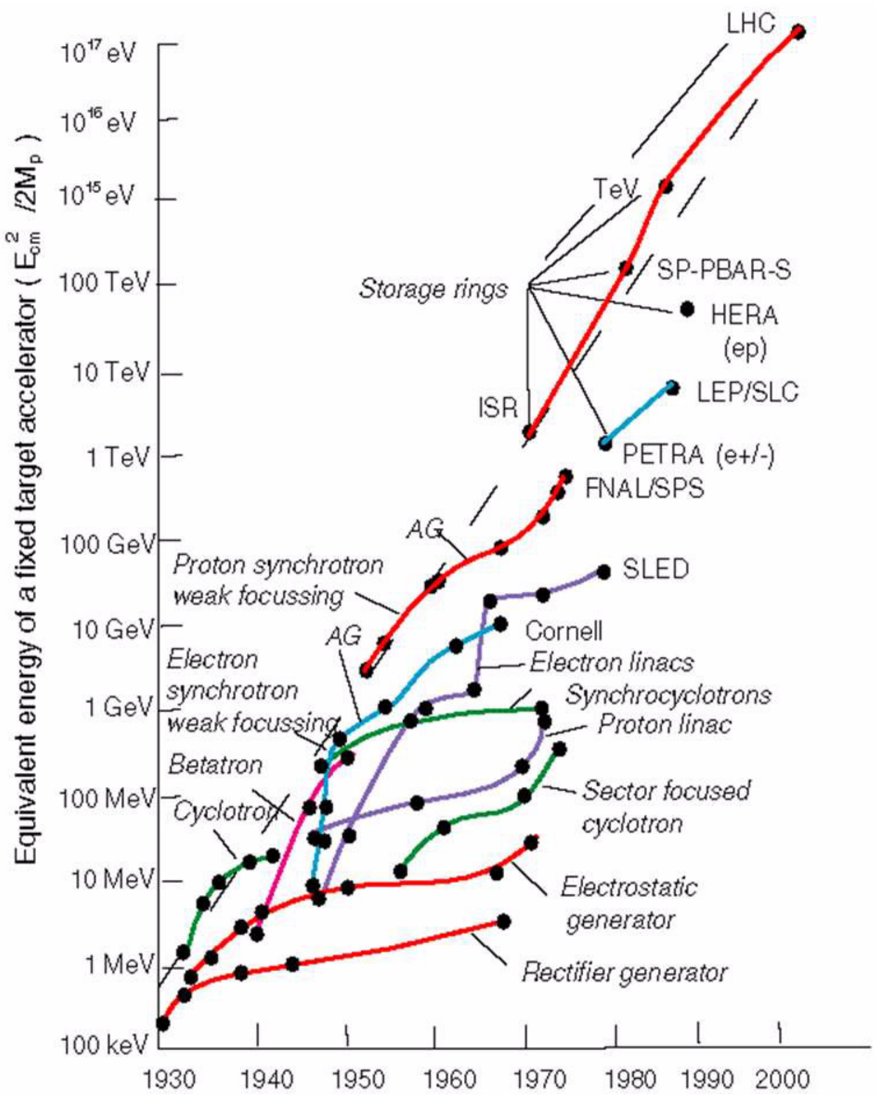



Figure 26: The history of accelerators (by E.Wilson); colors indicate different accelerator types

# *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

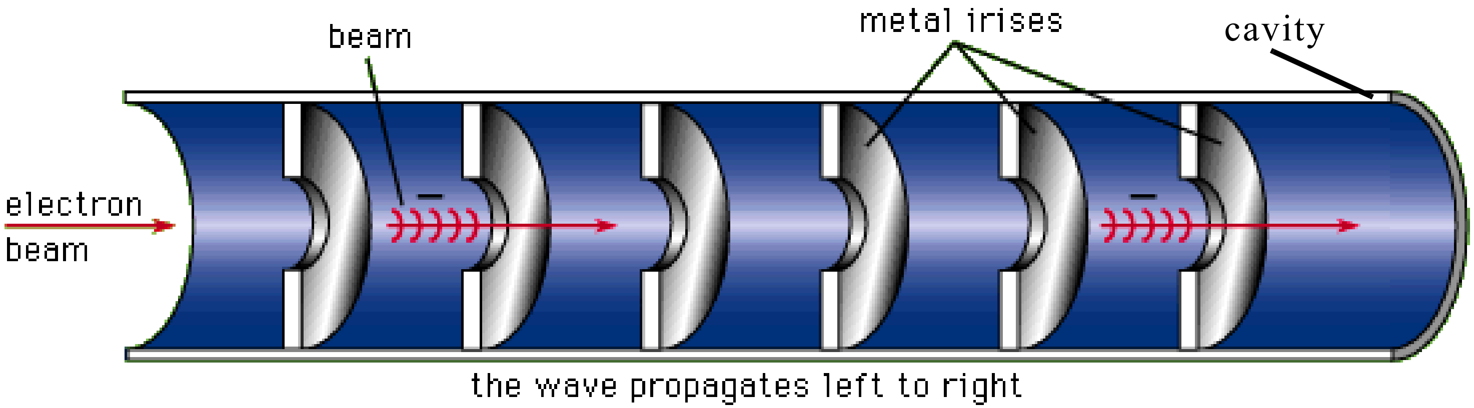



Figure 27: A traveling-wave linear accelerator schematics

- 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

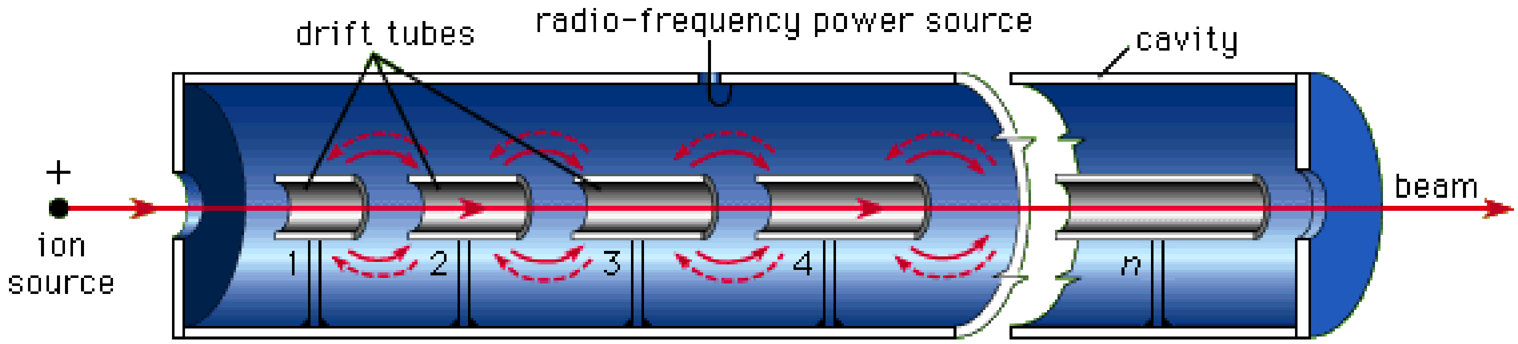



Figure 28: Standing-wave linac

- 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

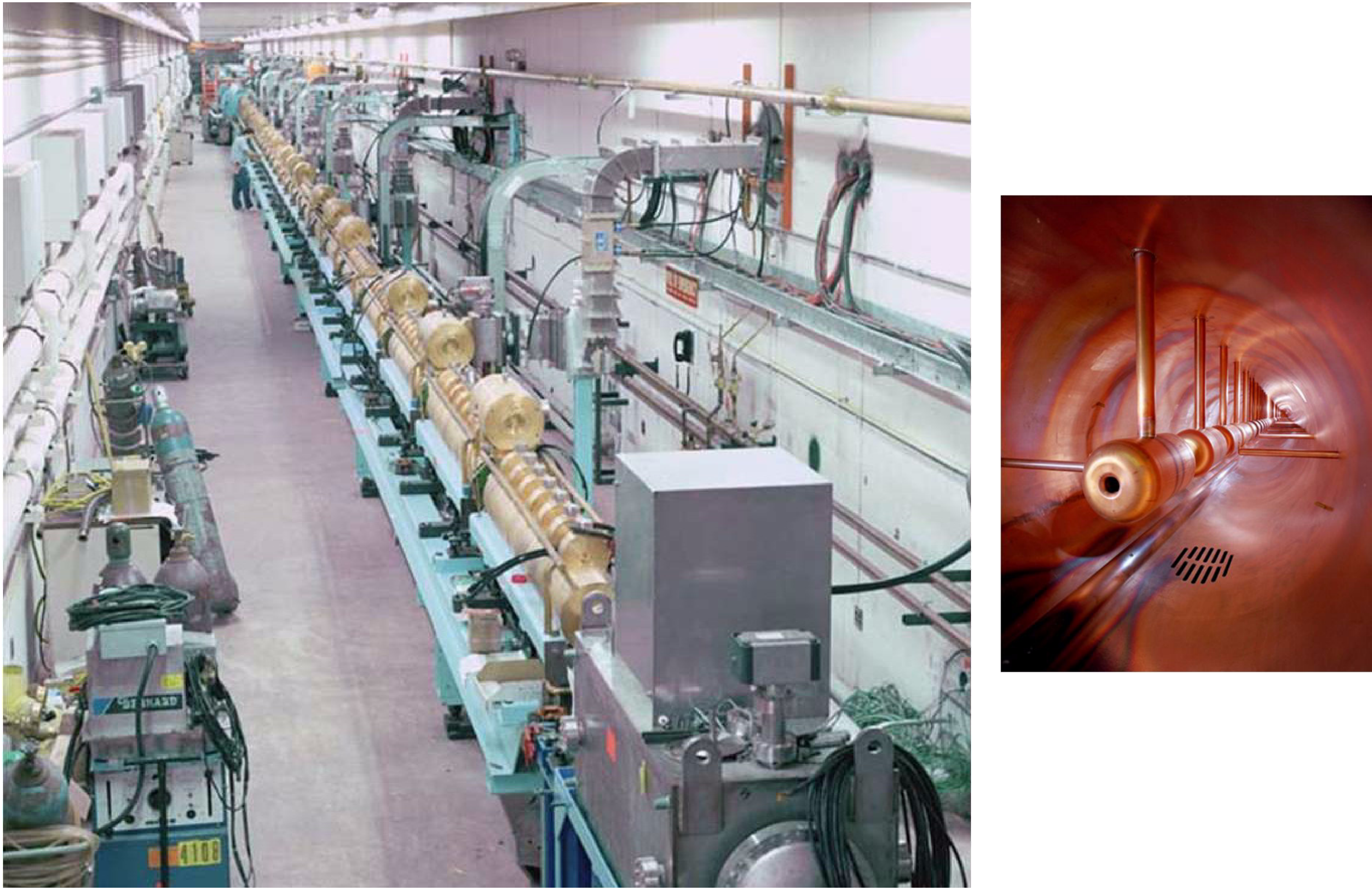
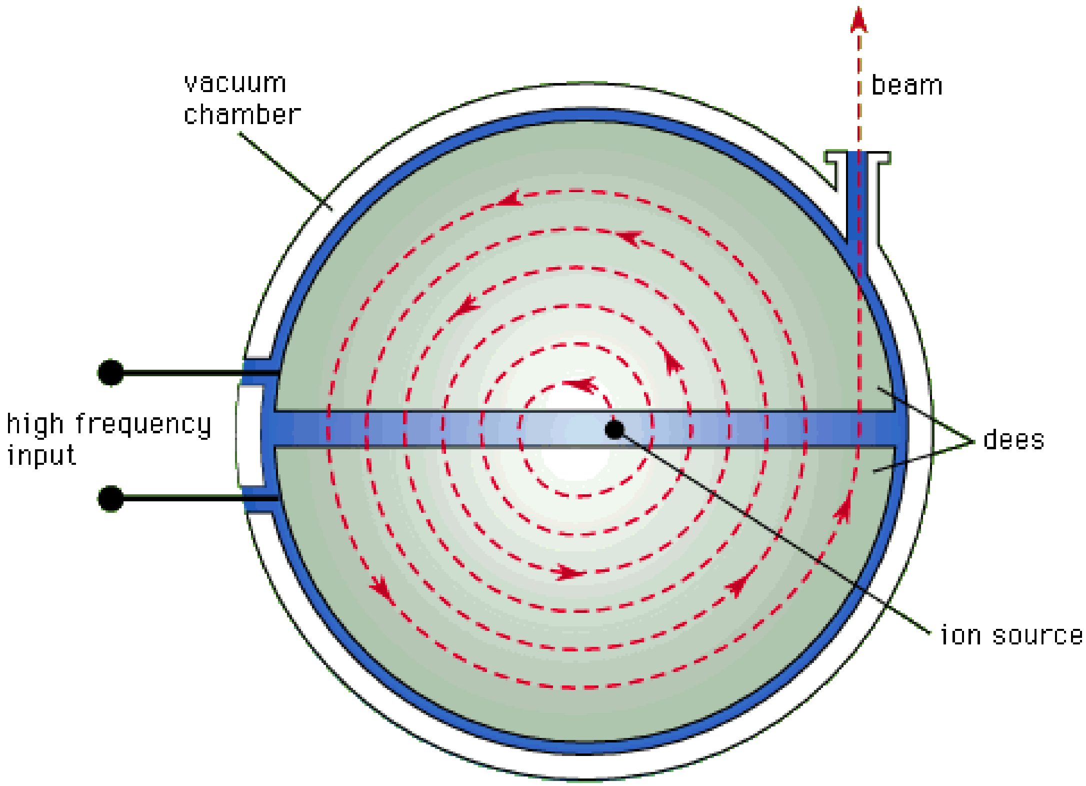


Figure 29: LINAC a Fermilab (400 MeV) - outside and inside

# 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 30: 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 $\overline{E}=0$ ($\overline{F}=q\,\overline{v}\times\overline{B}$)

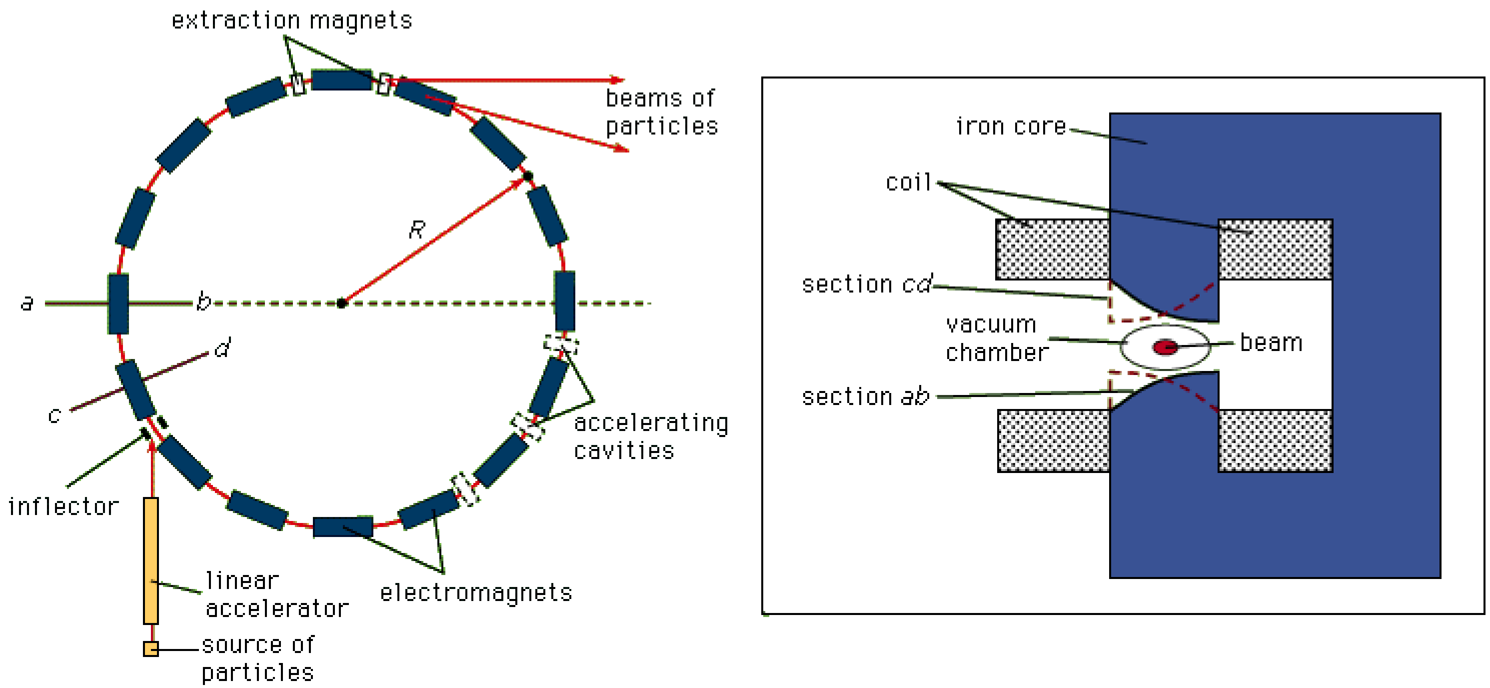



Figure 31: Schematic layout of a synchrotron

## ❖ 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 32: Large Hadron Collider at CERN accelerates protons

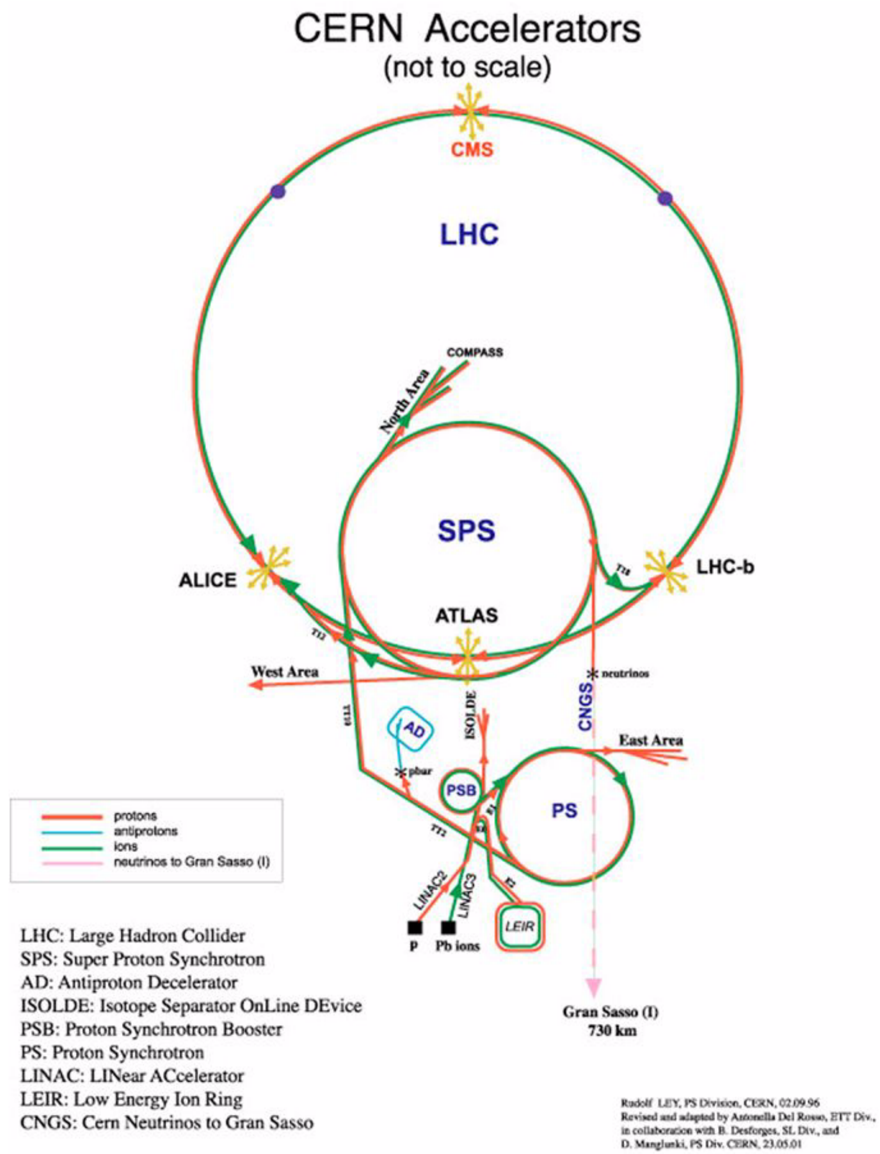



Figure 33: Scheme of the accelerator complex at CERN

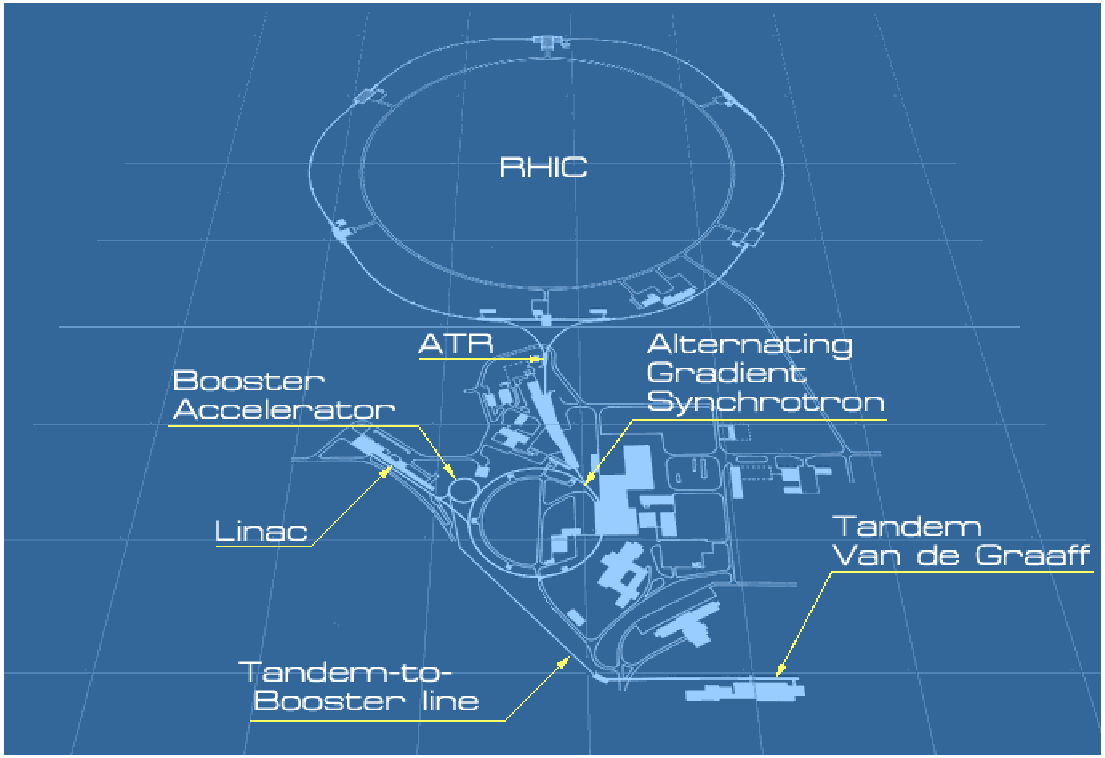



Figure 34: Scheme of the Relativistic Heavy Ion Collider (RHIC) accelerator complex at BNL (left) and its RF cavity system (right).
RHIC accelerates ions, from protons to gold

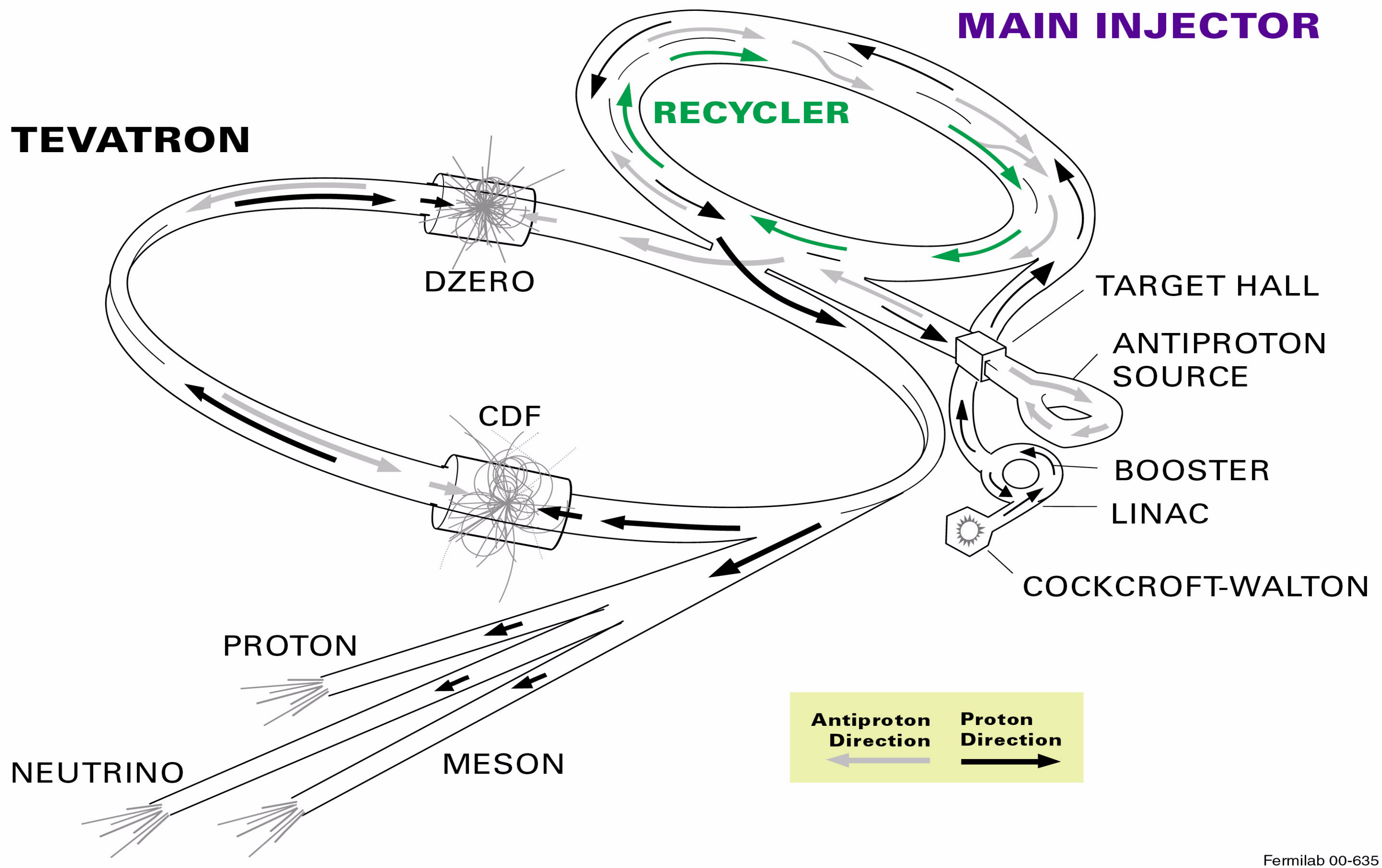



Figure 35: Tevatron accelerator chain at Fermilab.
Tevatron accelerates protons and antiprotons

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

Amount of energy radiated per turn is:

$$\Delta E = \frac{q^2\beta^3\gamma^4}{3\varepsilon_0\rho} \tag{31}$$

Here $q$ is electric charge of a particle, $\beta \equiv v/c$ , $\gamma \equiv (1-\beta^2)^{-1/2}$, and $\rho$ 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 $\rho$) 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 $\rho$ 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.

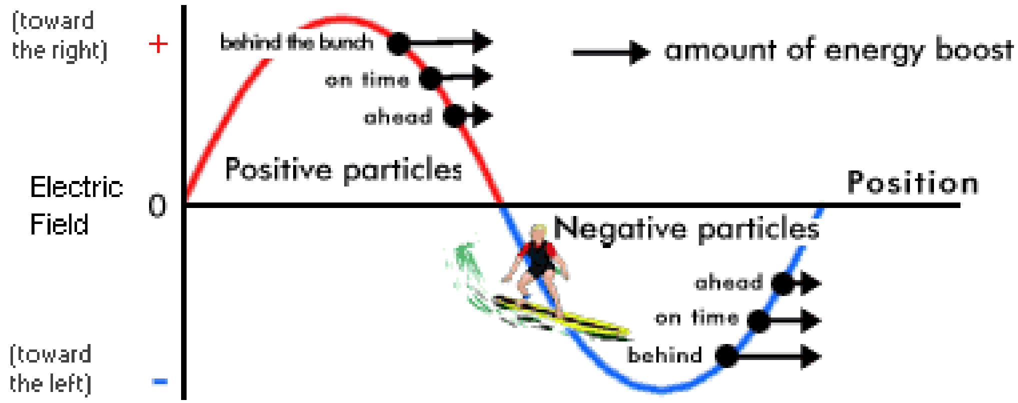



Figure 36: Effect of the electric field onto particles in accelerator cavities (*phase stability*)

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

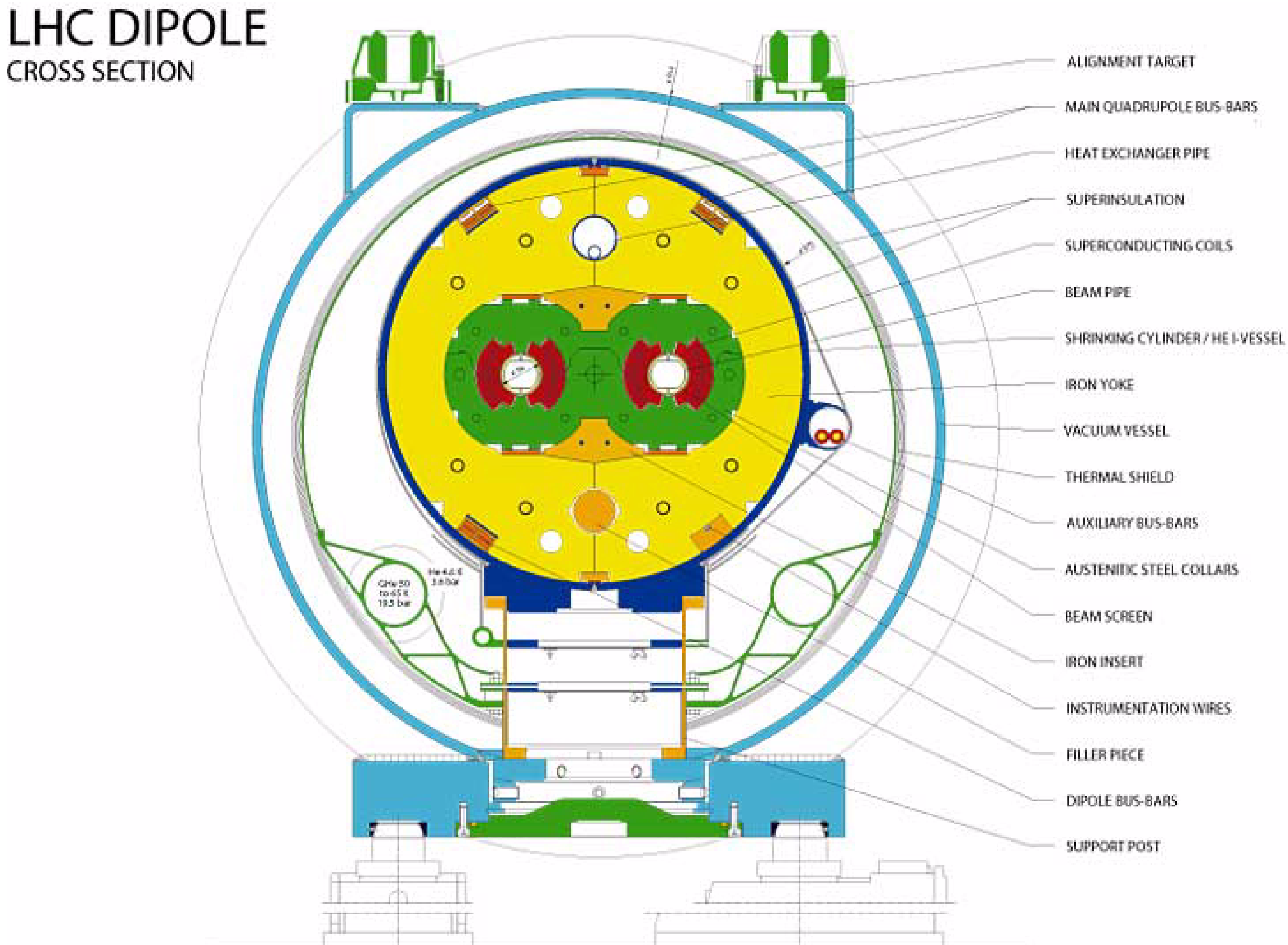



Figure 37: LHC dipole cross-section

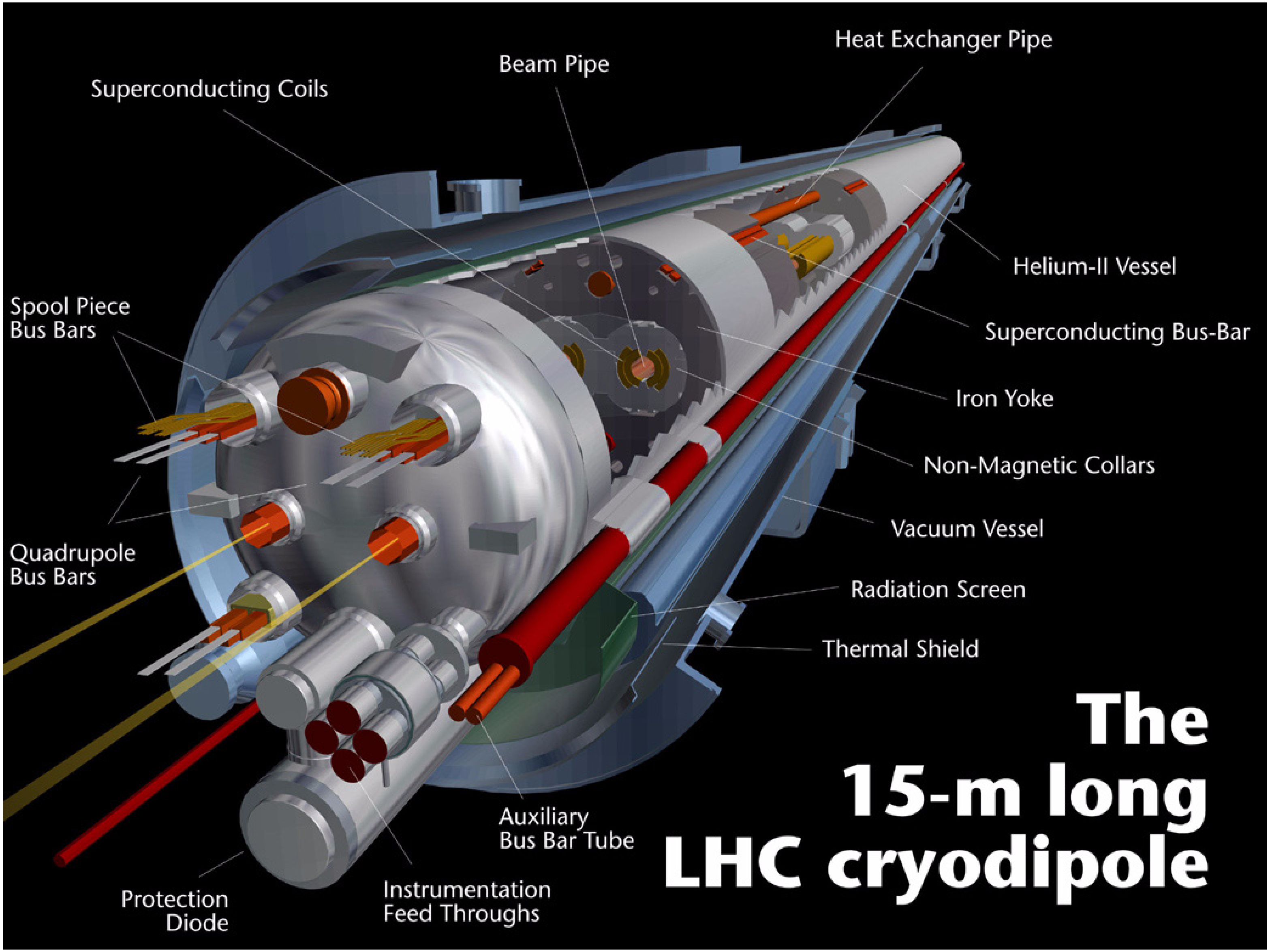
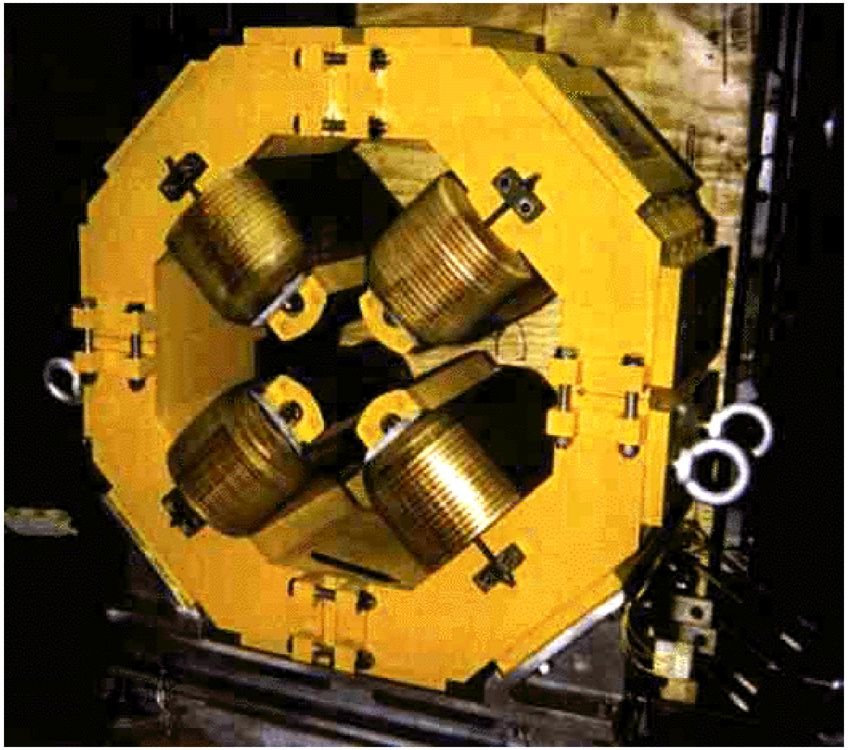



Figure 38: LHC dipole weighs 30 tons



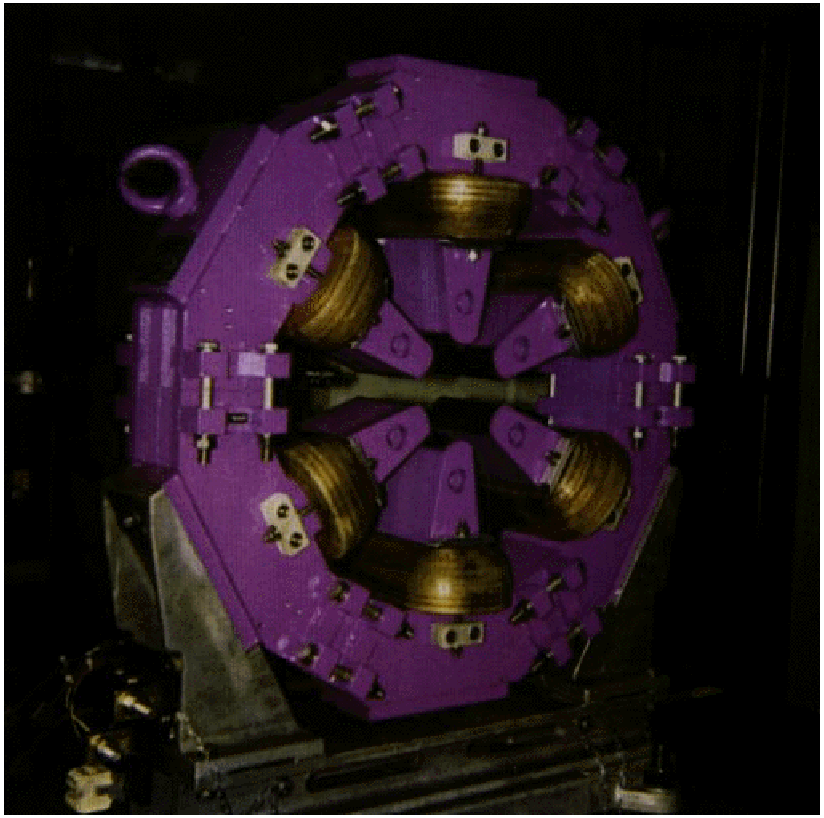


Figure 39: Quadrupole (left) and sextupole (right) magnets

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

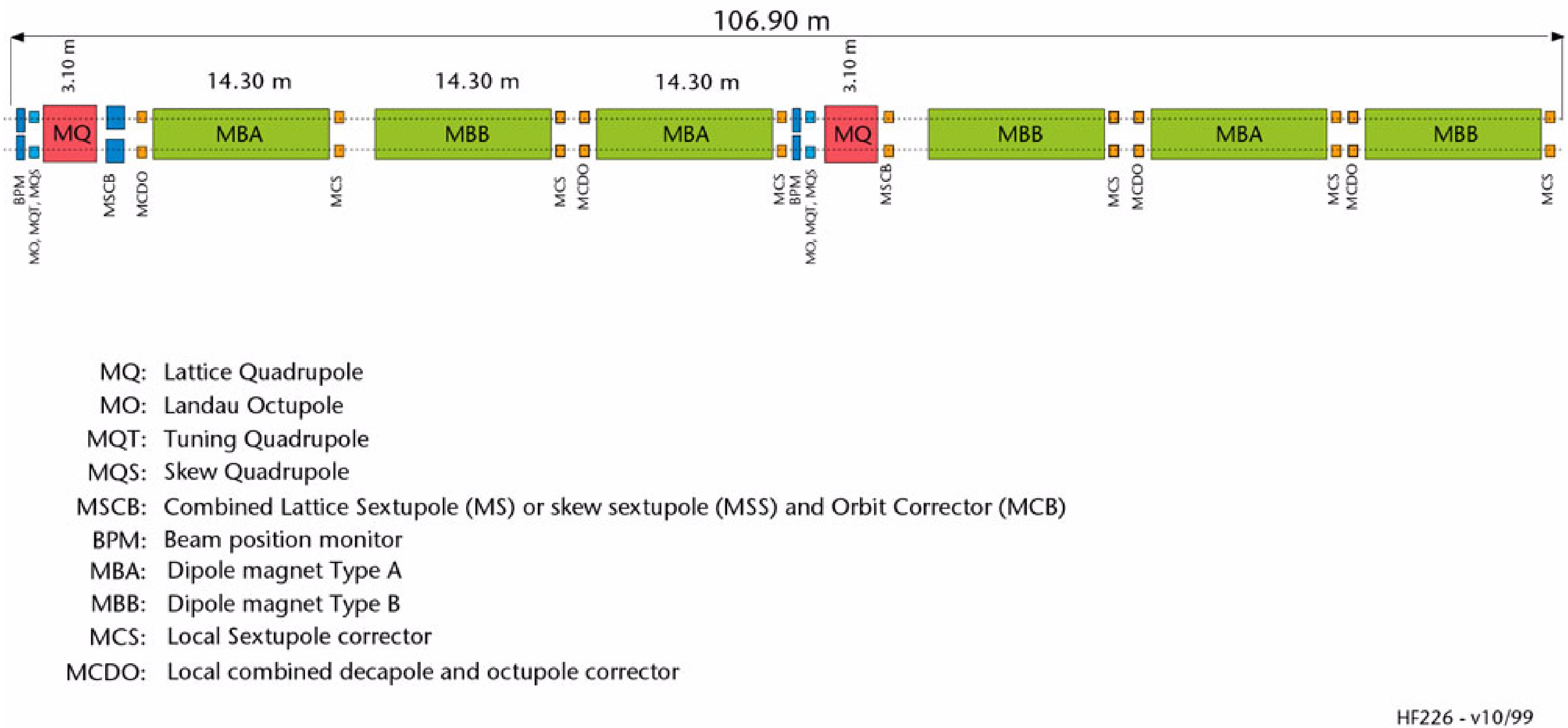



Figure 40: LHC cell (23 periods per arc)

# 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)

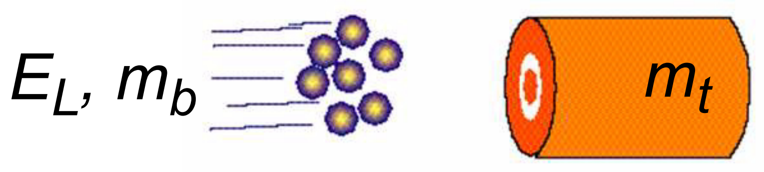



Figure 41: Scheme of a beam colliding with a fixed target; $m_b$ is the beam particle mass and $m_t$ is the target material mass, $E_L$ is the beam energy

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

$$E_{CM} = \sqrt{m_b^2 c^4 + m_t^2 c^4 + 2 m_t c^2 E_L} \quad (32)$$

- 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.

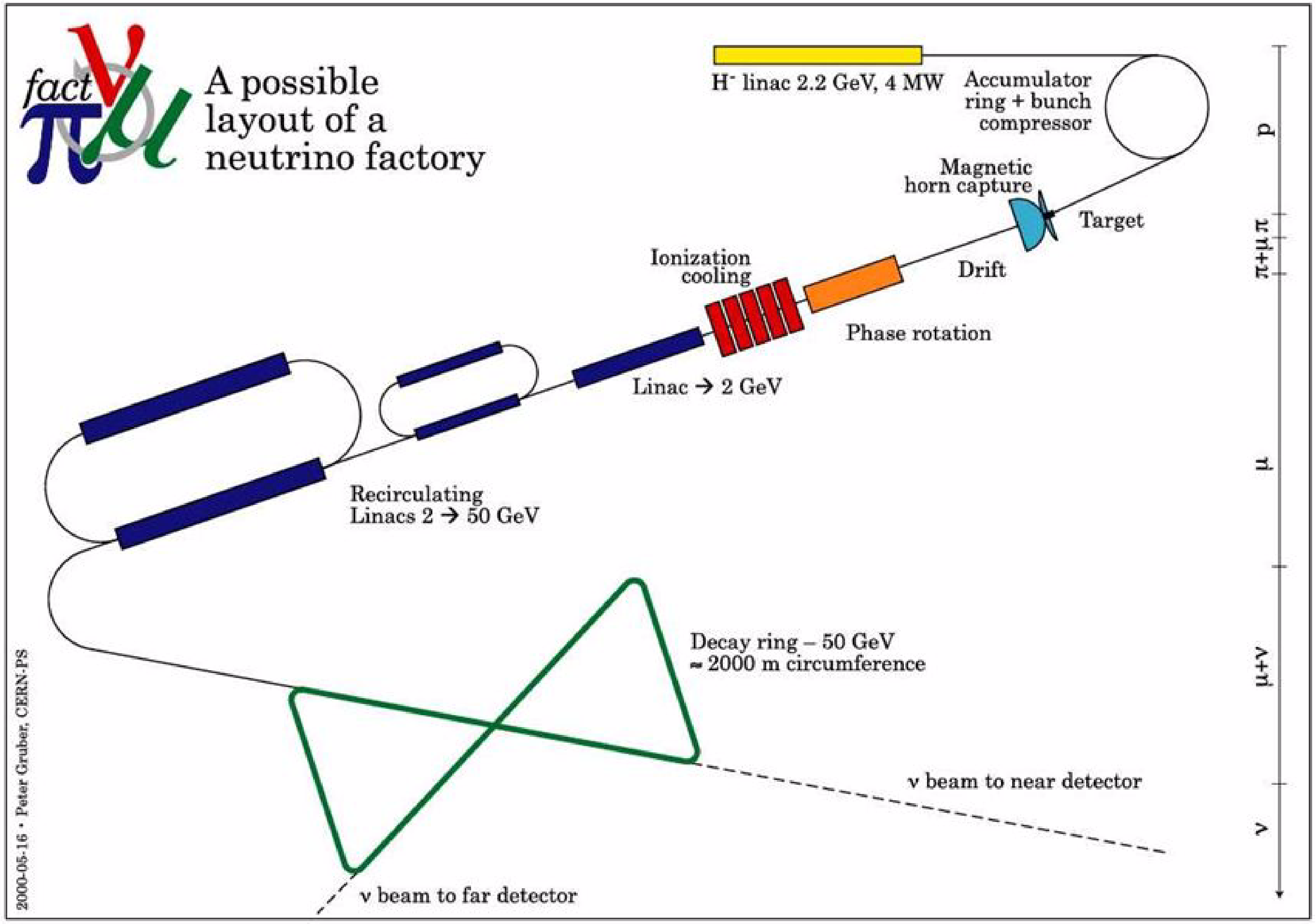



Figure 42: A possible neutrino factory

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

$$E_{CM}^2 = 2E_AE_B(1 + \cos\theta) \quad (33)$$

Problem: smaller probability for particles to collide

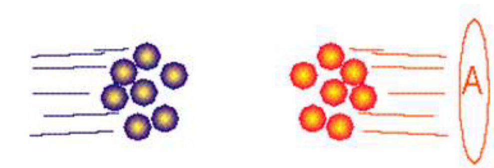
$E_A$  $E_B$



Figure 43: Scheme of colliding beams; $E_A$ and $E_B$ are respective beam energies

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

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

– N : number of particles per bunch

– f : frequency of bunch collisions

– $\sigma$ : 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- | p, $\bar{p}$ | 1000 |
| **LHC** (CERN, Geneva, Switzerland) | 2008- | p, p | 7000 |

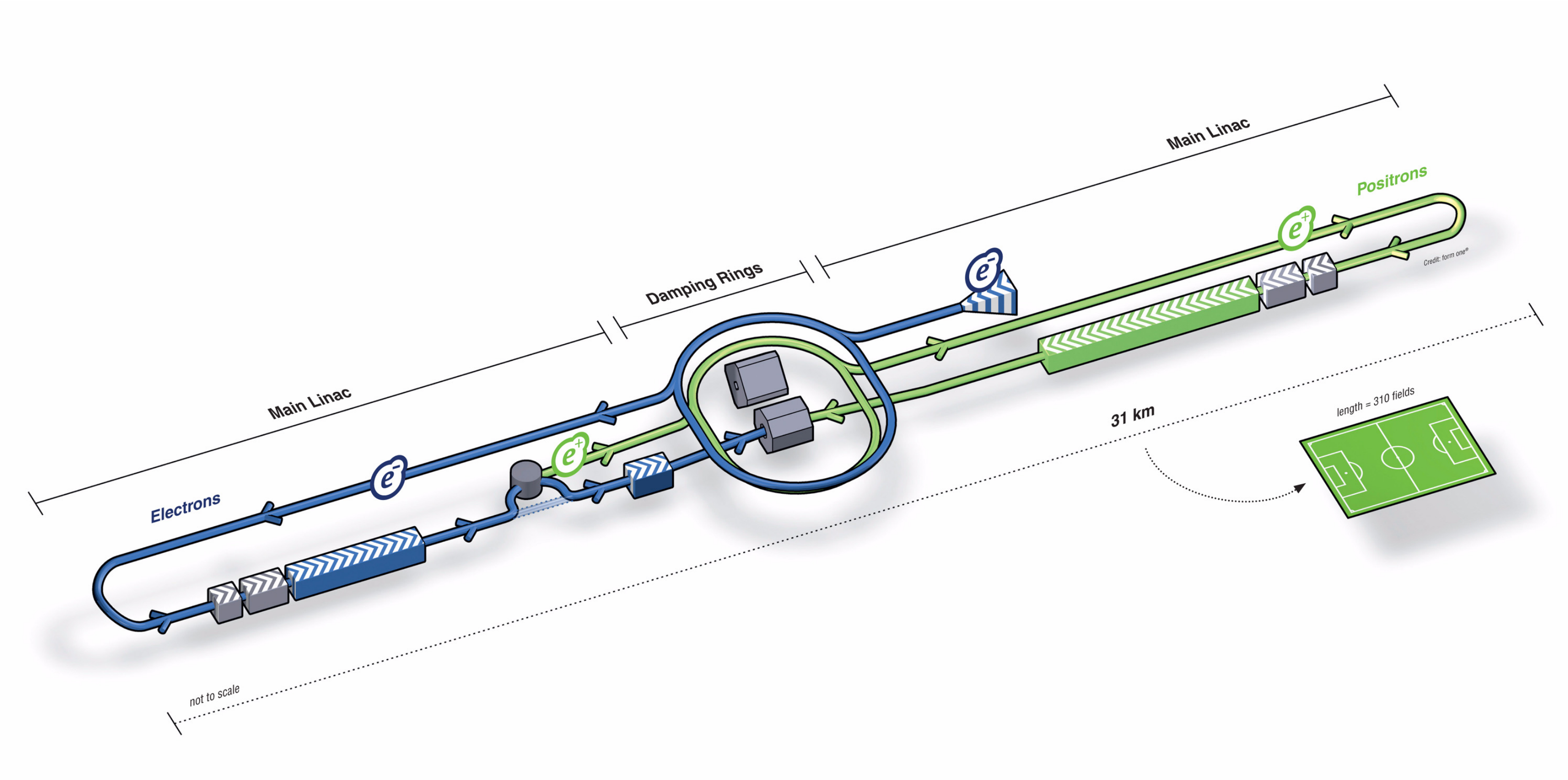
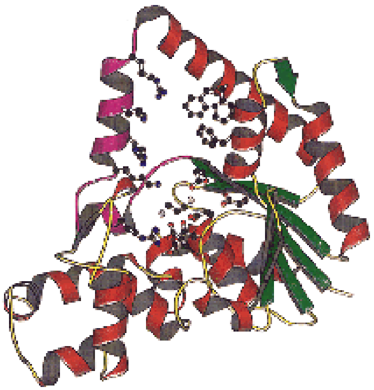
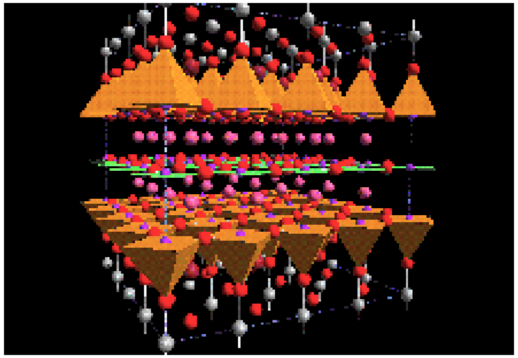



Figure 44: Future International Linear Collider (ILC)

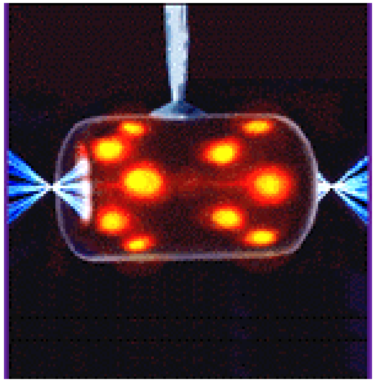
- Future accelerators will be dedicated to precision measurements: have to provide electron-positron collisions at very high energies, up to 1 TeV



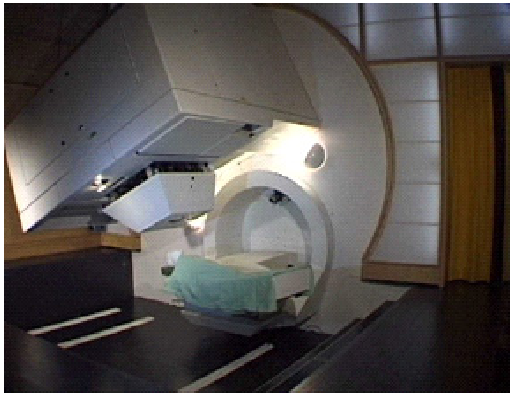
**Synchrotron light radiation (ESRF)**
5' exonuclease from bacteriofage T5



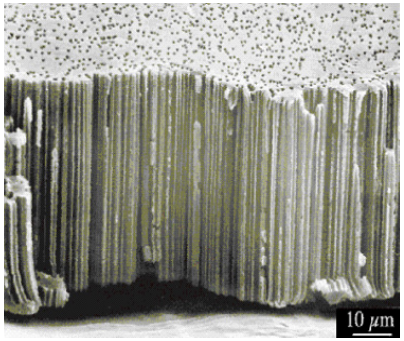
**Spallation Neutron diffraction (ISIS)**
Structure of HighTC semiconductor



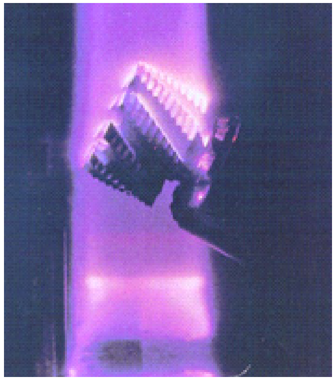
**Heavy ion fusion**
Laser beam simulation



**Proton therapy (PSI)**
Gantry




**Ion beams (GSI)**
Etched ion tracks in polymer foil



**Surface treatment**
**Sterilisation**
**Polymerisation etc etc**

Figure 45: Application of accelerators outside HEP (by E.Wilson)