

## 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 Cockcroft-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*” )

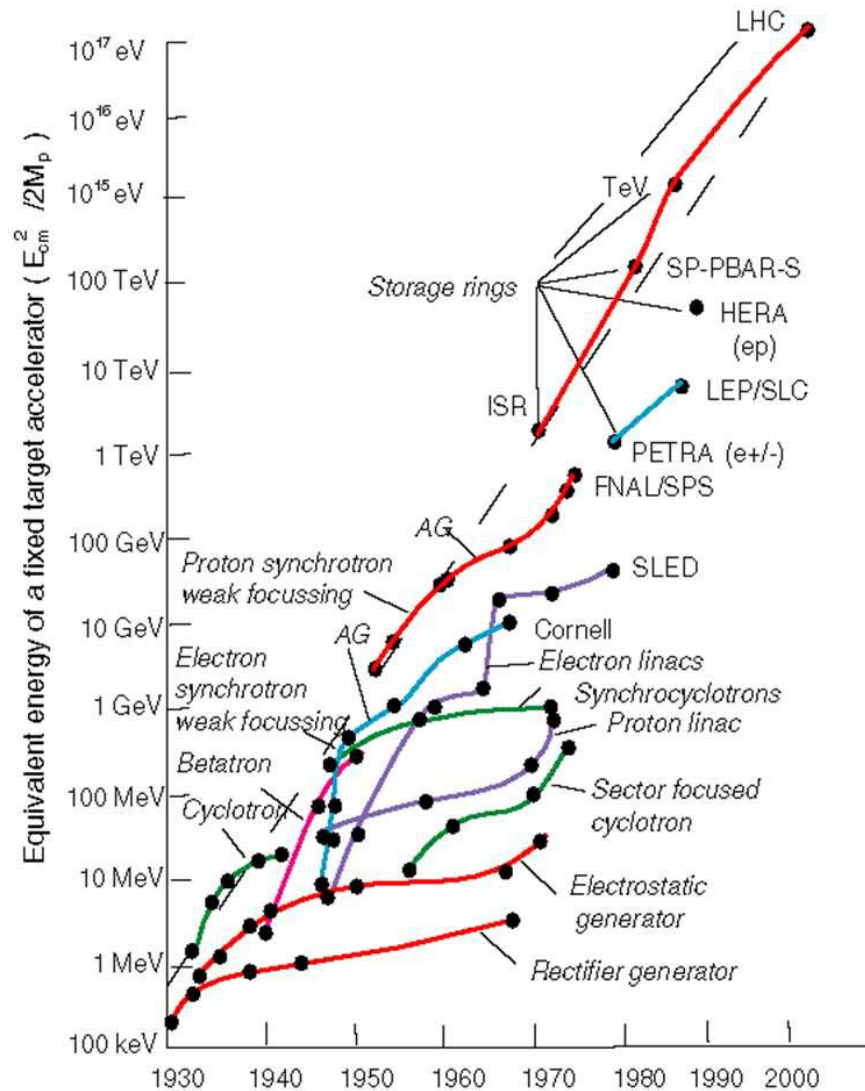


Figure 20: The history of accelerators (by E.Wilson); colors indicate different accelerator types

## 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 in 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

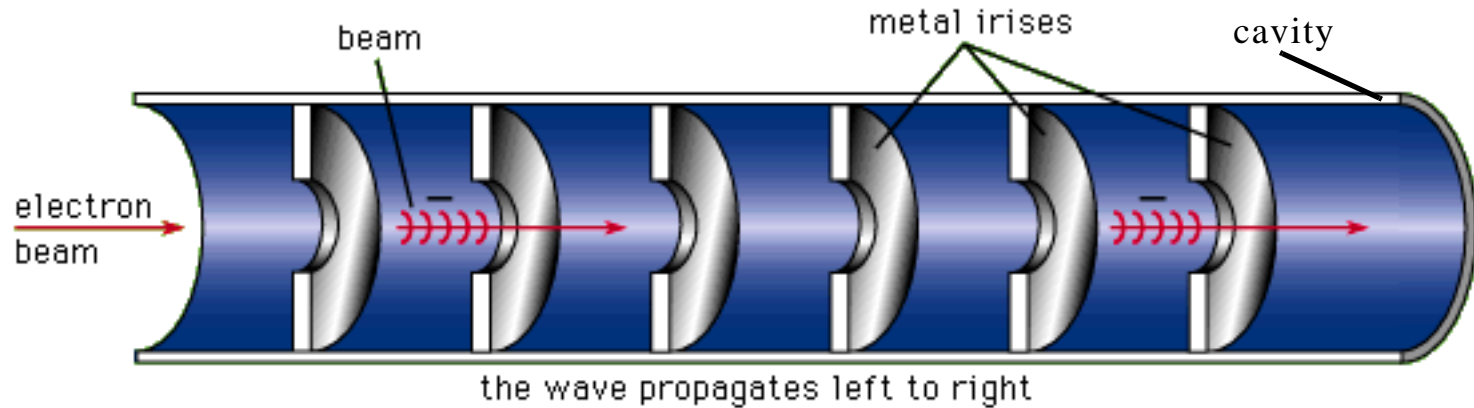


Figure 21: A traveling-wave linear accelerator schematics

- ❖ 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 ( $\vec{F}=q\vec{E}$ )
  - ☉ Electrons arrive into each cavity at the same phase as the electric wave

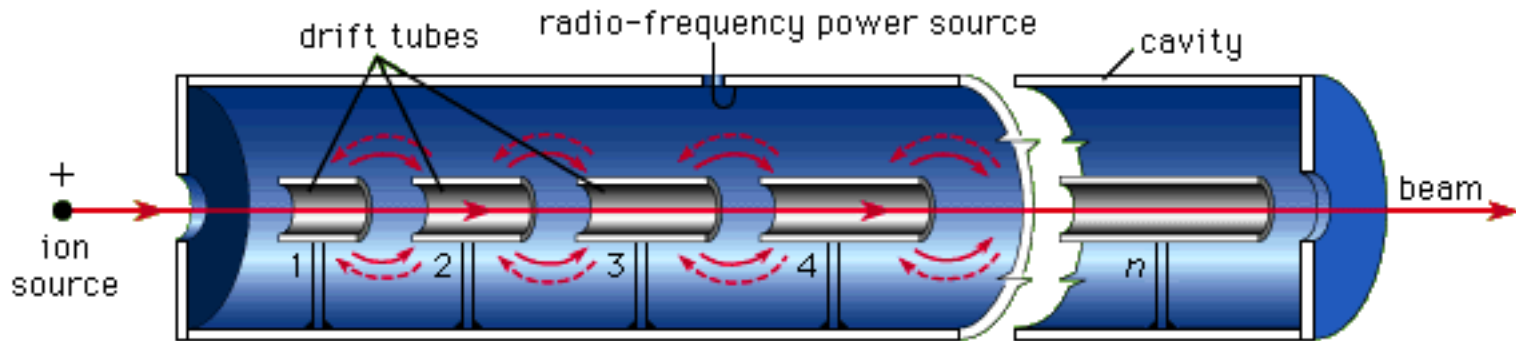


Figure 22: Standing-wave linac

- ❖ 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



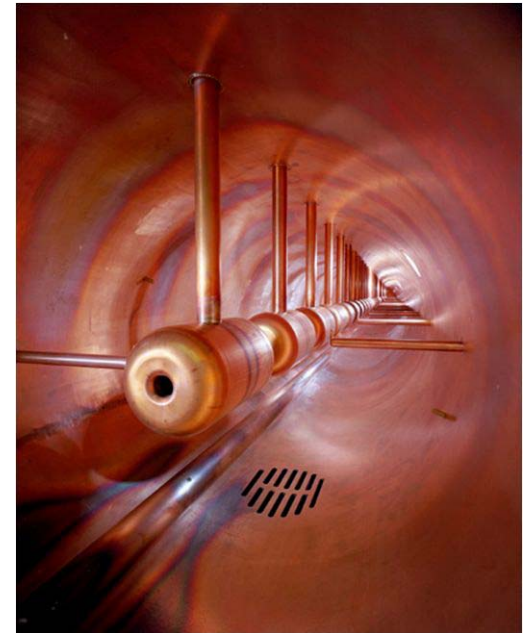
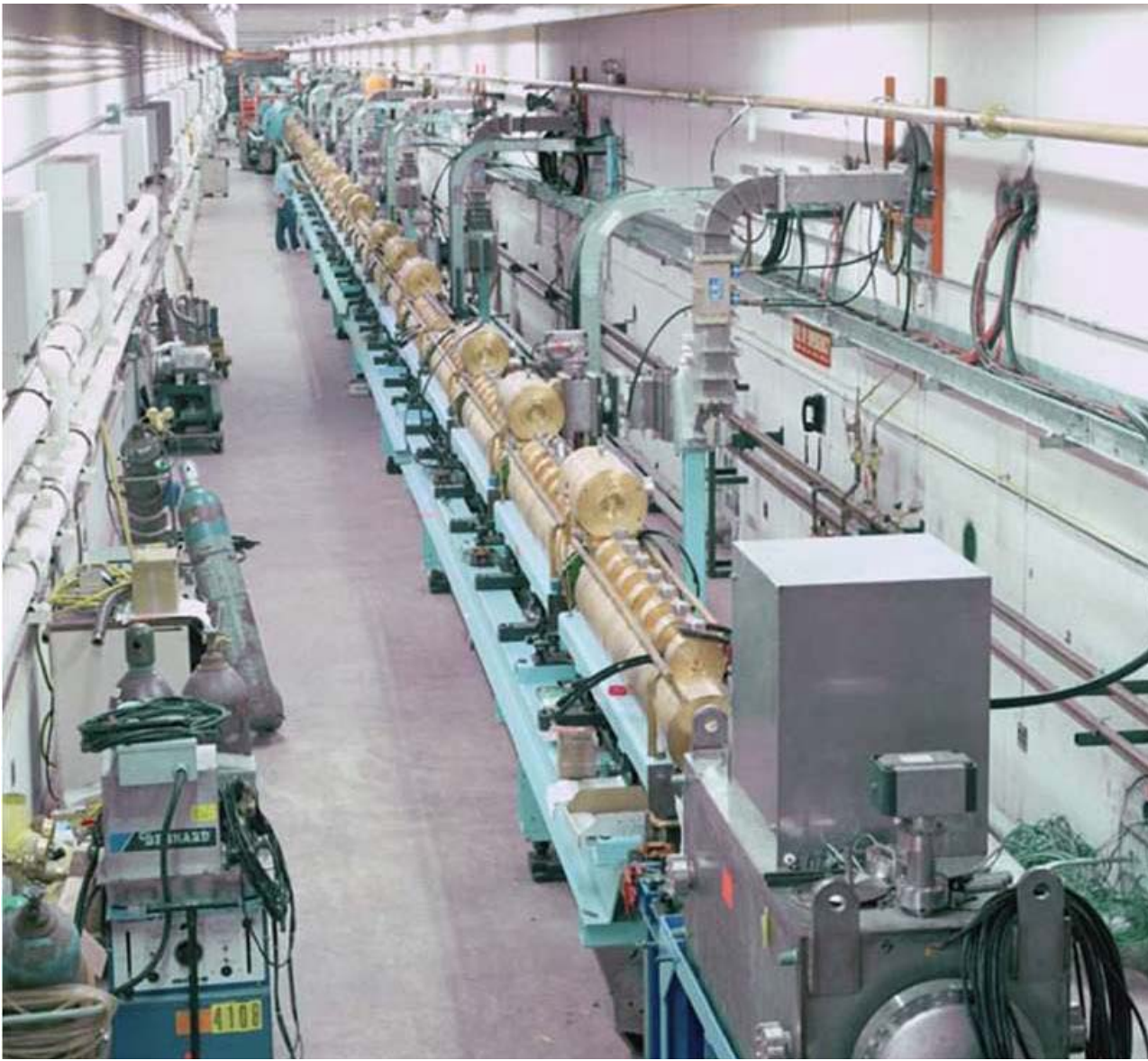
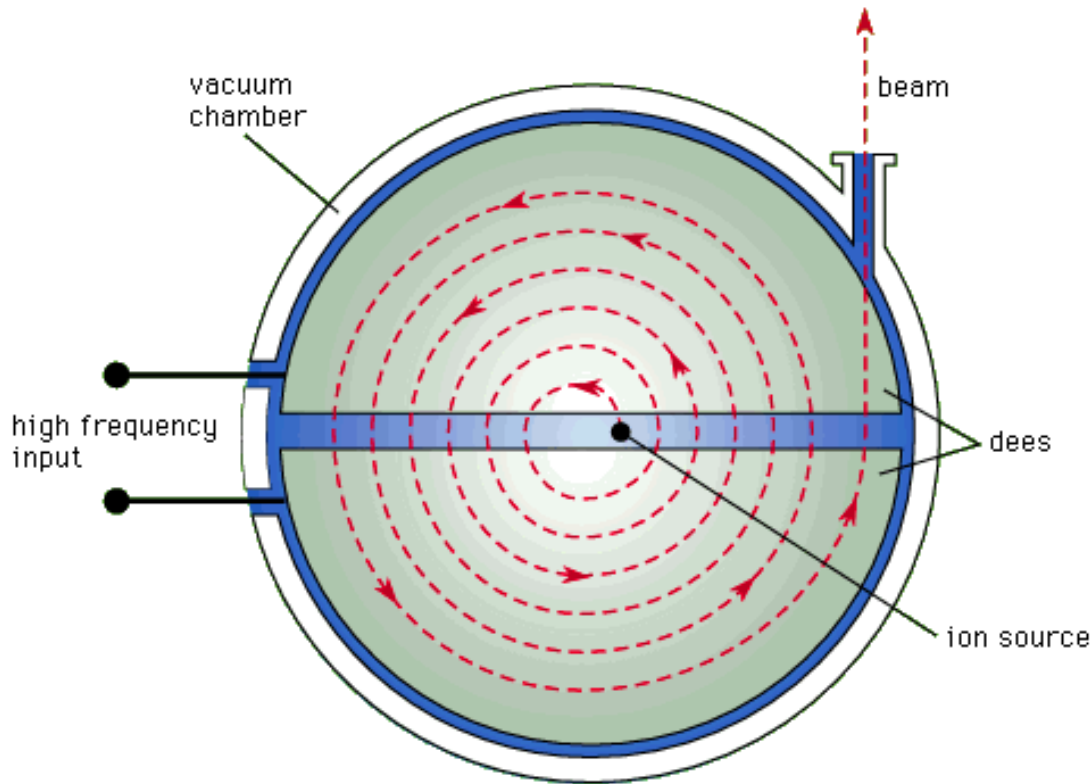


Figure 23: LINAC a Fermilab (400 MeV) - side-coupled (left) and drift-tube (right)

## Cyclic accelerators.



$$\diamond \vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- $\diamond$  Particle is accelerated by the high frequency field  $\vec{E}$  between the dees ( $\vec{F} = q\vec{E}$ )

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

- The vacuum chamber is placed inside a magnetic field  $\vec{B}$ , perpendicular to the rotation plane
- Dees (“D”) are empty “boxes” working as electrodes; inside the dees  $\vec{E} = 0$  ( $\vec{F} = q\vec{v} \times \vec{B}$ )



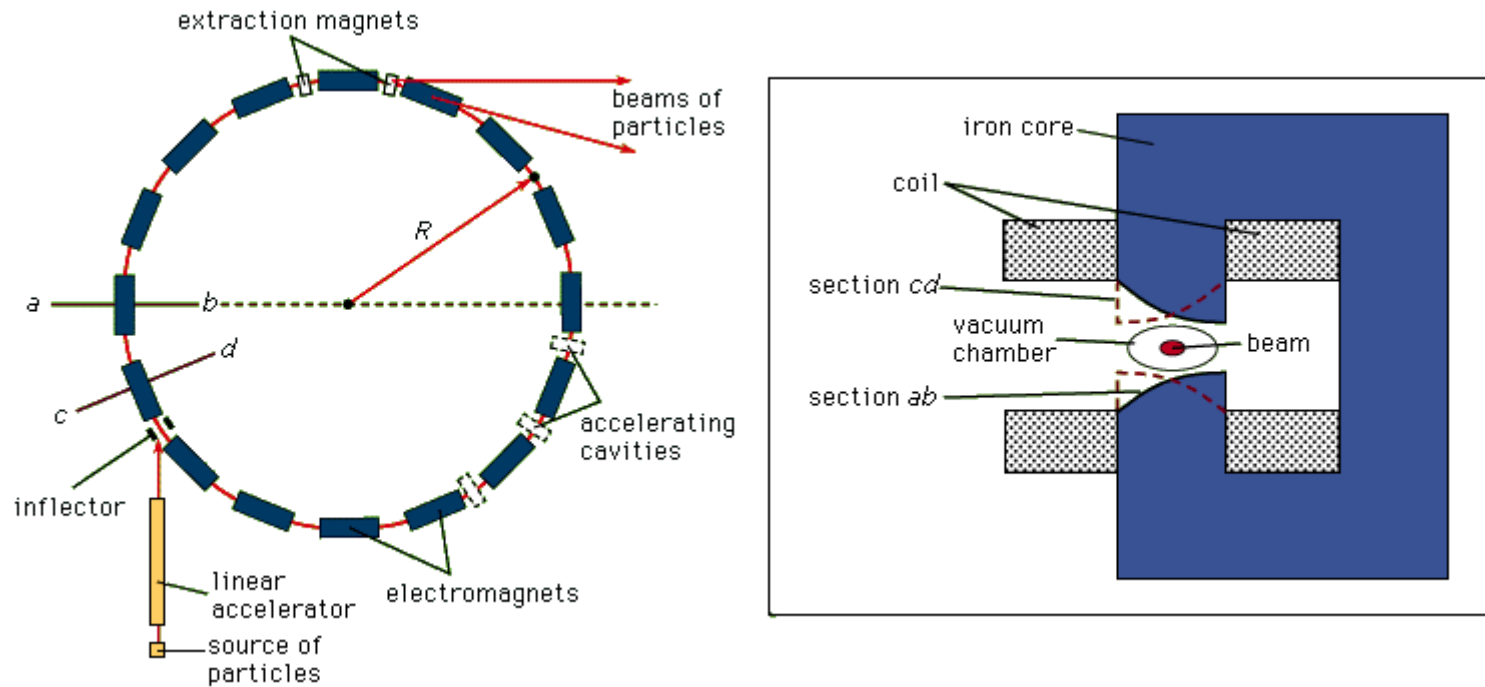


Figure 25: Schematic layout of a synchrotron

❖ **Synchrotrons are the most widely used circular accelerators**

- Particle beam is constrained in a circular path by bending dipole magnets ( $\vec{F} = q \vec{v} \times \vec{B}$ )
- Accelerating cavities are placed along the ring ( $\vec{F} = q \vec{E}$ )



Figure 26: Large Hadron Collider at CERN accelerates protons

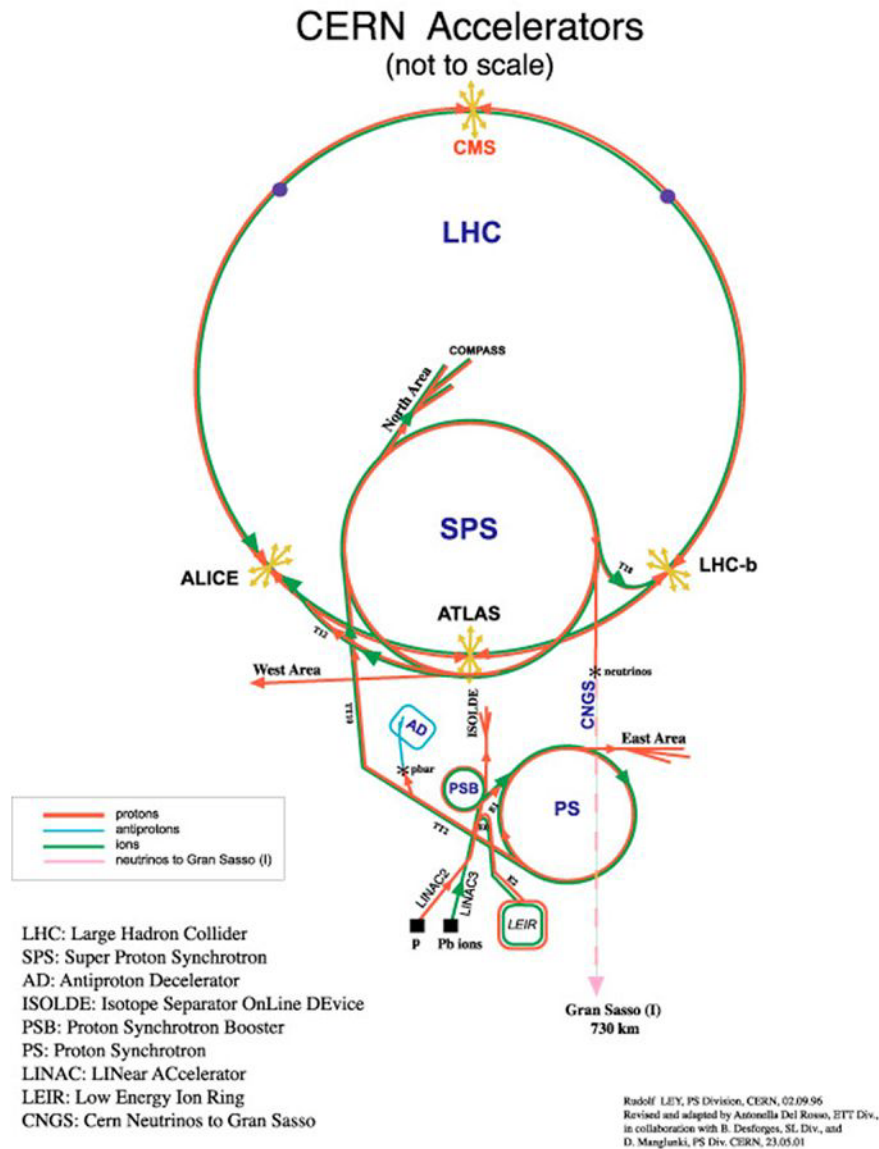


Figure 27: Scheme of the accelerator complex at CERN

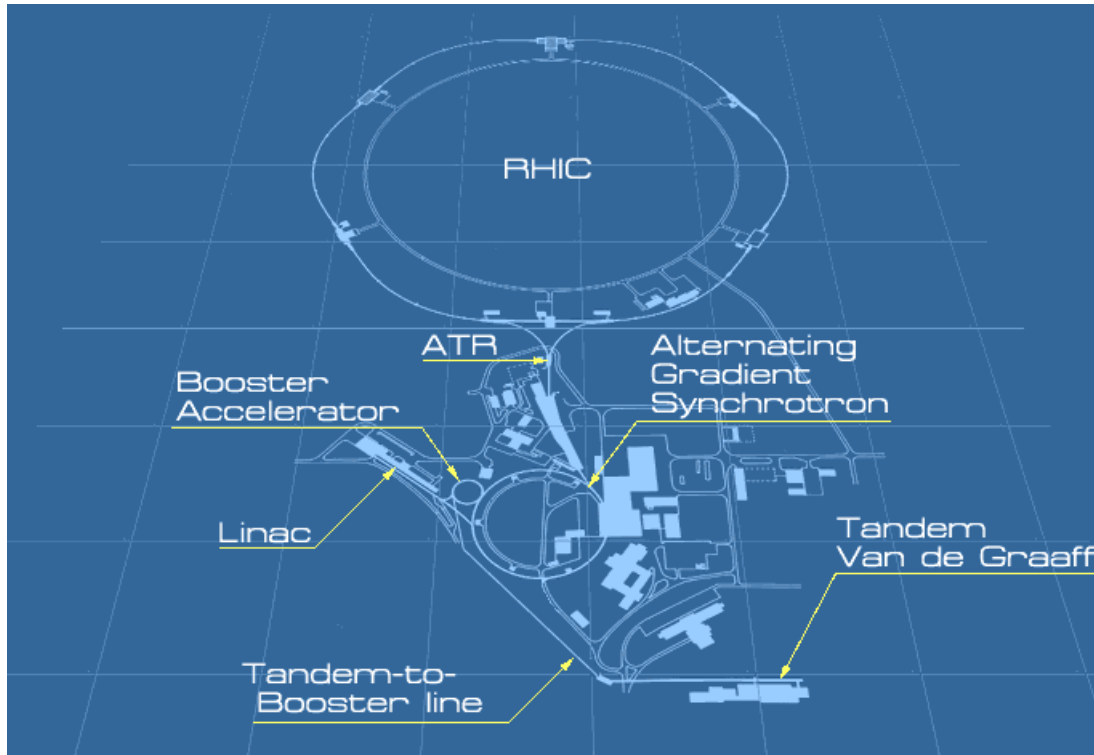


Figure 28: Scheme of the Relativistic Heavy Ion Collider (RHIC) accelerator complex at Brookhaven National Laboratory (left) and its RF cavity system (right).  
RHIC accelerates ions, from protons to gold



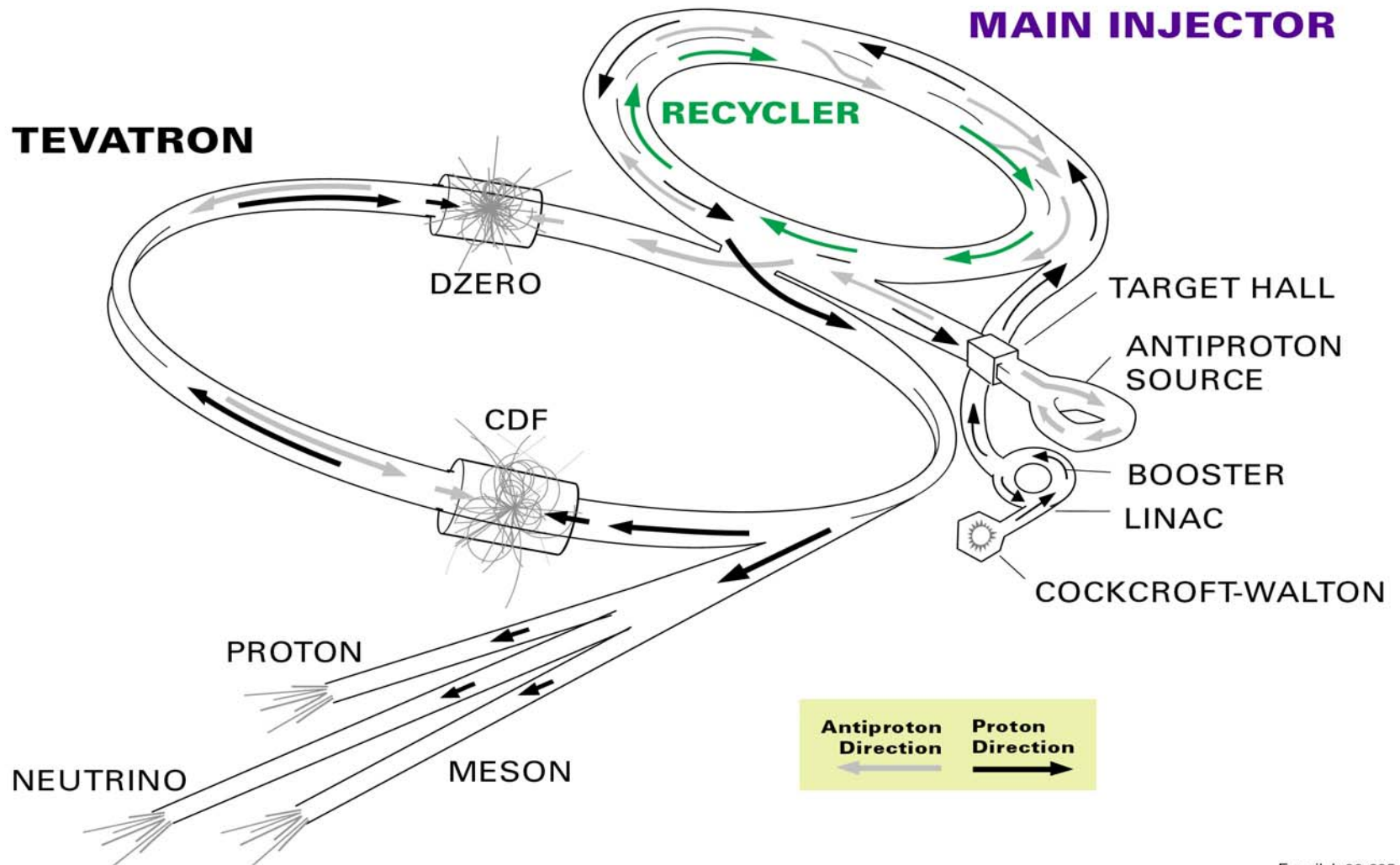


Figure 29: Tevatron accelerator chain at Fermilab.

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:

$$\Delta E = \frac{q^2 \beta^3 \gamma^4}{3 \epsilon_0 \rho} \quad (27)$$

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

$$p = 0.3B\rho \quad ([B]=\text{Tesla}, [\rho]=\text{meters}, [p]=\text{GeV}/c)$$

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  $\sim 2.8$  km, and magnetic field of  $\sim 8.3$  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.

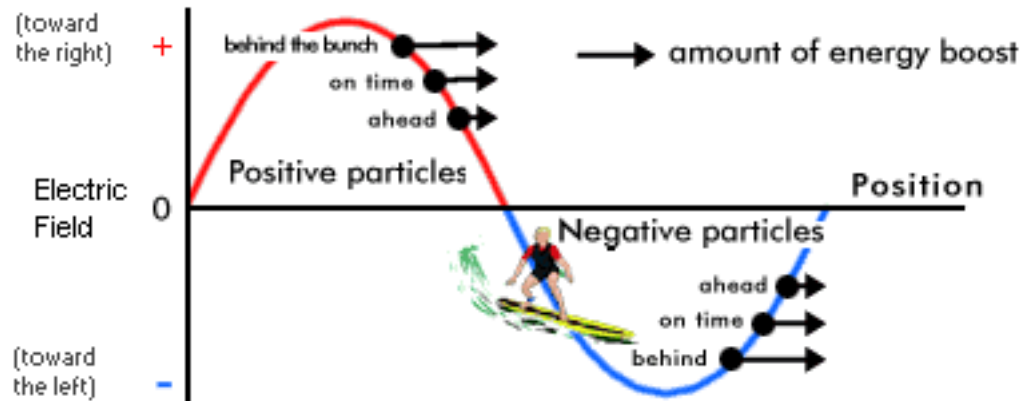


Figure 30: Effect of the electric field onto particles in accelerator cavities  
(*phase stability*)

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

# LHC DIPOLE CROSS SECTION

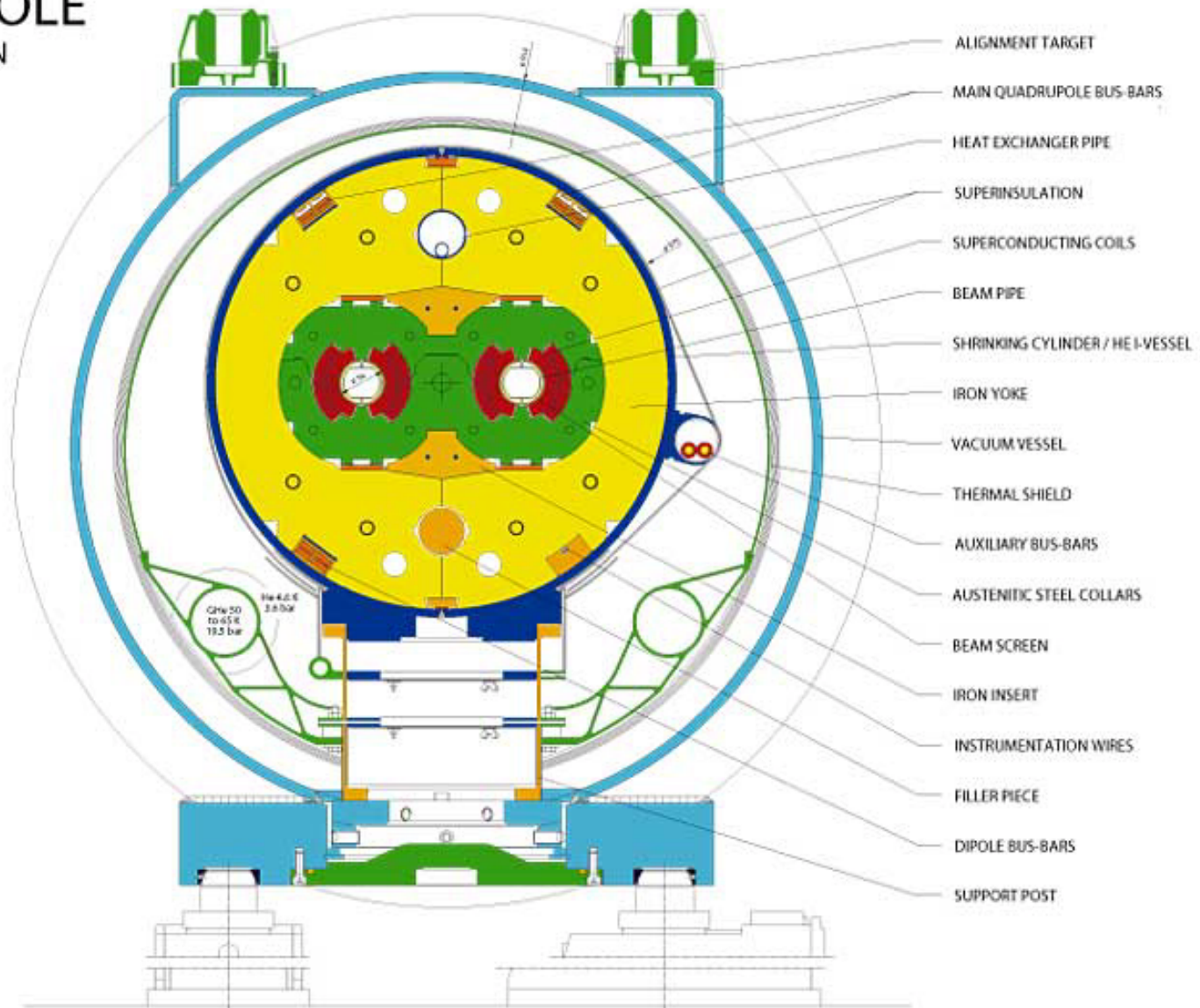


Figure 31: LHC dipole cross-section (note two pipes for proton beams)

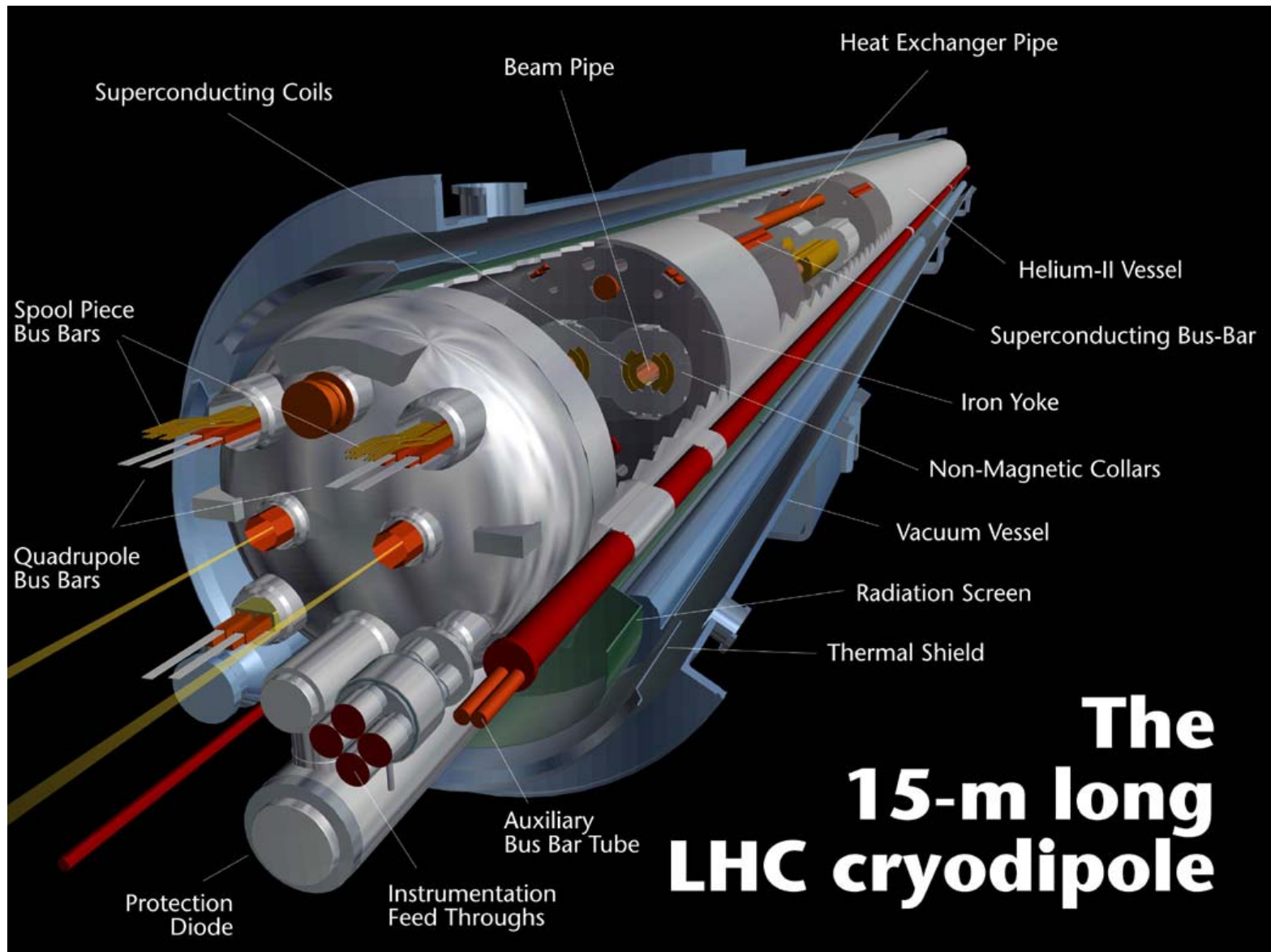


Figure 32: LHC dipole weighs 30 tons



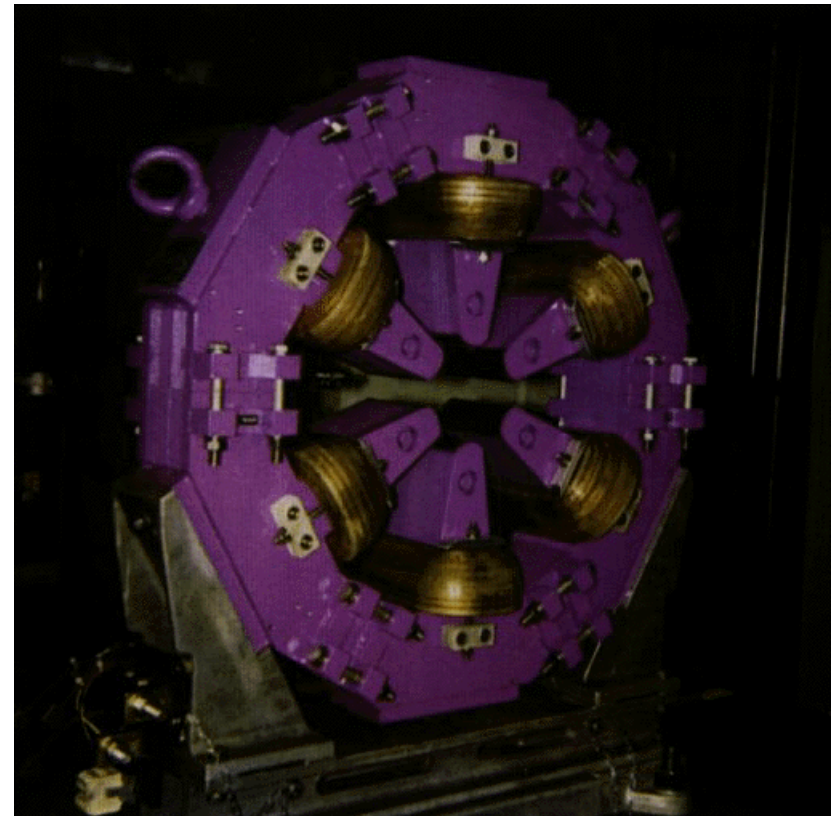
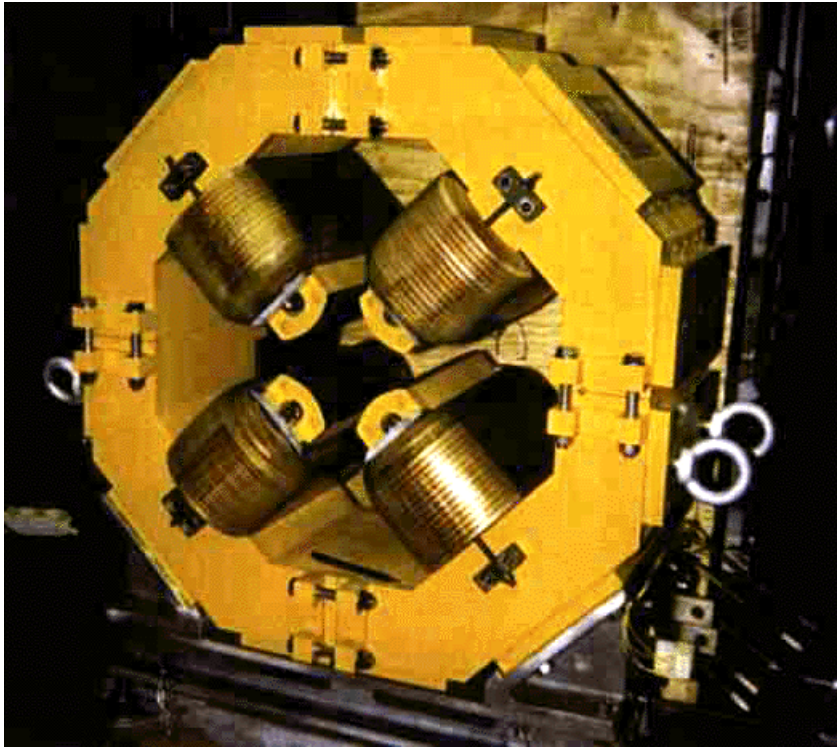
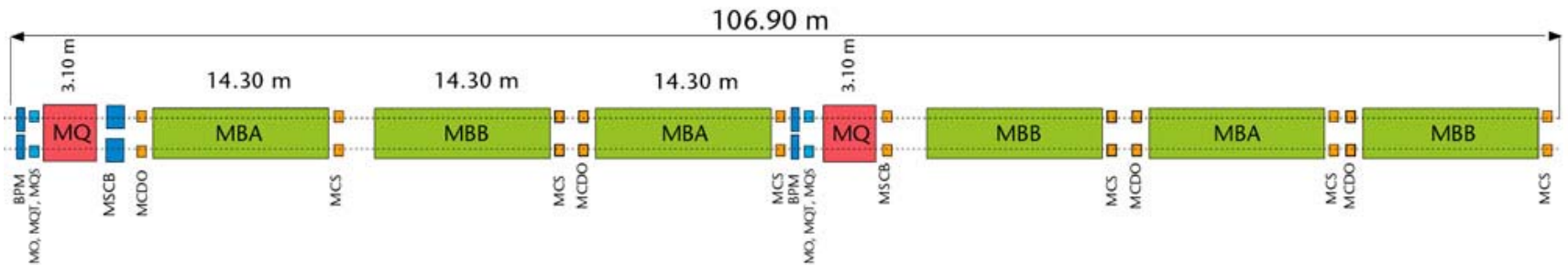


Figure 33: Quadrupole (left) and sextupole (right) magnets (not LHC)

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



- MQ: Lattice Quadrupole
- MO: Landau Octupole
- MQT: Tuning Quadrupole
- MQS: Skew Quadrupole
- MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
- BPM: Beam position monitor
- MBA: Dipole magnet Type A
- MBB: Dipole magnet Type B
- MCS: Local Sextupole corrector
- MCDO: Local combined decapole and octupole corrector

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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)

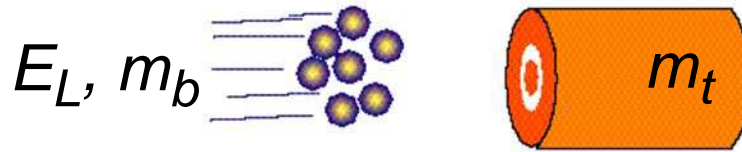


Figure 36: Scheme of a beam colliding with a fixed target;  $m_b$  is the beam particle mass and  $m_t$  is the target material mass,  $E_L$  is the beam energy

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

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

- ❖ 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	$E_{\text{beam}}$ (GeV)
<b>Tevatron II</b> (Fermilab, Illinois, USA)	synchrotron	p	1000
<b>SPS</b> (CERN, Geneva, Switzerland)	synchrotron	p	450
<b>SLAC</b> (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.



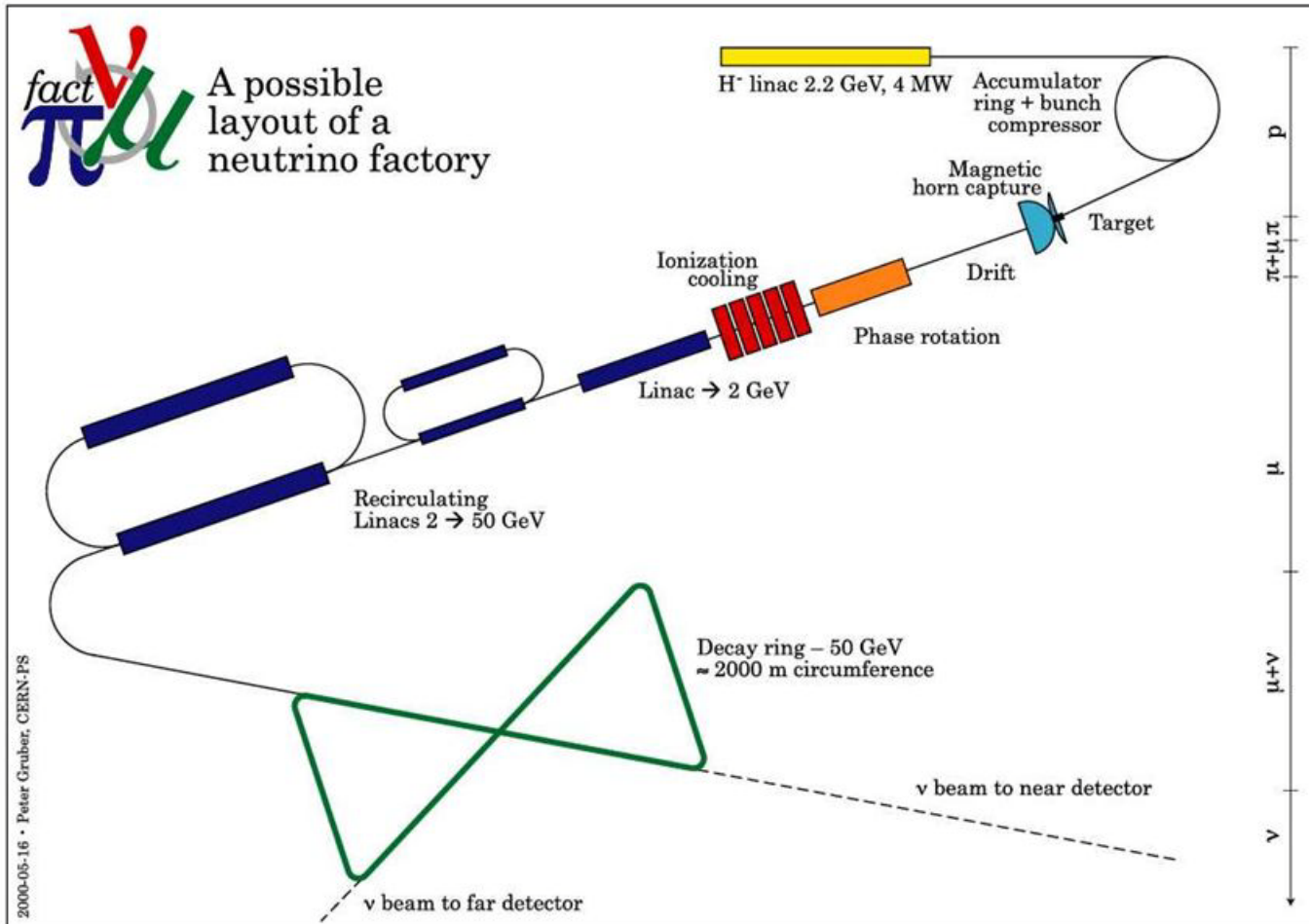


Figure 37: A possible neutrino factory

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

$$E_{CM}^2 = 2E_A E_B (1 + \cos\theta) \quad (29)$$

Problem: smaller probability for particles to collide

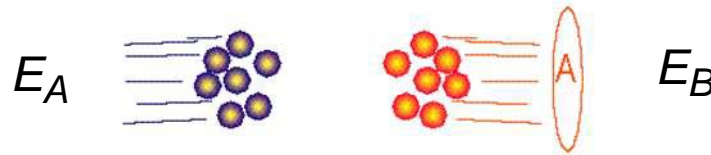


Figure 38: Scheme of colliding beams;  $E_A$  and  $E_B$  are respective beam energies

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

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

- $N$  : 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<sup>-2</sup>s<sup>-1</sup> at 7 TeV

Some colliders:

Machine	In operation	Particles	$E_{\text{beam}}$ (GeV)
<b>KEKB</b> (KEK, Tokyo, Japan)	1999-2010	$e^-, e^+$	8, 3.5
<b>PEP-II</b> (SLAC, California, USA)	1999-2008	$e^-, e^+$	9, 3.1
<b>LEP</b> (CERN, Geneva, Switzerland)	1989-2000	$e^-, e^+$	105
<b>HERA</b> (Hamburg, Germany)	1992-2007	$e^-, p$	30, 920
<b>Tevatron II</b> (Fermilab, Illinois, USA)	1987-2011	$p, \bar{p}$	1000
<b>LHC</b> (CERN, Geneva, Switzerland)	2008-	$p, p$ Pb	7000 for p
<b>RHIC</b> (Brookhaven, USA)	2000-	$p, Au, Cu, U$	28.3 - 250 for p

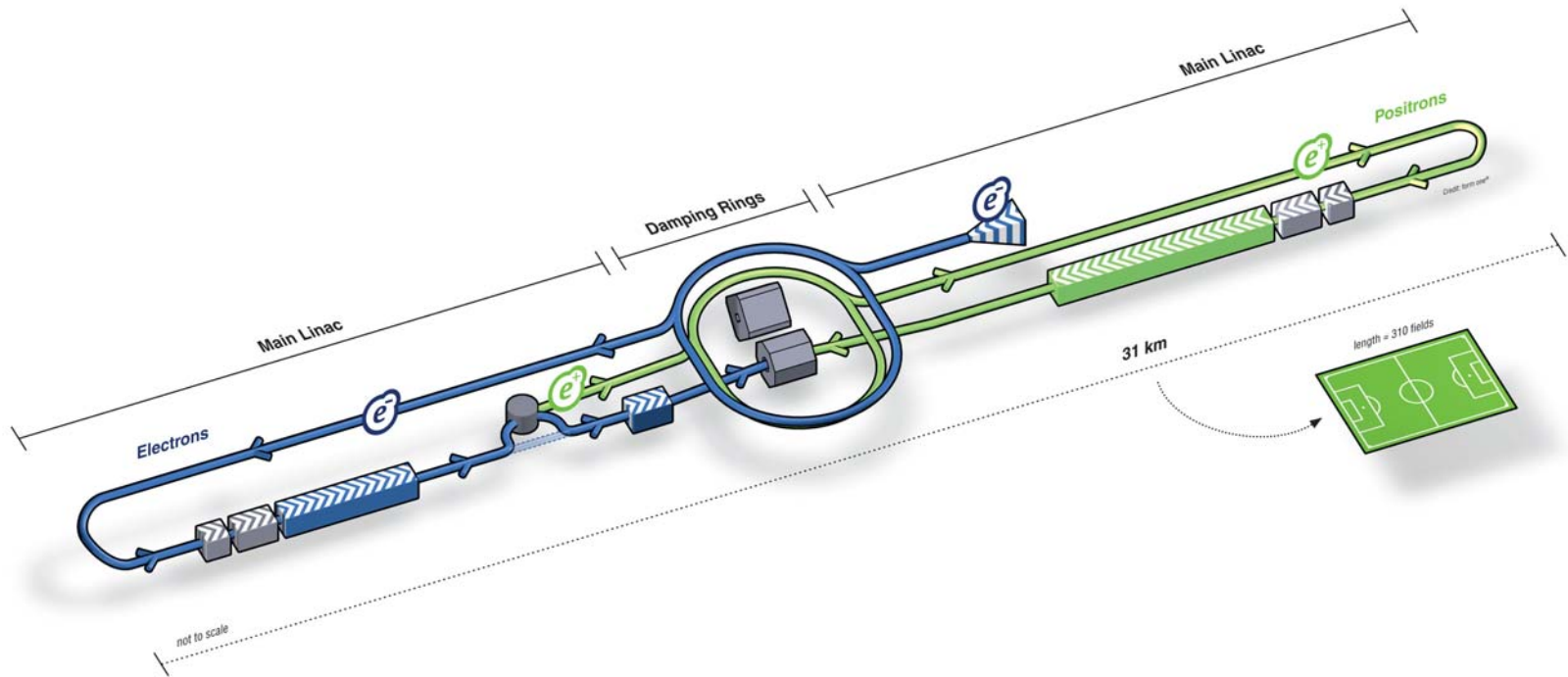
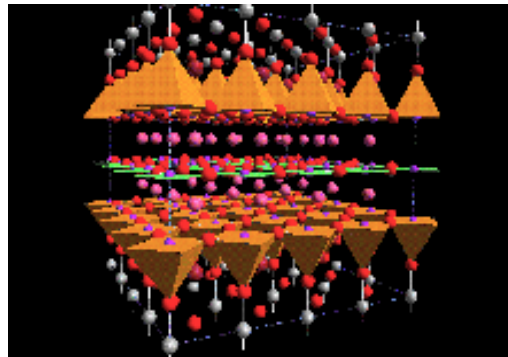


Figure 39: Possible future International Linear Collider (ILC)

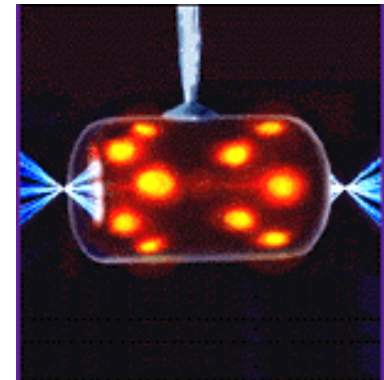
- ❖ Future research accelerators will be dedicated to precision measurements: have to provide electron-positron collisions at very high energies, up to 1 TeV



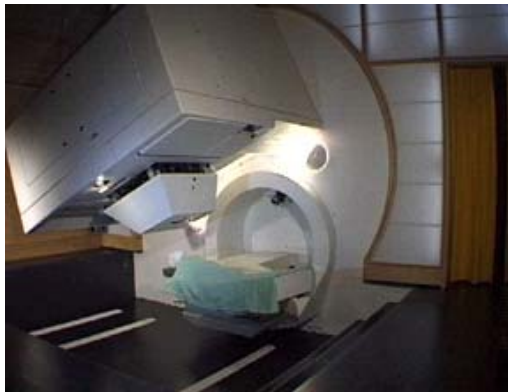
**Synchrotron light radiation (ESRF)**  
5' exonuclease from bacteriophage T5



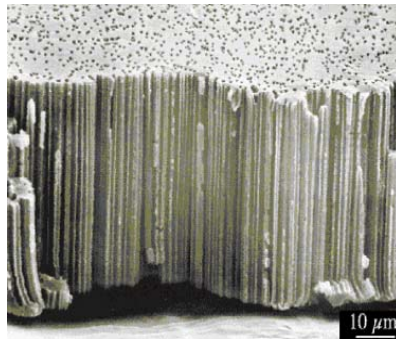
**Spallation Neutron diffraction (ISIS)**  
Structure of HighTC semiconductor



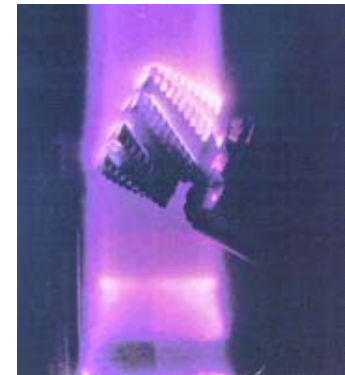
**Heavy ion fusion**  
Laser beam simulation



**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)