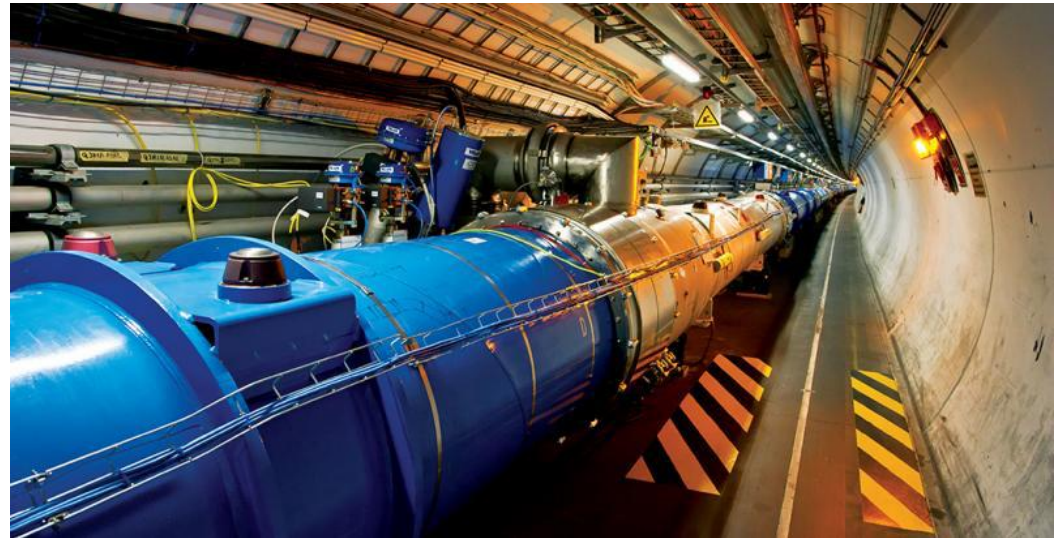


# Introduction to Accelerator Physics



**Frank Tecker**  
CERN - Beams Department

Many thanks to **Rende Steerenberg** for many of these slides!



# Contents

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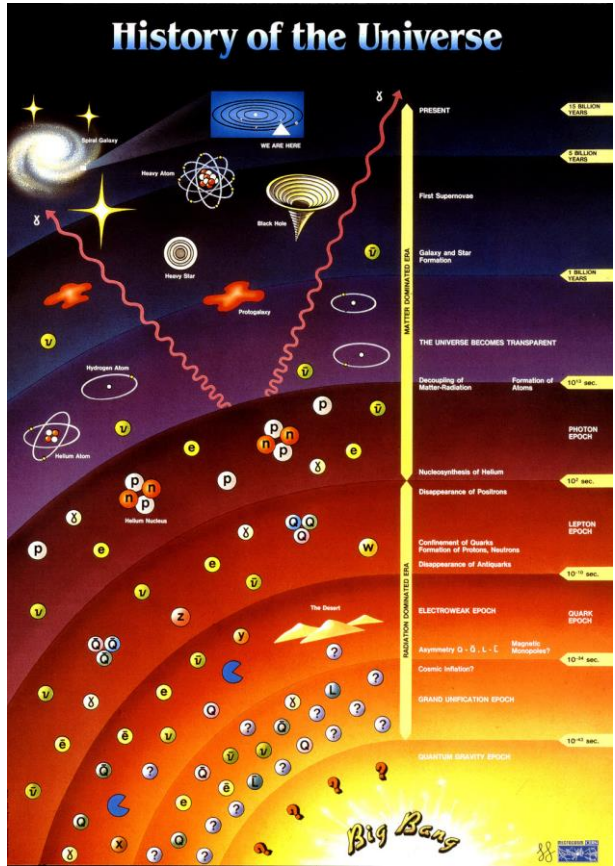
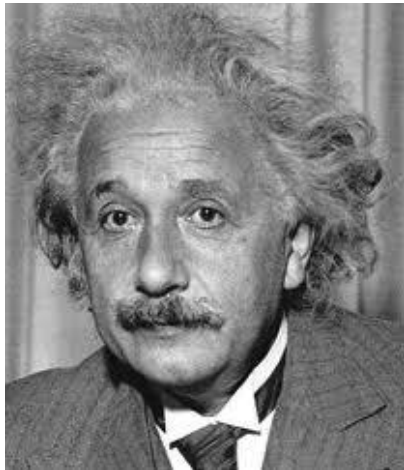
- Why Accelerators and Colliders ?
- A Brief Historic Overview
- The Main Ingredients of an Accelerator
- Some ways of using Accelerators

- 
- **Why Accelerators and Colliders ?**
  - A Brief Historic Overview
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  - Some ways of using Accelerators

# Matter versus Energy

$$E = m c^2$$

During the Big Bang  
Energy was transformed in matter



In our accelerators we provide energy to the particle we accelerate.  
In the detectors we observe the matter

# Looking to smaller dimensions

## Visible light

$\lambda = 400 \rightarrow 700 \text{ nm}$



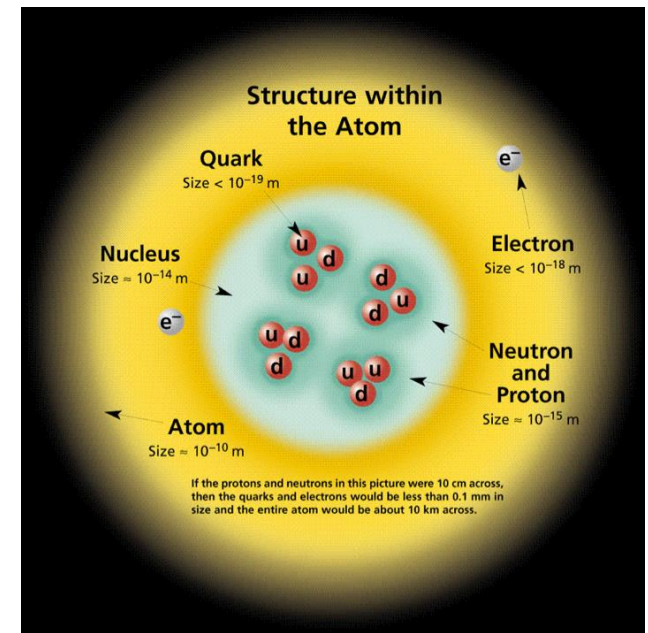
## X-ray

$\lambda = 0.01 \rightarrow 10 \text{ nm}$



## Particle accelerators

$\lambda < 0.01 \text{ nm}$



$$\lambda = \frac{h c}{E}$$

Increasing the energy will reduce the wavelength



# Fixed Target vs. Colliders

## Fixed Target



$$E \propto \sqrt{E_{beam}}$$

Much of the energy is lost in the target and only part results in usable secondary particles

## Collider



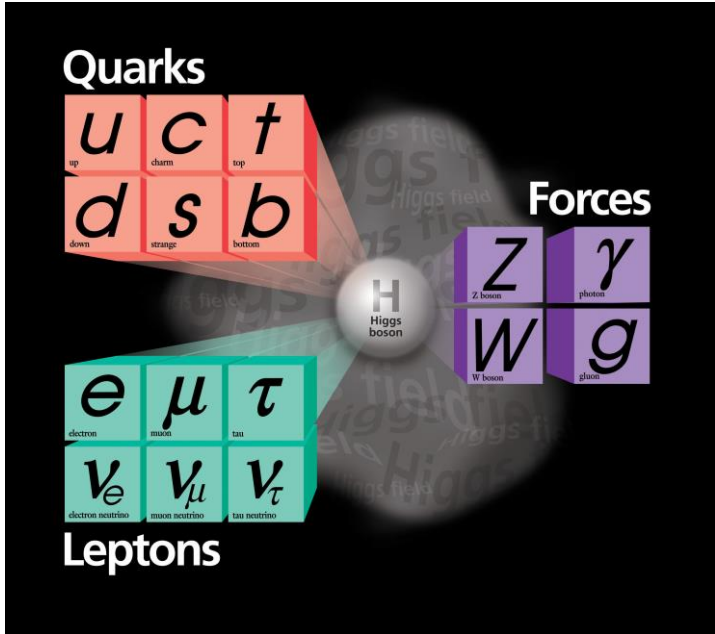
$$E = E_{beam1} + E_{beam2}$$

All energy will be available for particle production

# The Aim

Understanding Nature!

Verify and improve the Standard Model



Discover the Higgs boson

Search for physics beyond the Standard Model  
Such as dark matter and dark energy

- 
- Why Accelerators and Colliders ?
  - **A Brief Historic Overview**
  - The Main Ingredients of an Accelerator
  - Some ways of using Accelerators



# Accelerators and Their Use

*\*Source: Beschleuniger  
Komitee für Beschleunigerphysik*



Today: ~ **35'000 accelerators** operational world-wide\*

The **large majority** is used in **industry**  
and **medicine**

Industrial applications: ~ 24'000\*

- Ion doping
- Chip production
- Sterilisation
- X-ray analysis

Medical applications: ~ 11'000\*

- Cancer treatment
- Radioactive isotope production

**Less than a fraction of a percent** is used  
for **research** and discovery science

Cyclotrons

FFAG

Synchrotrons

Synchrotron light sources ( $e^-$ )

Lin. & Circ. accelerators/Colliders

# Unit of Energy

Today's high-energy accelerators and future projects work/aim at the **TeV energy** range.

LHC: 7 TeV -> 14 TeV

CLIC: 3 TeV

HE/VHE-LHC: 33/100 TeV

In fact, this energy unit comes from acceleration:

**1 eV (electron Volt)** is the energy that 1 elementary charge  $e$  (like one electron or proton) gains when it is accelerated in a potential (voltage) difference of 1 Volt.

**Basic Unit: eV (electron Volt)**

keV = 1000 eV =  $10^3$  eV

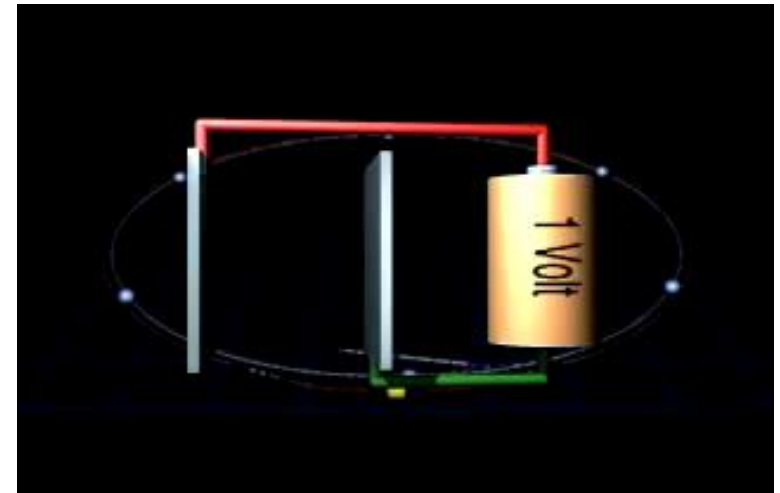
MeV =  $10^6$  eV

GeV =  $10^9$  eV

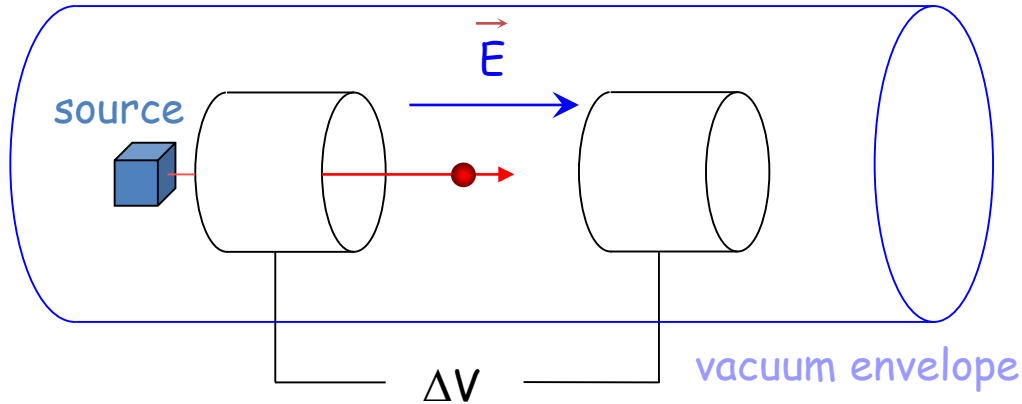
TeV =  $10^{12}$  eV

LHC = ~450 Million km of batteries!!!

3x distance Earth-Sun



# Electrostatic Acceleration



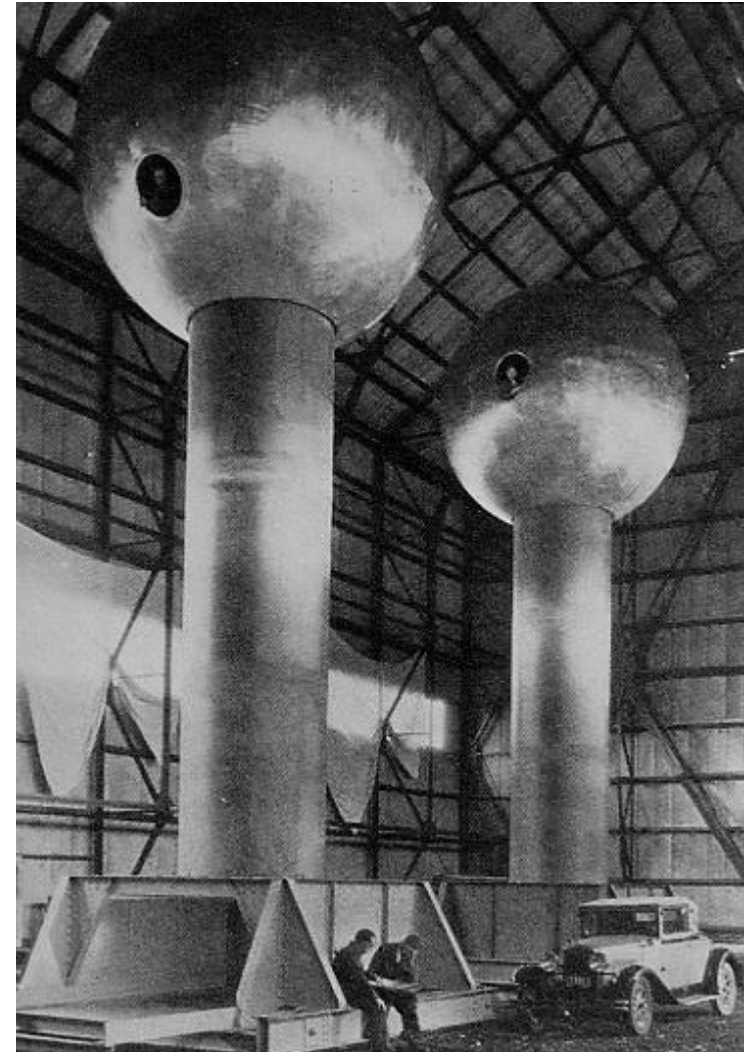
## Electrostatic Field:

Force: 
$$\vec{F} = \frac{d\vec{p}}{dt} = e \vec{E}$$

Energy gain:  $W = e \Delta V$

used for first stage of acceleration: particle sources, electron guns, x-ray tubes

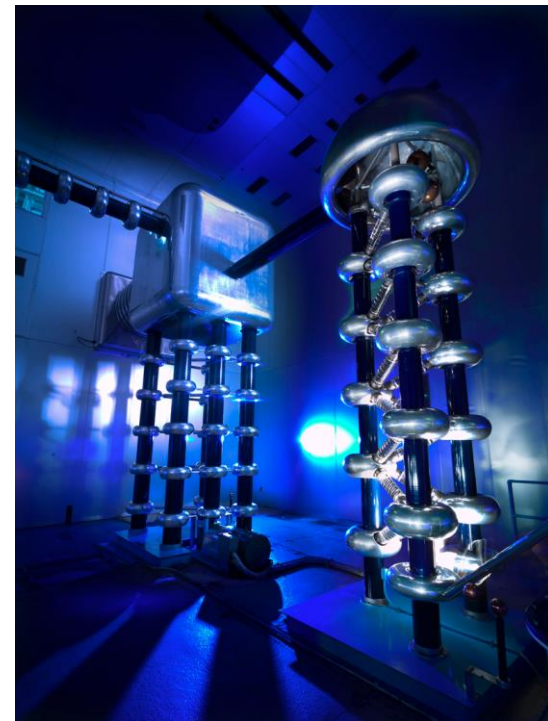
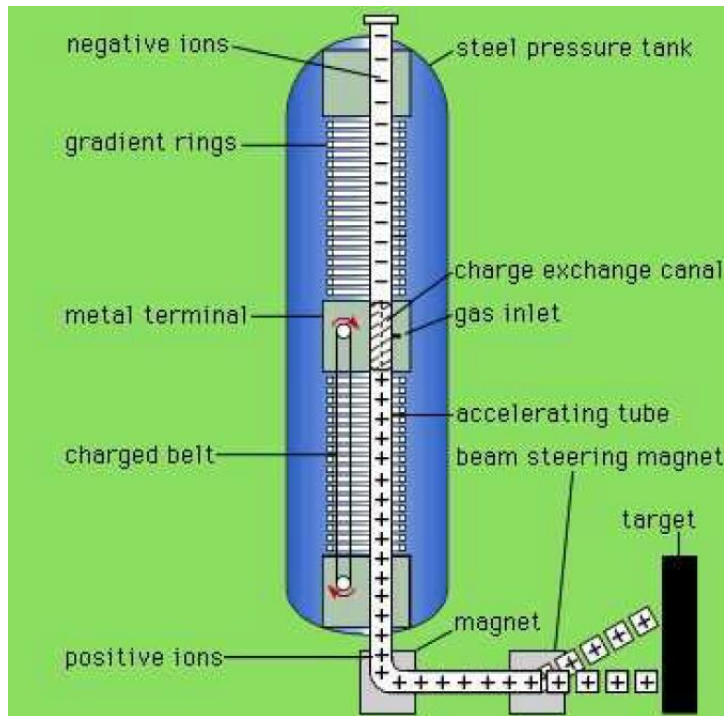
Limitation: **insulation problems**  
maximum high voltage ( $\sim 10$  MV)



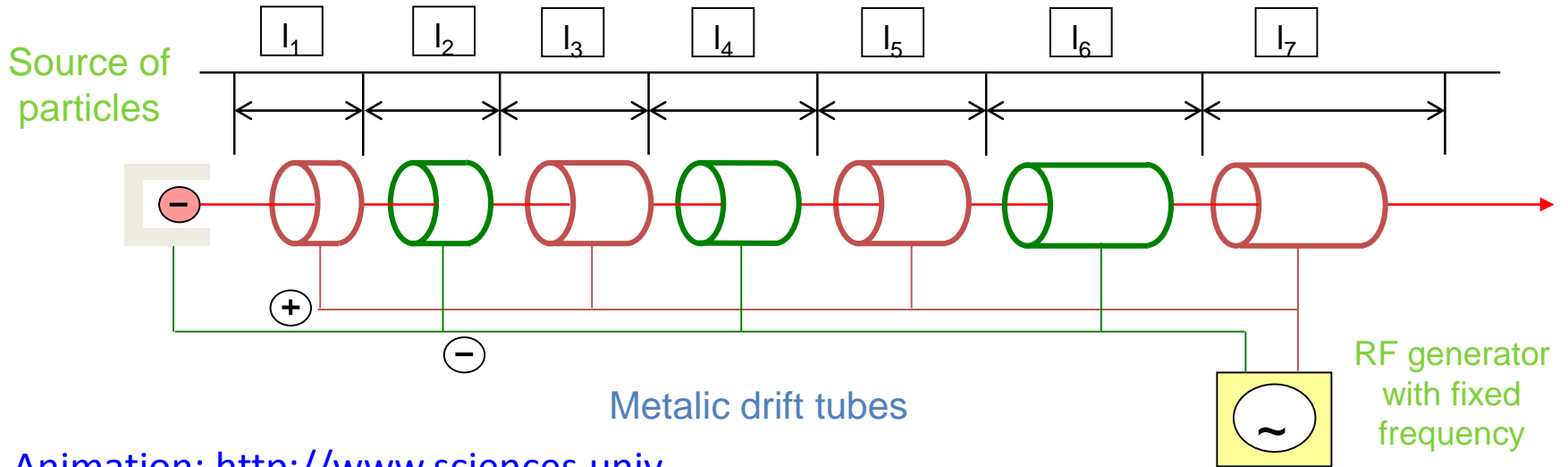
Van-de-Graaf generator at MIT

# Cockroft & Walton / van de Graaff

- 1932: First accelerator – single passage 160 - 700 keV
- Static voltage accelerator
- Limited by the high voltage needed



# Linear Accelerator



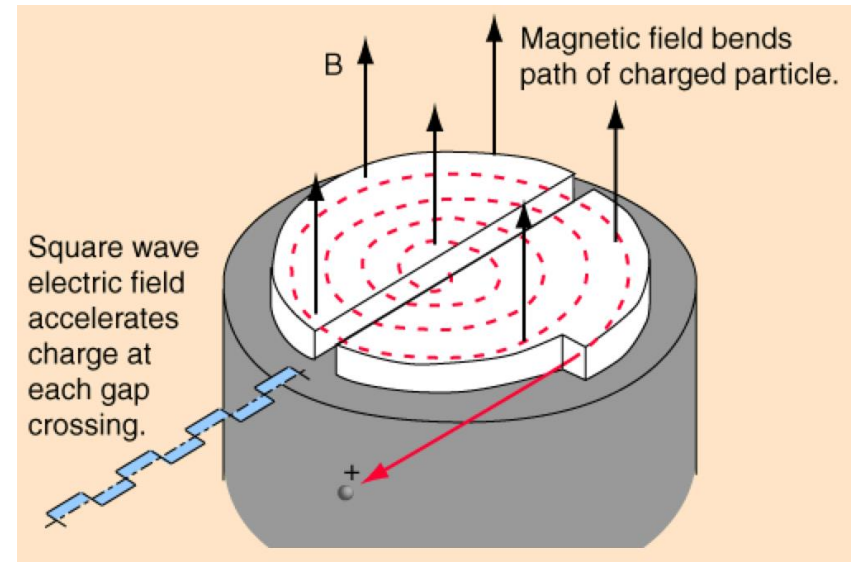
Animation: [http://www.sciences.univ-nantes.fr/sites/genevieve\\_tulloue/Meca/Charges/linac.html](http://www.sciences.univ-nantes.fr/sites/genevieve_tulloue/Meca/Charges/linac.html)

- Many people involved: Wideroe, Sloan, Lawrence, Alvarez,....
- Main development took place between 1931 and 1946.
- Development was also helped by the progress made on high power high frequency power supplies for radar technology.
- Today still the first stage in many accelerator complexes.
- Limited by energy due to length and single pass.

# Cyclotron

- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- Constant magnetic field
- Alternating voltage between the two hollow D's
- Increasing particle orbit radius
- Development lead to the synchro-cyclotron to cope with the relativistic effects.

In 1939 Lawrence received the Noble prize for his work.





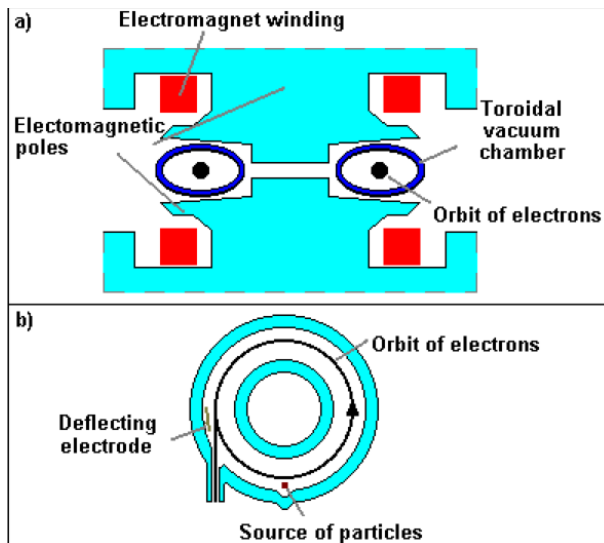
# Circular accelerators: Cyclotron



Courtesy Berkeley Lab,  
<https://www.youtube.com/watch?v=cutKuFxeXmQ>

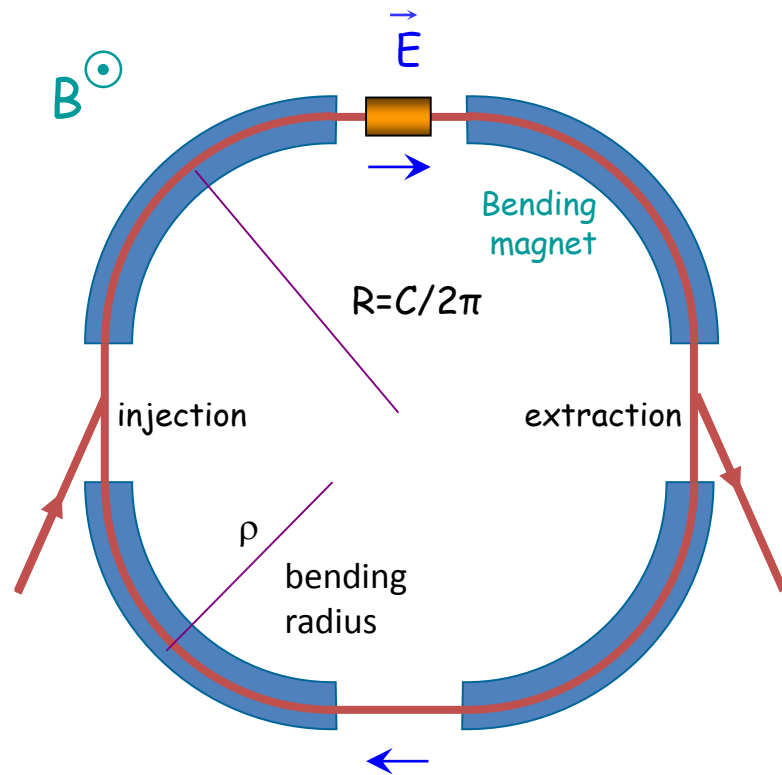
# Betatron

- 1940: Kerst 2.3 MeV and very quickly 300 MeV
- It is actually a transformer with a beam of electrons as secondary winding.
- The magnetic field is used to bend the electrons in a circle, but also to accelerate them.
- A deflecting electrode is used to deflect the particle for extraction.



# Synchrotrons

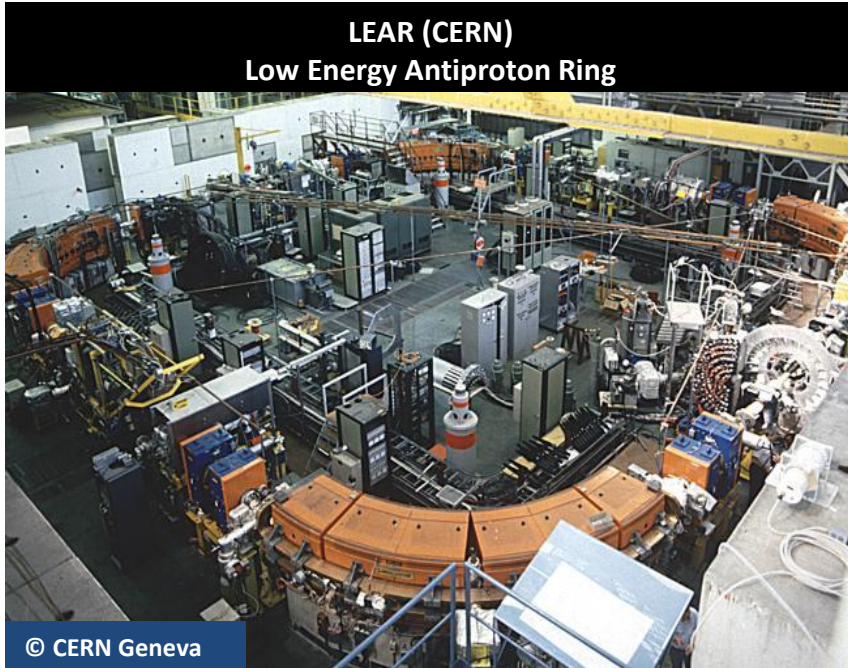
- 1943: M. Oliphant described his synchrotron invention in a memo to the UK Atomic Energy directorate



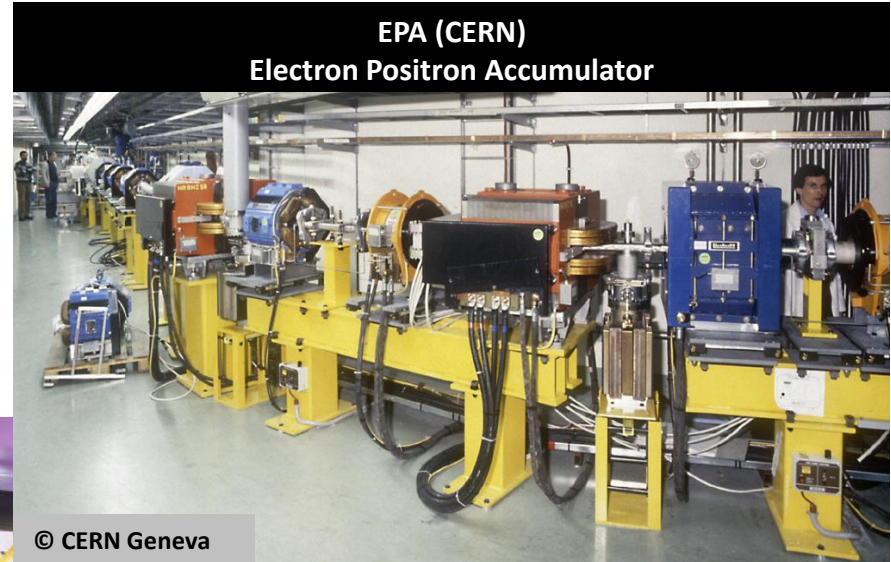
- 1959: CERN-PS and BNL-AGS
- Fixed radius for particle orbit
- Varying magnetic field and radio frequency
- Phase stability
- Important focusing of particle beams (Courant – Snyder)
- Providing beam for fixed target physics
- Paved the way to colliders

# Circular accelerators: The Synchrotron

**LEAR (CERN)**  
Low Energy Antiproton Ring

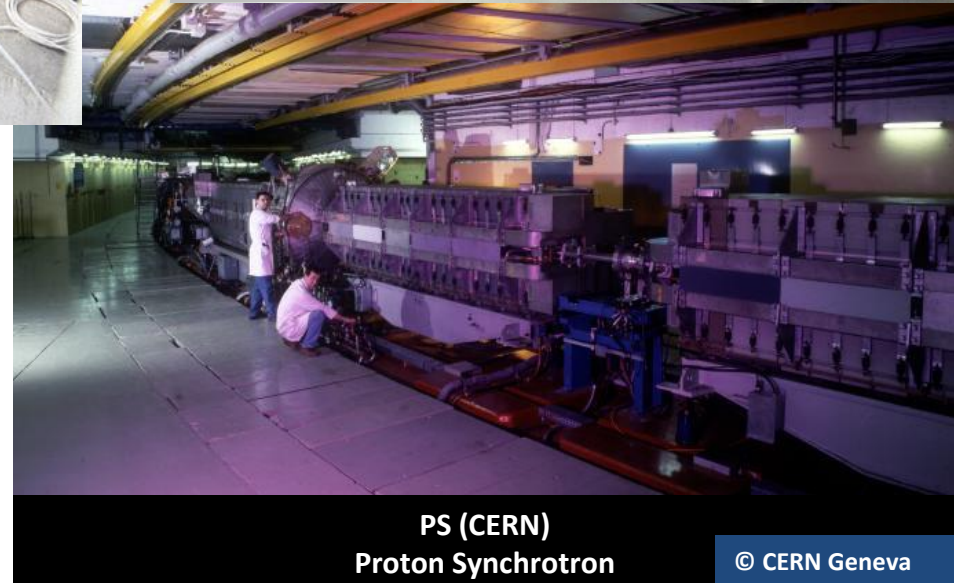


**EPA (CERN)**  
Electron Positron Accumulator



Examples of different  
proton and electron  
synchrotrons at CERN

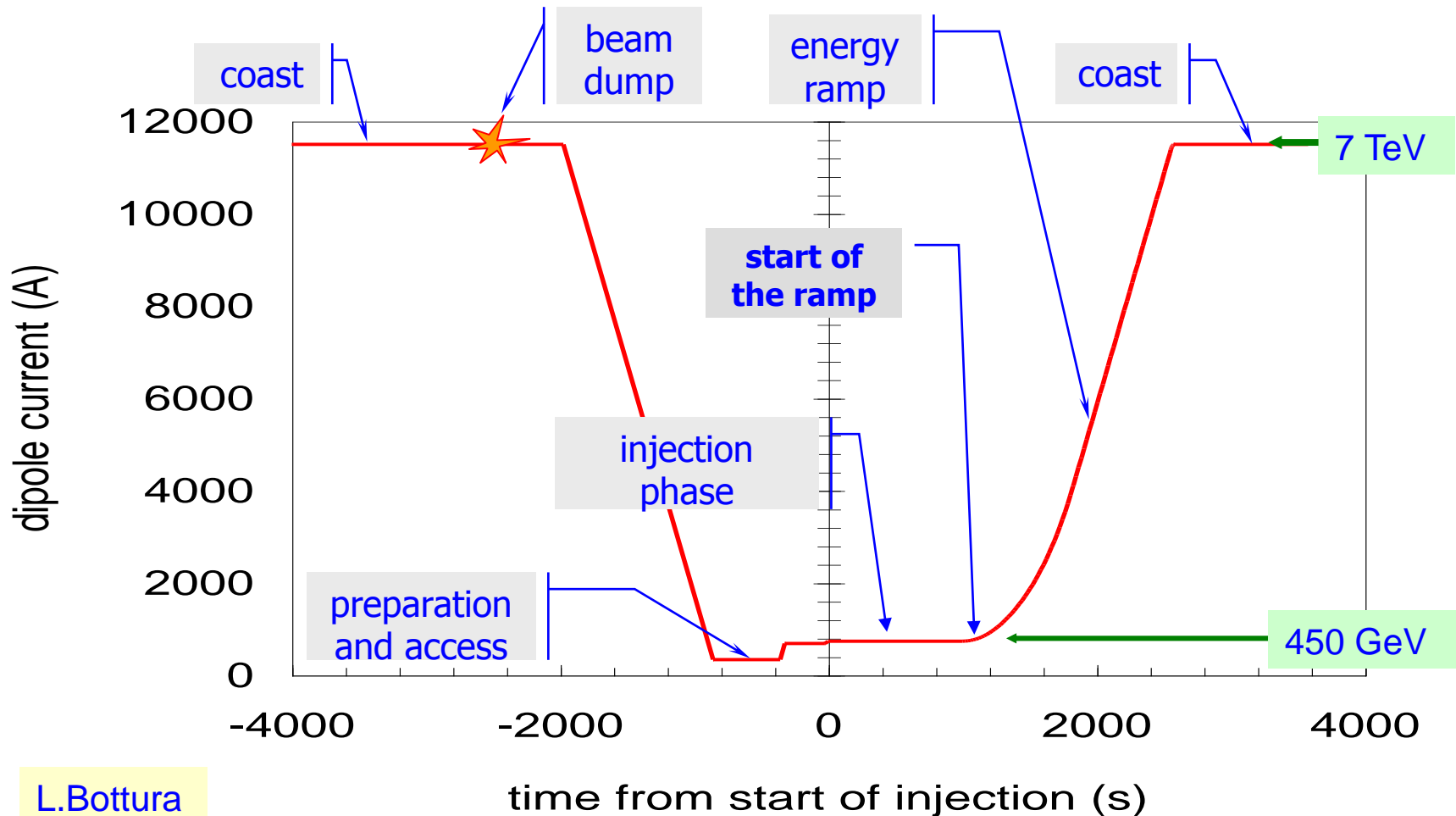
+ LHC (of course!)





# The Synchrotron – LHC Operation Cycle

The magnetic field (dipole current) is **increased during the acceleration**.

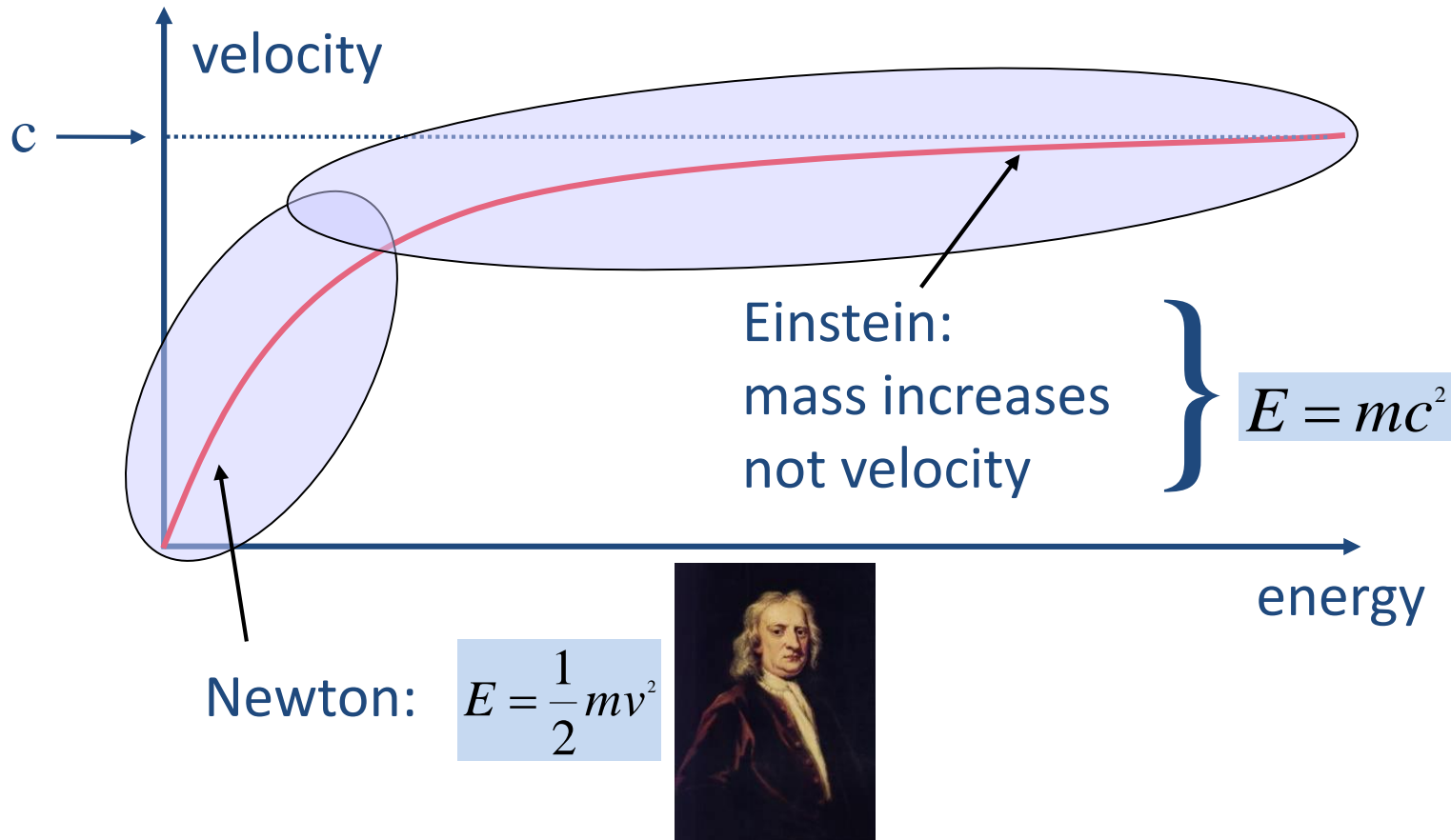


L.Bottura

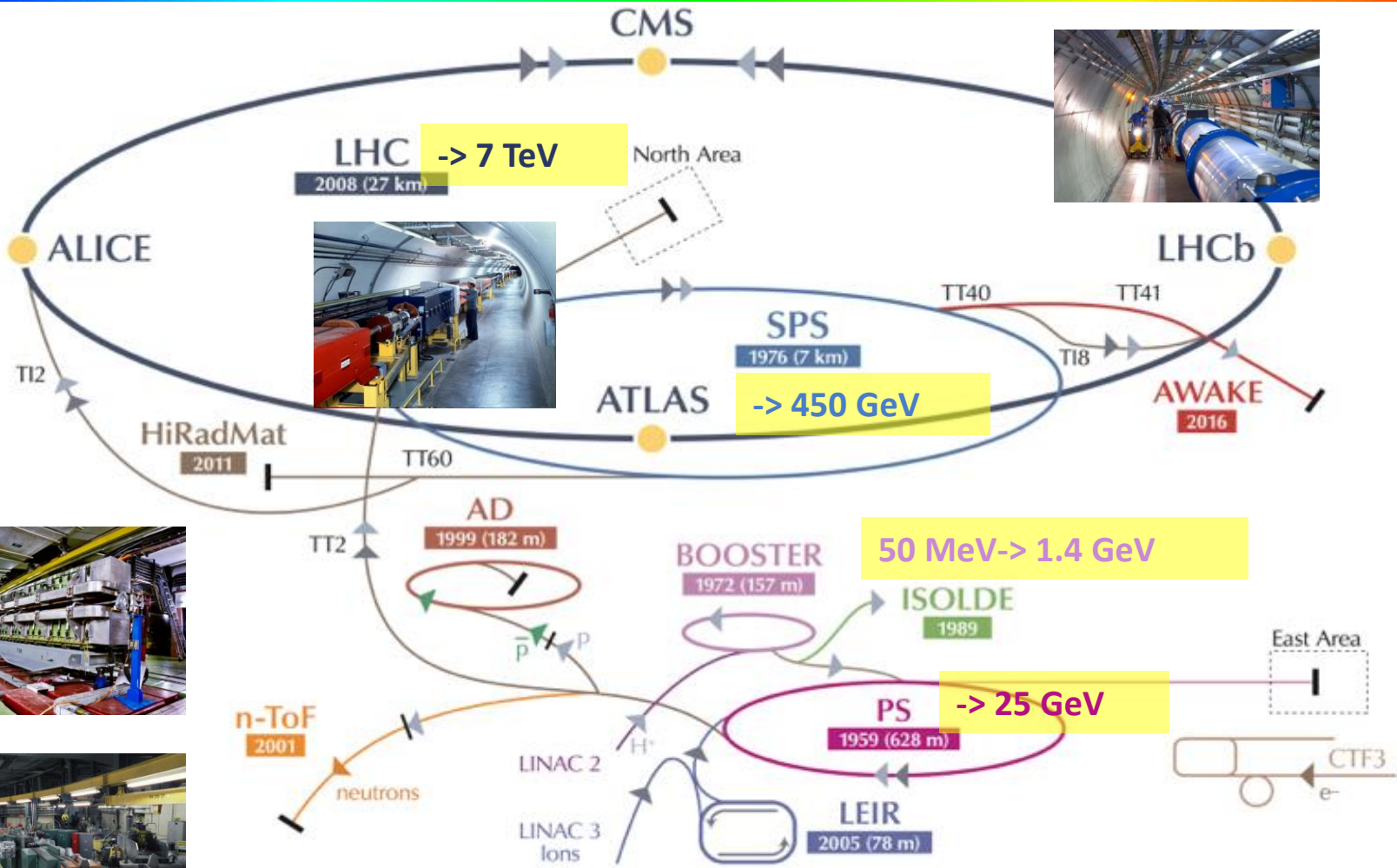
- Why Accelerators and Colliders ?
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# Towards Relativity



# The CERN Accelerator Complex



▶ p (proton)    ▶ ion    ▶ neutrons    ▶  $\bar{p}$  (antiproton)    ▶ electron    ▶  $\leftrightarrow$  proton/antiproton conversion



# A Guided Tour

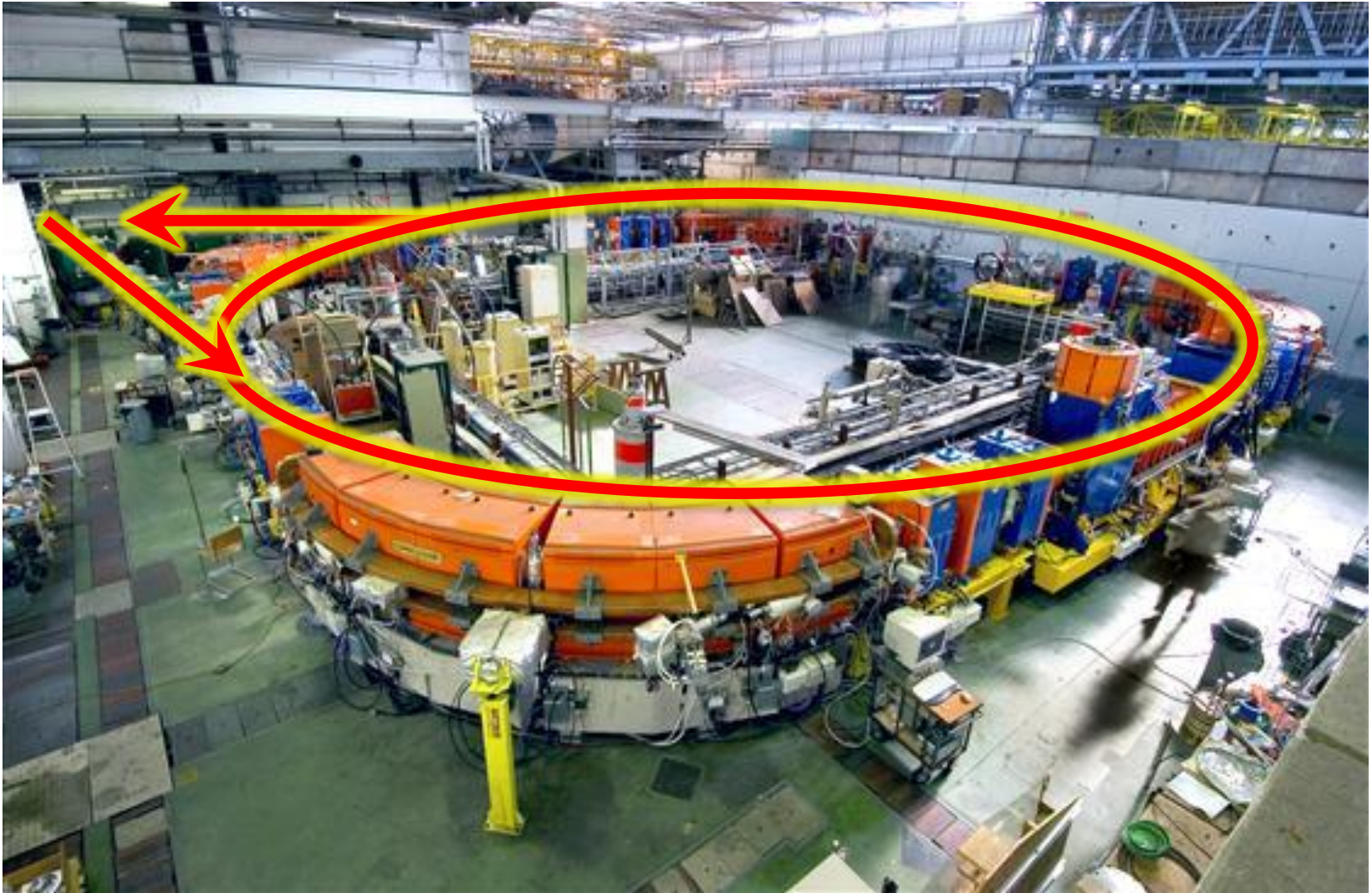
Lets have a look at a synchrotron:

- Identify the main components and processes
- Briefly address their function

As an example I took a machine at CERN that can be seen from the top, even when it is running.

**LEIR**  
**Low Energy Ion Ring**

# CERN - LEIR as an Example





# LEIR as an Example

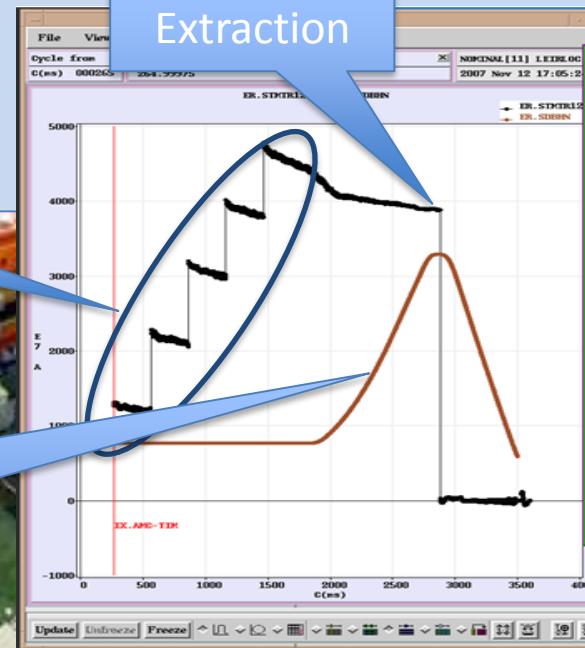
The particle beam:

- arrives through a transfer line from a LINAC
- is injected
- is accelerated and guided over many turns in a “circular” machine
- is extracted
- leaves through a transfer line

Injection(s)

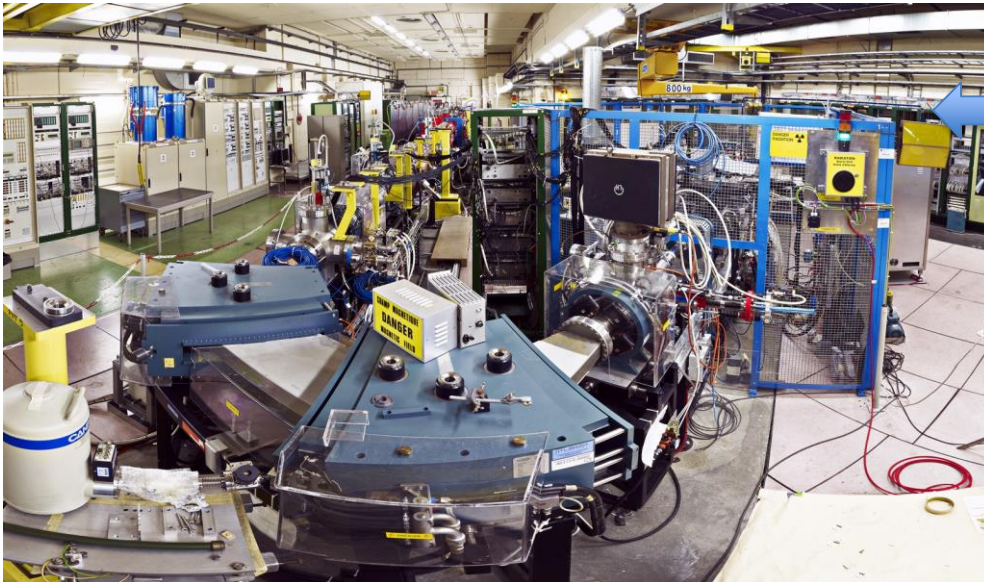
Acceleration  
&  
Increase of magnetic field

Extraction

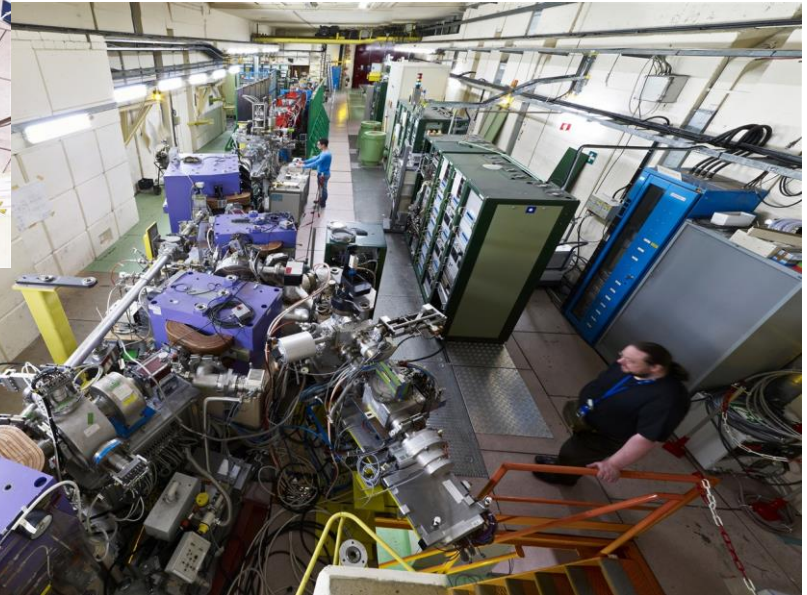


# LINAC 3, injector of LEIR

The CERN LINAC 3 provides different ion species to LEIR



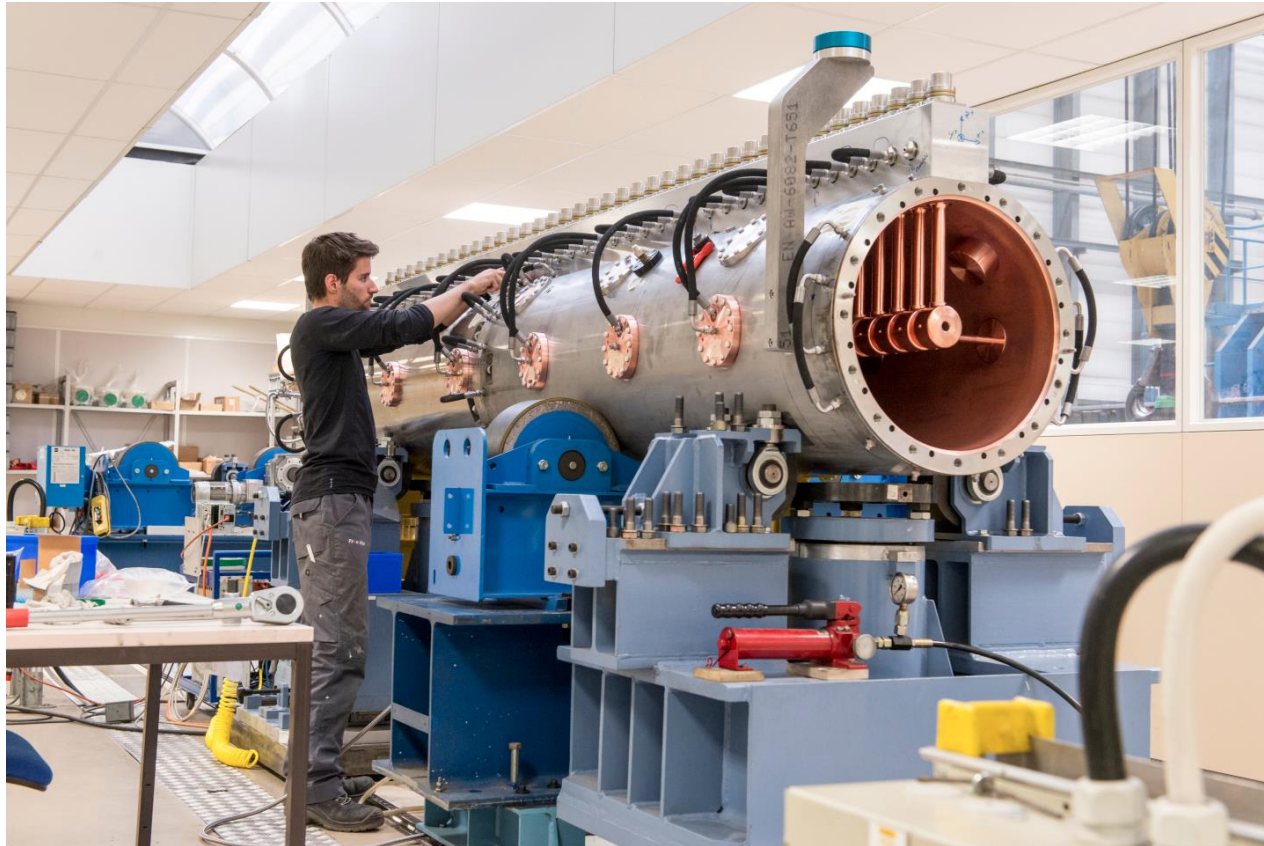
The ion source in the blue cage with the spectrometer in the front, follow by the LINAC behind



The downstream part of the LINAC with the accelerating structures (Alvarez) in the back of the image and transfer and measurement lines in the front

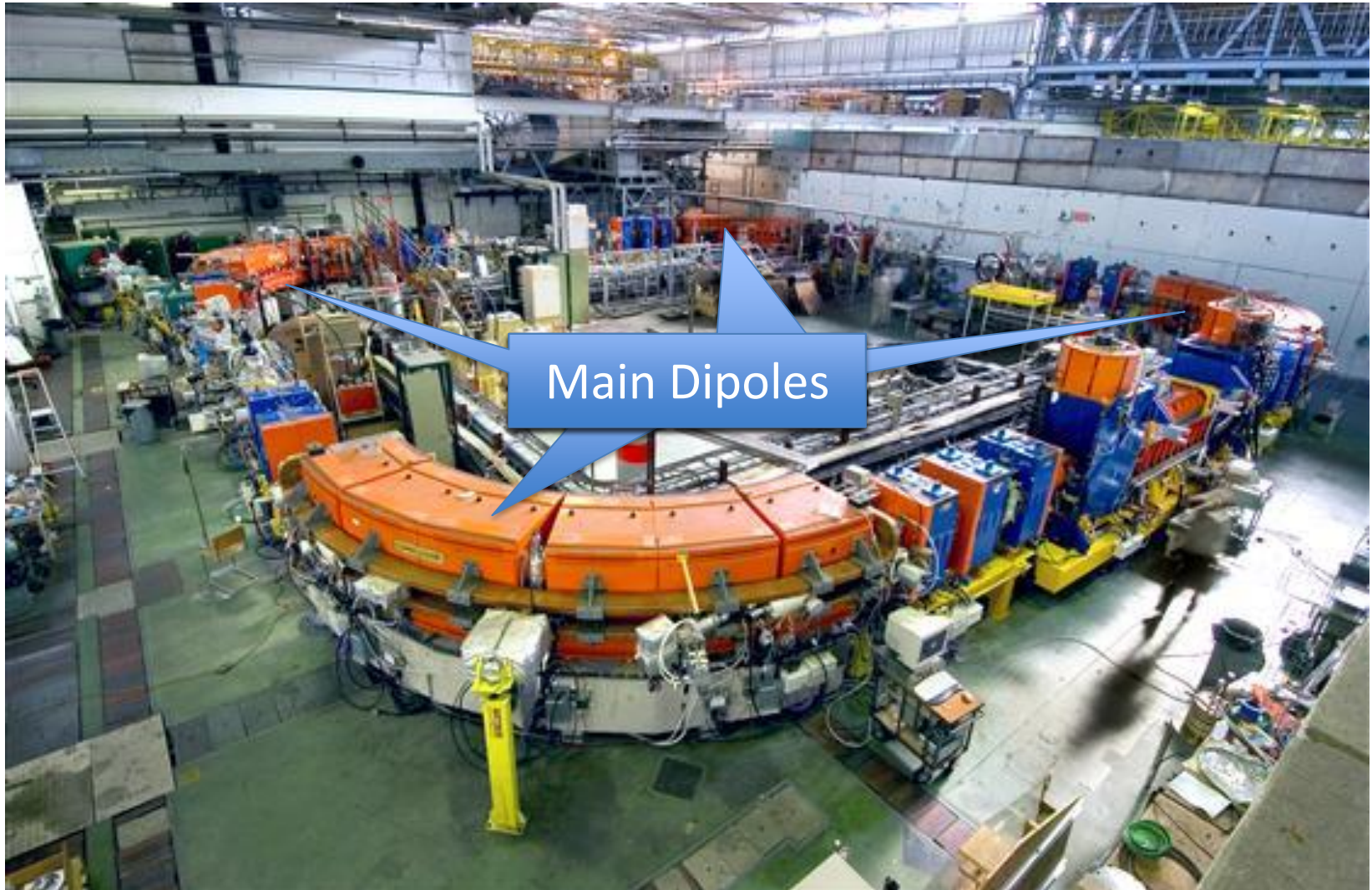


# LINAC Accelerating Structure



The CERN LINAC 4 drift tube

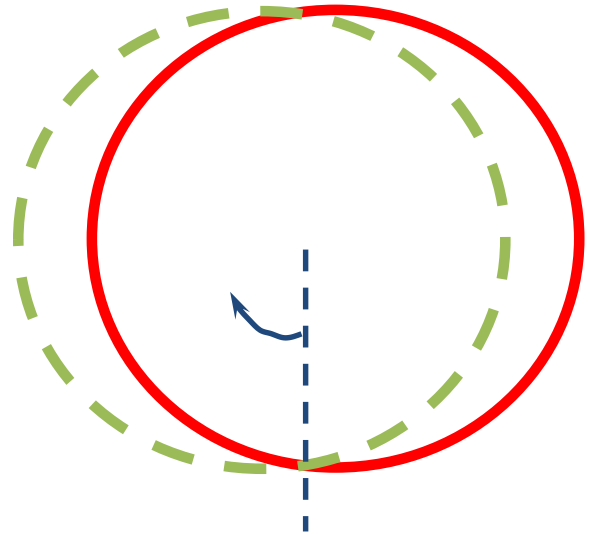
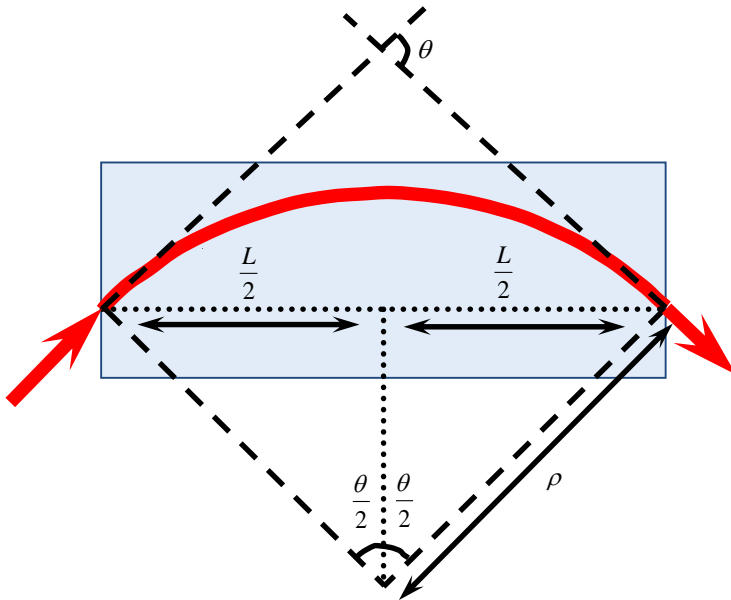
# Make Particles Circulate



# Charged Particles Deviated - Dipoles

Charged Particles are deviated in magnetic fields

Two charged Particles in a homogeneous magnetic field



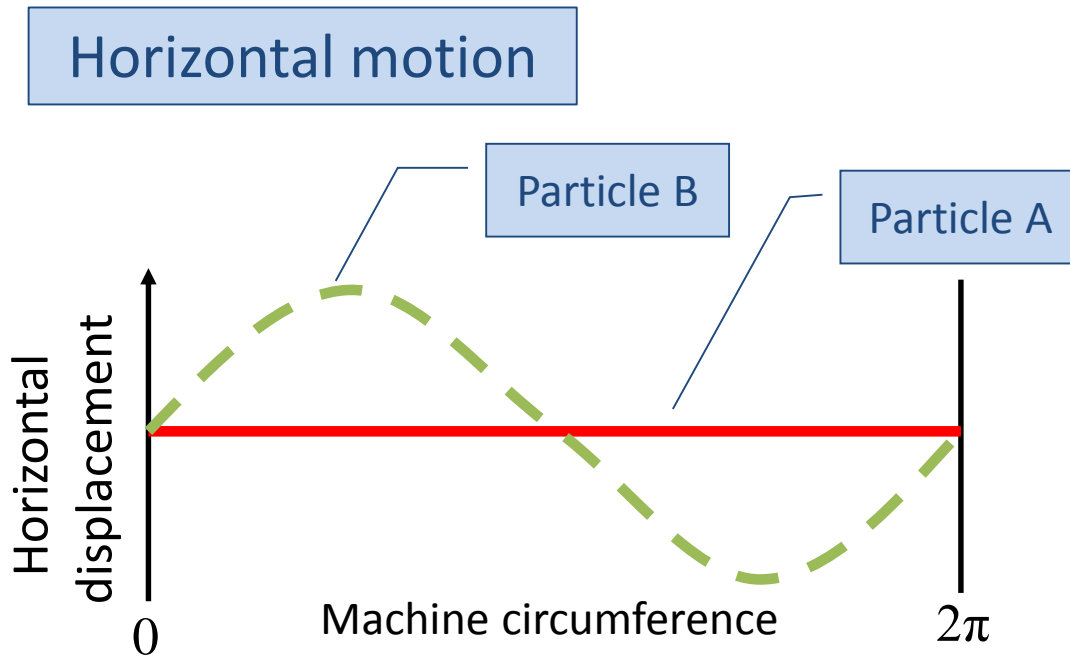
Lorentz force:

$$F = e(\vec{v} \times \vec{B})$$

— Particle A  
 - - - Particle B

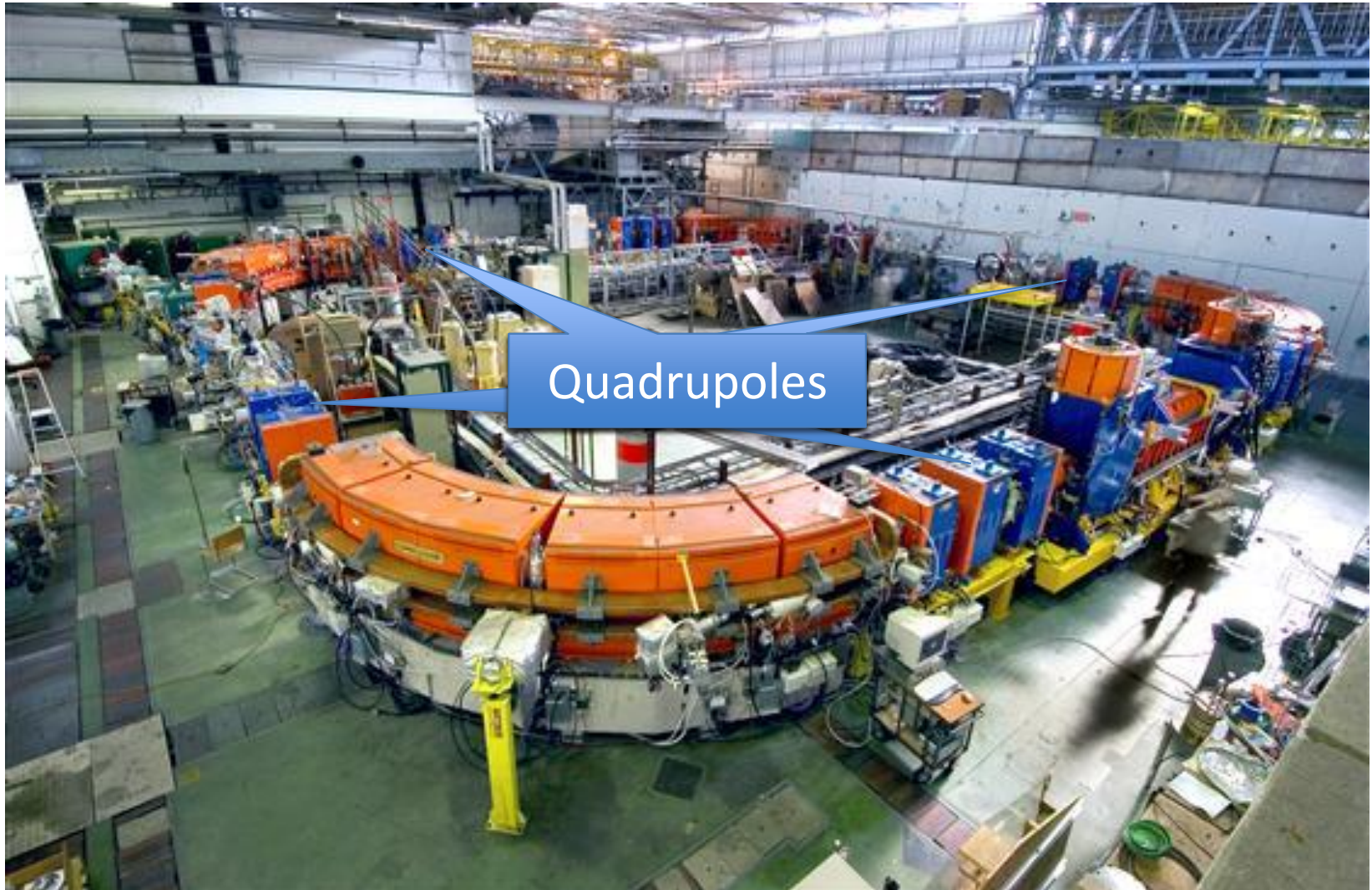


# Oscillatory Motion of Particles



Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane → **Betatron Oscillations**

# Focusing the Particles - Quadrupoles



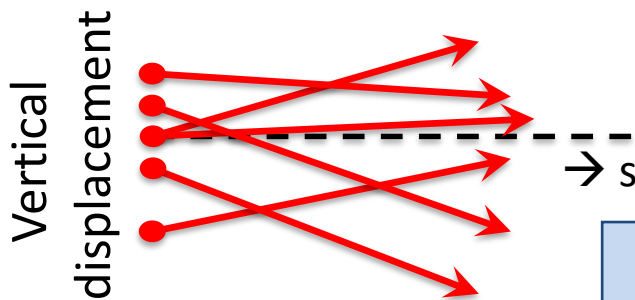


# Oscillatory Motion of Particles

The horizontal motion seems to be “stable” ... What about the vertical plane ?

Many particles many initial conditions

⇒ Beam gets dispersed  
⇒ We need focusing

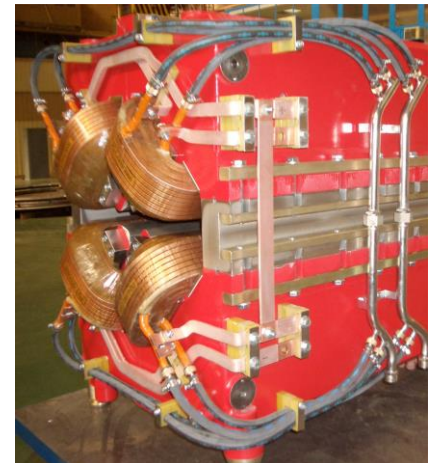
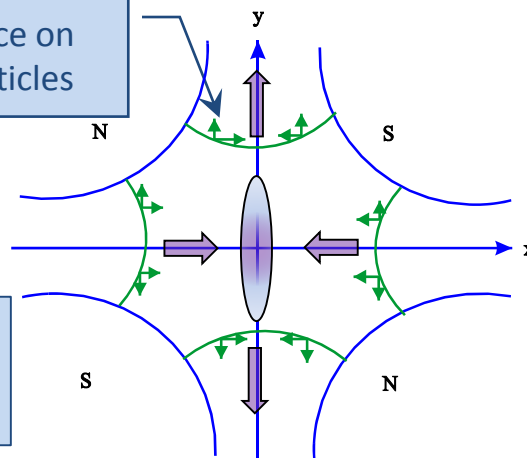


Many different angles

**Quadrupoles:** Focusing particles, a bit like lenses for light

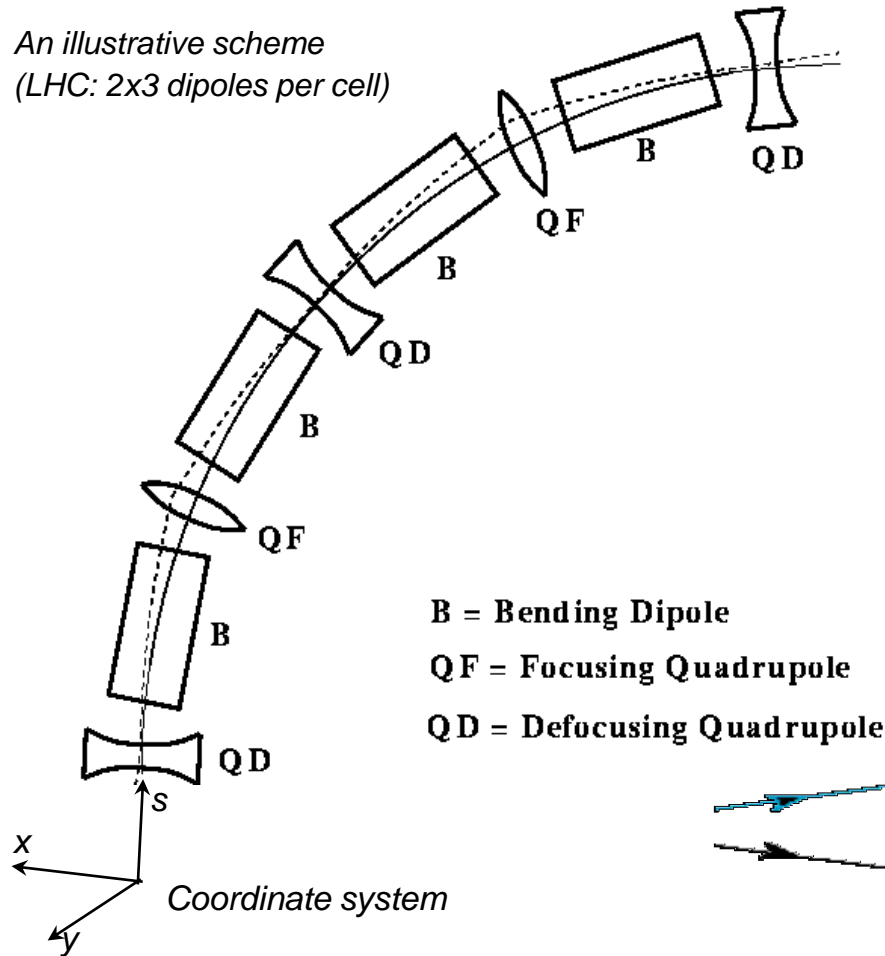
Quadrupoles focus in one plane and defocus in the other!

Force on particles



# Alternating gradient lattice

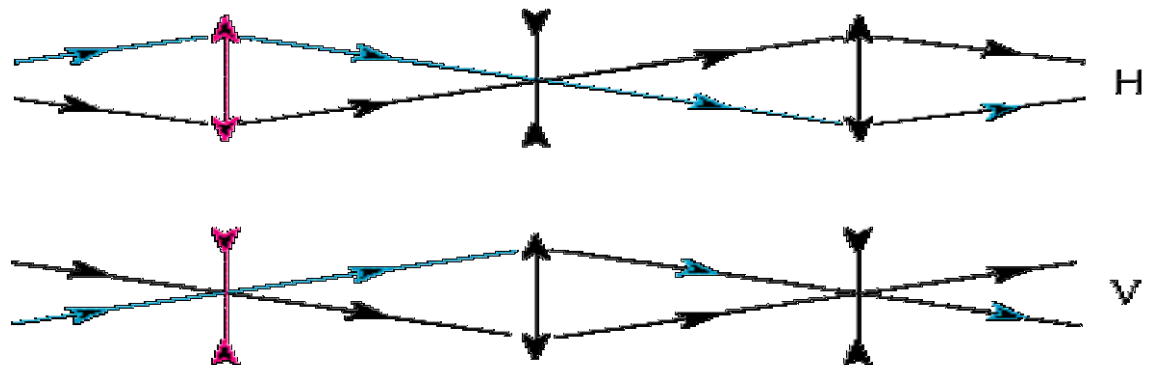
An illustrative scheme  
(LHC: 2x3 dipoles per cell)



One can find an arrangement of quadrupole magnets that provides net focusing in both planes (“strong focusing”).

Dipole magnets keep the particles on the circular orbit.

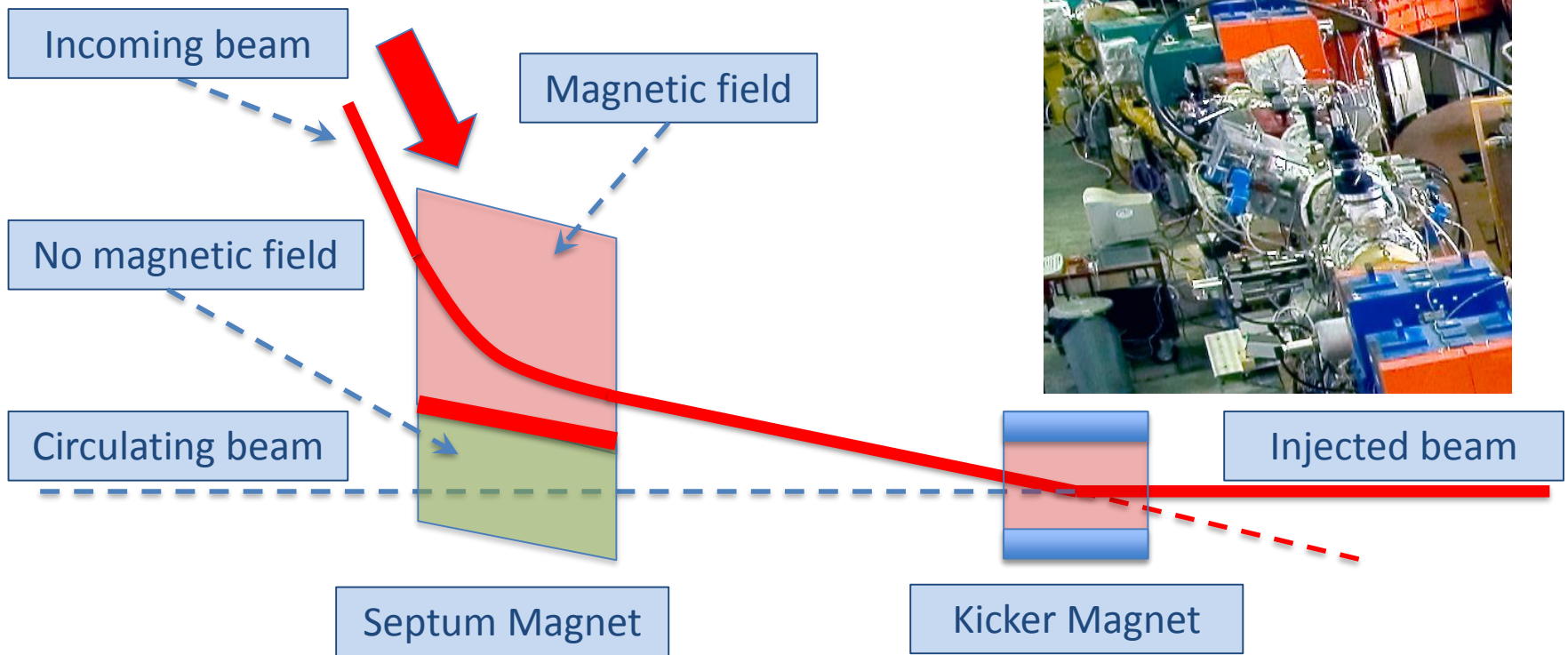
Quadrupole magnets focus alternatively in both planes.



# Injecting & Extracting Particles

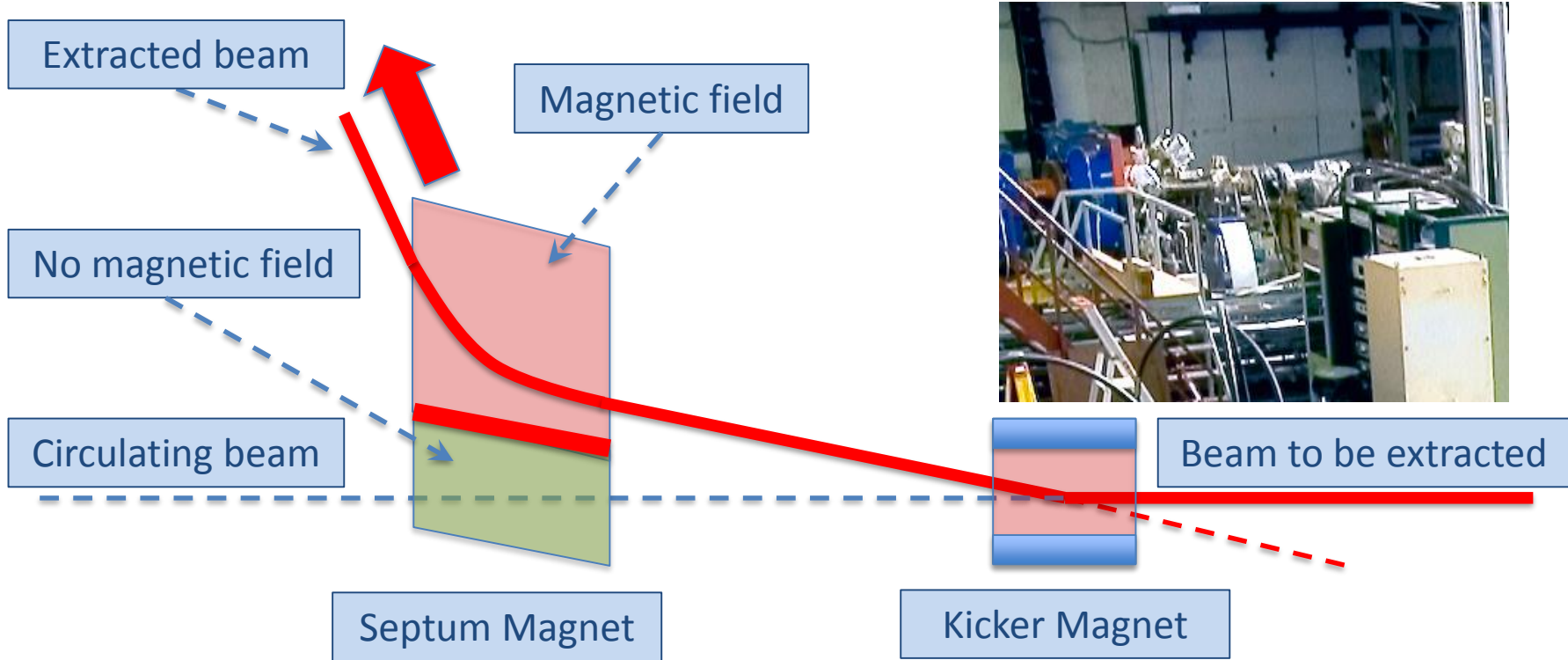


# Injecting & Extracting Particles



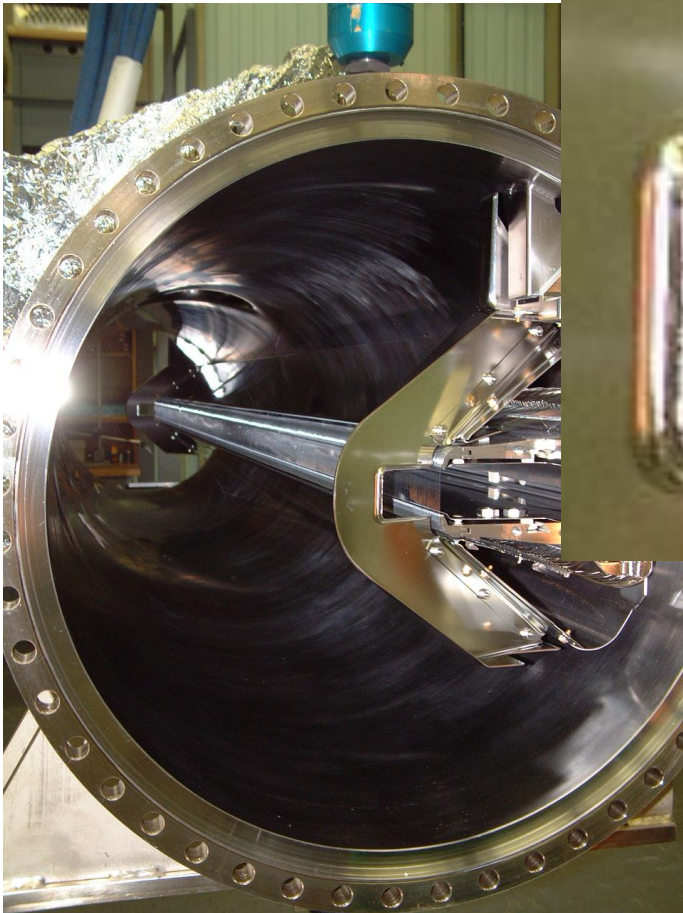


# Injecting & Extracting Particles

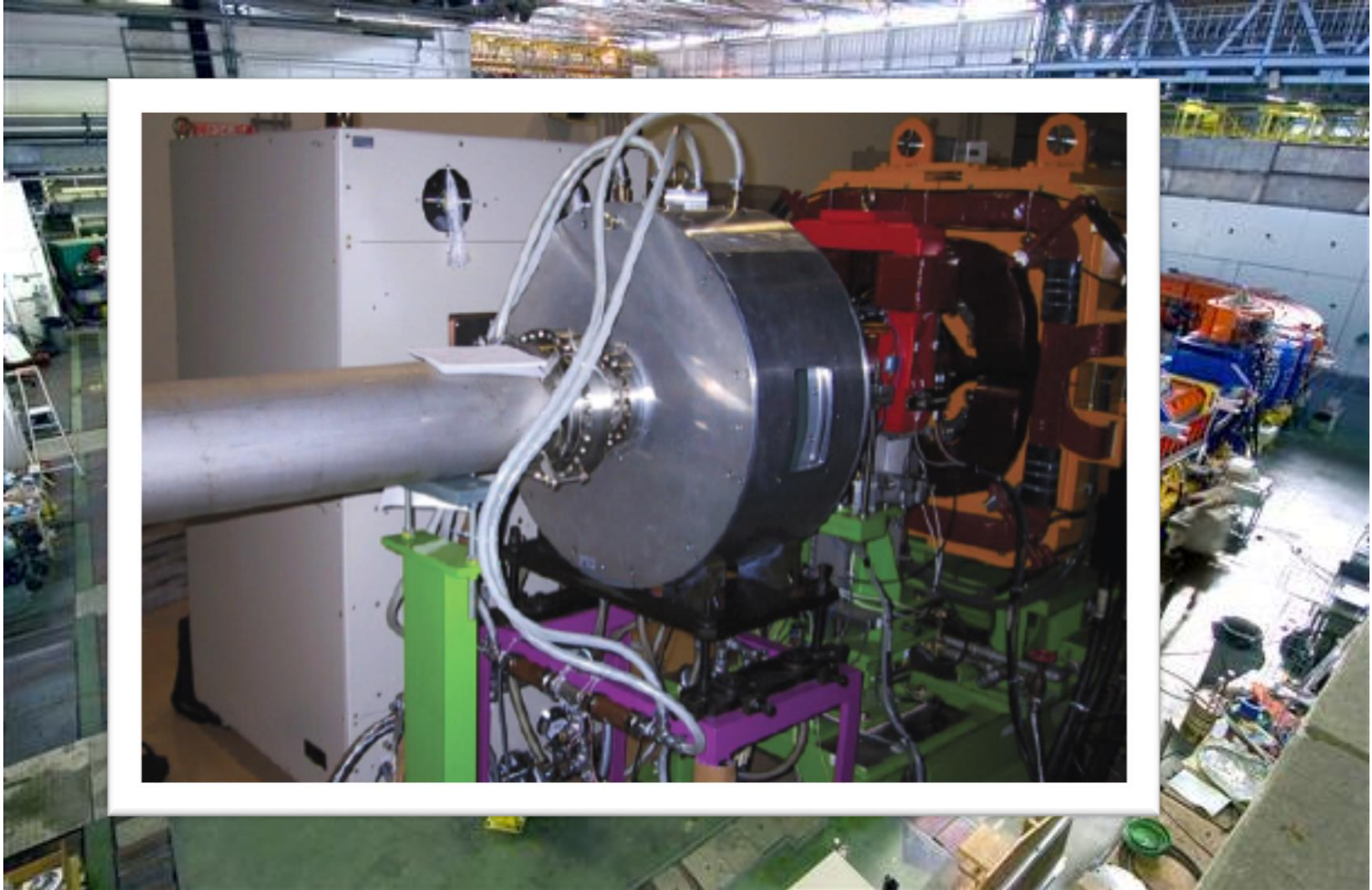




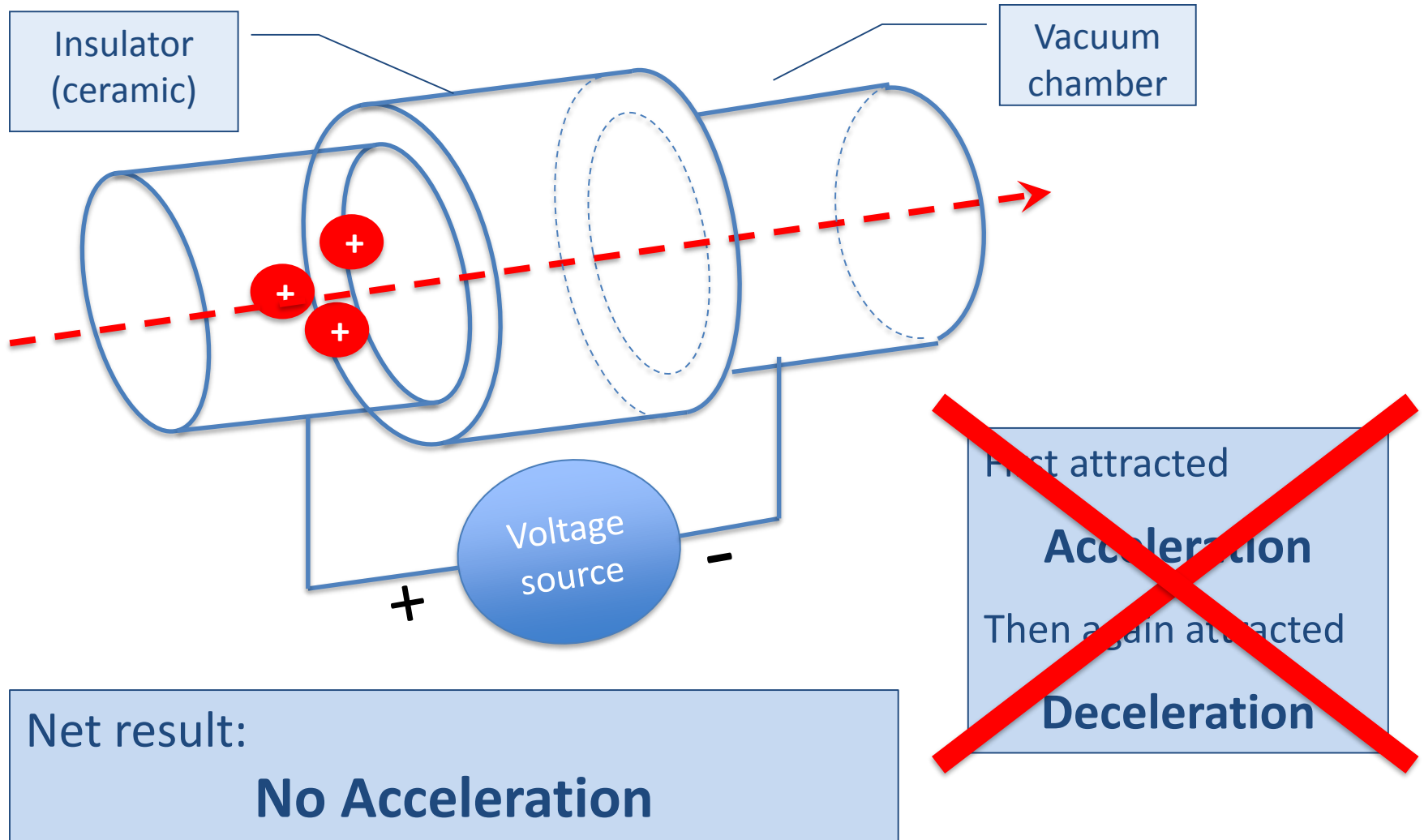
# Septum and Kicker Magnets



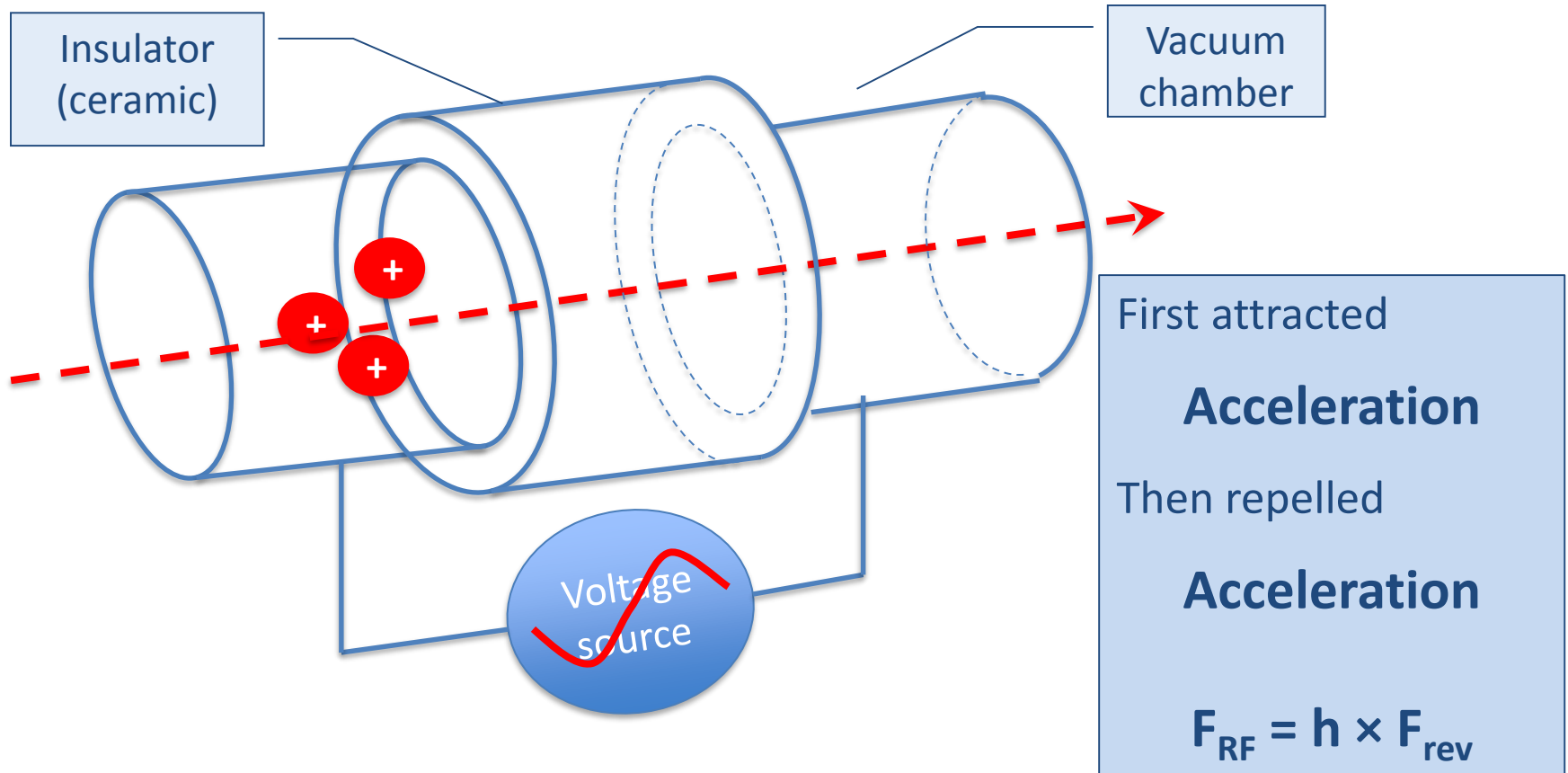
# Accelerating Particles



# Accelerating Beams



# Accelerating Beams





# Some RF Cavities and feedbacks

Fixed frequency cavities  
(Superconducting) in the LHC



Variable frequency cavities (normal  
conducting) in the CERN PS



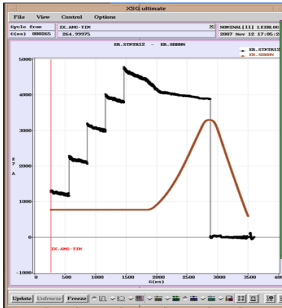
RF cavities are not only used to accelerate beams, but also to shape the beam:

- Longitudinal emittance
- Number of bunches
- Bunch spacing, shaping, etc.

They also make up for lost energy in case of lepton machines.



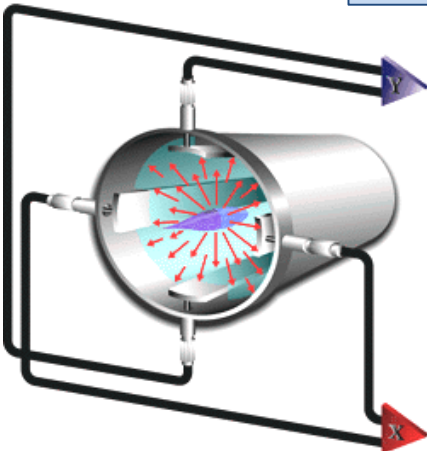
# Measuring Beam Characteristics



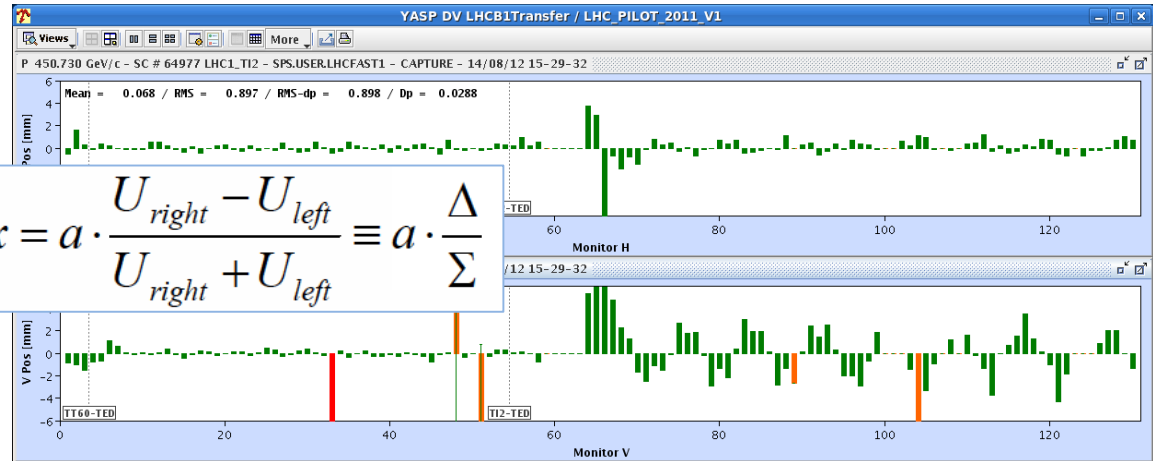
Beam intensity or current measurement:

- Working as classical transformer
- The beam acts as a primary winding

Beam position/orbit measurement:

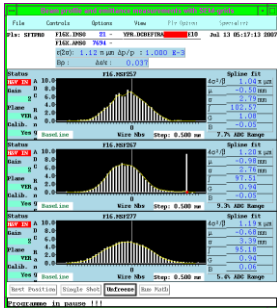


$$x = a \cdot \frac{U_{right} - U_{left}}{U_{right} + U_{left}} \equiv a \cdot \frac{\Delta}{\Sigma}$$



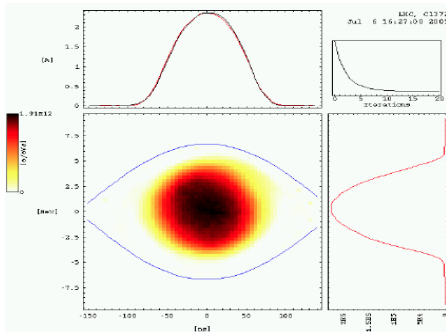
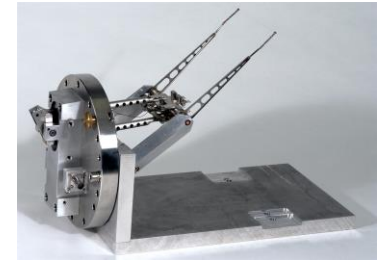
Correcting orbit using automated beam steering

# Measuring Beam Characteristics



## Transverse profile/size measurement:

- Secondary Emission Grids
- (Fast) Wire scanners

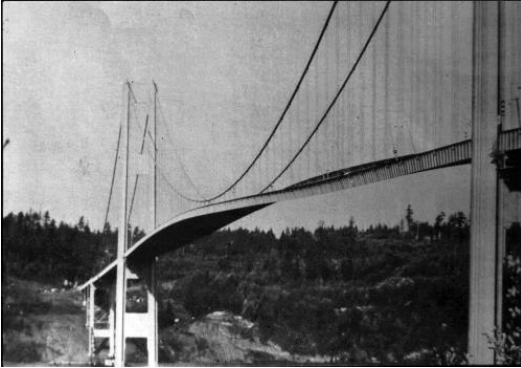


## Longitudinal beam profile/size measurement:

- Tomogram using wall current monitor data
- Use synchrotron motion for reconstruction

Any many more beam properties.....

# Possible Limitations



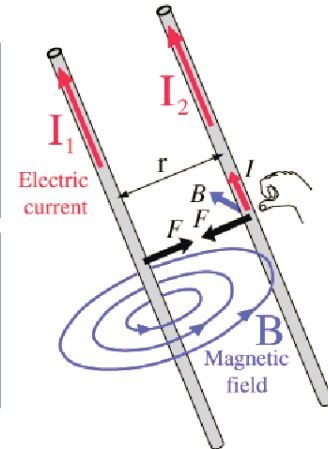
Machines and elements cannot be built and aligned with infinite precision

Same phase and frequency for driving force and the system can cause **resonances**



Neighbouring charges with the same polarity experience **repelling forces**

Parallel moving particles create parallel currents, resulting in **attracting or repelling magnetic fields**



These effects can degrade beam quality and increase losses

# Special Systems



Ever increasing energies and beam intensities, require special techniques

Super conducting magnets, with 8 T or even 11 T instead of 2 T for normal conducting magnets, requiring cryogenics

High stored beam energies require sophisticated machine protection systems to prevent beam induced damage

- Why Accelerators and Colliders ?
- A Brief Historic Overview
- The Main Ingredients of an Accelerator
- **Some ways of using Accelerators**



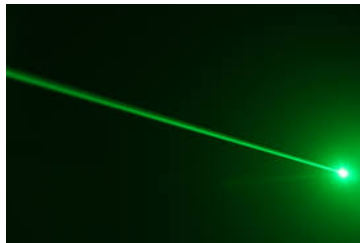
# Figures of Merit in accelerators

For different accelerators and experiments different beam characteristics are important. However, a major division can be made between:

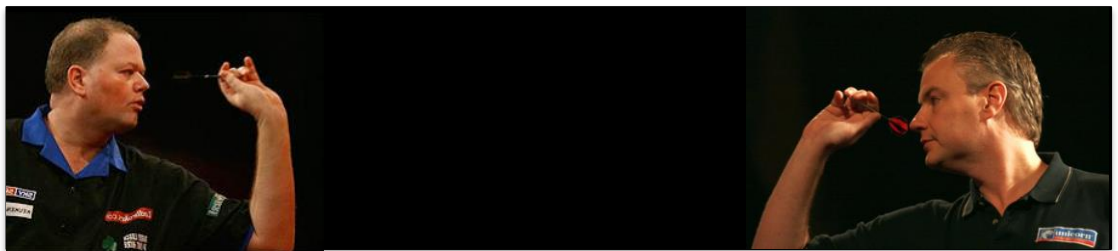
Fixed Target Physics:



Light Sources:

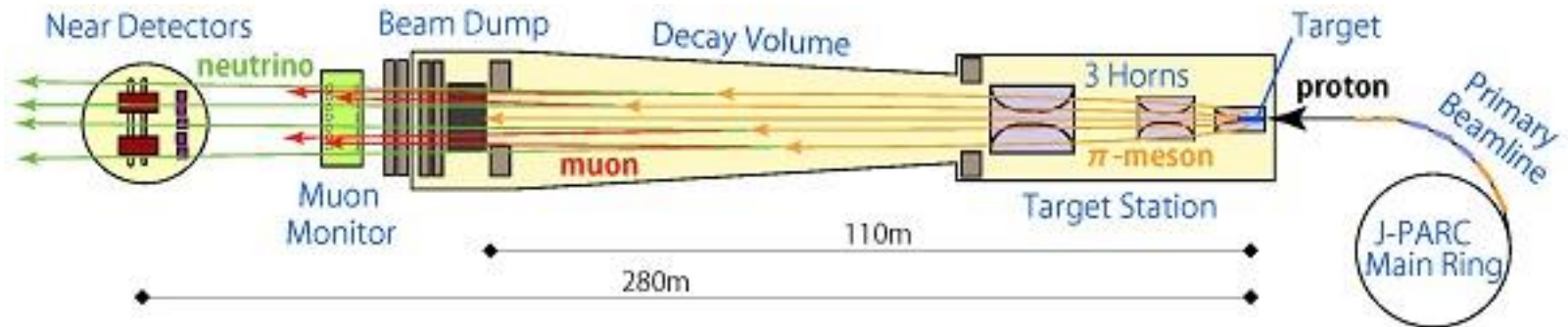


Collider Physics:



# Fixed Target Physics

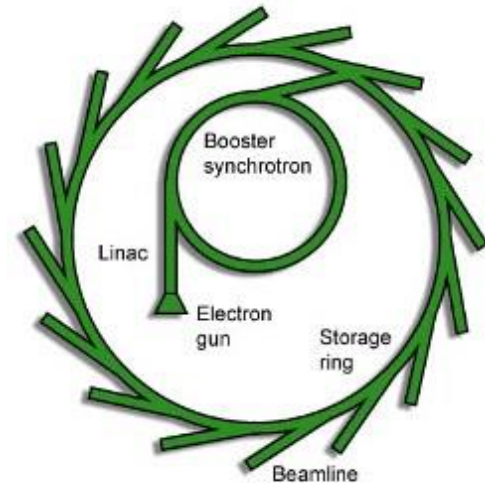
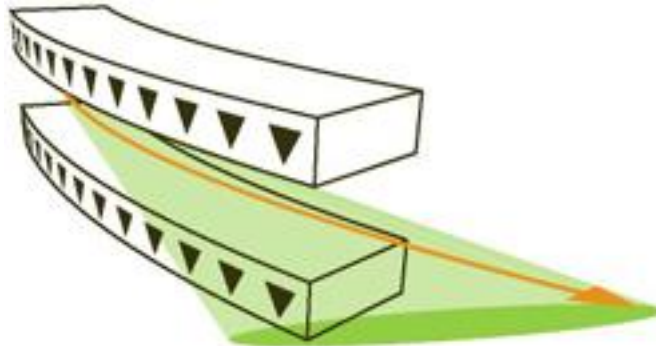
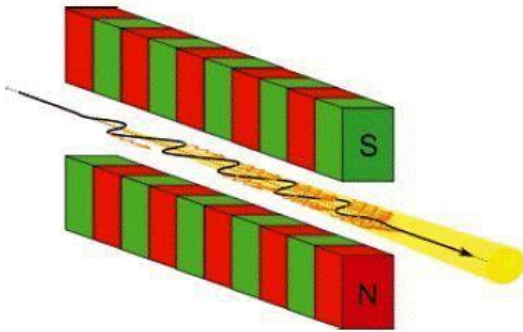
Just a few examples among many:



- Neutrino physics and Spallation sources: high beam power
  - High beam **intensity** with small beam size
  - High beam **energy** and / or high **repetition rate**
- J-PARC – Japan
- FermiLab - USA
- Previously CERN to CNGS – Europe
- Spallation Neutron Source (SNS) Oak Ridge - USA

# Synchrotron Light Sources

Just a few examples among many:



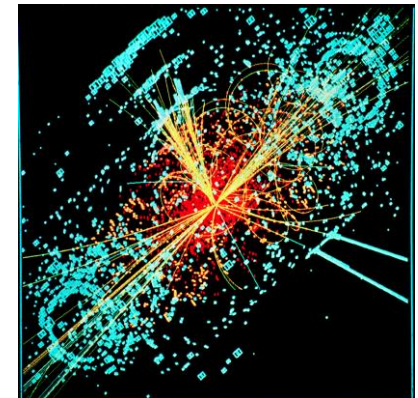
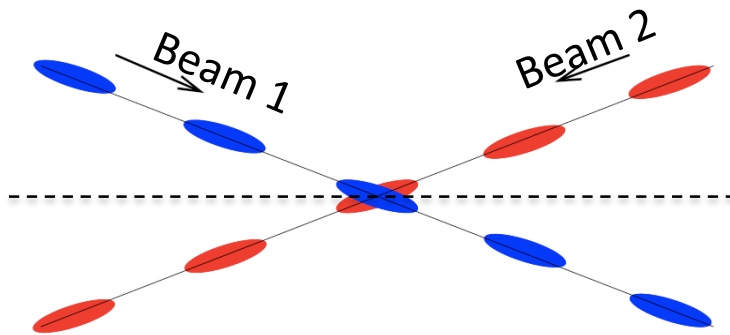
- Photon beam from stored (highly relativistic) electron beam
  - High electron beam intensity (Accelerator & Storage Ring)
  - Use of **undulators** to enhance photon emission
- Swiss Light Source (SLS) – Europe
- European Synchrotron Radiation Facility (ESRF) – Europe
- National Synchrotron Light Source (NSLS II) – USA
- Super Photon Ring (SPRing) – Japan ..... And many more....

# Collider Physics

The aim is to have a high duty cycle of collision, but not too many collisions at the same time in order to allow disentangling of individual events in the detectors (avoid pile-up)

Beams in clockwise and anti-clockwise direction:

- Proton – Proton  $\rightarrow$  2 separate rings
- Electron – Positron or Proton – Antiproton  $\rightarrow$  single ring





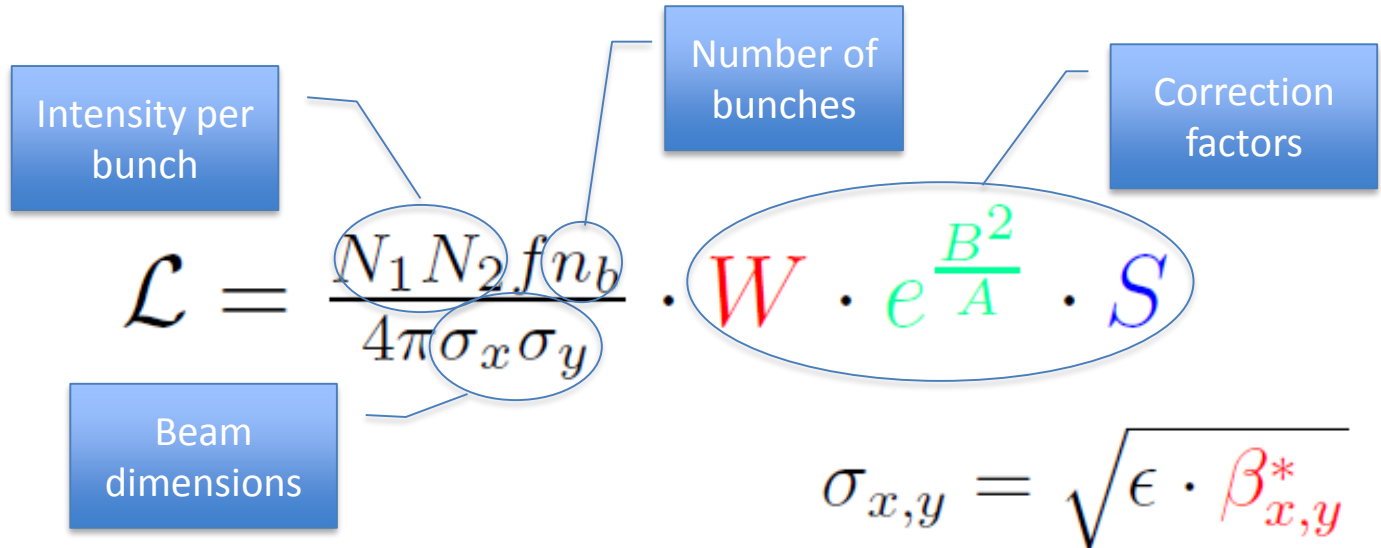
# Collider Luminosity

For collider physics the integrated luminosity is the figure of merit

Number of events:

$$N = \sigma \cdot \int \mathcal{L}$$

$\sigma$  production cross-section



The diagram shows the luminosity formula  $\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi \sigma_x \sigma_y} \cdot W \cdot e \frac{B^2}{A} \cdot S$  with callouts:
 

- Intensity per bunch** points to  $N_1 N_2$ .
- Number of bunches** points to  $f n_b$ .
- Beam dimensions** points to  $4\pi \sigma_x \sigma_y$ .
- Correction factors** points to the entire product term  $W \cdot e \frac{B^2}{A} \cdot S$ .

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi \sigma_x \sigma_y} \cdot W \cdot e \frac{B^2}{A} \cdot S$$

$$\sigma_{x,y} = \sqrt{\epsilon \cdot \beta_{x,y}^*}$$

- The instantaneous luminosity is the amount of events per unit of surface per second [ $\text{cm}^{-2}\text{s}^{-1}$ ]
- Integrating this over time results in the integrated luminosity.
- The LHC produced in total for ATLAS and CMS each  $189 \text{ fb}^{-1}$   
*Note: Cross section is expressed in units of barns (1 barn =  $10^{-28}\text{m}^2$ )*



# Future Circular Collider (FCC) study

## International collaboration :



Alignment Shafts Query

Choose alignment option  
 100km quasi-circular

Tunnel elevation at centre: 261mASL

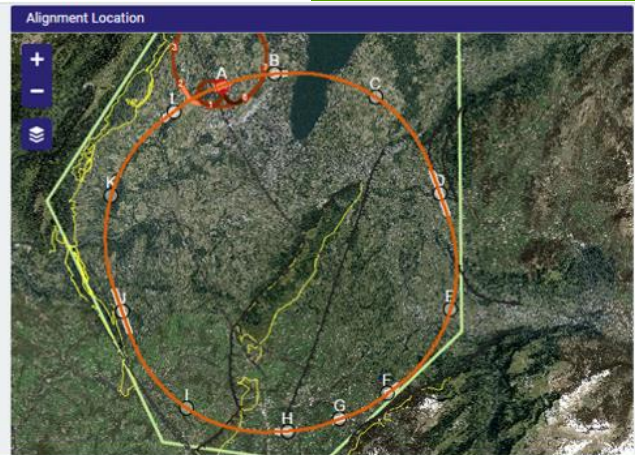
Grad. Params

Azimuth (°): -20  
 Slope Angle x-x(%): 0.65  
 Slope Angle y-y(%): 0

LOAD SAVE CALCULATE

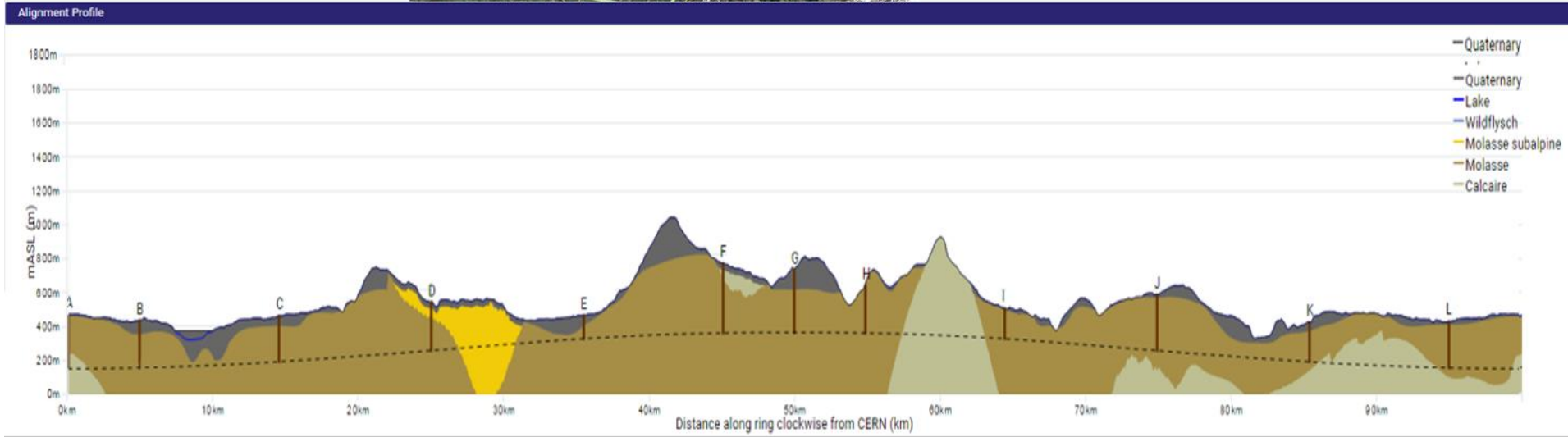
Alignment centre  
 X: 2499731 Y: 1108403

	Angle	CP 1	Angle	CP 2
		Depth		Depth
LHC	-64°	220m	64°	172m
SPS		242m		241m
TI2		235m		241m
TI8		242m		170m



Geology Intersected by Shafts Shaft Depths

Point	Actual	Shaft Depth (m)				Geology (m)	
		Molasse SA	Wildfysch	Quaternary	Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	272	52	0	40	181	0	0
E	132	0	0	64	68	0	0
F	392	0	0	40	296	0	56
G	354	0	0	116	237	0	0
H	268	0	0	0	268	0	0
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109



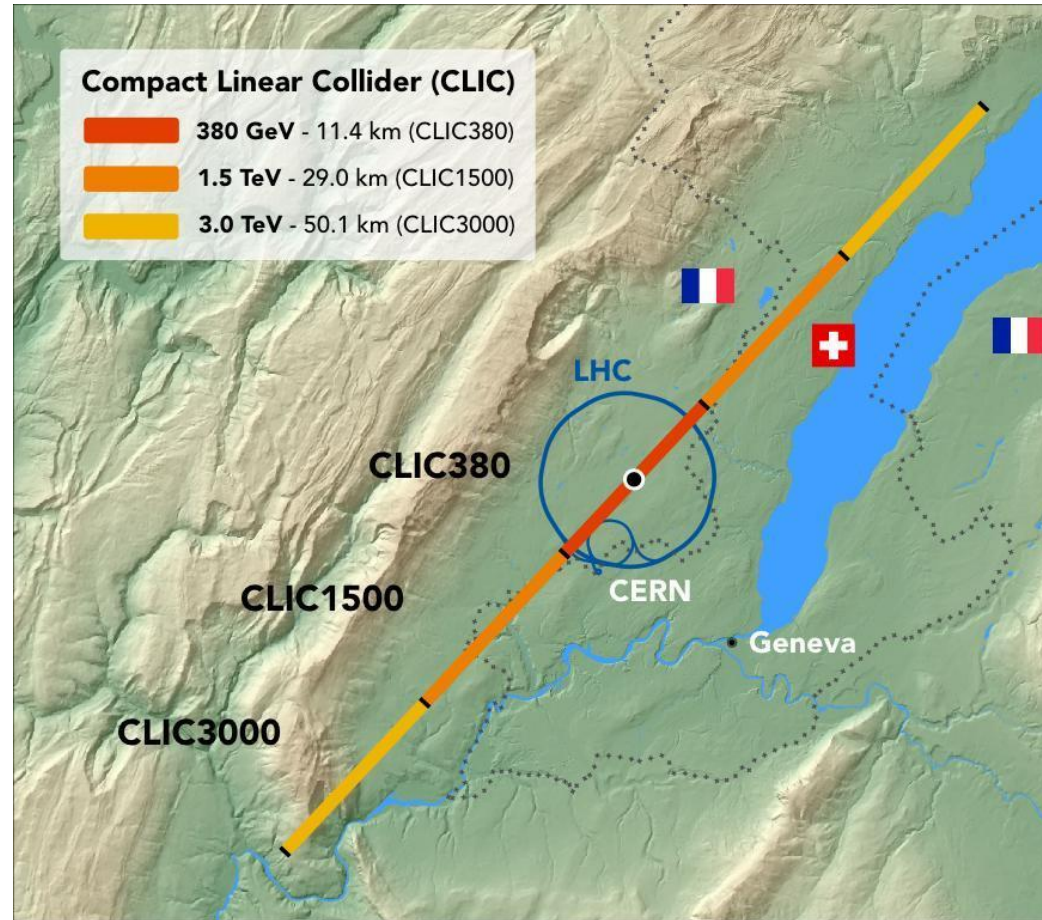
# Linear Collider (ILC/CLIC) studies

- **Electron – Positron Collider**
  - **Precision physics**
  
- **International Linear Collider (ILC)**
  - Superconducting accelerating cavities

**31.5 MV/m  $\Rightarrow$  500 GeV in 35 km**

- **Compact Linear Collider (CLIC)**
  - Room-temperature cavities

**100 MV/m  $\Rightarrow$  380 GeV in 11 km  
3 TeV in 50 km**



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Thank you very much for your attention!