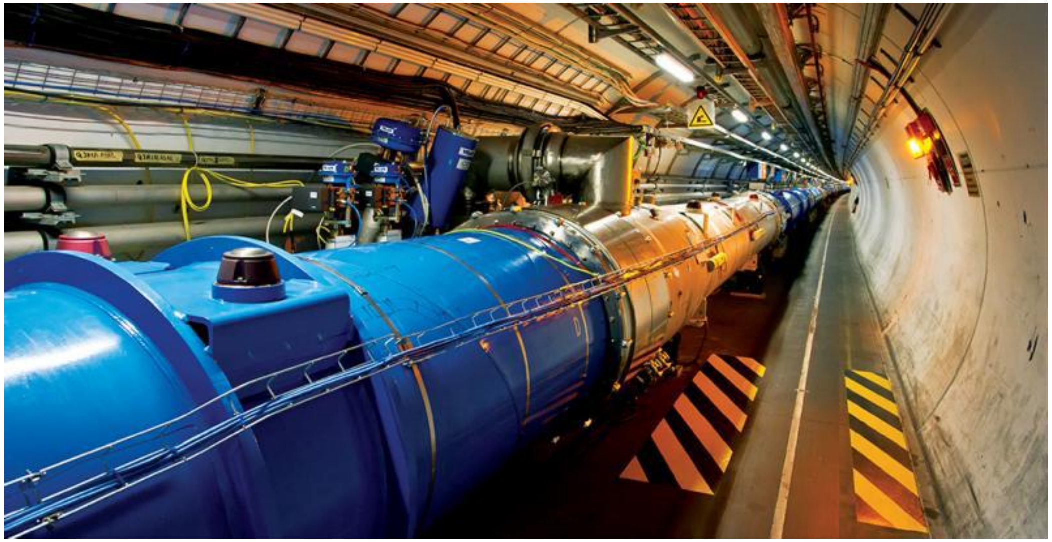
Introduction to Accelerator Physics



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

Contents

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

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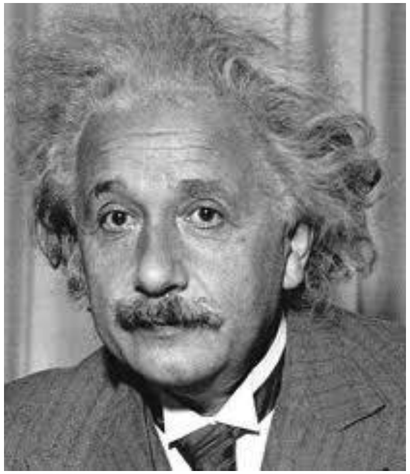
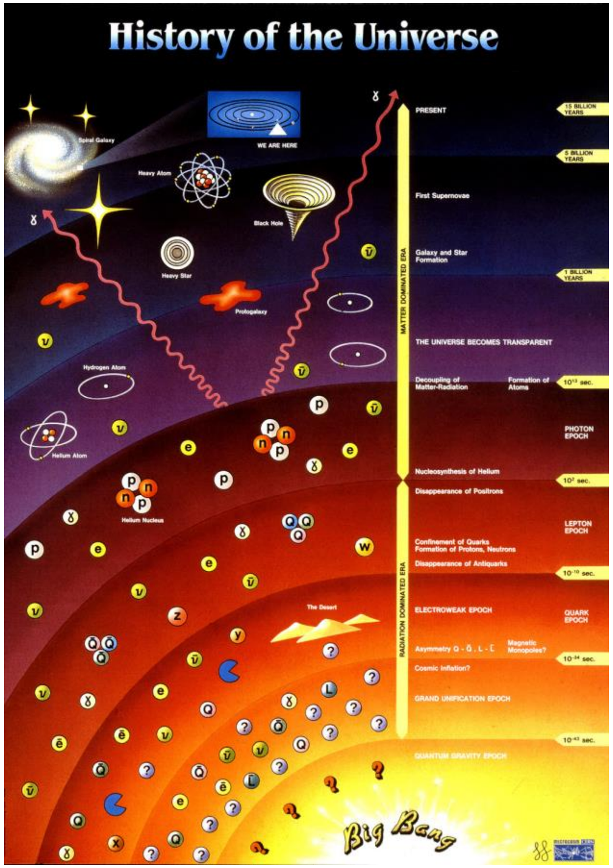
Matter versus Energy

$$E = m c^2$$

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

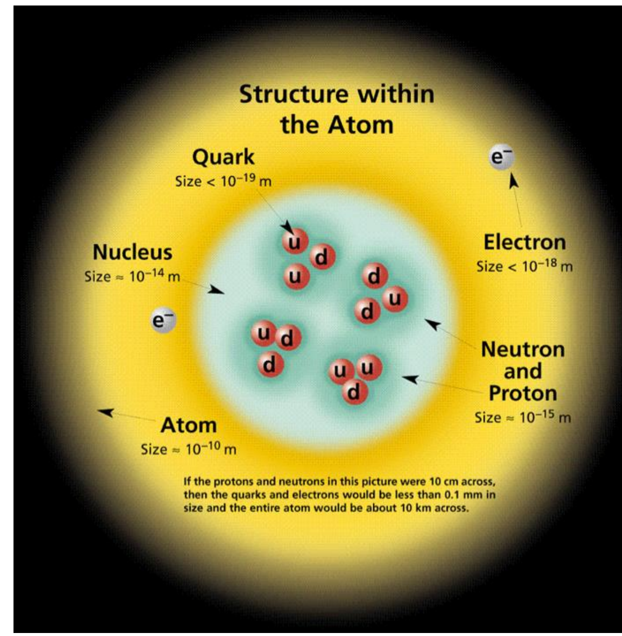
λ = 400 ➔ 700 nm

X-ray

λ = 0.01 ➔ 10 nm

Particle accelerators

λ < 0.01 nm



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

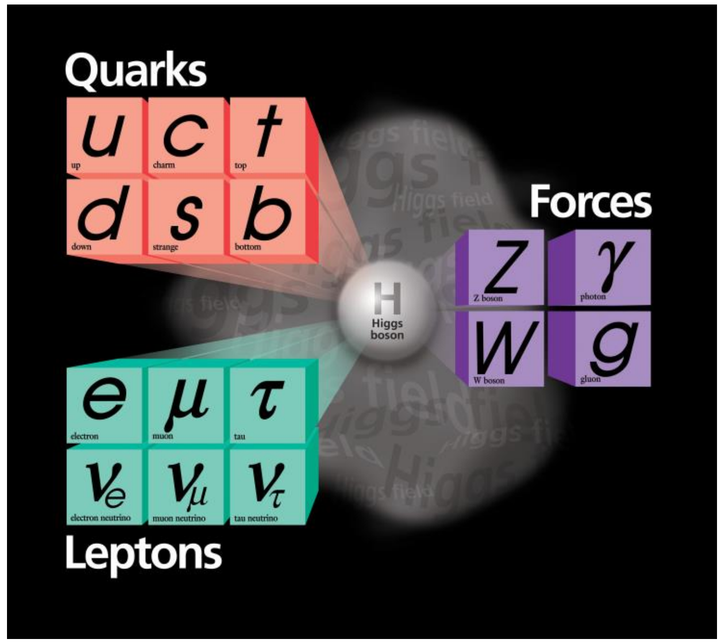
Increasing the energy will reduce the wavelength

Fixed Target vs. Colliders

Fixed Target	Collider
	
$E \propto \sqrt{E_{beam}}$	$E = E_{beam1} + E_{beam2}$
Much of the energy is lost in the target and only part results in usable secondary particles	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

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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

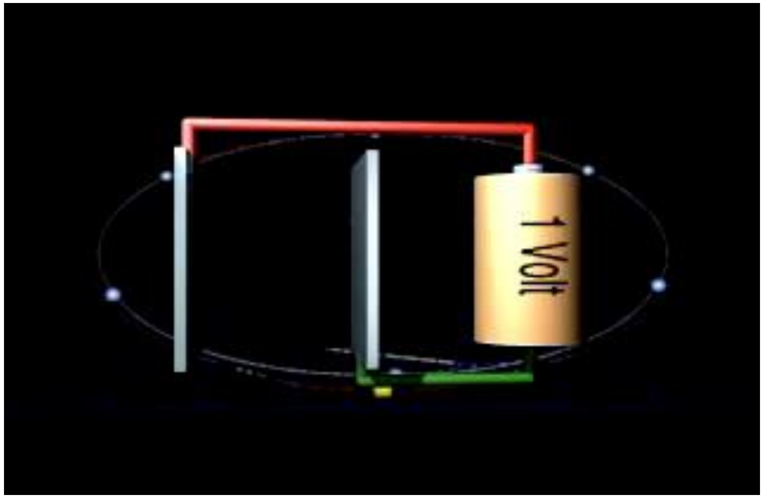
MeV = 10^6 eV

GeV = 10^9 eV

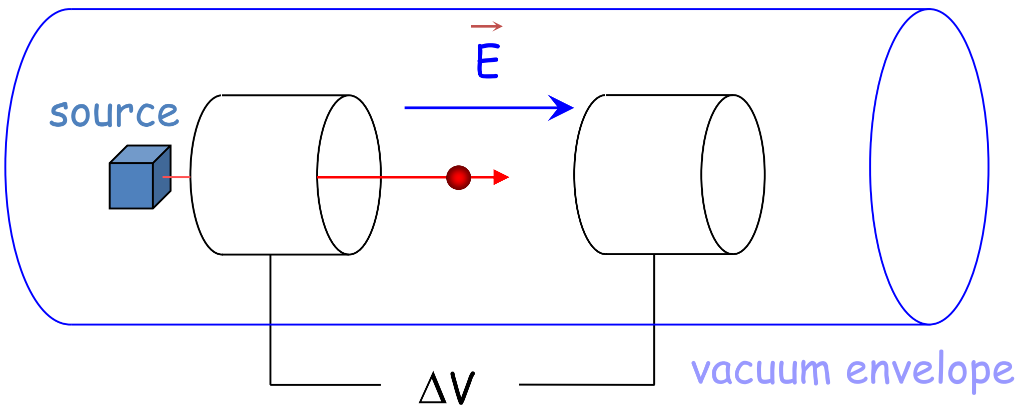
TeV = 10^{12} eV

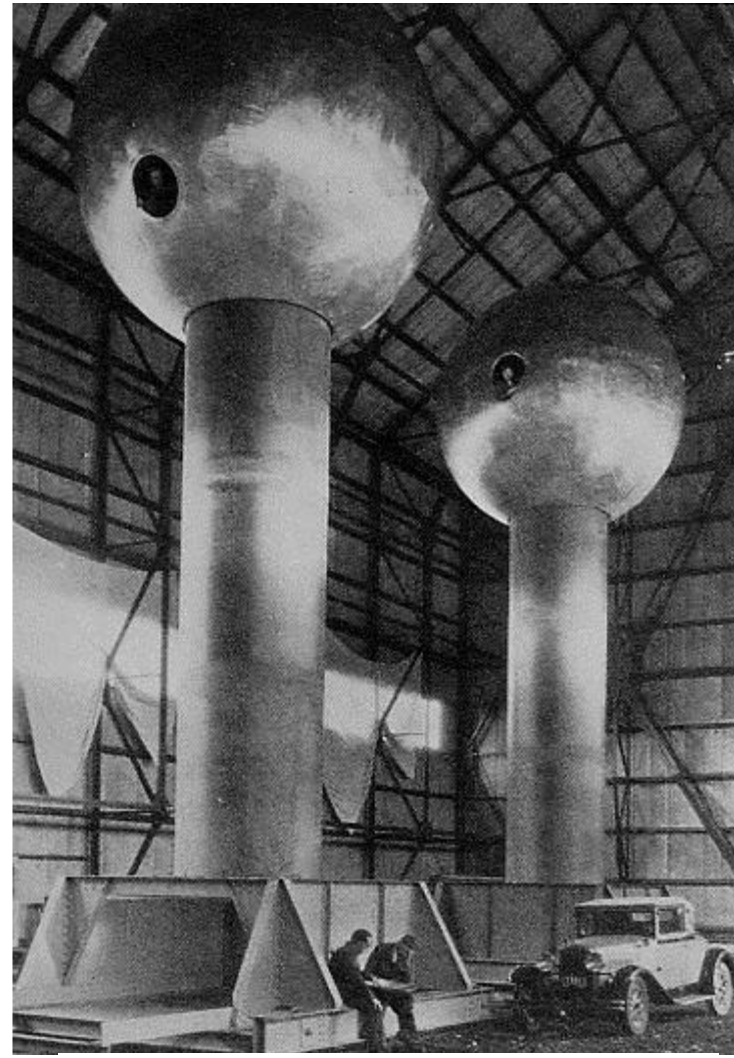
LHC = ~450 Million km of batteries!!!

3x distance Earth-Sun



Electrostatic Acceleration




Van-de-Graaf generator at MIT

Electrostatic Field:

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

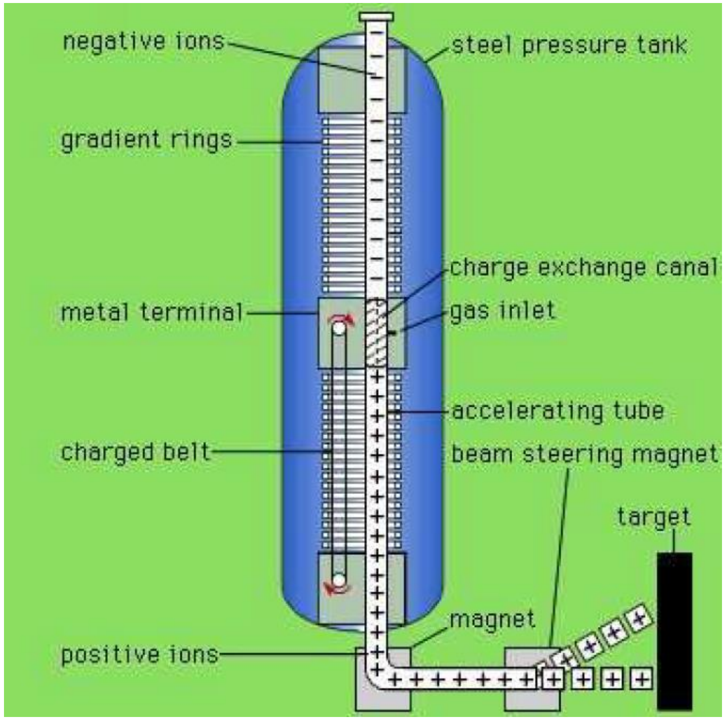
Energy gain: $W = e\,\Delta V$

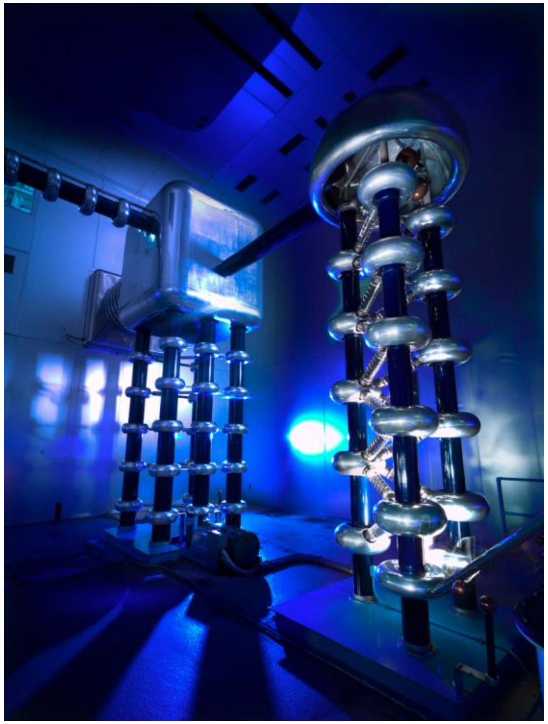
used for first stage of acceleration: particle sources, electron guns,
x-ray tubes

Limitation: insulation problems
maximum high voltage (~ 10 MV)

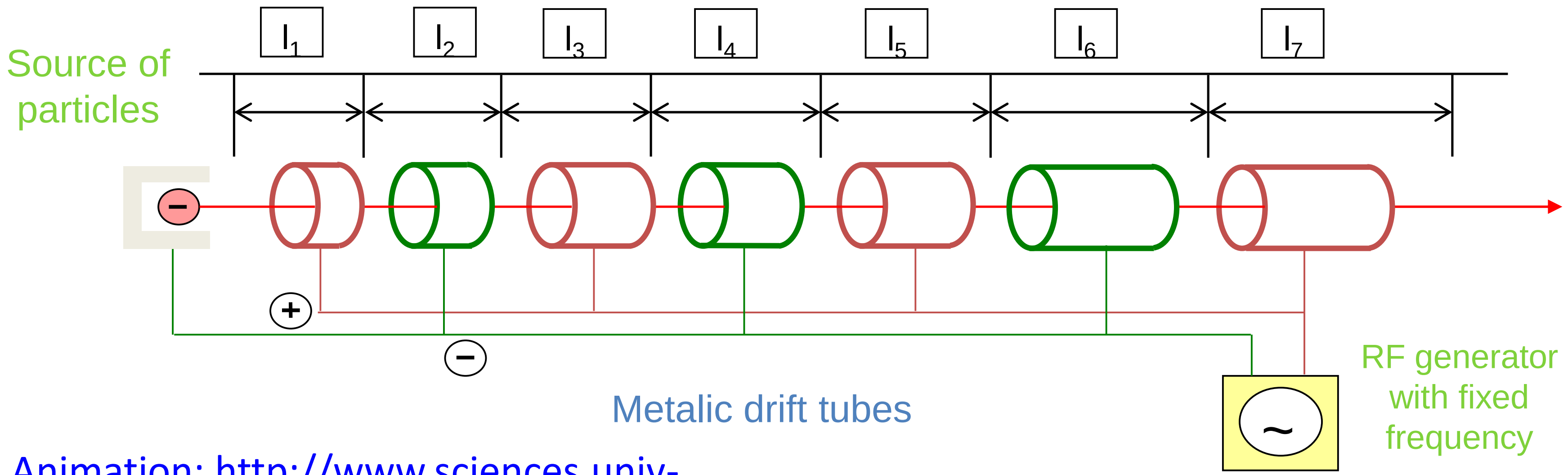
Cockroft & Walton / van de Graaff

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





Linear Accelerator



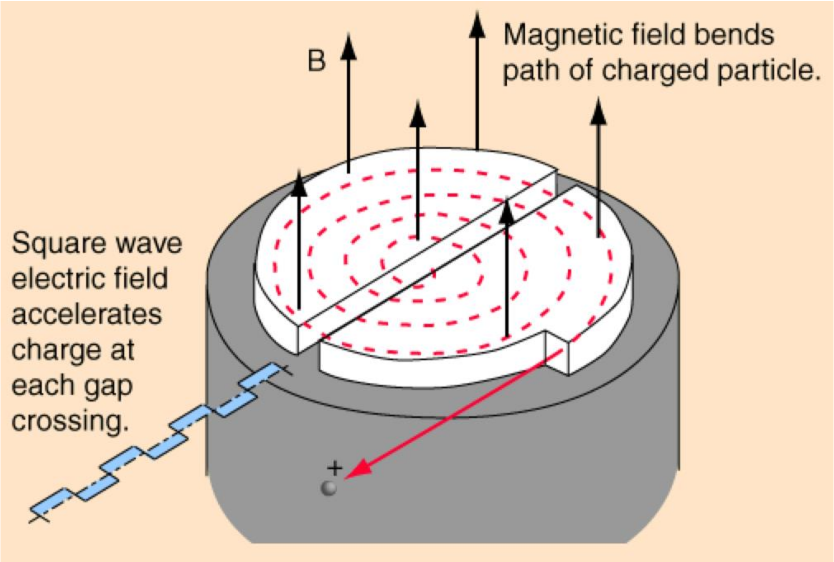
[Animation: http://www.sciences.univ-nantes.fr/sites/genevieve_tulloue/Meca/Charges/linac.html](http://www.sciences.univ-nantes.fr/sites/genevieve_tulloue/Meca/Charges/linac.html)

- 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.

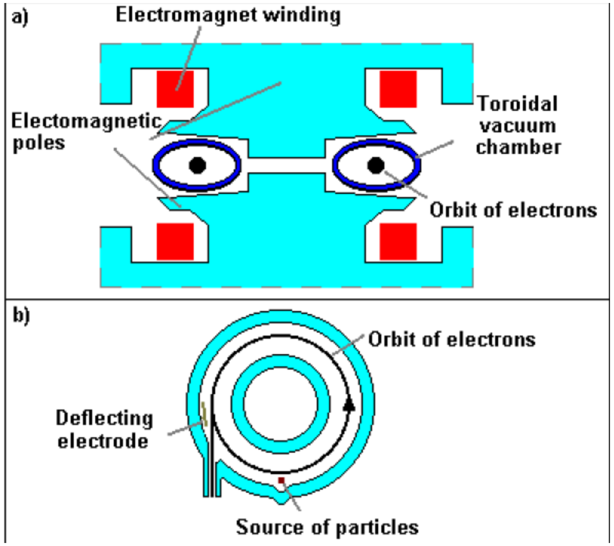


Circular accelerators: Cyclotron

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

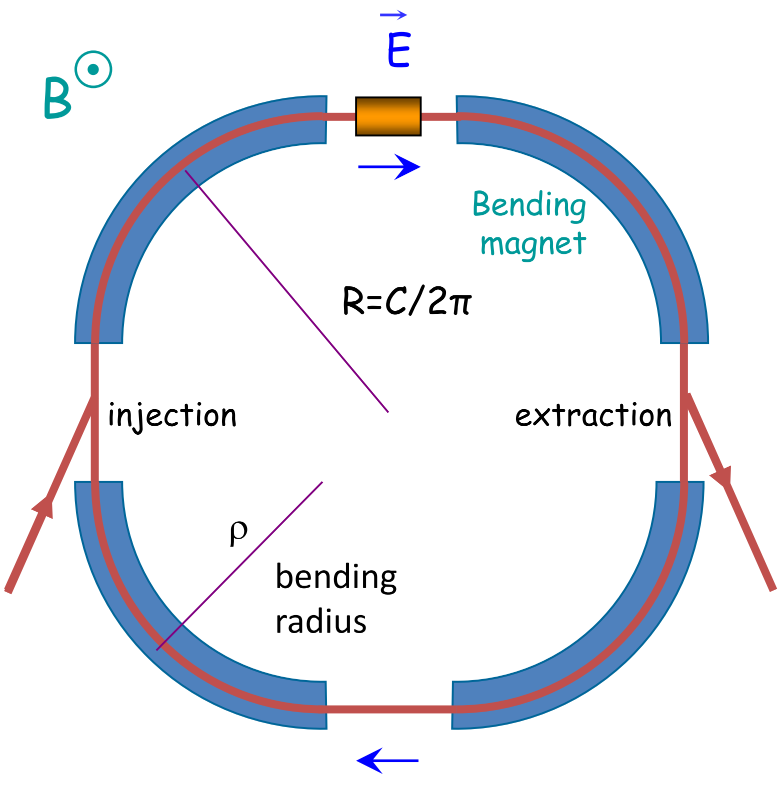
Betatron

- 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 use 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

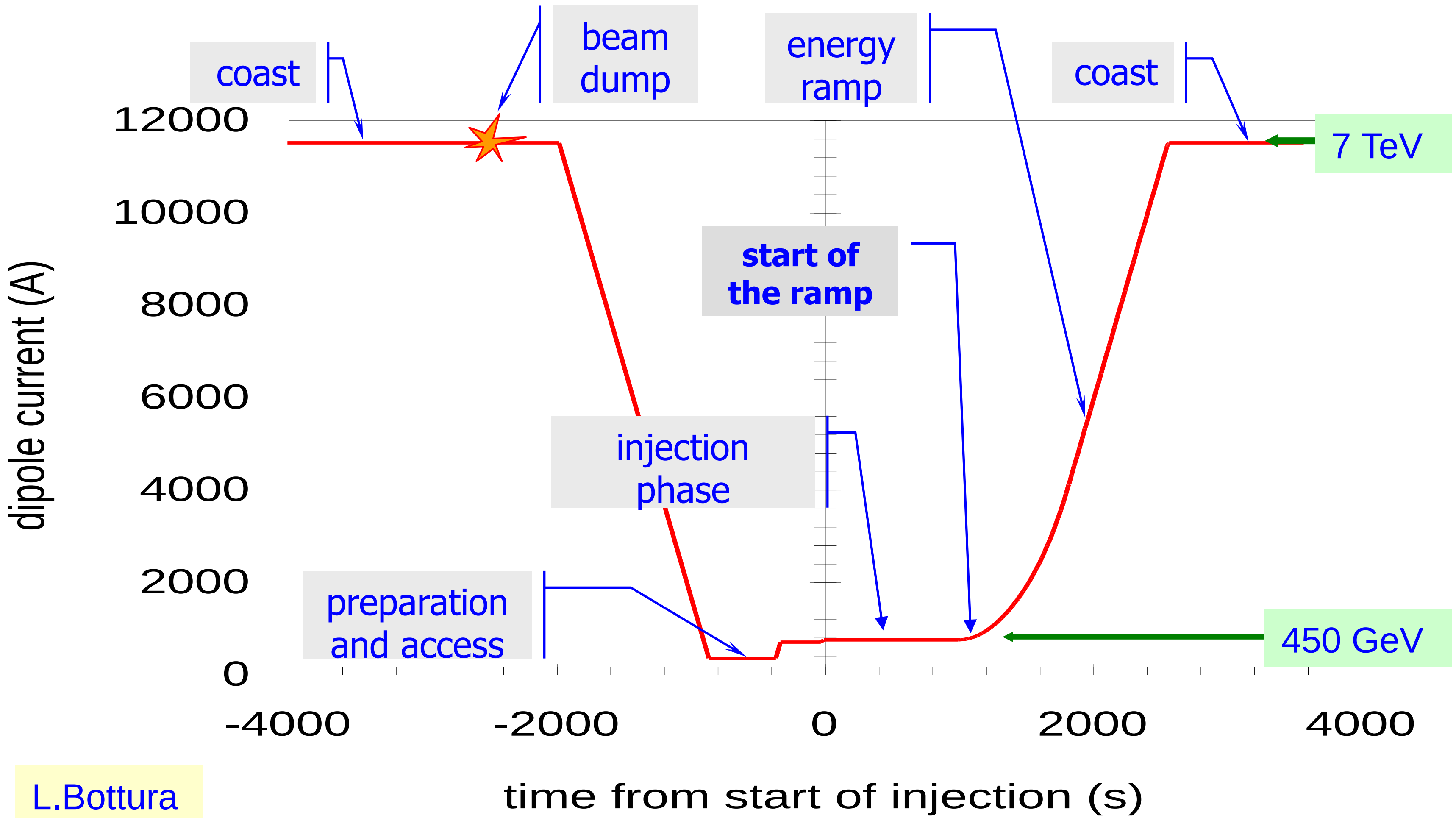
PS (CERN)
Proton Synchrotron

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.



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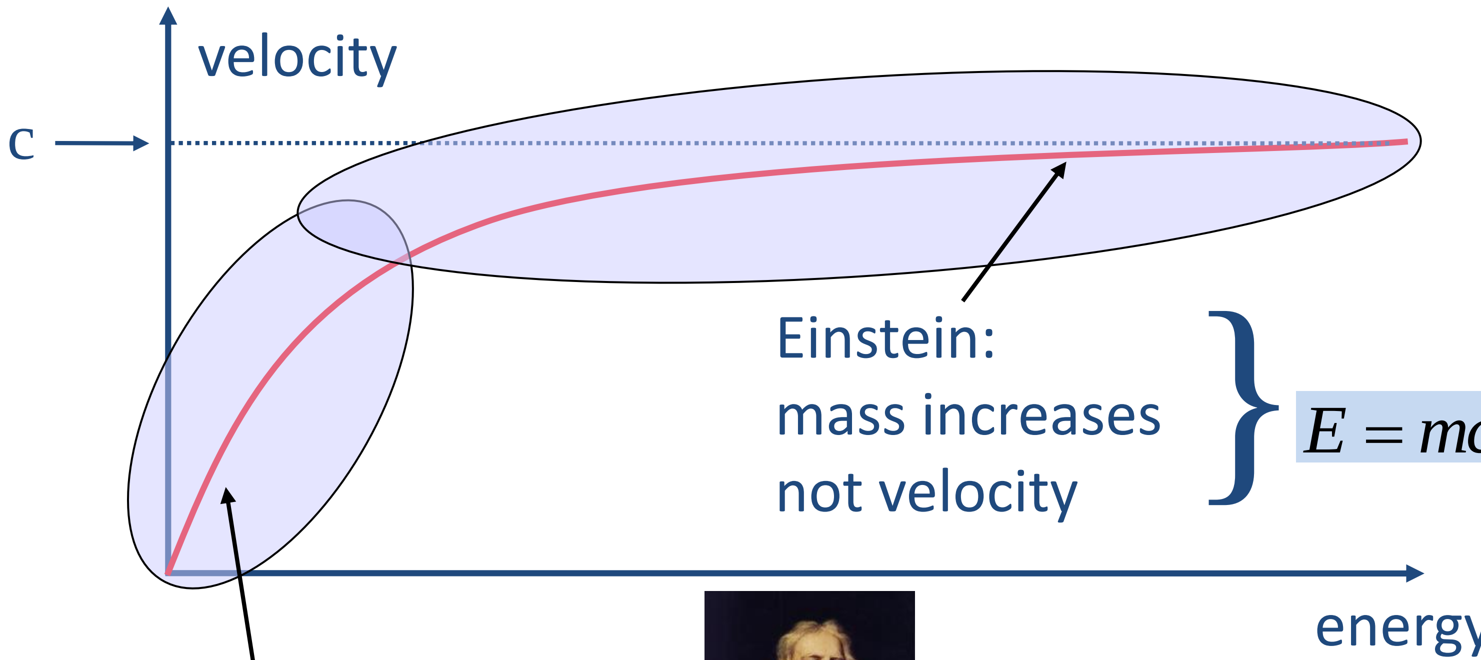
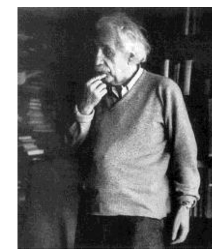
Towards Relativity

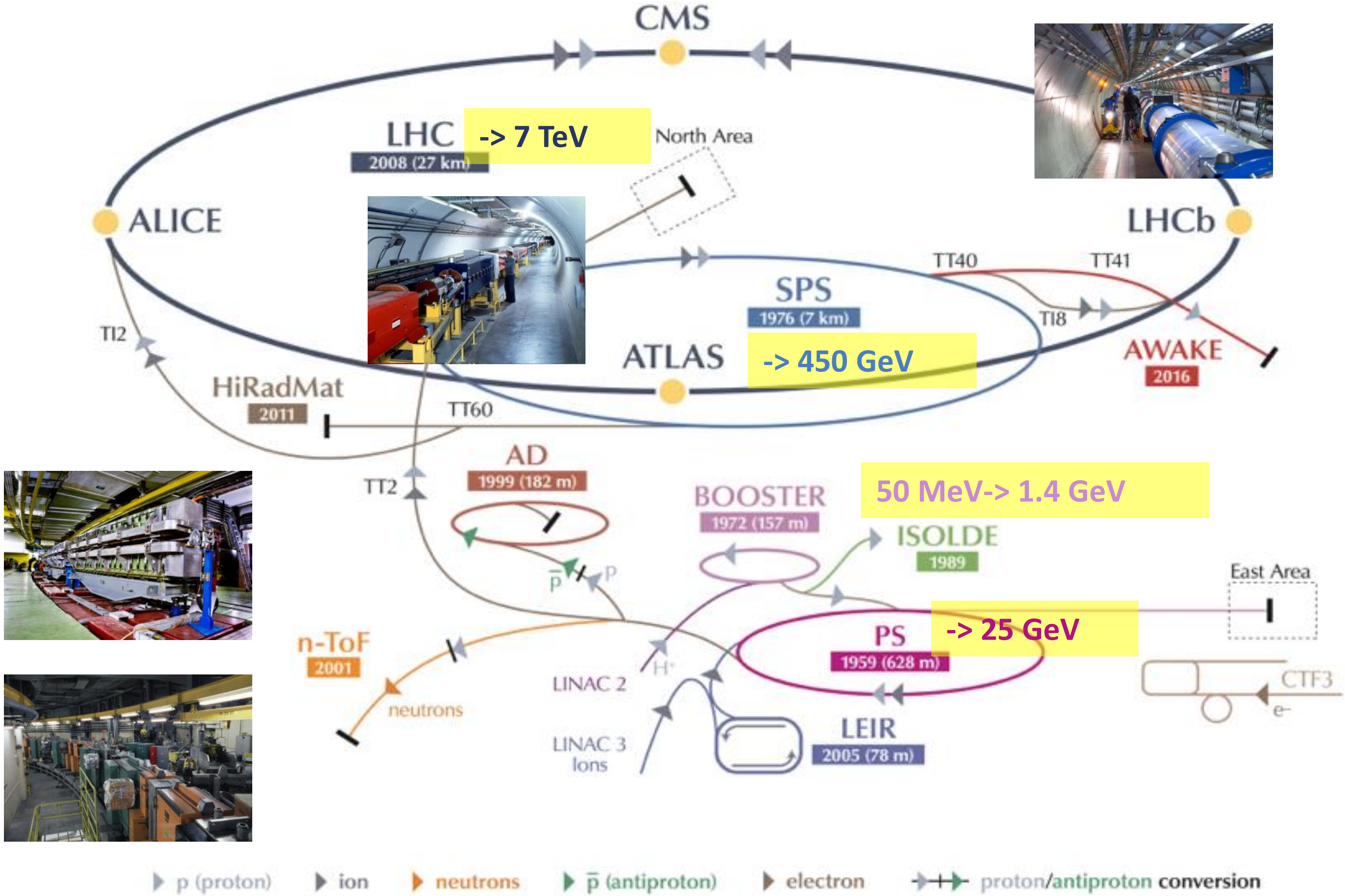


$$E = mc^2$$



Newton: $E = \frac{1}{2} m v^2$

The CERN Accelerator Complex



A Guided Tour

Lets have a look at a synchrotron:

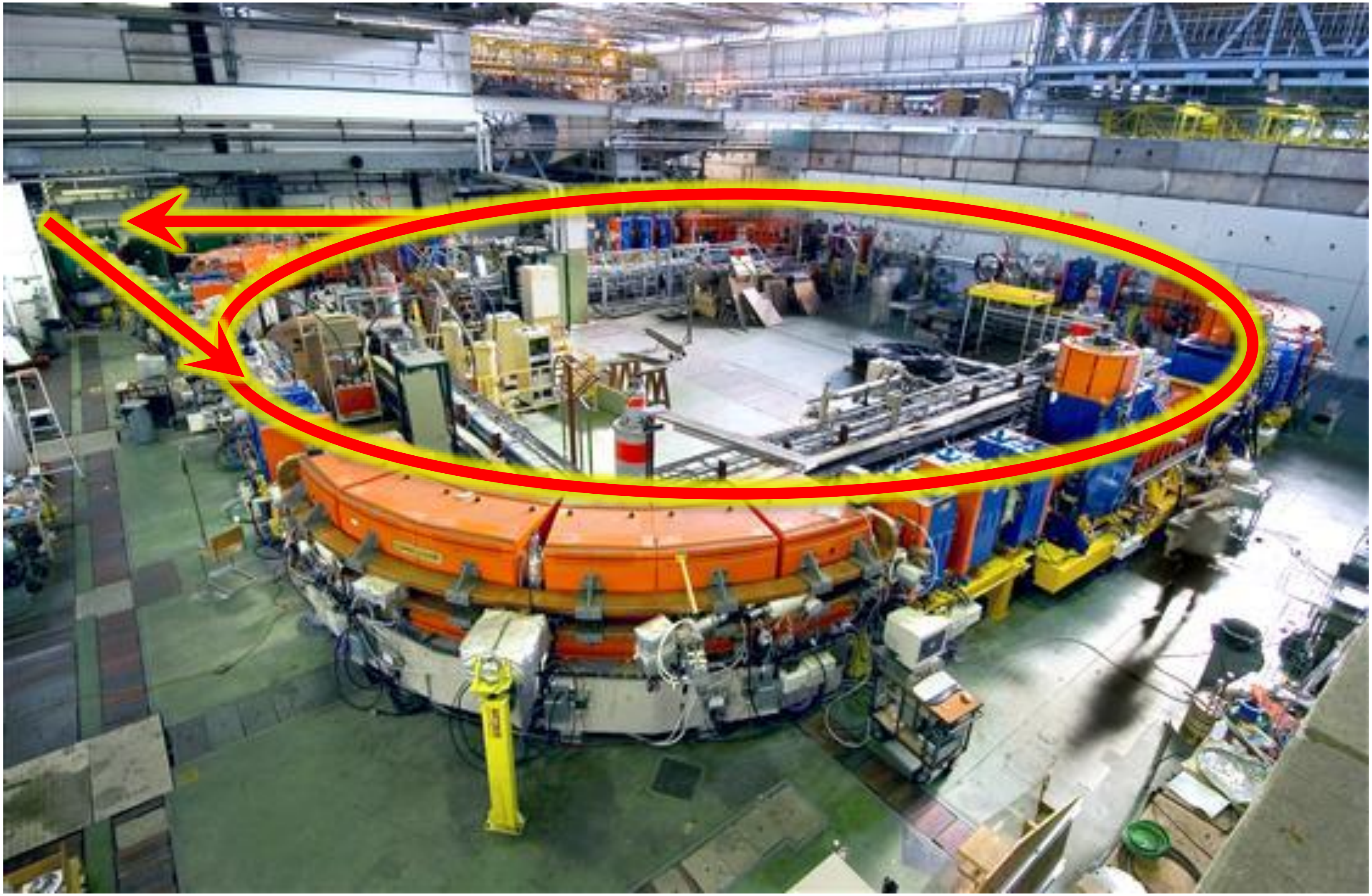
- Identify the main components and processes
- Briefly address their function

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

LEIR

Low **E**nergy **I**on **R**ing

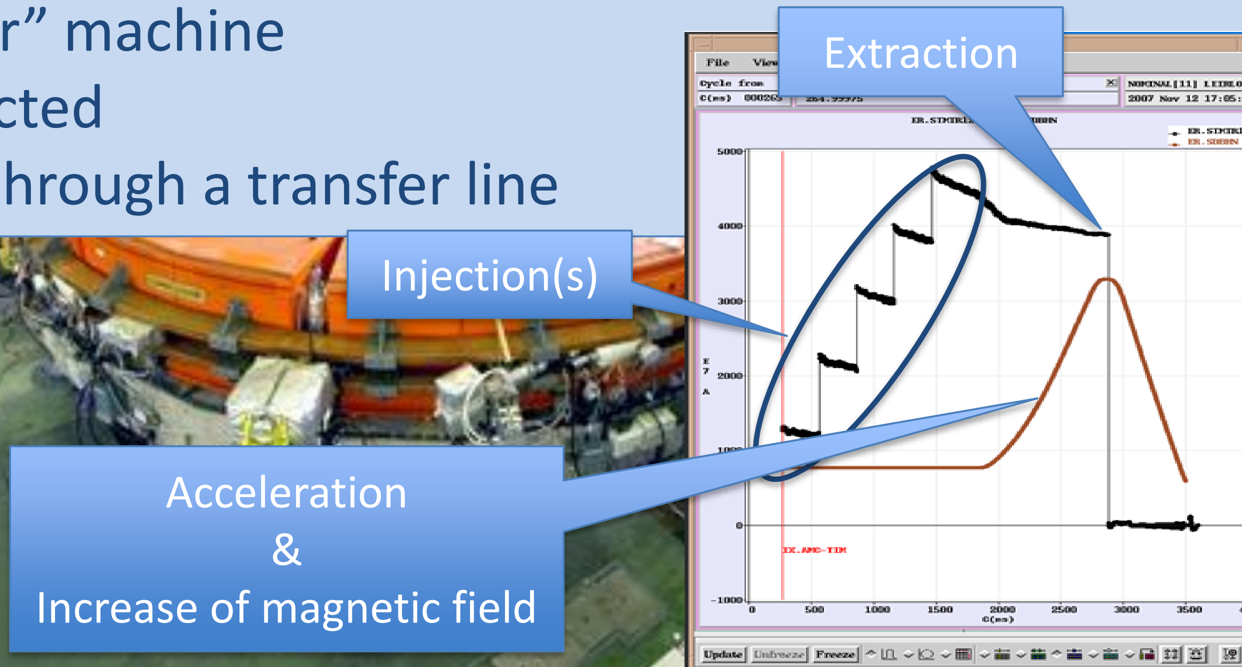
CERN - LEIR as an Example



LEIR as an Example

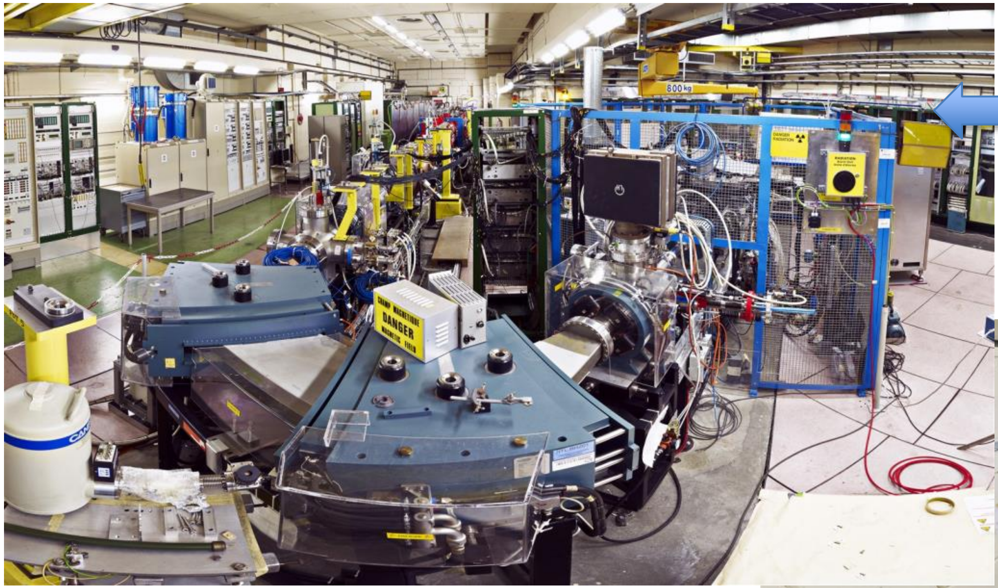
The particle beam:

- 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

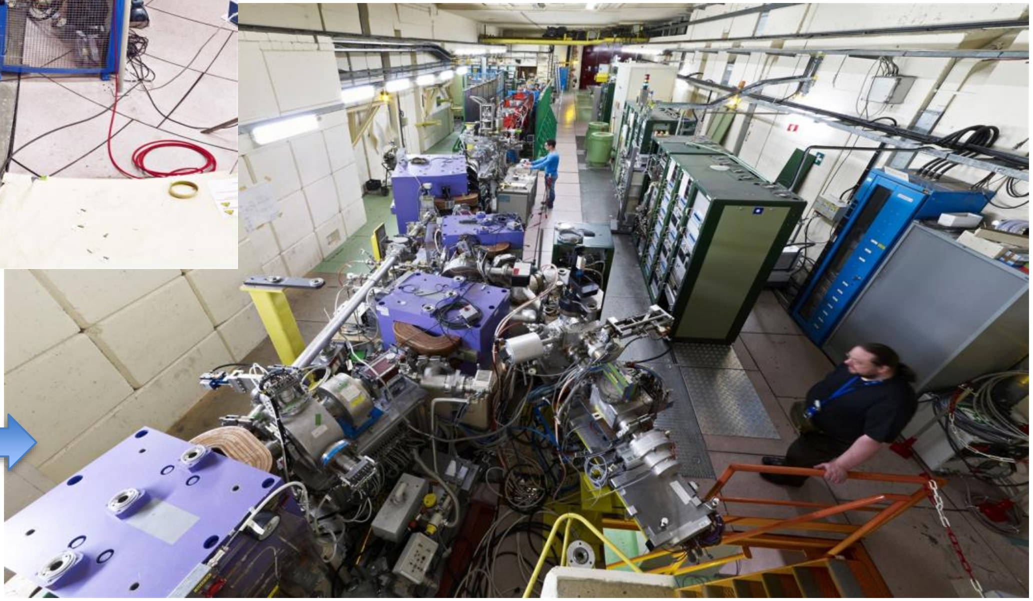


LINAC 3, injector of LEIR

The CERN LINAC 3 provides different ion species to LEIR

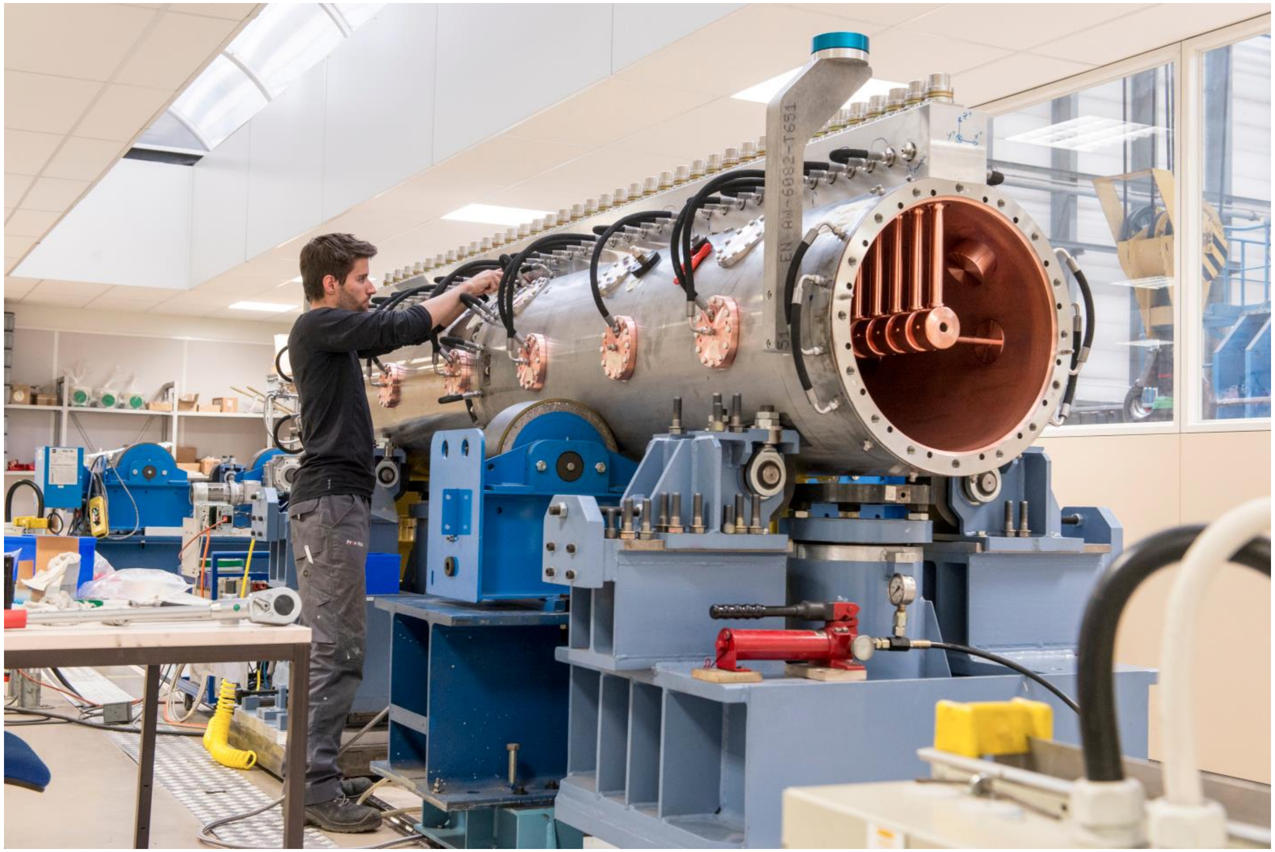


The ion source in the blue cage with the spectrometer in the front, follow by the LINAC behind



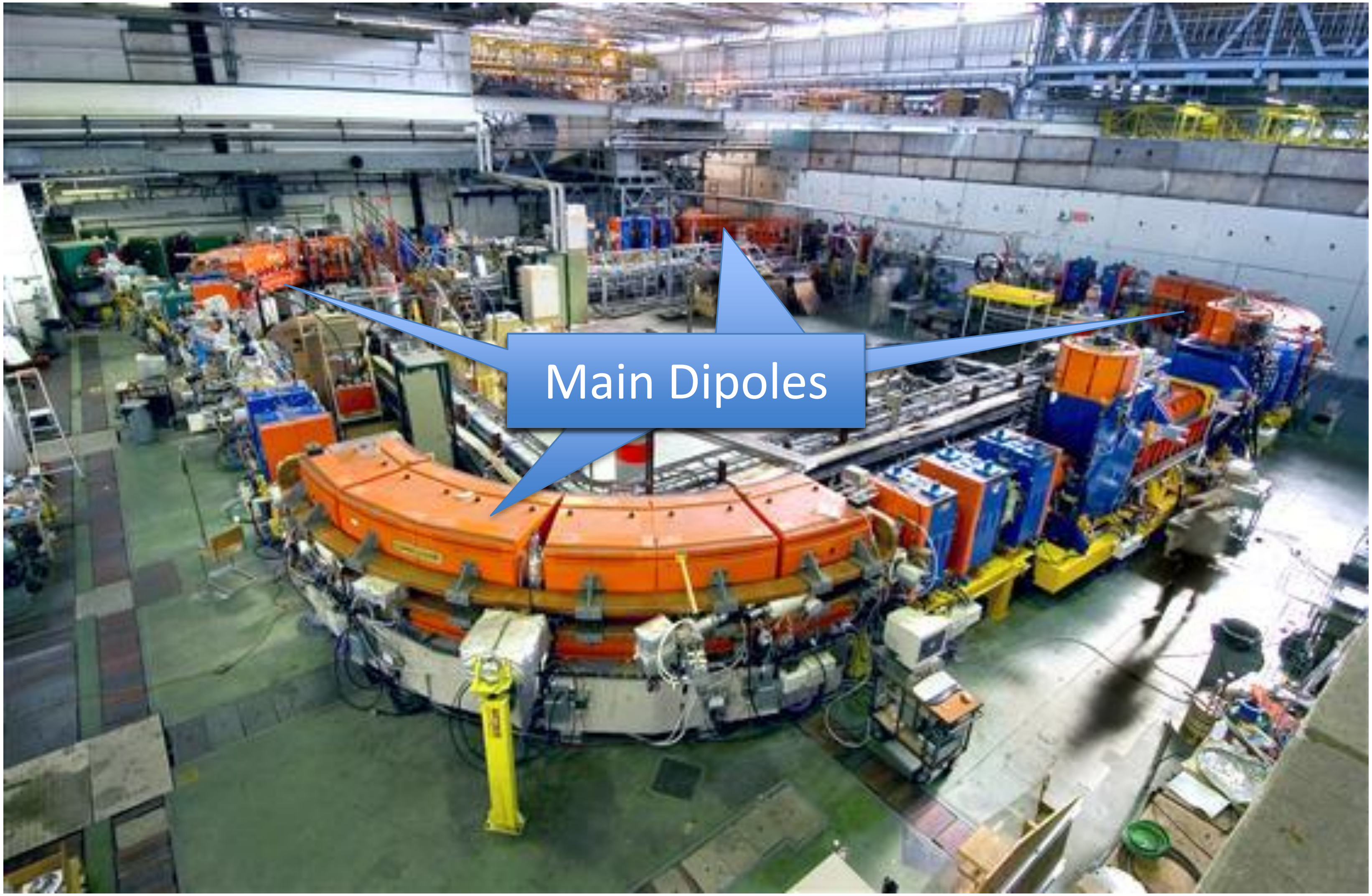
The downstream part of the LINAC with the accelerating structures (Alvarez) in the back of the image and transfer and measurement lines in the front

LINAC Accelerating Structure



The CERN LINAC 4 drift tube

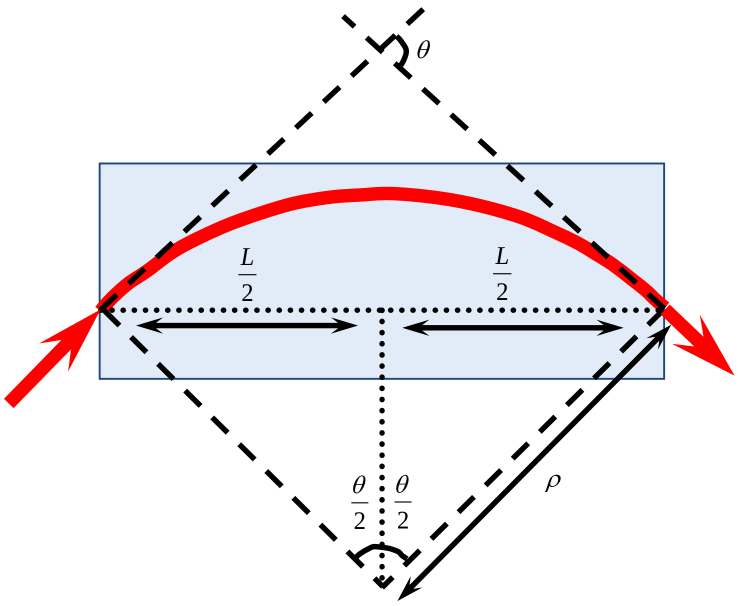
Make Particles Circulate

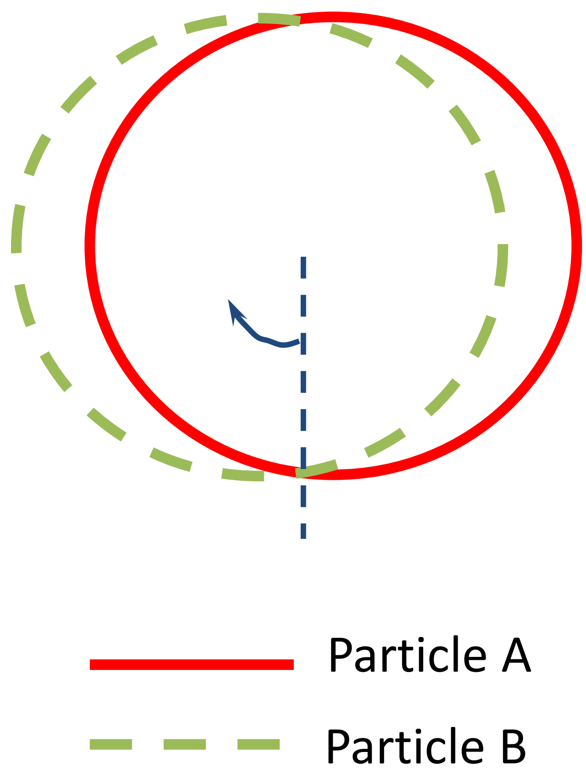


Charged Particles Deviated - Dipoles

Charged Particles are deviated in magnetic fields

Two charged Particles in a homogeneous magnetic field



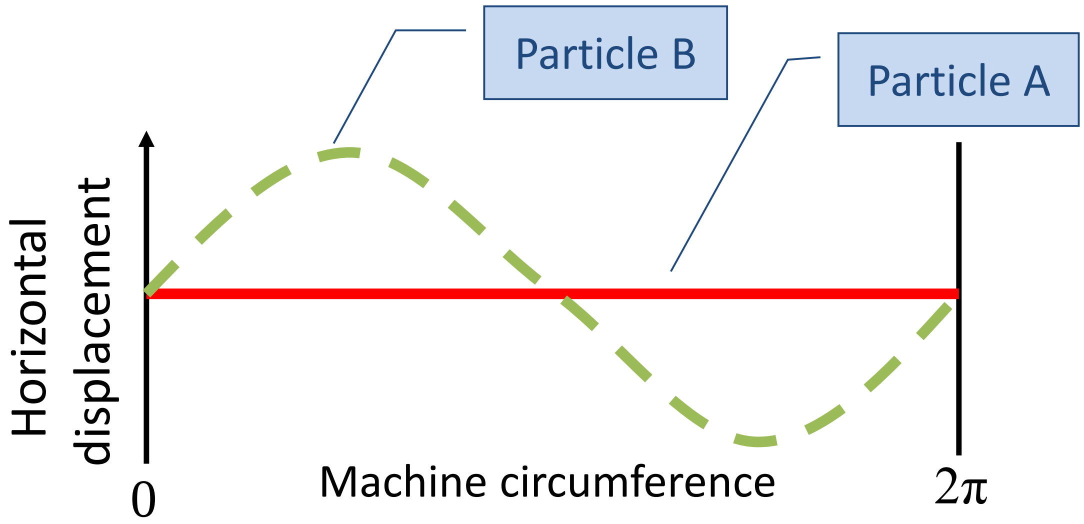


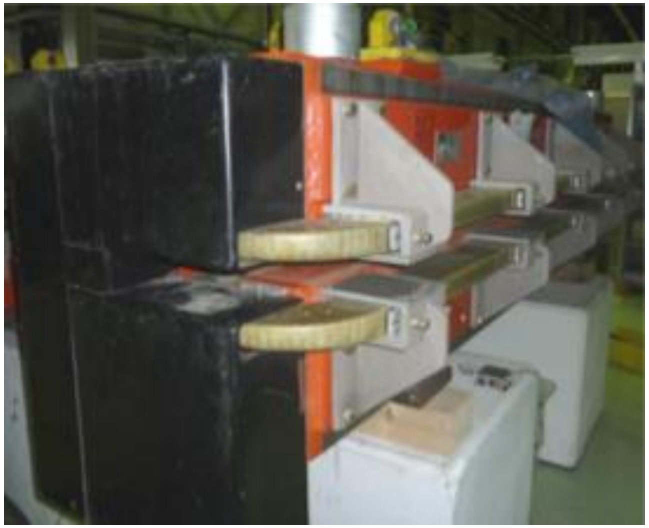
Lorentz force:

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

Oscillatory Motion of Particles

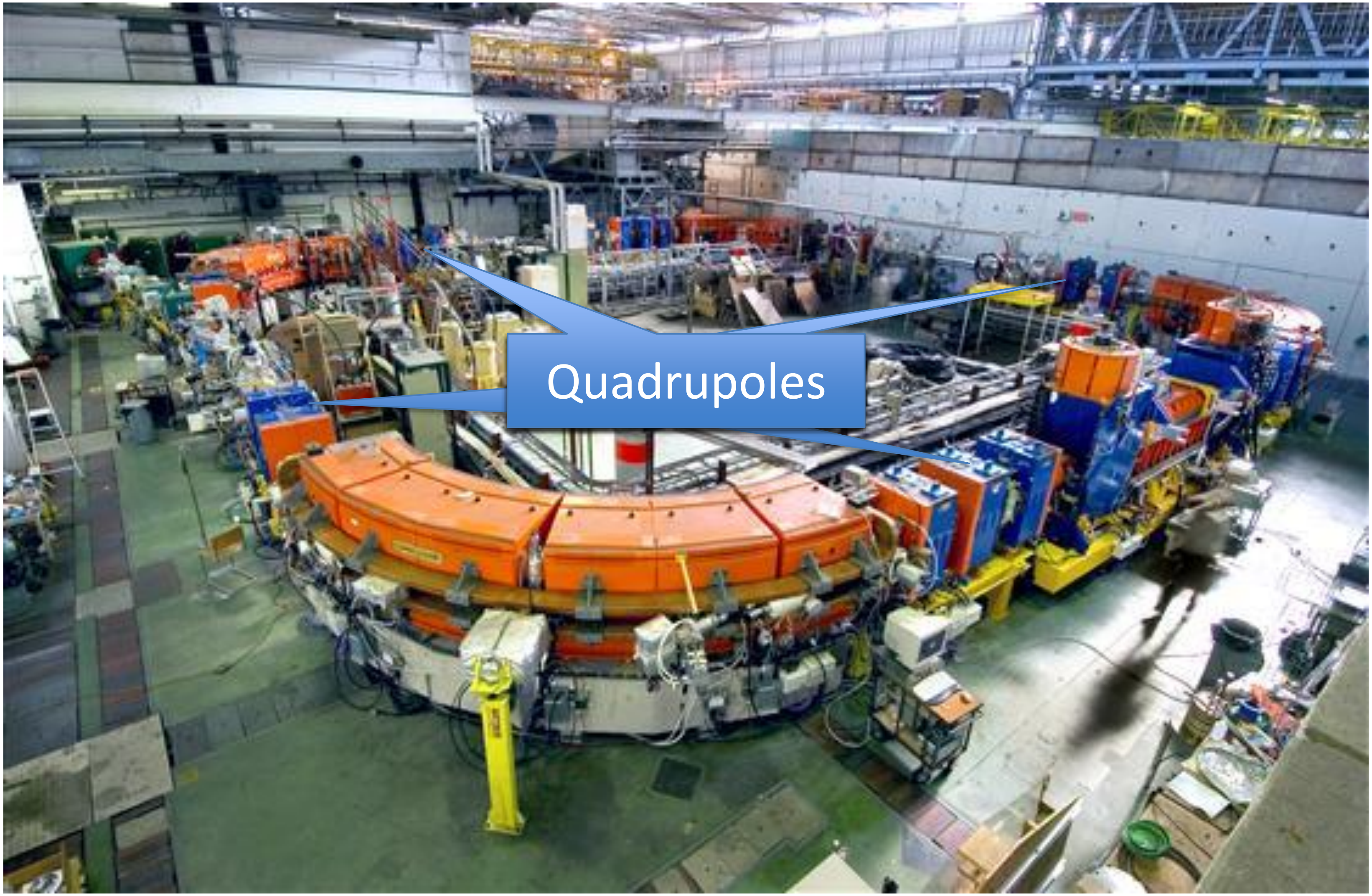
Horizontal motion





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

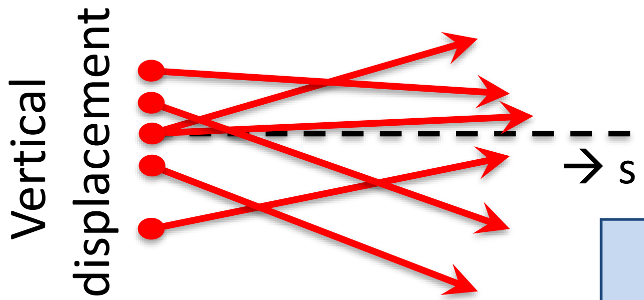


Oscillatory Motion of Particles

The horizontal motion seems to be "stable"…. What about the vertical plane ?

Many particles many initial conditions

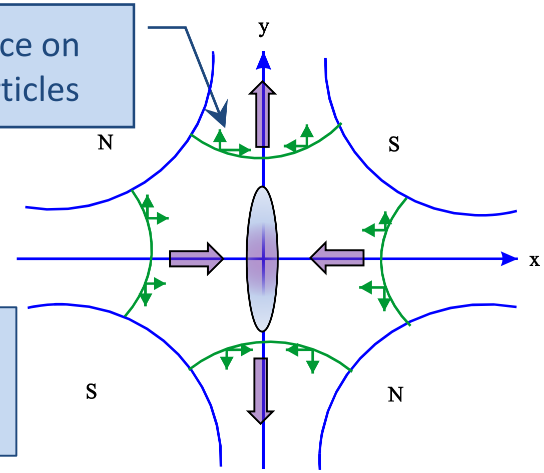
⇒ Beam gets dispersed
⇒ We need focusing



Many different angles

Quadrupoles: Focusing particles, a bit like lenses for light

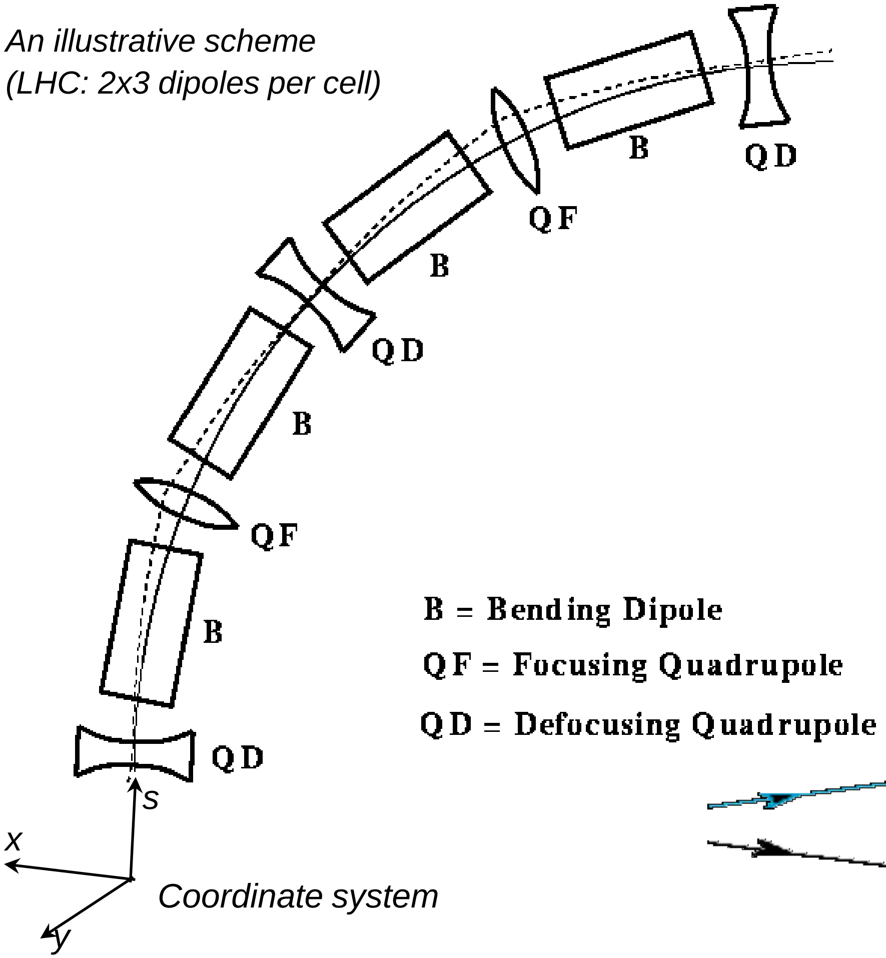
Force on particles



Quadrupoles focus in one plane and defocus in the other!

Alternating gradient lattice

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

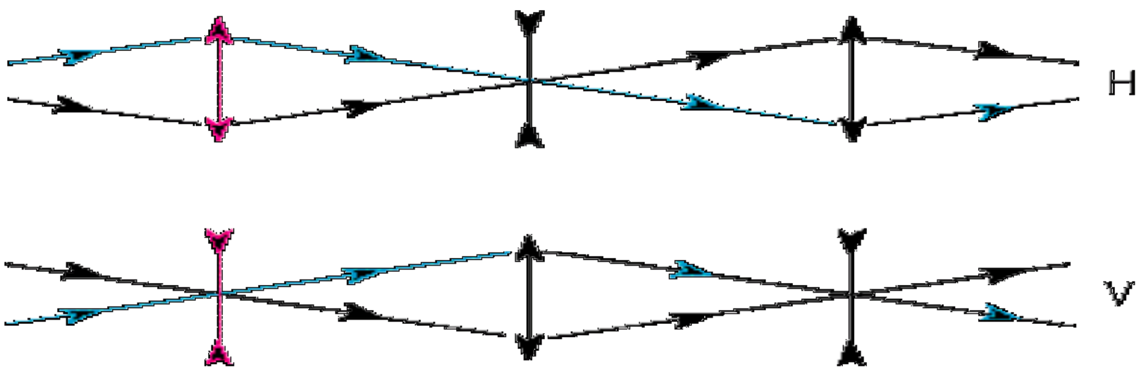


Coordinate system

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

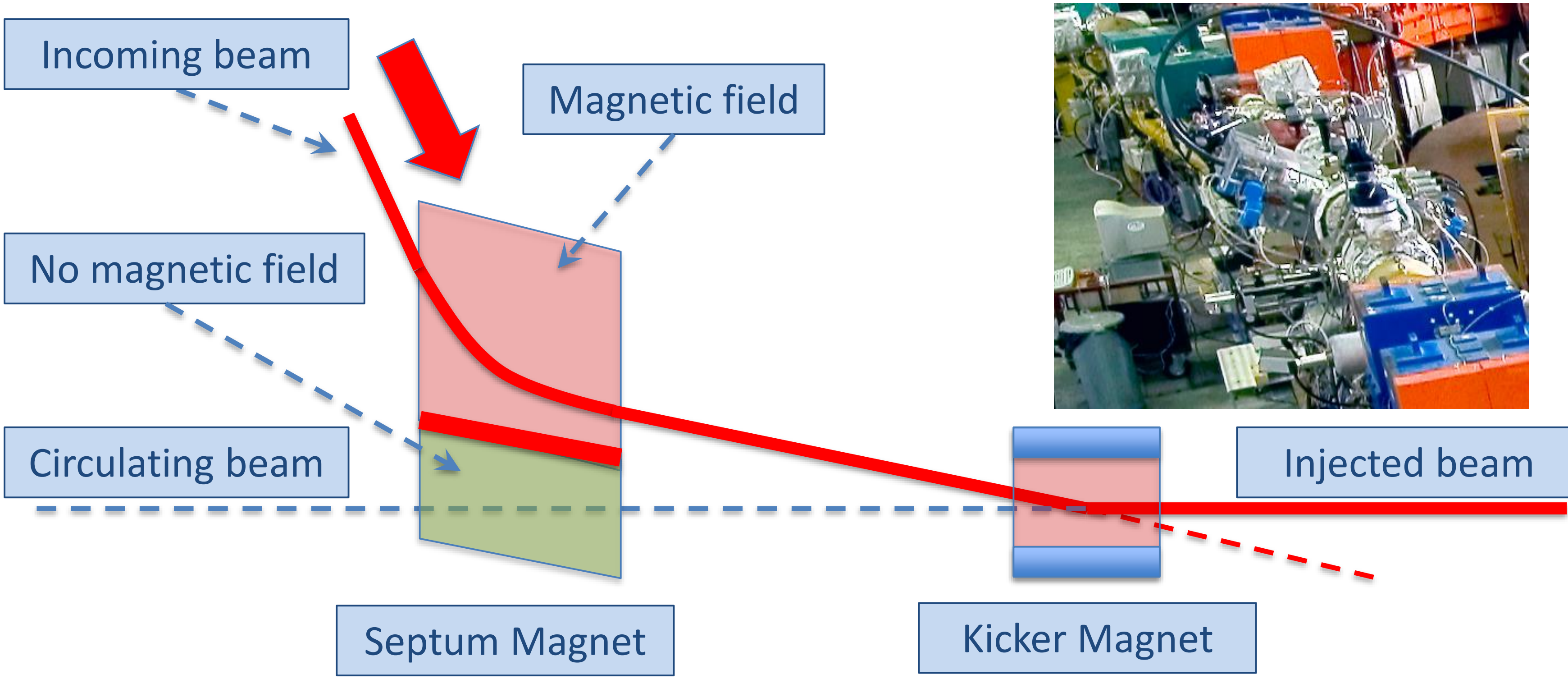
Dipole magnets keep the particles on the circular orbit.

Quadrupole magnets focus alternatively in both planes.

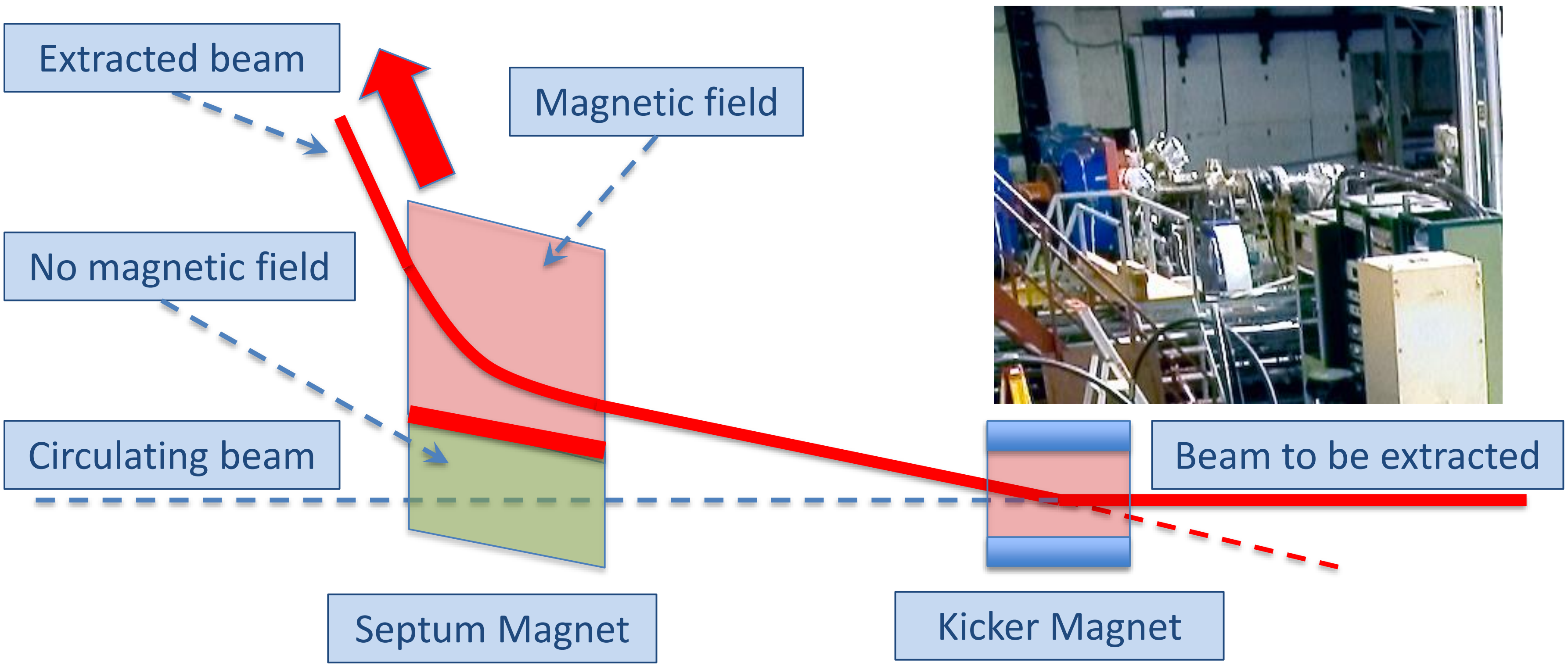


Injecting & Extracting Particles

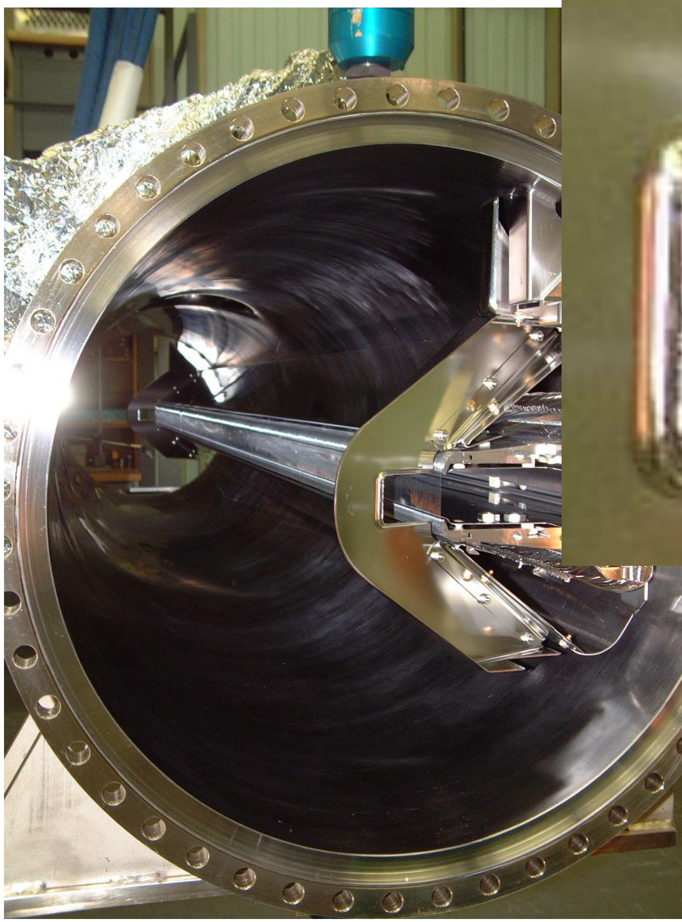
Injecting & Extracting Particles



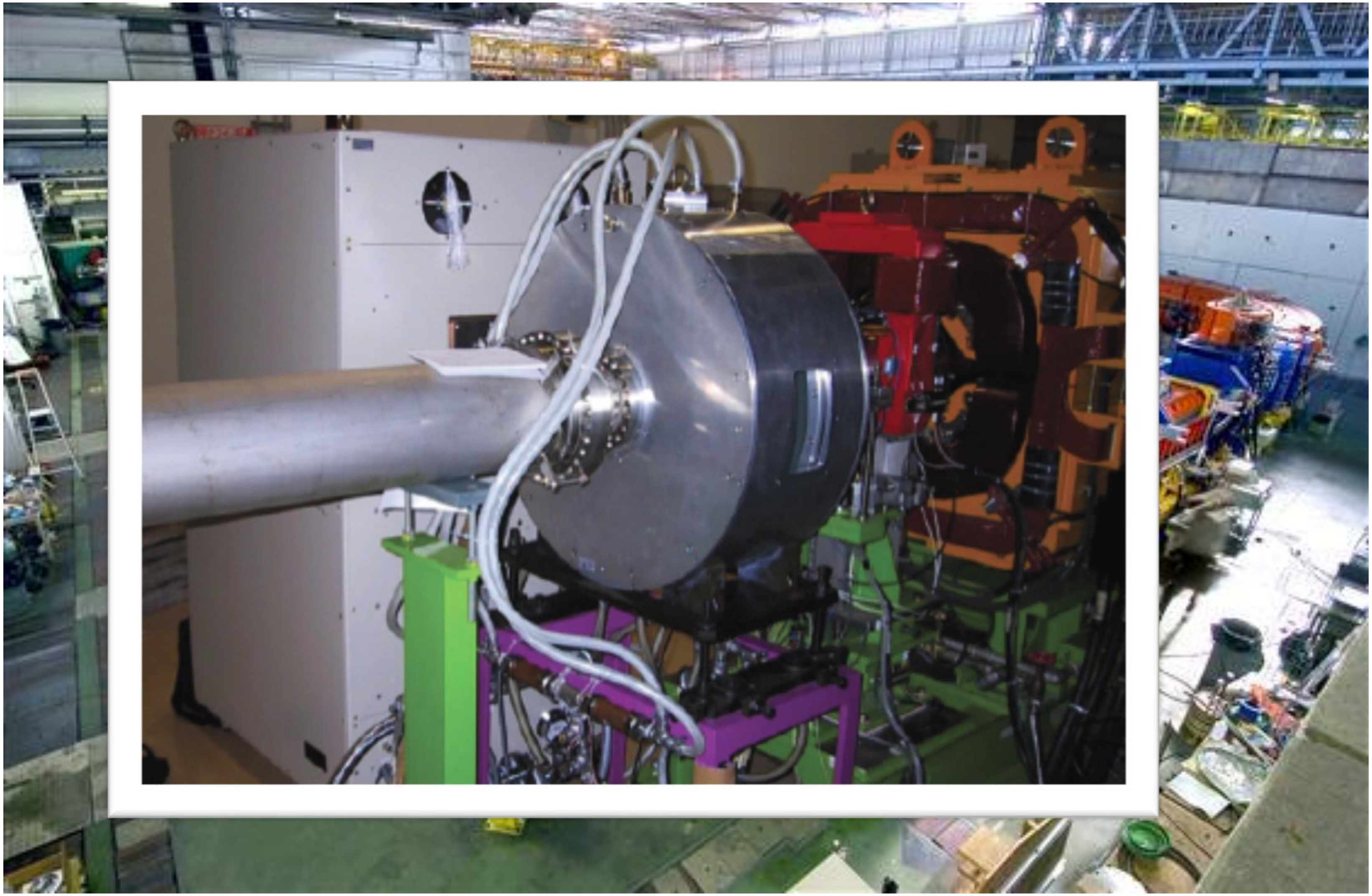
Injecting & **Extracting** Particles



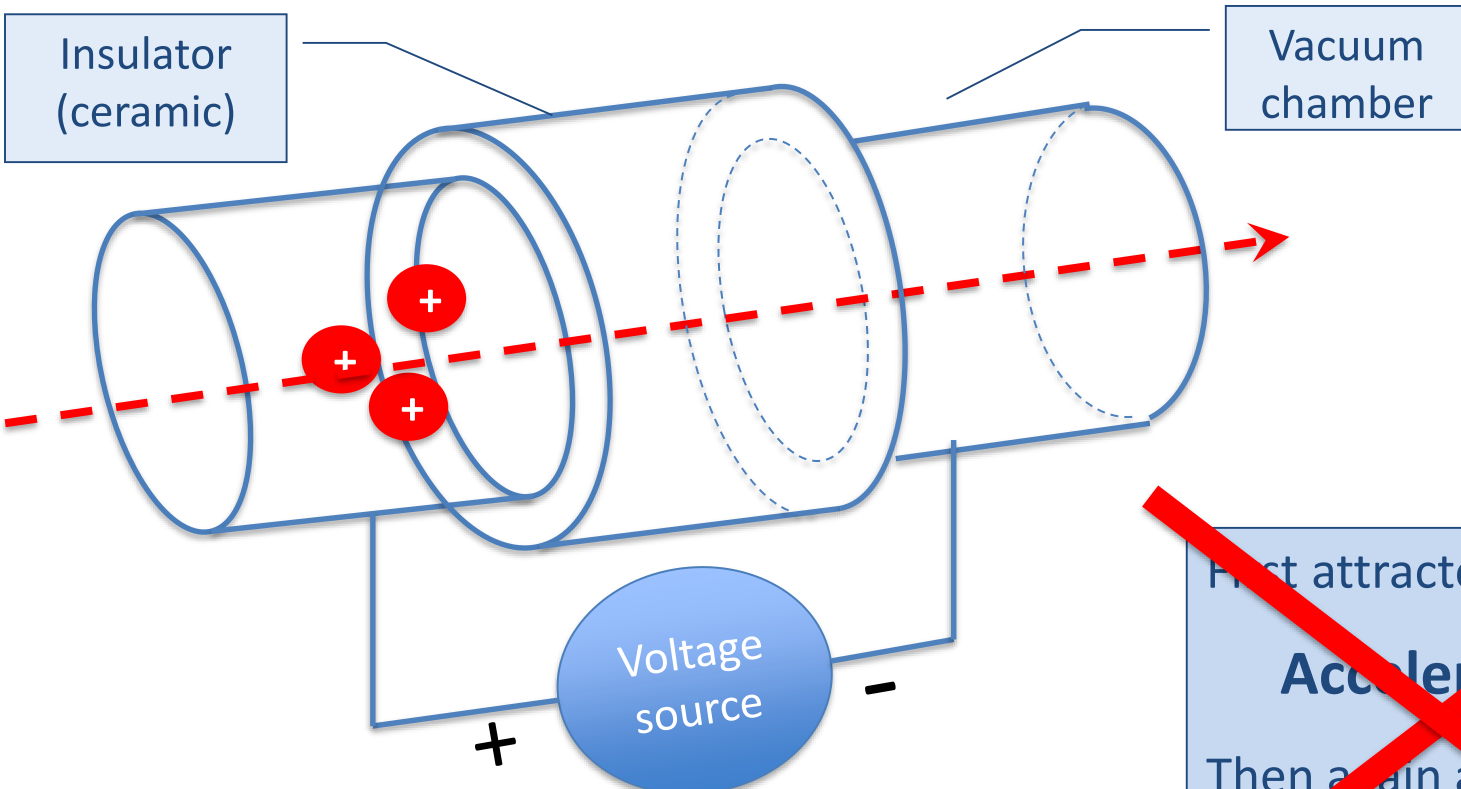
Septum and Kicker Magnets



Accelerating Particles



Accelerating Beams



~~First attracted~~

~~**Acceleration**~~

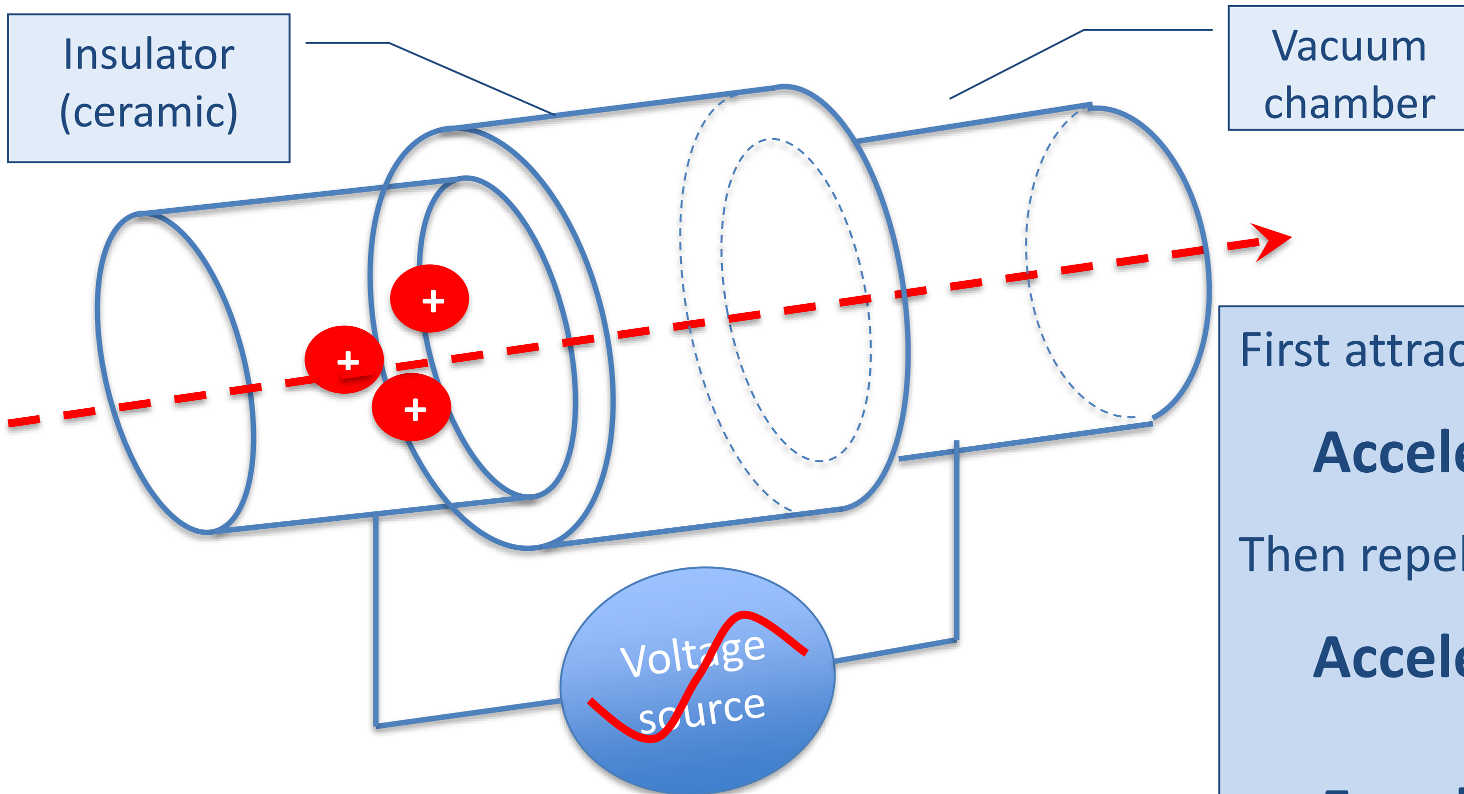
~~Then again attracted~~

~~**Deceleration**~~

Net result:

No Acceleration

Accelerating Beams



First attracted

Acceleration

Then repelled

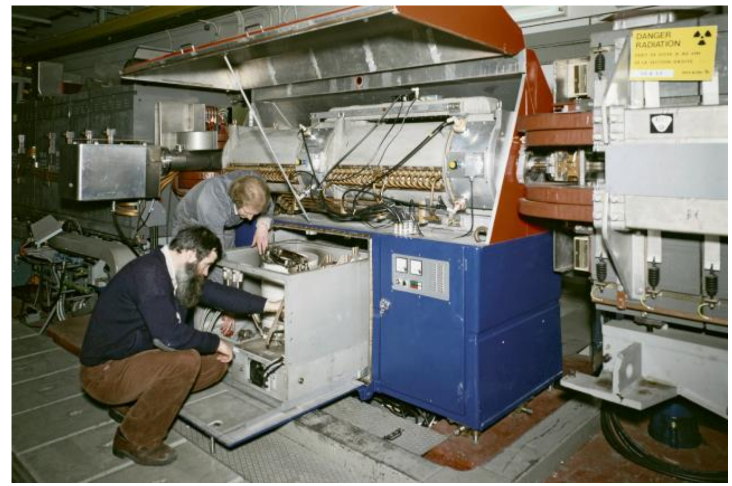
Acceleration

$$\mathbf{F_{RF} = h \times F_{rev}}$$

Some RF Cavities and feedbacks

Fixed frequency cavities (Superconducting) in the LHC

Variable frequency cavities (normal conducting) in the CERN PS

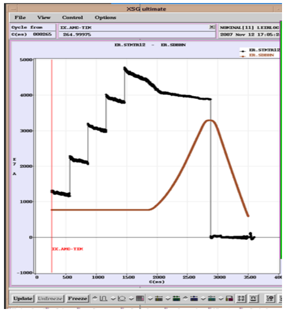


RF cavities are not only used to accelerate beams, but also to shape the beam:

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

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

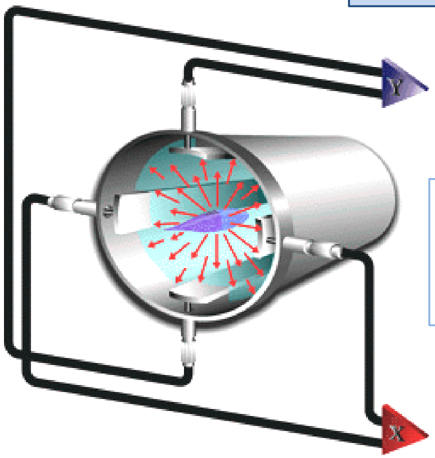
Measuring Beam Characteristics

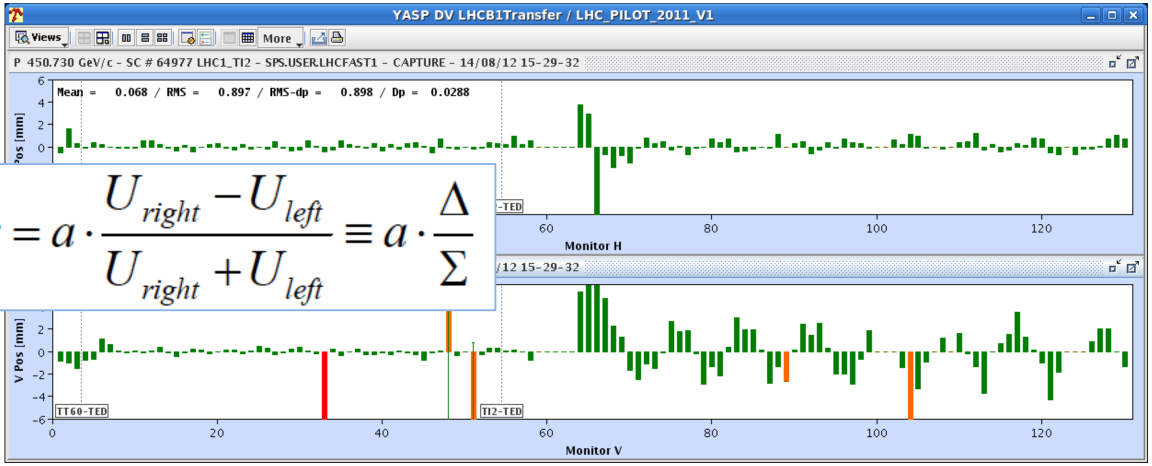


Beam intensity or current measurement:

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

Beam position/orbit measurement:

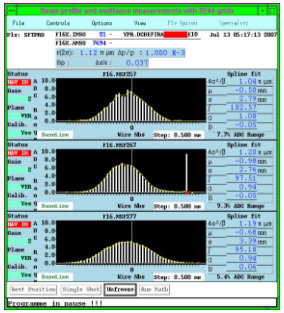




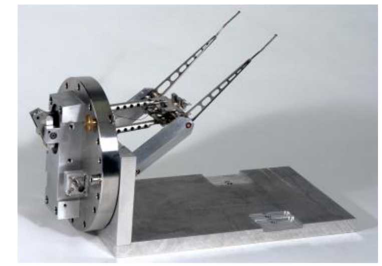
$$x = a \cdot \frac{U_{right} - U_{left}}{U_{right} + U_{left}} \equiv a \cdot \frac{\Delta}{\Sigma}$$

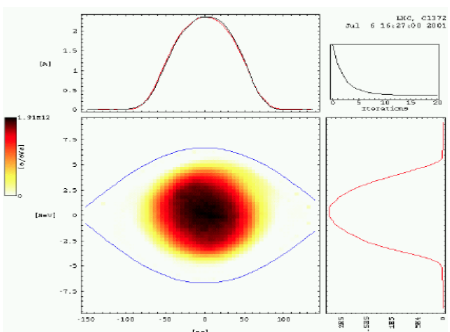
Correcting orbit using automated beam steering

Measuring Beam Characteristics



Transverse profile/size measurement:
- Secondary Emission Grids
- (Fast) Wire scanners

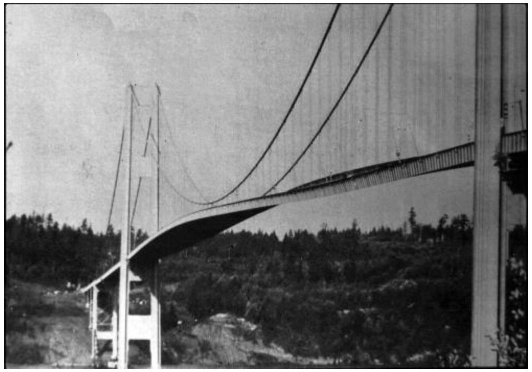




Longitudinal beam profile/size measurement:
- Tomogram using wall current monitor data
- Use synchrotron motion for reconstruction

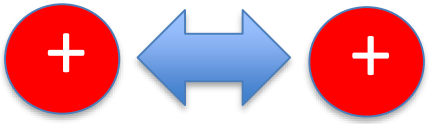
Any many more beam properties…..

Possible Limitations

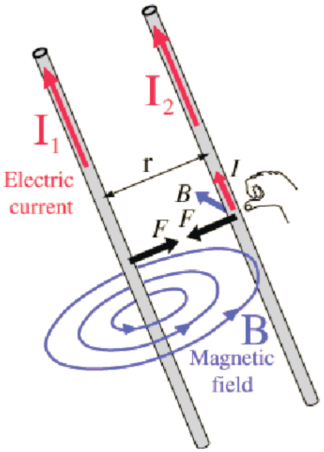


Machines and elements cannot be built and aligned with infinite precision

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

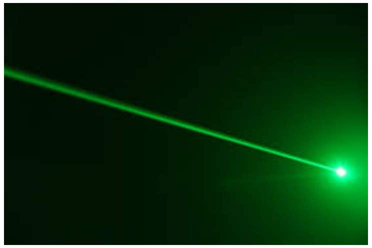
- Why Accelerators and Colliders ?
- A Brief Historic Overview
- The Main Ingredients of an Accelerator
- **Some ways of using Accelerators**

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:

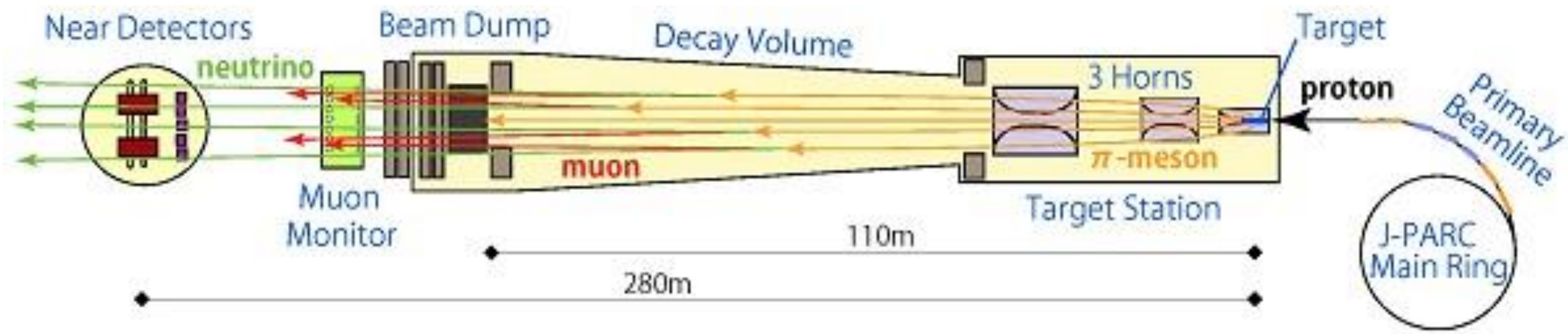
Light Sources:



Collider Physics:

Fixed Target Physics

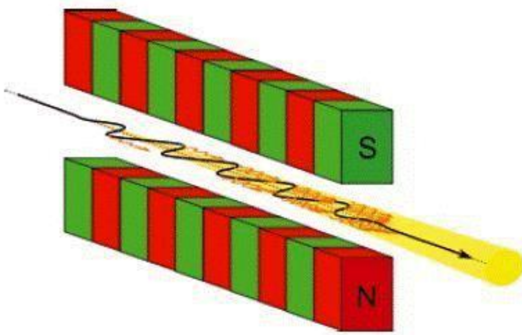
Just a few examples among many:

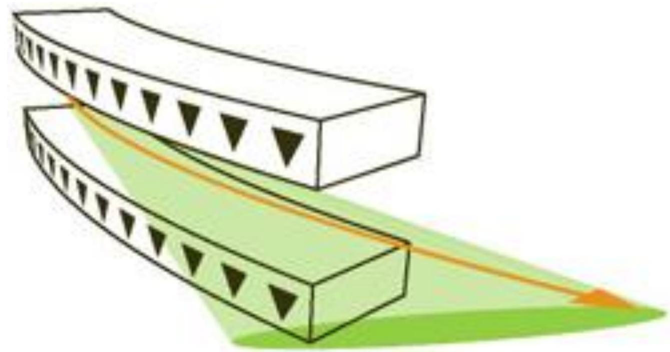


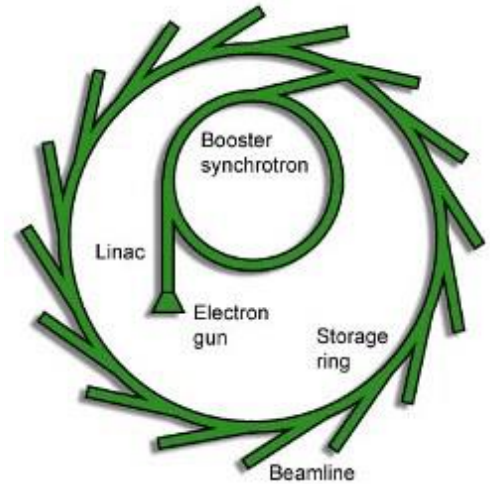
- Neutrino physics and Spallation sources: high beam power
  - High beam **intensity** with small beam size
  - High beam **energy** and / or high **repetition rate**
- J-PARC – Japan
- FermiLab - USA
- Previously CERN to CNGS – Europe
- Spallation Neutron Source (SNS) Oak Ridge - USA

Synchrotron Light Sources

Just a few examples among many:







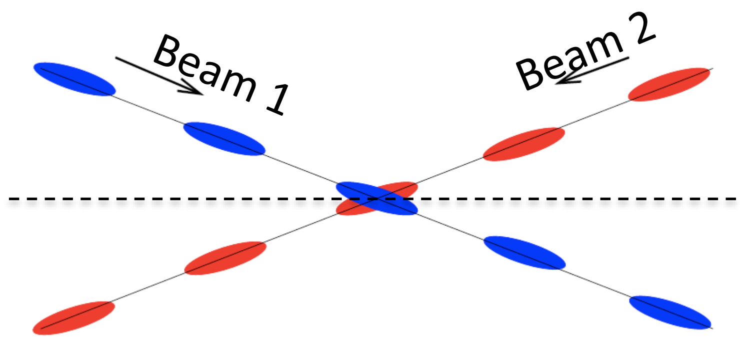
- Photon beam from stored (highly relativistic) electron beam
  - High electron beam intensity (Accelerator & Storage Ring)
  - Use of **undulators** to enhance photon emission
- Swiss Light Source (SLS) – Europe
- European Synchrotron Radiation Facility (ESRF) – Europe
- National Synchrotron Light Source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

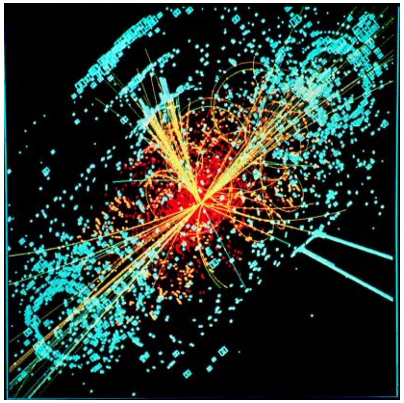
Collider Physics

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 → 2 separate rings
- Electron – Positron or Proton – Antiproton → single ring





Collider Luminosity

For collider physics the integrated luminosity is the figure of merit

Intensity per bunch

Number of bunches

Correction factors

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

Beam dimensions

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

- The instantaneous luminosity is the amount of events per unit of surface per second [$cm^{-2}s^{-1}$]
- Integrating this over time results in the integrated luminosity.
- The LHC produced in 2016 for ATLAS and CMS each > 30 fb^{-1}

Note: Cross section is expressed in units of barns (1 barn = $10^{-28}m^2$)

Ways to Increase Luminosity

Increase the beam brightness from the injectors (N and σ)

- More particle in smaller beams (increase brightness)

Increase number of bunches

- Higher harmonic RF systems

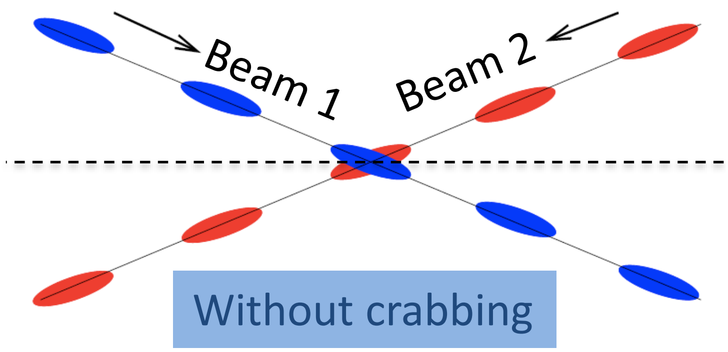
$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S$$

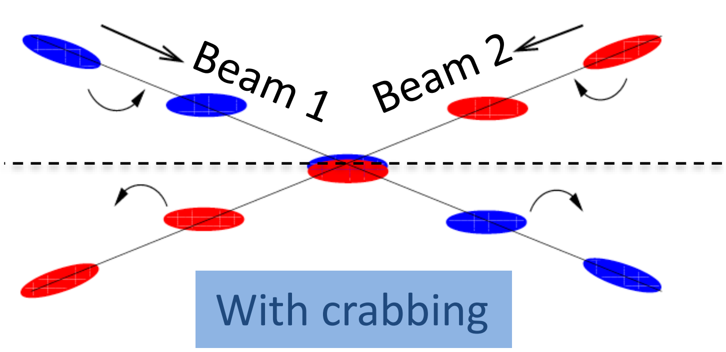
Reduce the β* (σ)

- Stronger focusing around the interaction points

Use crab cavities to reduce the crossing angle effect (s)

- Tilt the bunches to have more head-on collision effect





Future Circular Collider (FCC) study

International collaboration :

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

Point	Shaft Depth (m) Actual	Molasse SA	Wildflysch	Quaternary	Geology (m) 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

M. Benedikt

Thank you very much for your attention!