Introduction to Accelerators

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CERN **A**ccelerator **S**chool
Introduction to Accelerator Physics
2 – 14 October 2016
Budapest – Hungary

Contents

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

- **Why Accelerators and Colliders ?**
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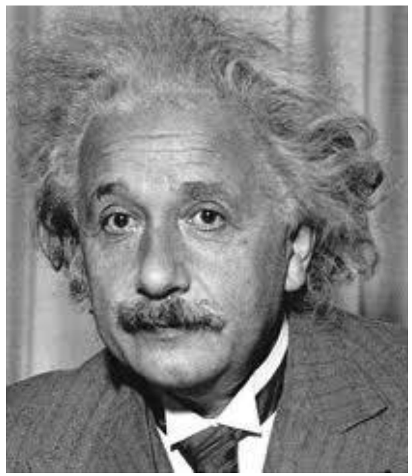
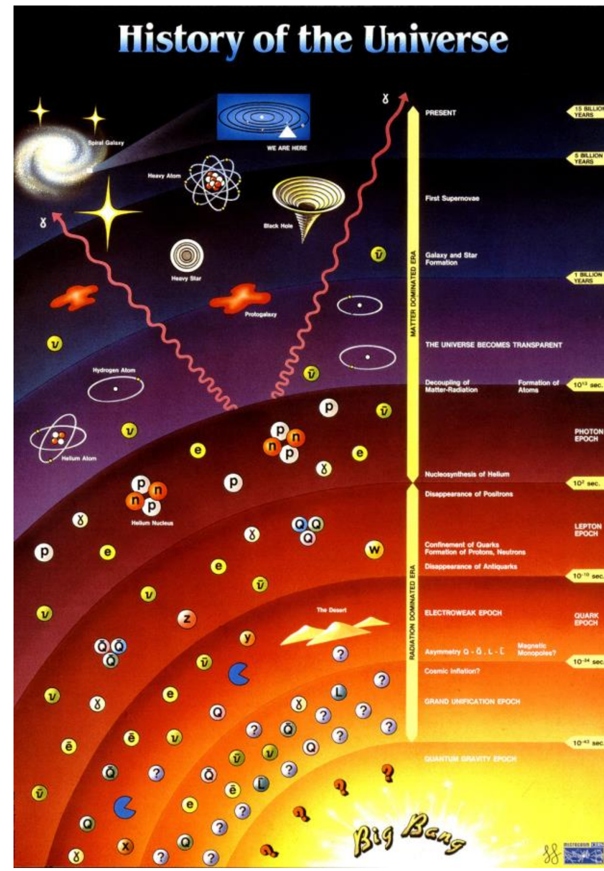
Matter versus Energy

$$E = m c^2$$

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

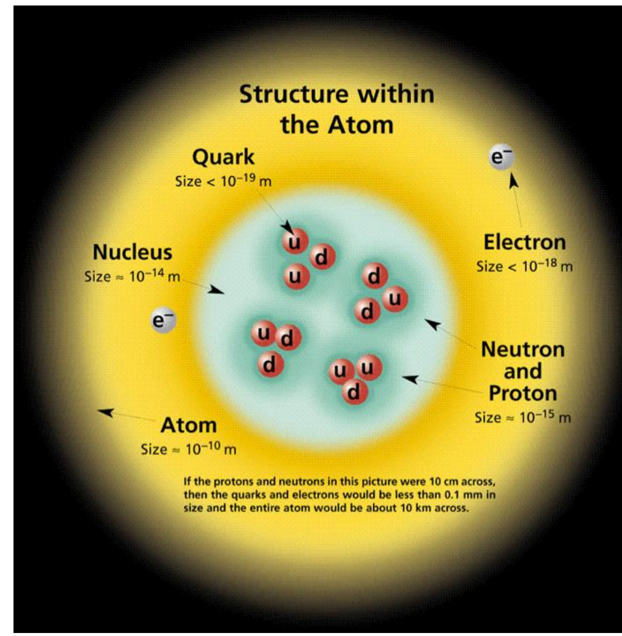
$\lambda = 400 \rightarrow 700$ nm

X-ray

$\lambda = 0.01 \rightarrow 10$ nm

Particle accelerators

$\lambda < 0.01$ nm



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

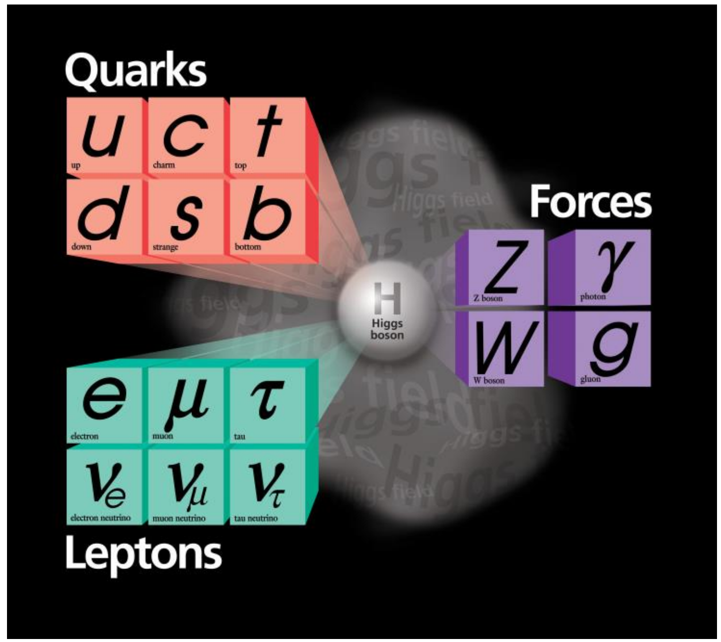
Increasing the energy will reduce the wavelength

Fixed Target vs. Colliders

Fixed Target	Collider
	
$E \, \mu \, \sqrt{E_{beam}}$	$E = E_{beam1} + E_{beam2}$
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

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 very Brief Historic Overview**
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- Some ways of using Accelerators

Accelerators and Their Use

Today: ~ **30’000 accelerators** operational world-wide*

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

- Industrial applications: ~ 20’000*
- Medical applications: ~ 10’000*

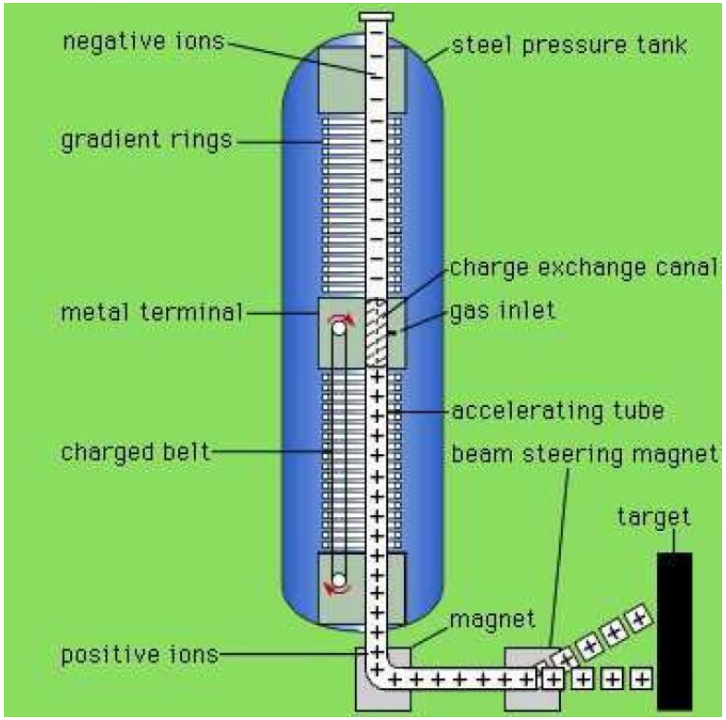
Les than a fraction of a percent is used for **research** and discovery science

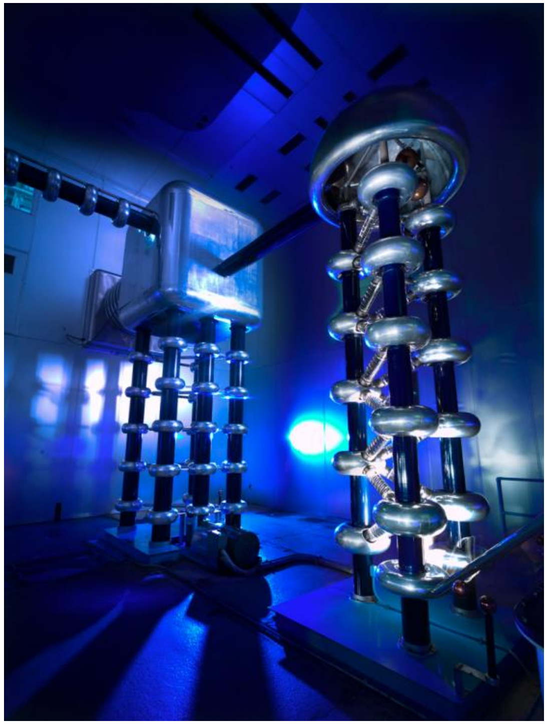
- Cyclotrons
- FFAG
- Synchrotrons
- Synchrotron light sources (e^-)
- Lin. & Circ. accelerators/Colliders

**Source: World Scientific Reviews of Accelerator Science and Technology A.W. Chao*

Cockroft & Walton / van de Graaff

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

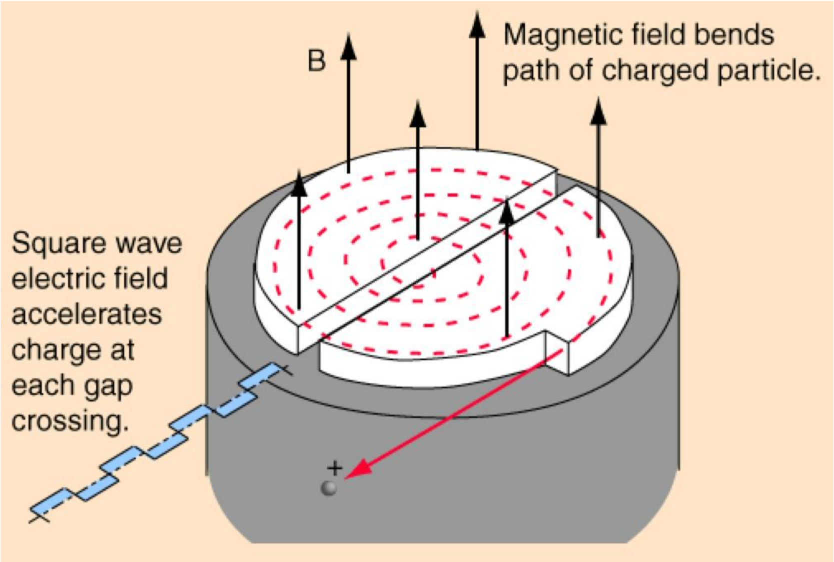




Cyclotron

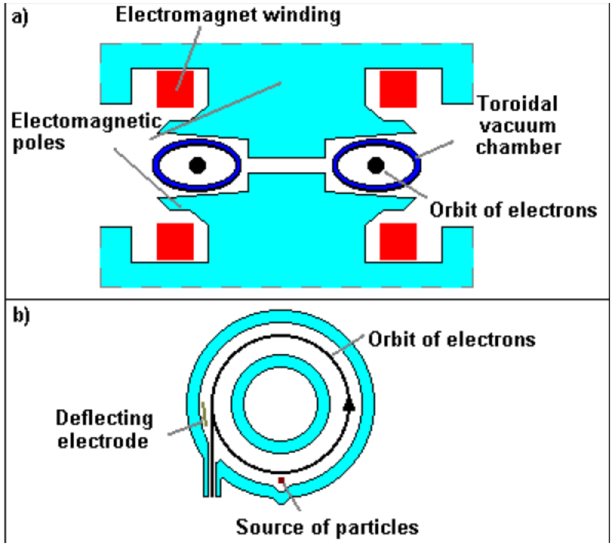
- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- Constant magnetic field
- Alternating voltage between the two D's
- Increasing particle orbit radius
- Development lead to the synchro-cyclotron to cope with the relativistic effects.

In 1939 Lawrence received the Noble prize for his work.

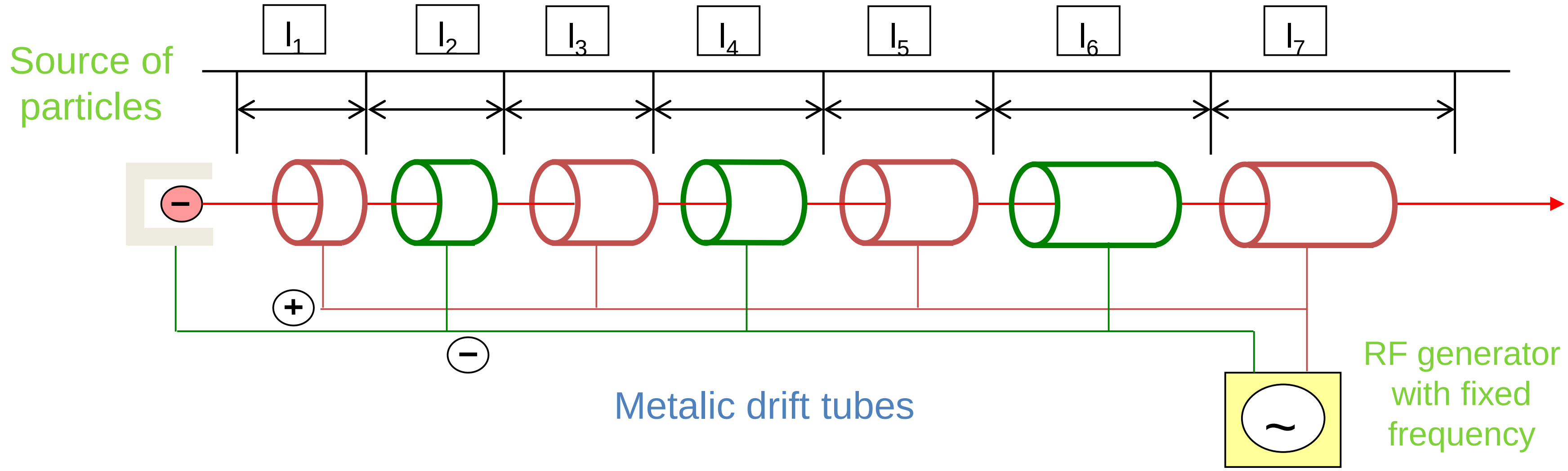


Betatron

- 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.



Linear Accelerator

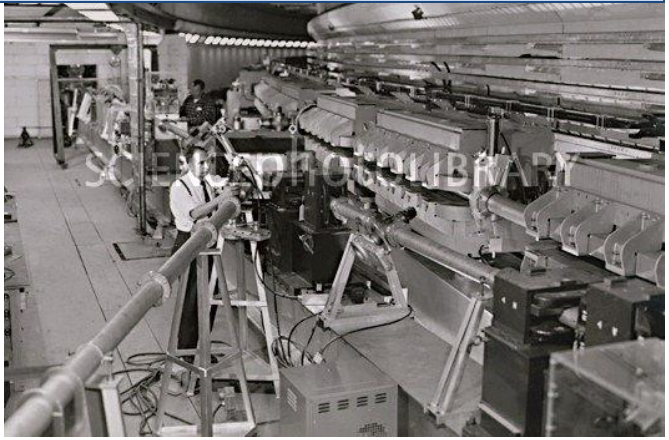


- Many people involved: Wideroe, Sloan, Lawrence, Alvarez,….
- Main development took place between 1931 and 1946.
- Development was also helped by the progress made on high power high frequency power supplies for radar technology.
- Today still the first stage in many accelerator complexes.
- Limited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

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



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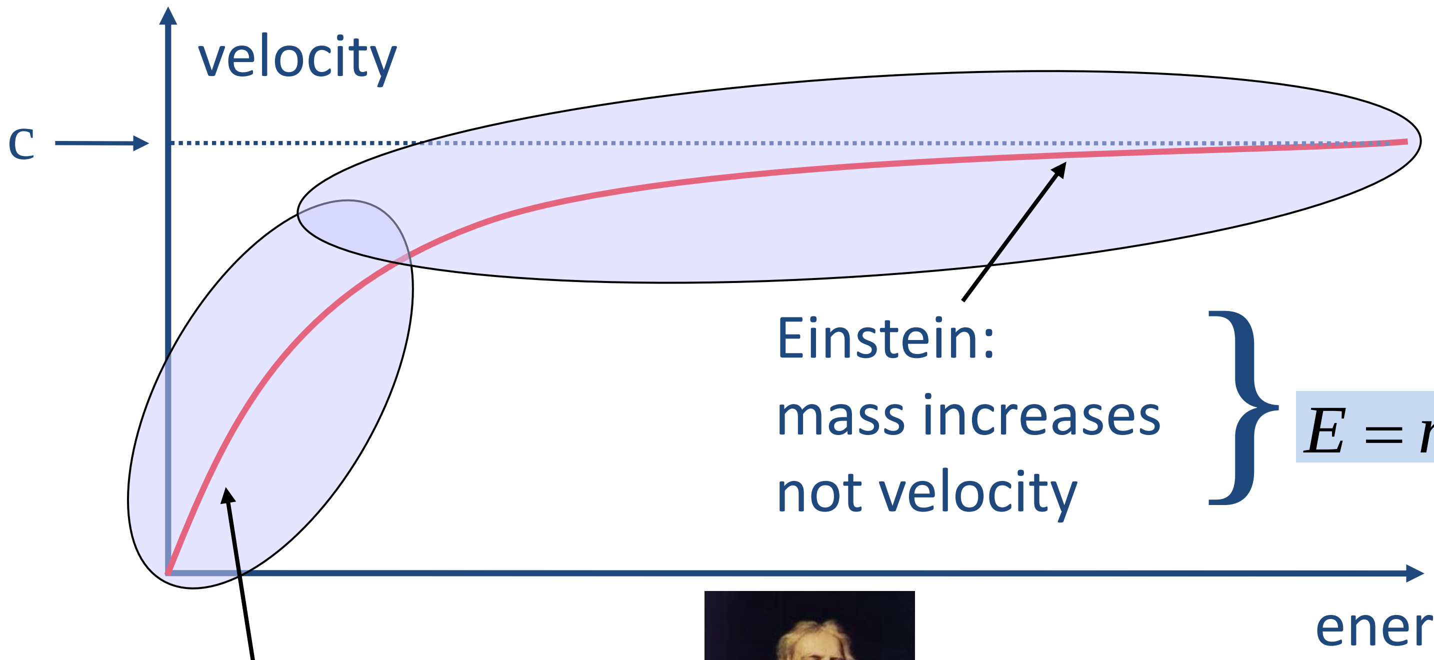
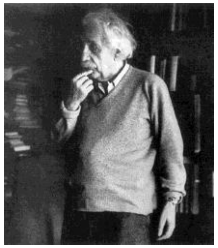
Towards Relativity



Einstein:
mass increases
not velocity

$$E = mc^2$$

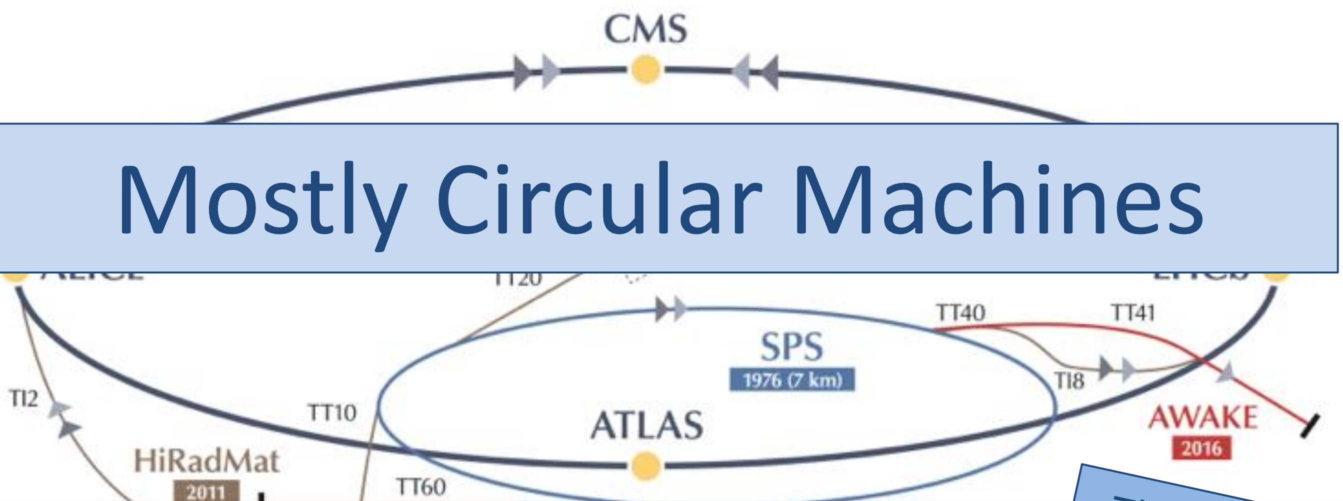


Newton: $E = \frac{1}{2} m v^2$

"**Relativity**" by W. Herr

This afternoon

The CERN Accelerator Complex



Mostly Circular Machines

- “**Sources**” by D. Faircloth — Thursday next week
- “**Linear Accelerators**” by D. Alesini — Tuesday
- “**Cyclotrons**” by M. Seidel — Wednesday
- “**Luminosity & Colliders**” by G. Papotti — Friday
- “**FFAG**” by S. Sheehy — Friday
- “**Synchrotron Light Machines & FEL**” by L. Rivkin — Tuesday & Wednesday Next week

A Guided Tour

Lets have a look at a synchrotron:

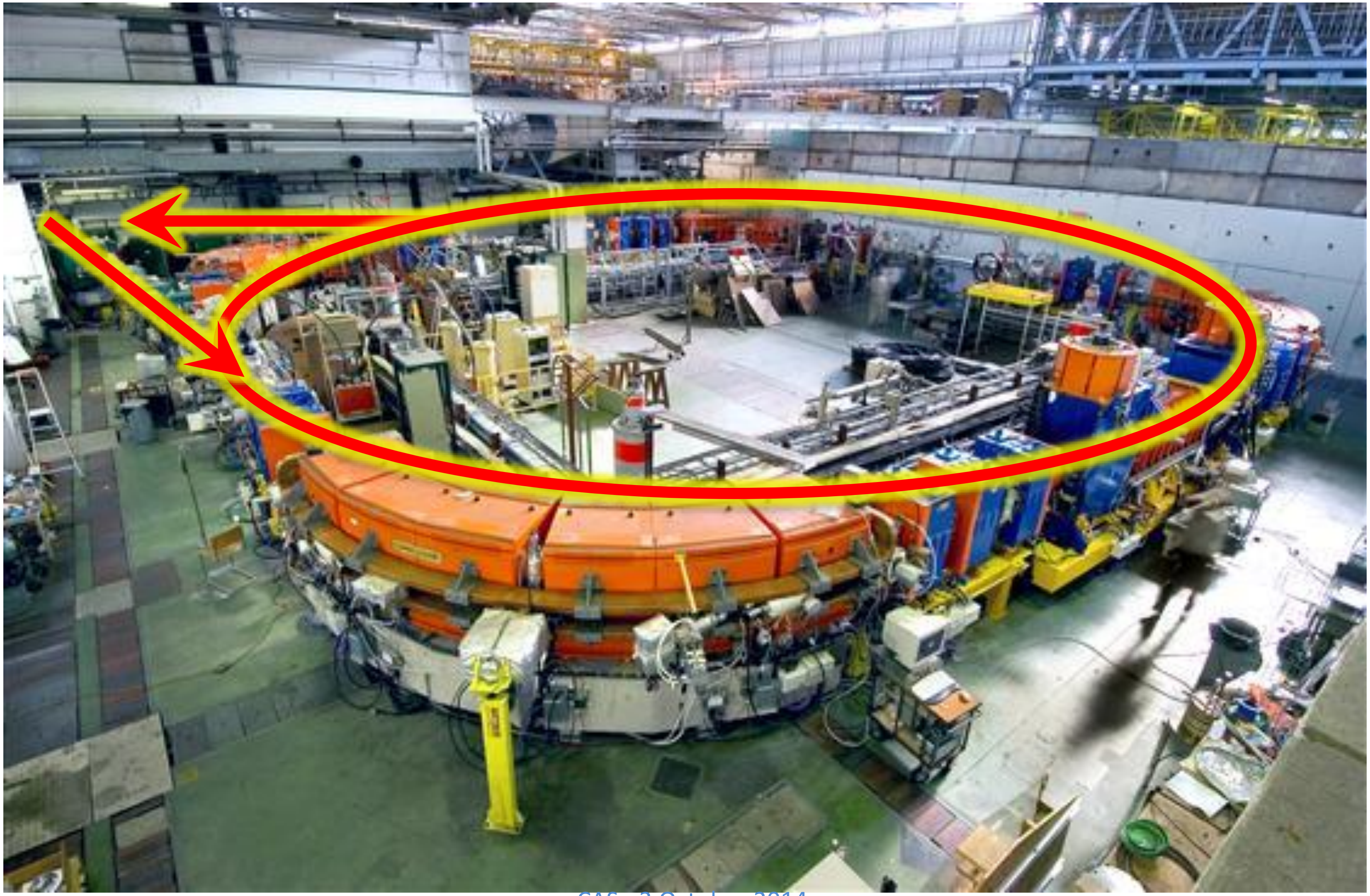
- Identify the main components and processes
- Briefly address their function

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

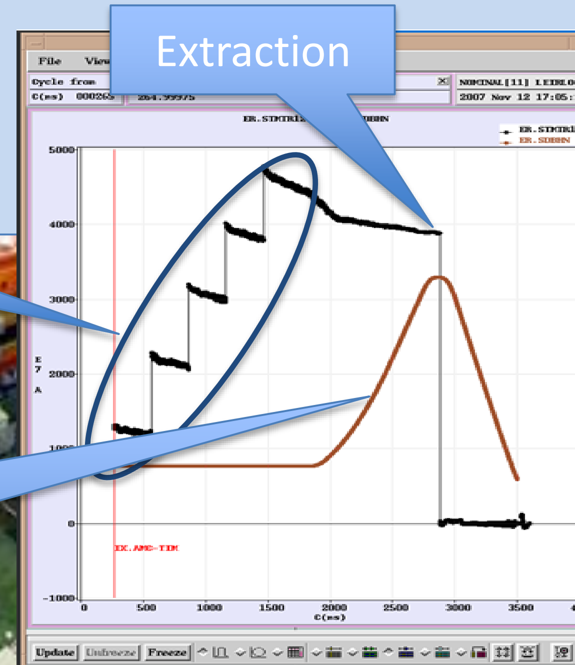
CERN - LEIR as an Example



LEIR as an Example

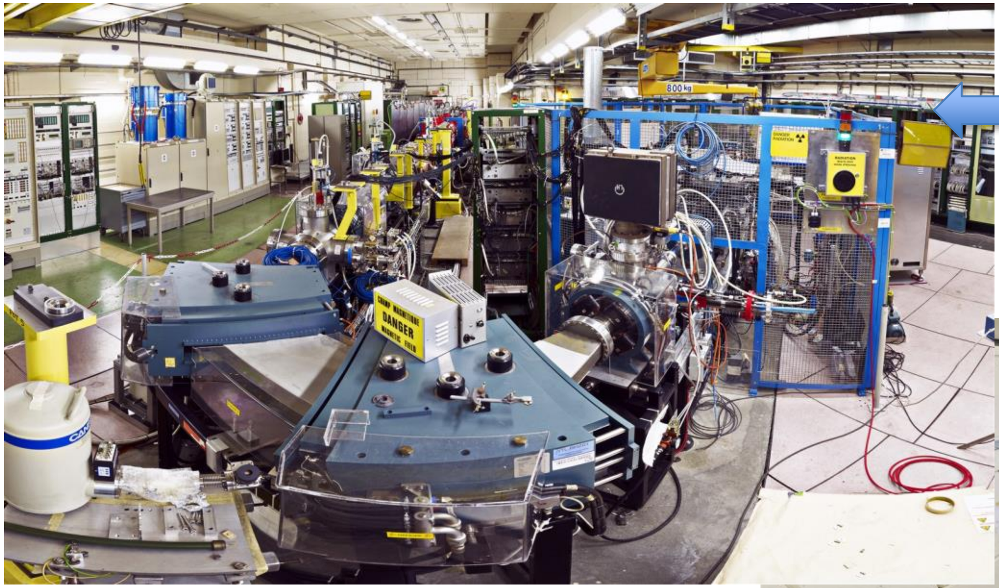
The particle beam:

- 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

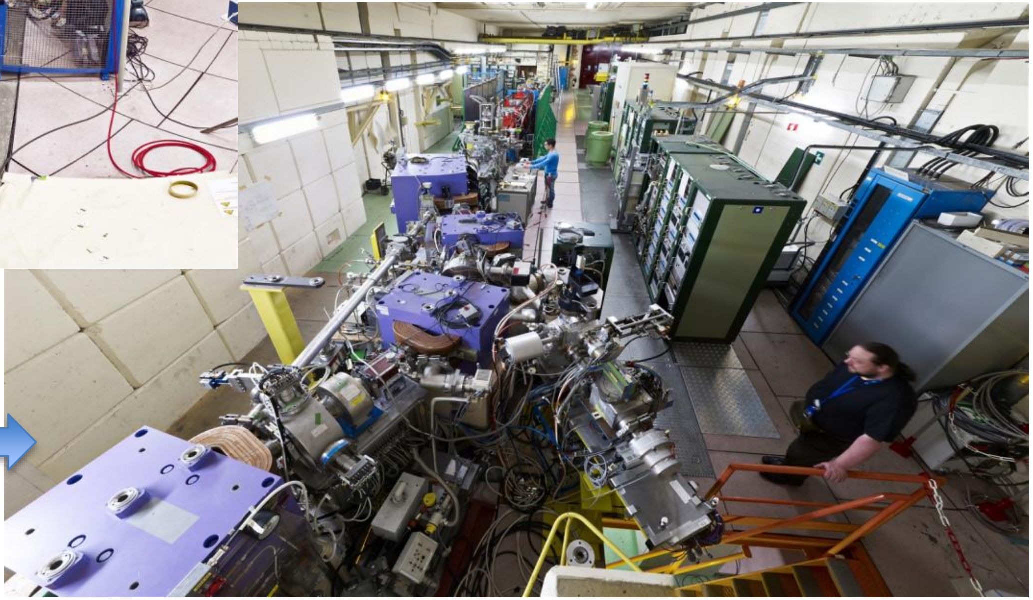


LINAC 3, injector of LEIR

The CERN LINAC 3 provides different ion species to LEIR

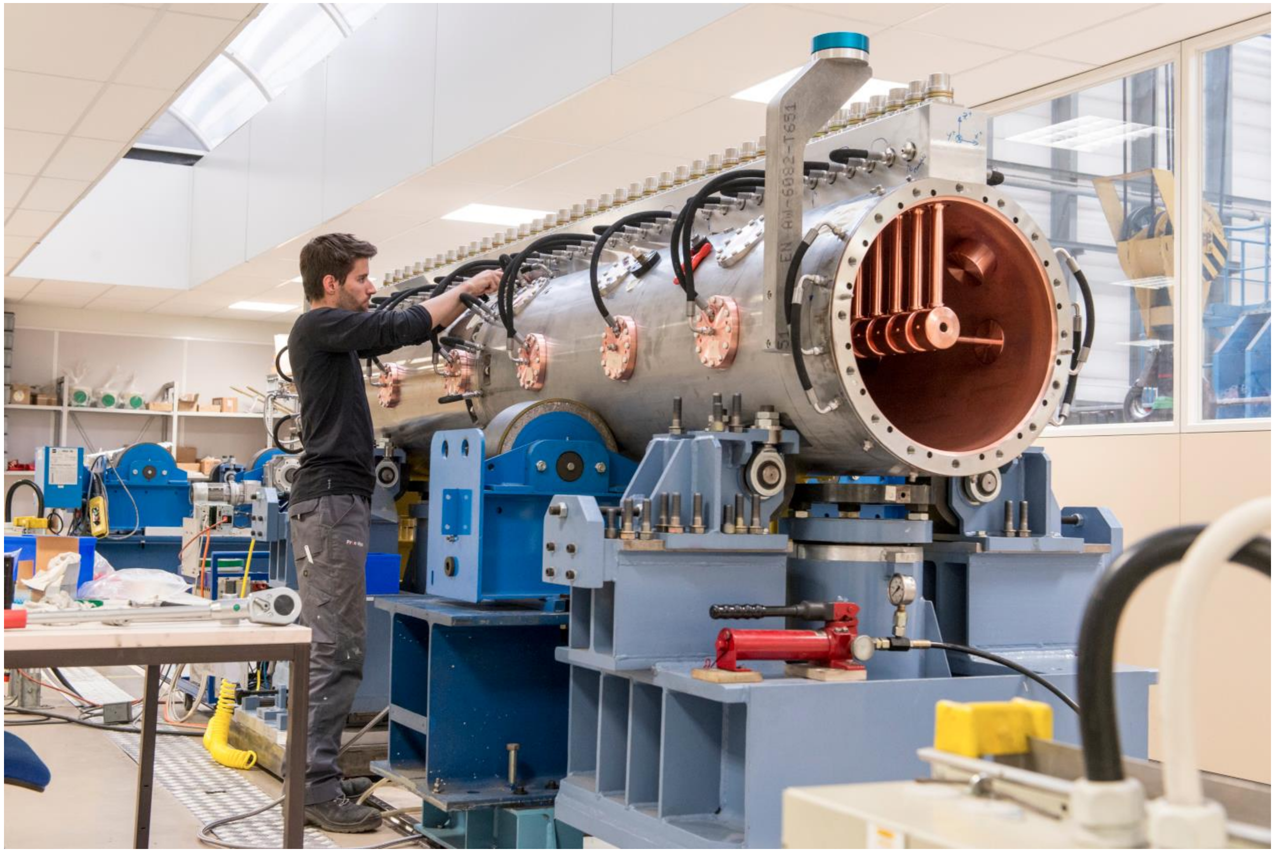


The ion source in the blue cage with the spectrometer in the front, follow by the LINAC behind



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

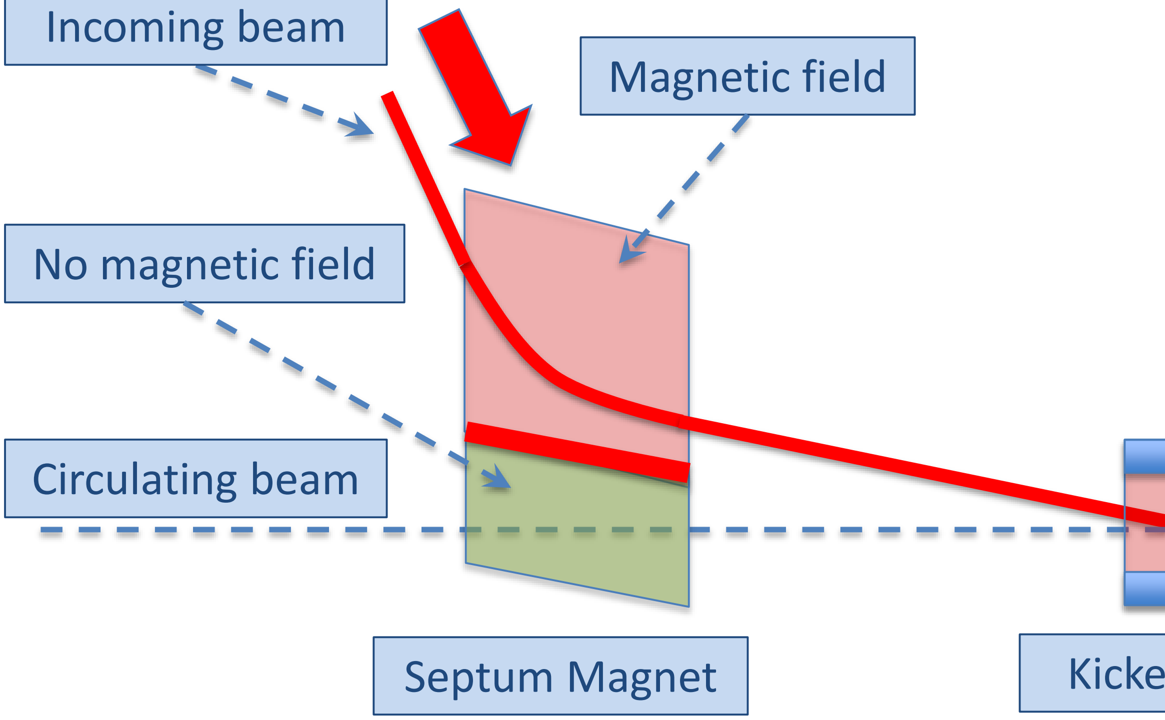
LINAC Accelerating Structure



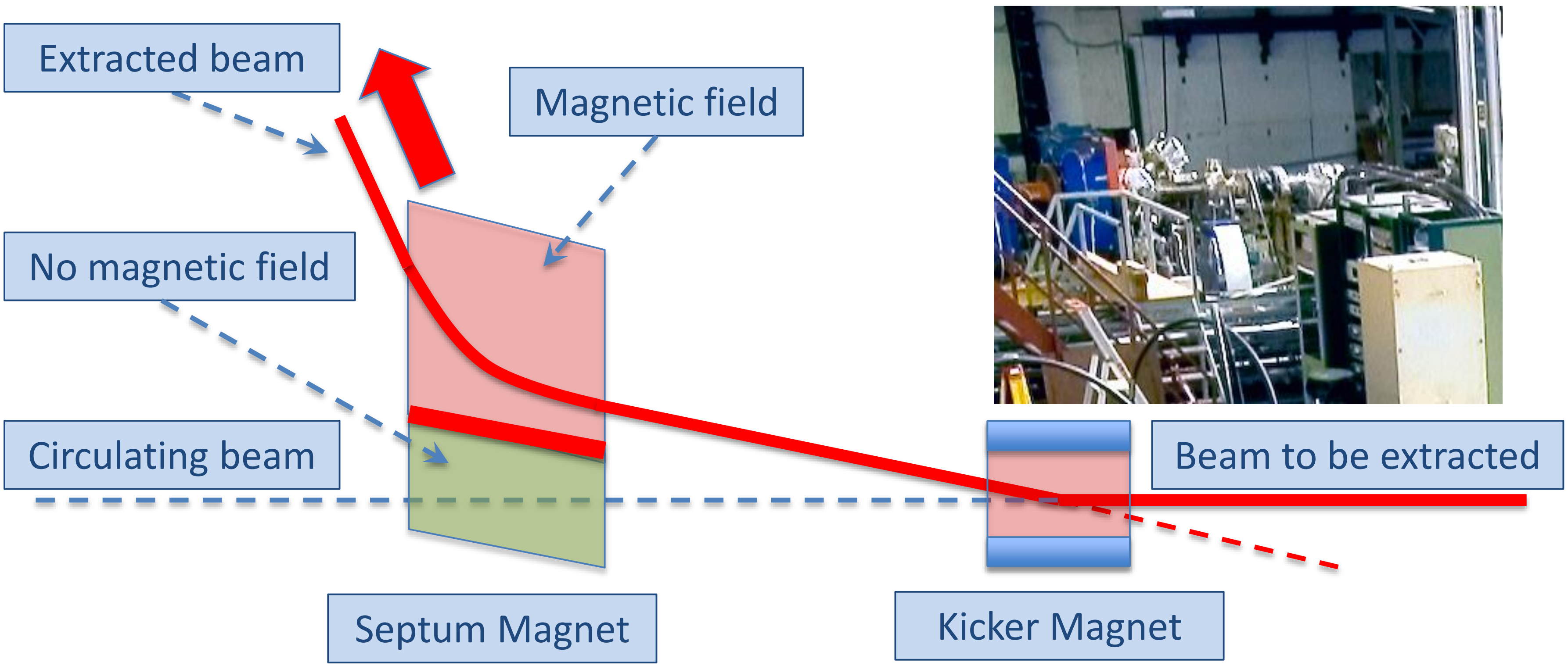
The CERN LINAC 4 drift tube

Injecting & Extracting Particles

Injecting & Extracting Particles



Injecting & **Extracting** Particles



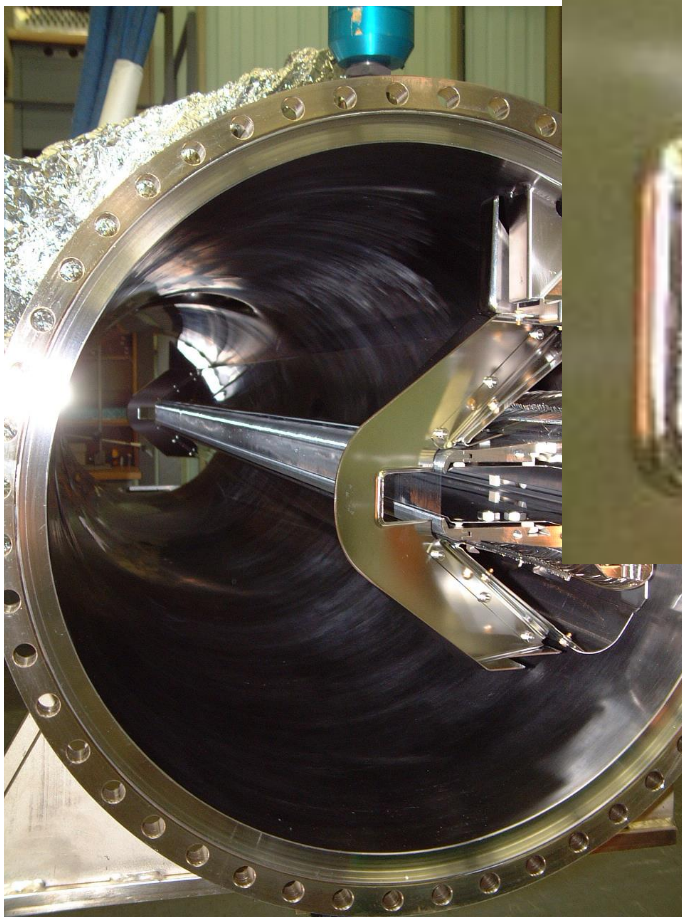
Wednesday next week

"**Injection and Extraction**" by M. Fraser

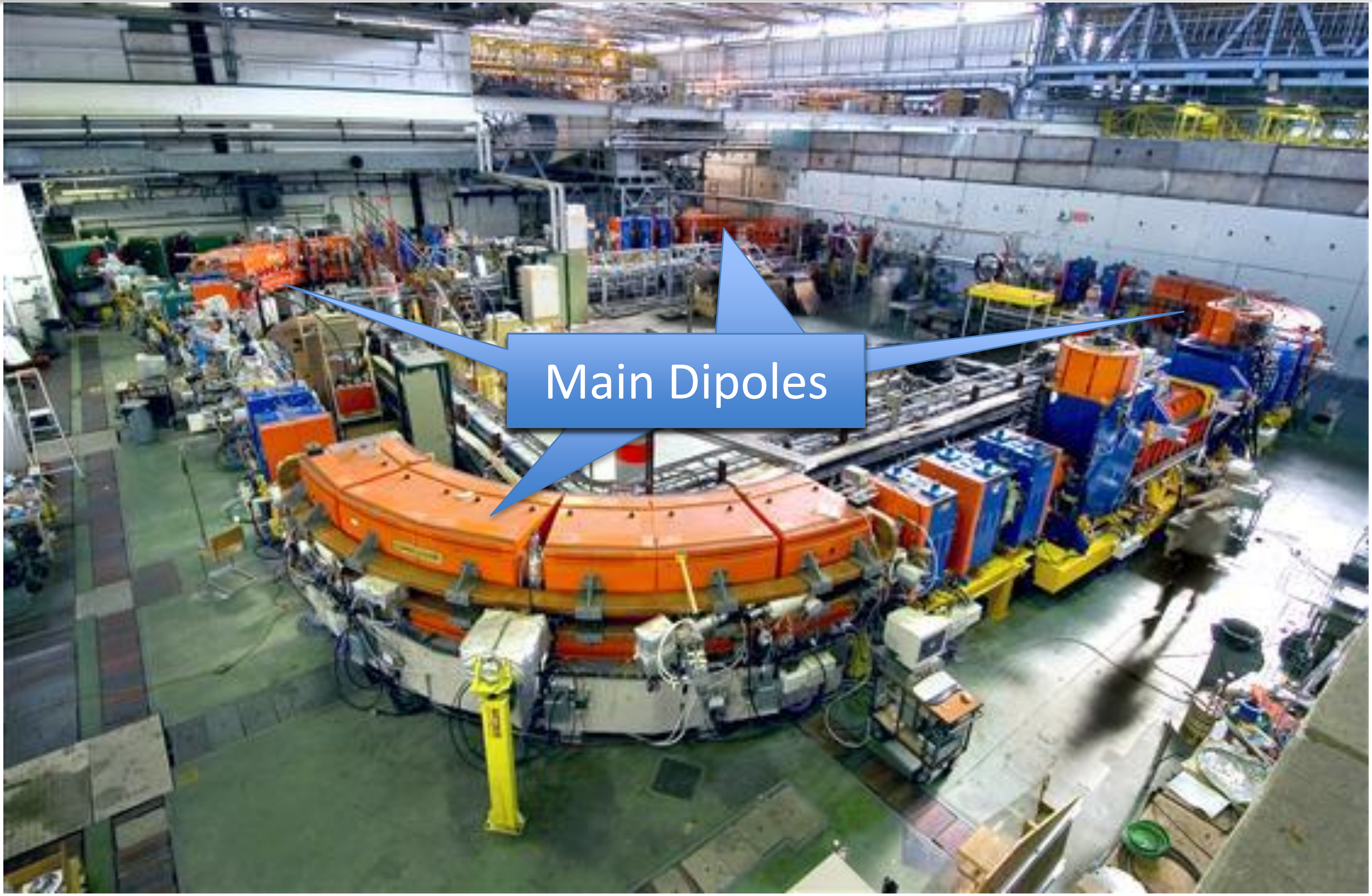
"**Kicker, Septa and Beam Transfer**" by M. Fraser

Thursday next week

Septum and Kicker Magnets

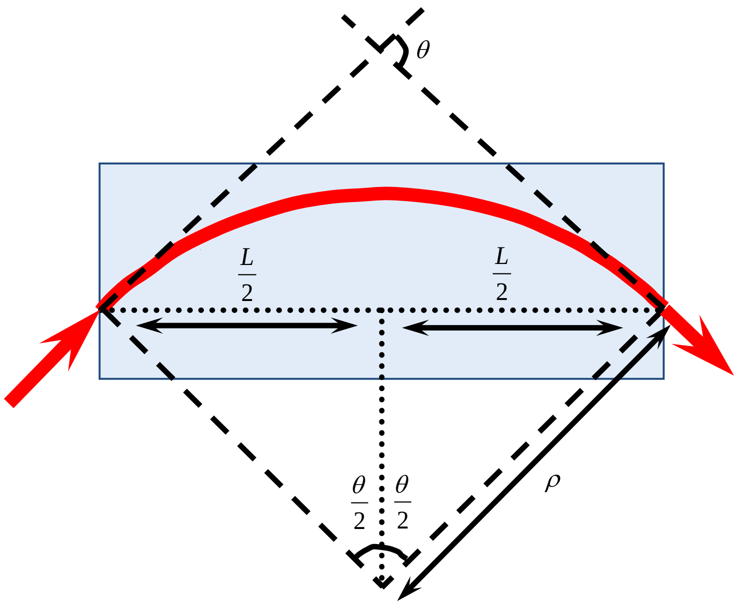


Make Particles Circulate



Charged Particles Deviated

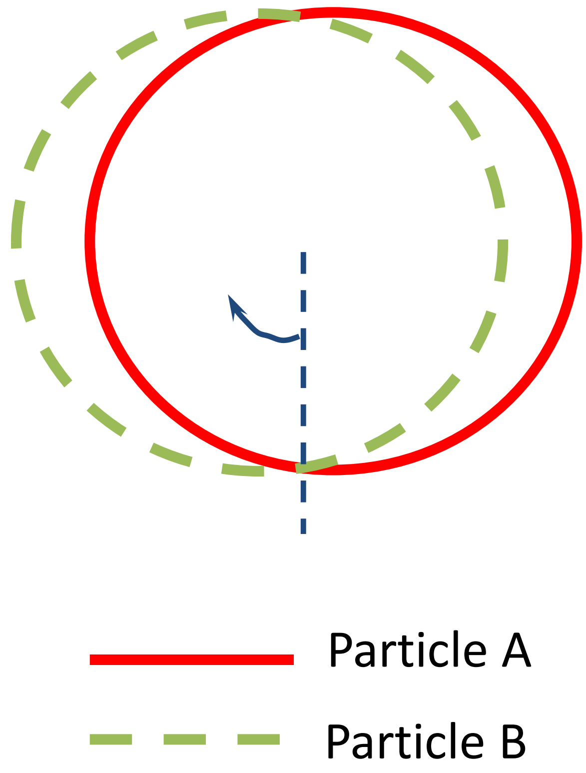
Charged Particles are deviated in magnetic fields



Lorentz force:

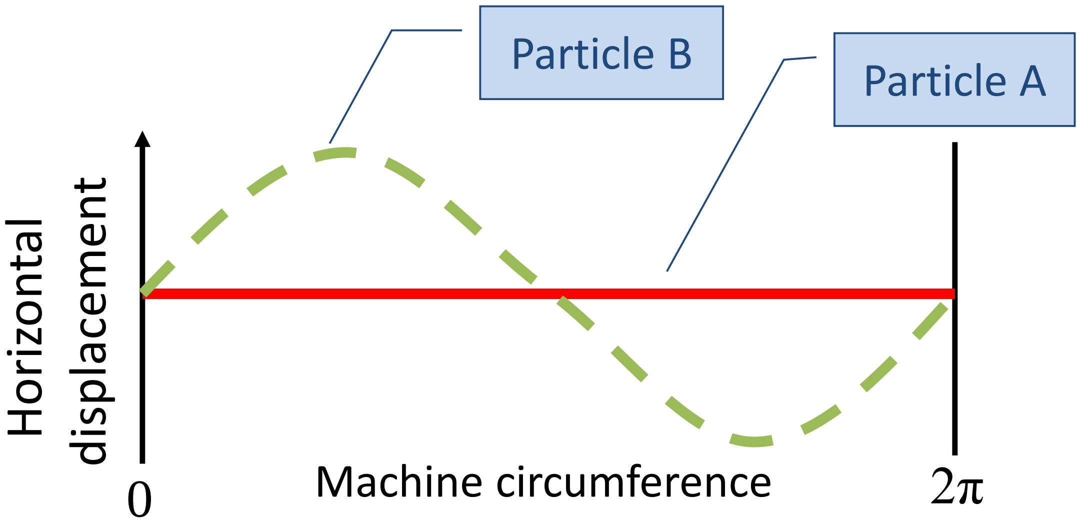
$$\vec{F} = e(\vec{v} \times \vec{B})$$

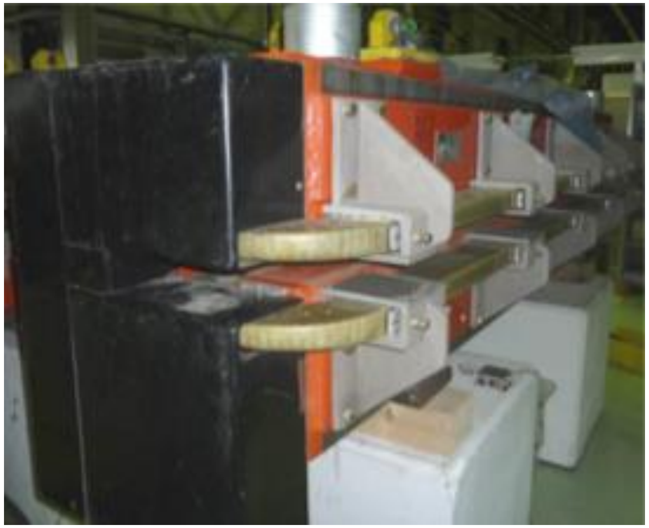
Two charged Particles in a homogeneous magnetic field



Oscillatory Motion of Particles

Horizontal motion



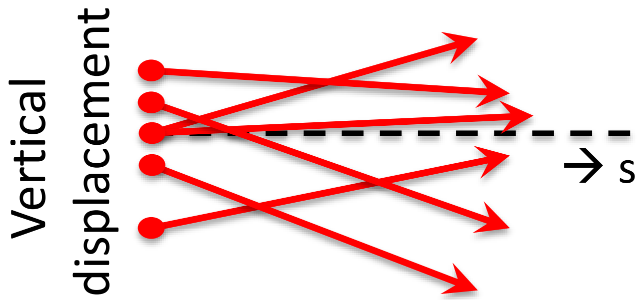


Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane → **Betatron Oscillations**

Oscillatory Motion of Particles

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

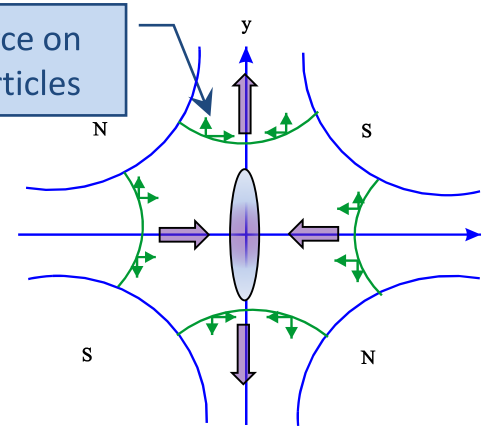
Many particles many initial conditions



Many different angles

Focusing particles, a bit like light

Force on particles



Tuesday & Wednesday

“**Transverse Beam Dynamics**” by B. Holzer

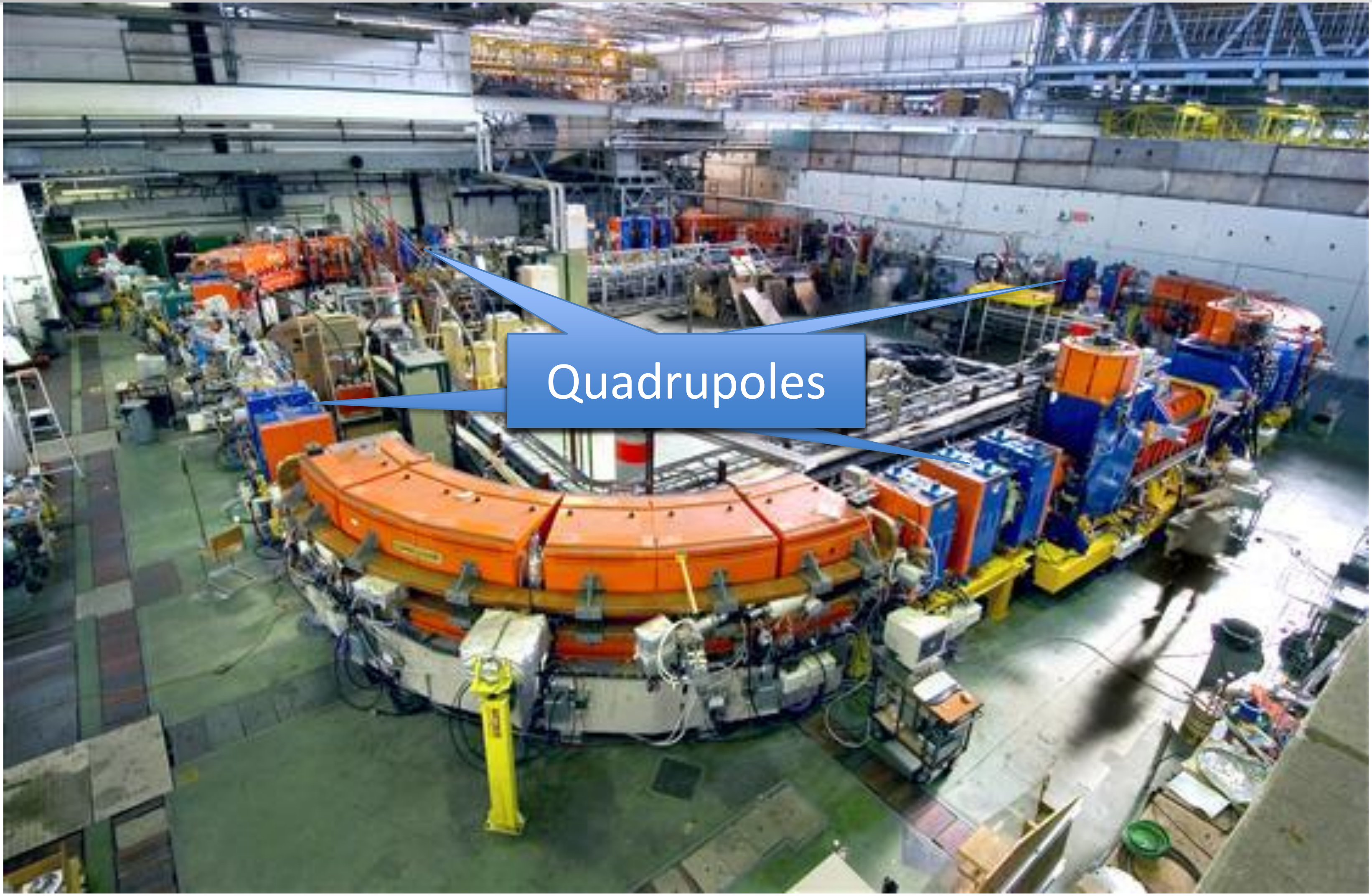
“**Warm Magnets**” by G. de Rijk

Friday

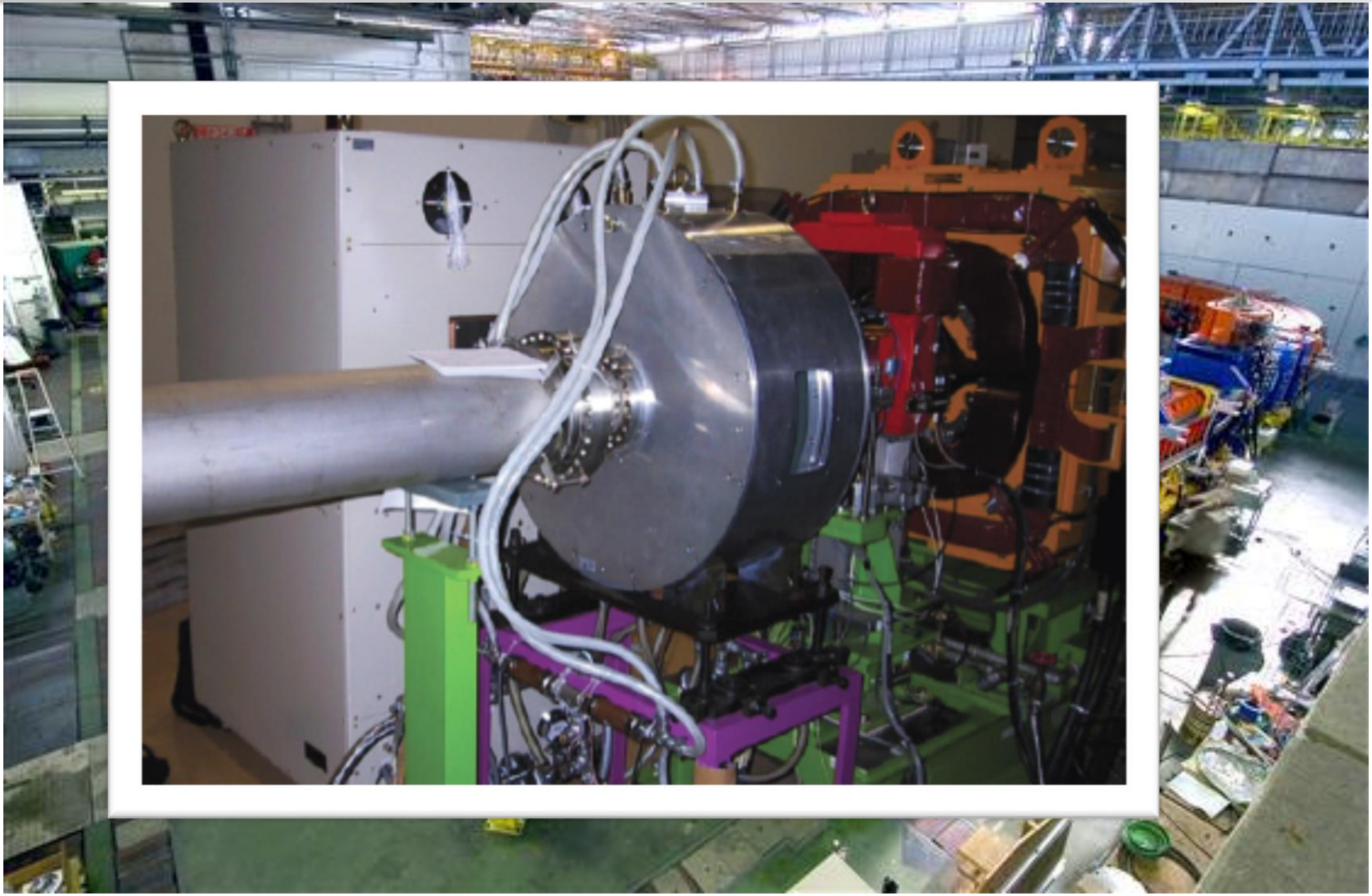
Saturday

“**Power Converters**” by J.-P. Burnet

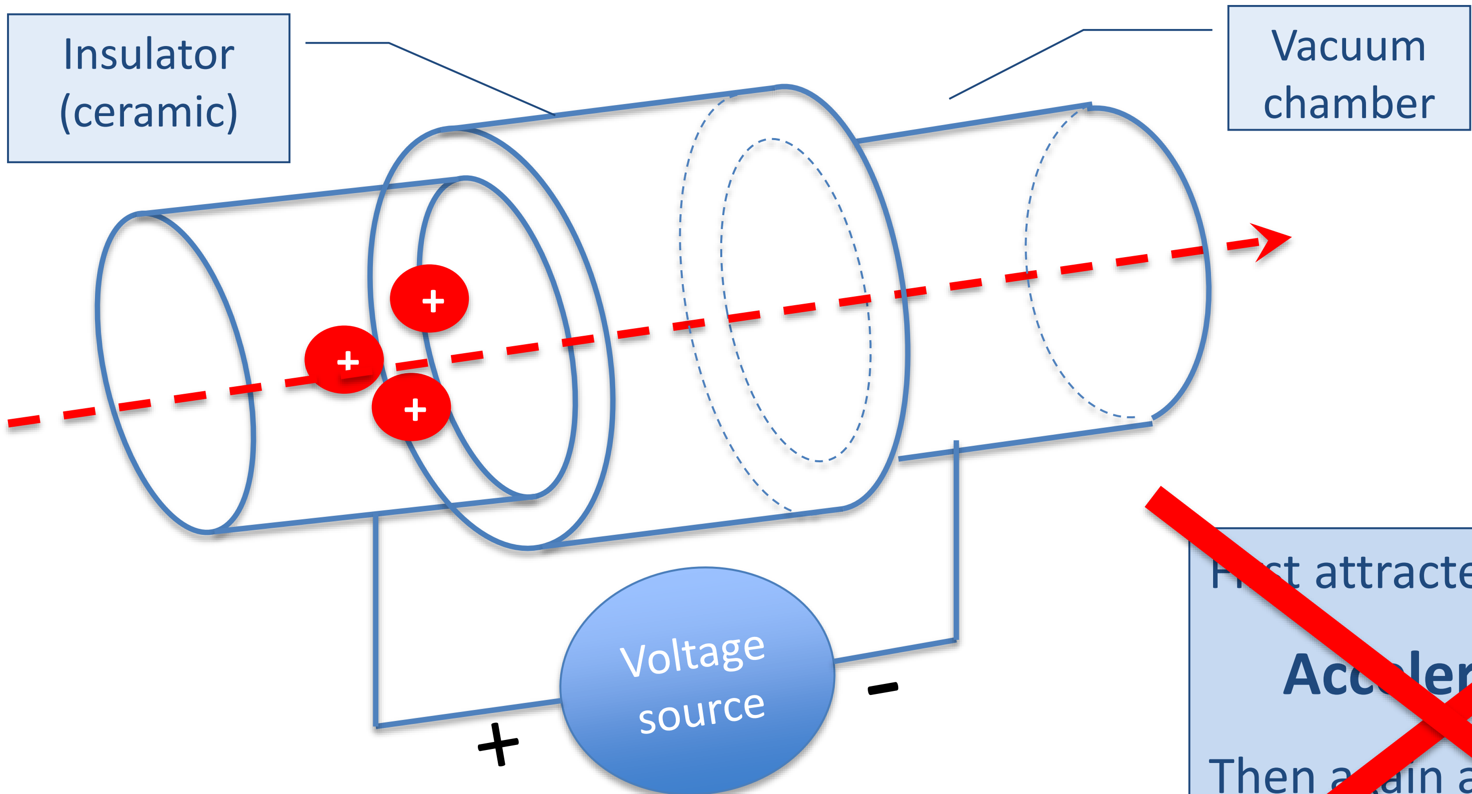
Focusing the Particles



Accelerating Particles



Accelerating Beams



~~First attracted~~

~~**Acceleration**~~

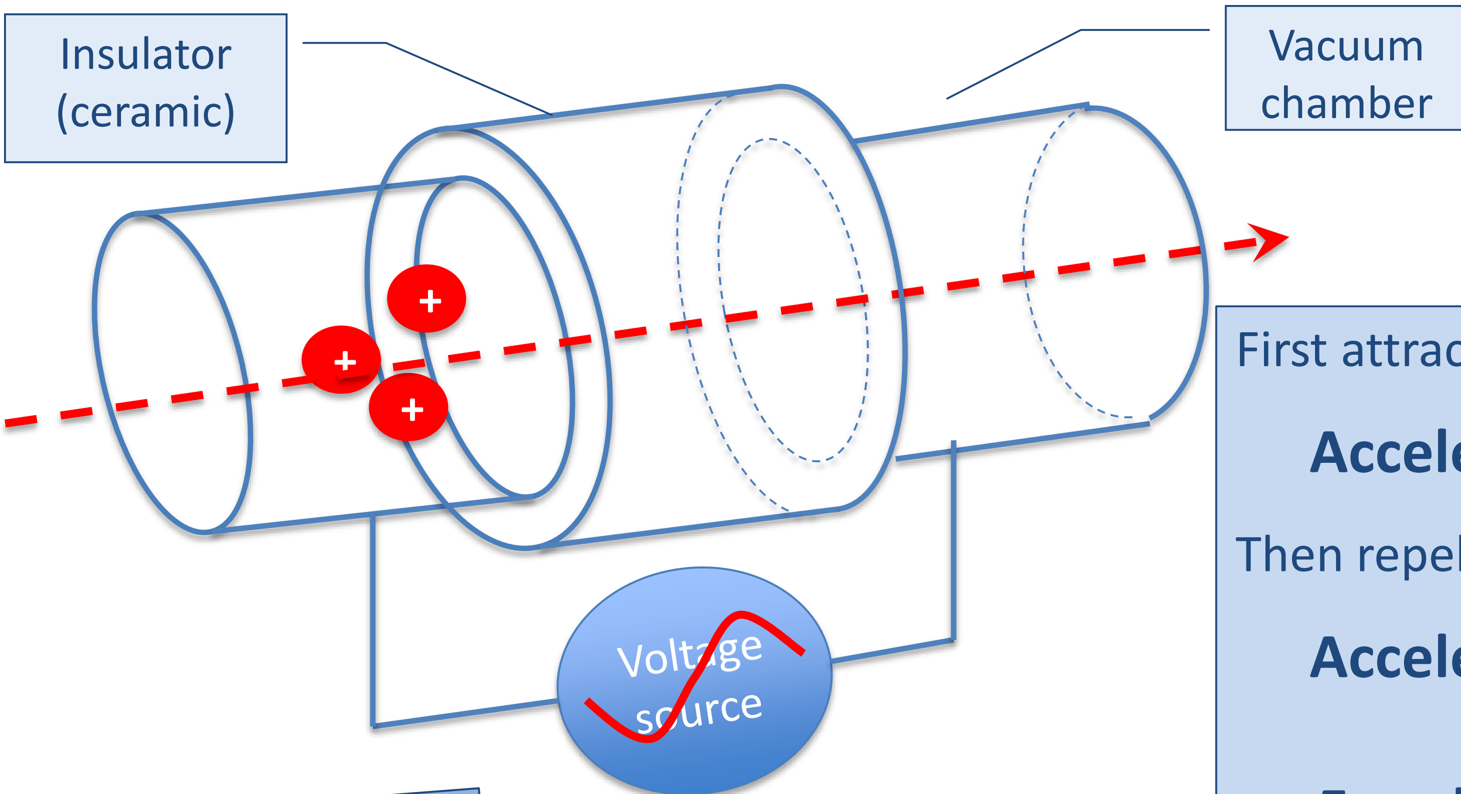
~~Then again attracted~~

~~**Deceleration**~~

Net result:

No Acceleration

Accelerating Beams



First attracted

Acceleration

Then repelled

Acceleration

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

Wednesday & Thursday

“**Longitudinal Beam Dynamics in Circular Machines**” by F. Tecker

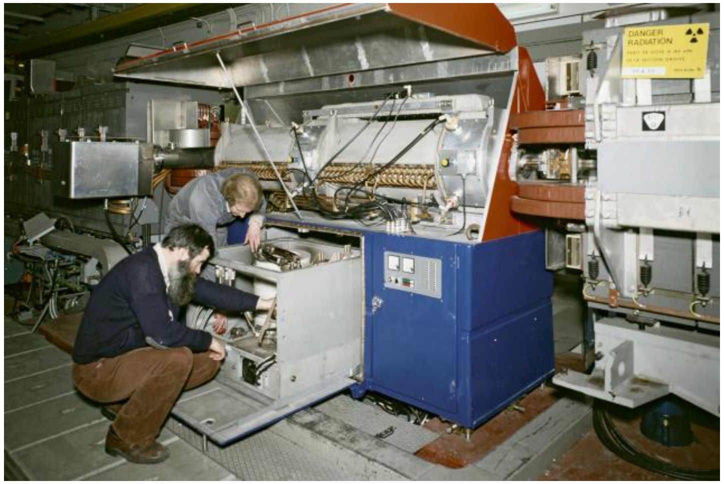
“**RF Systems**” by F. Tecker

Wednesday

Some RF Cavities and feedbacks

Fixed frequency cavities (Superconducting) in the LHC

Variable frequency cavities (normal conducting) in the CERN PS

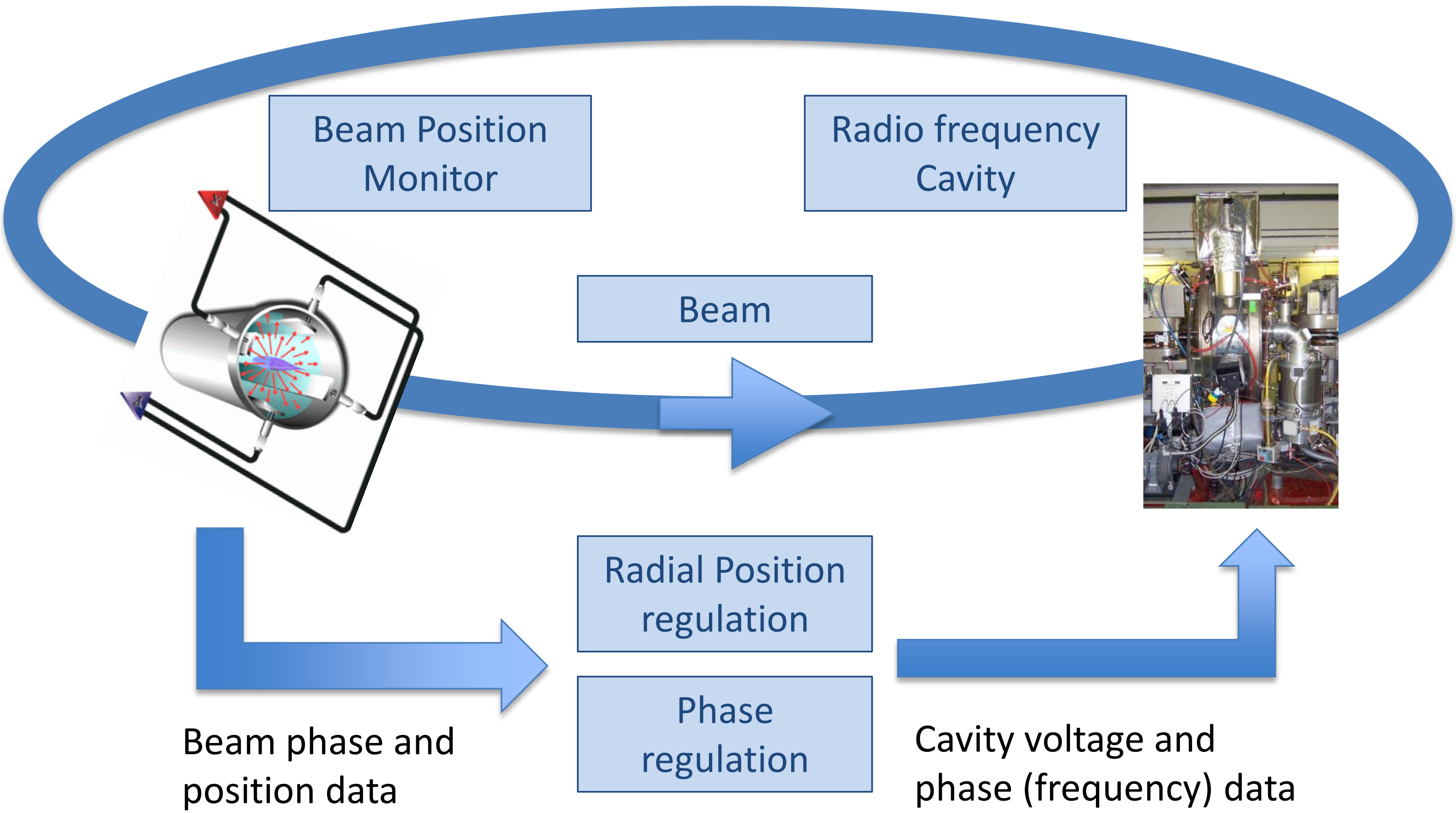


RF cavities are not only used to accelerate beams, but also to shape the beam:

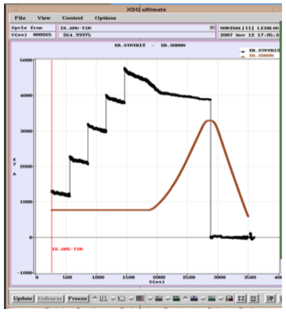
- Longitudinal emittance
- Number of bunches
- Bunch spacing, shaping, etc.

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

RF Beam Control



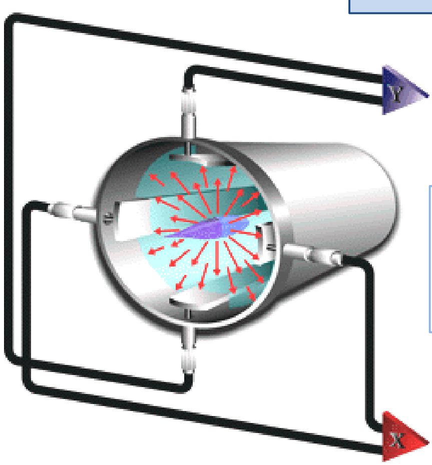
Measuring Beam Characteristics

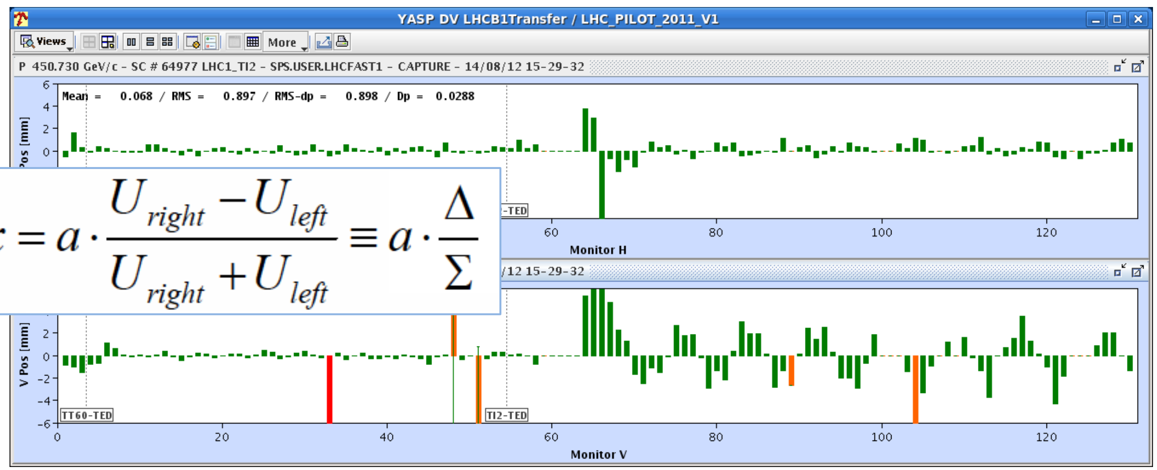


Beam intensity or current measurement:

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

Beam position/orbit measurement:

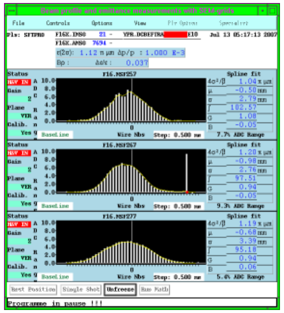




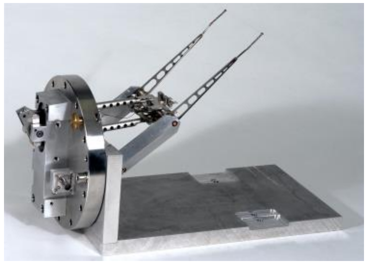
$$x = a \cdot \frac{U_{right} - U_{left}}{U_{right} + U_{left}} \equiv a \cdot \frac{\Delta}{\Sigma}$$

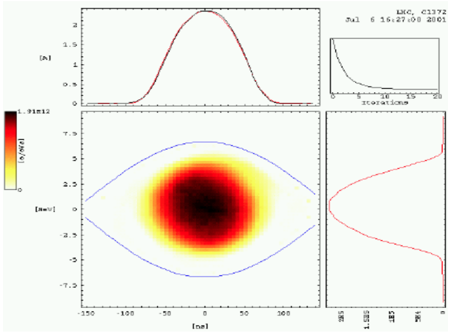
Correcting orbit using automated beam steering

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…..

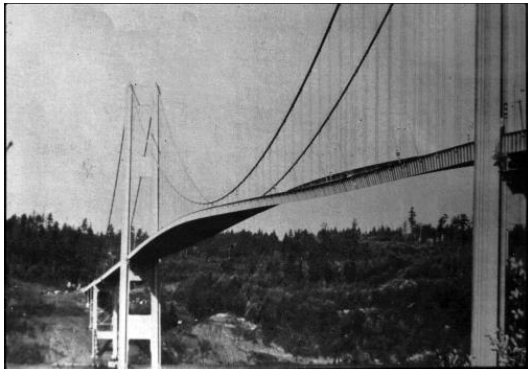
Monday next week

"**Beam Instrumentation**" by E Holzer

"**Beam Diagnostics**" by E. Holzer

Monday next week

Possible Limitations

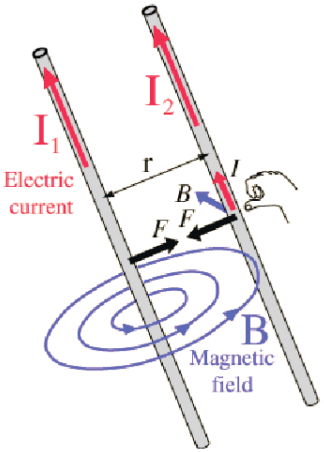


Machines and elements cannot be built and aligned with infinite precision

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

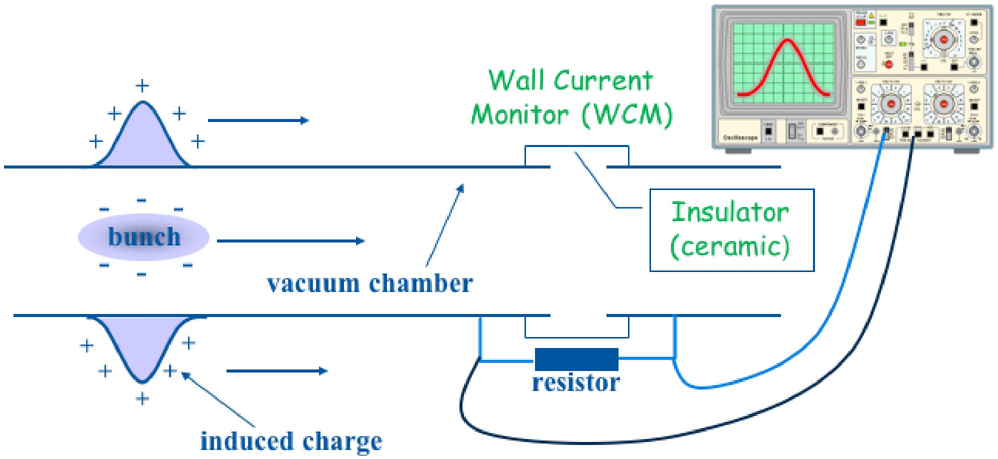
Neighbouring charges with the same polarity experience **repelling forces**

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



These effects can degrade beam quality and increase losses

Possible Limitations



Coupled Bunch Instabilities

Induced currents in the vacuum chamber (impedance) can result in electric and magnetic fields acting back on the bunch or beam

Thursday "**Linear Imperfection**"

Saturday "**Non-Linear Beam Dynamics**" by A. Wolski

"**Collective effects**" by G. Franchetti

Monday & Tuesday next week

Special Systems

Ever increasing energies and beam intensities, require specials 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

Friday

“**SC Magnets**” by G. de Rijk

“**Beam Losses and Machine Protection**” by I. Strasik

Tuesday next week

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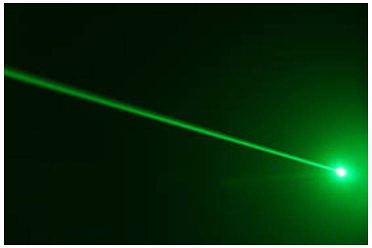
- The Main Ingredients of an Accelerator
- **Some ways of using Accelerators**

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:

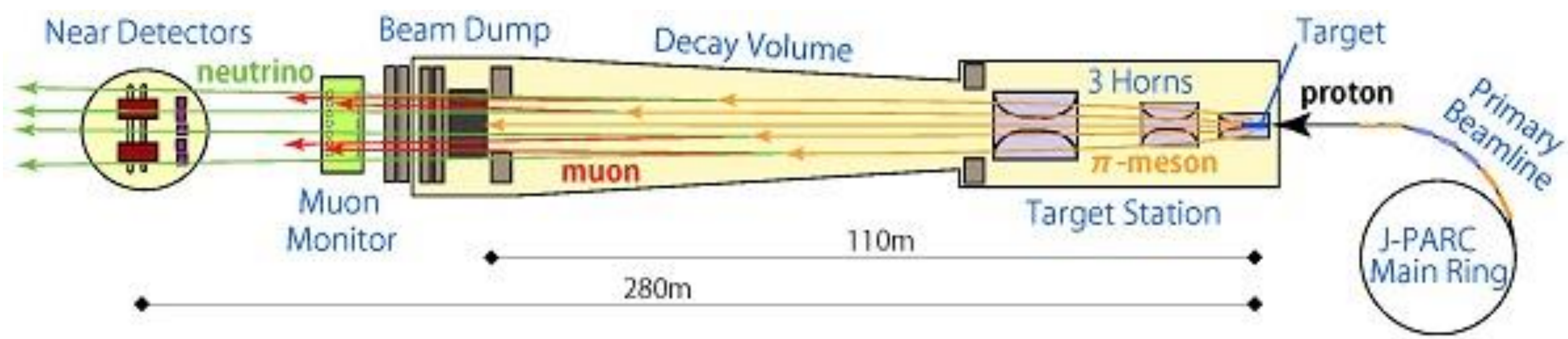
Light Sources:



Collider Physics:

Fixed Target Physics

Just a few examples among many:



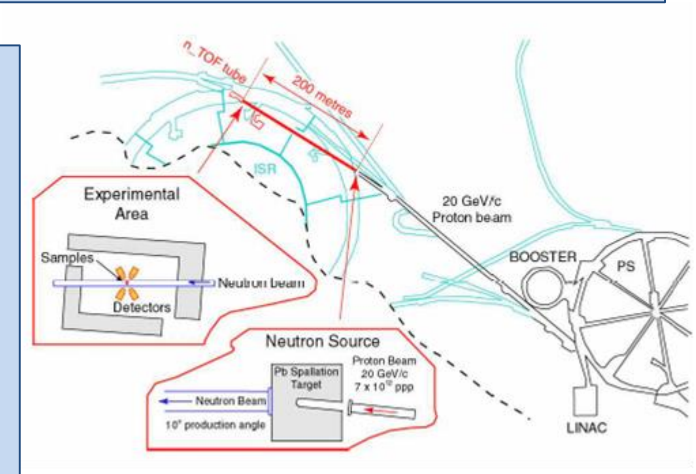
- Neutrino physics and Spallation sources: high beam power
  - High beam **intensity** with small beam size
  - High beam **energy** and / or high **repetition rate**
- J-PARC – Japan
- FermiLab - USA
- Previously CERN to CNGS – Europe
- Spallation Neutron Source (SNS) Oak Ridge - USA

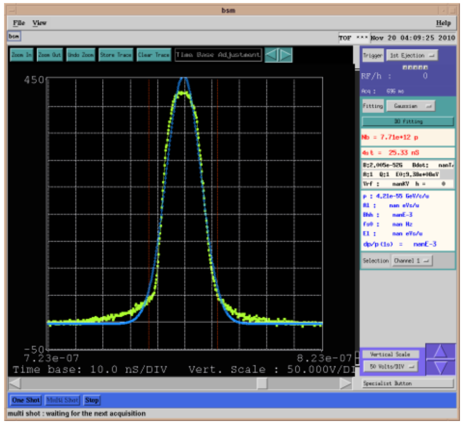
Fixed Target Physics

Just a few examples among many:

CERN (neutron) Time of flight facility (nTOF):

- **Very short intense pulse** of protons on a spallation target with a rather low repetition rate
- Large amount of neutrons produced in a wide range of energies (from a few MeV to several GeV)
- With the time of flight over 200 m the momentum of neutrons can be determined/selected

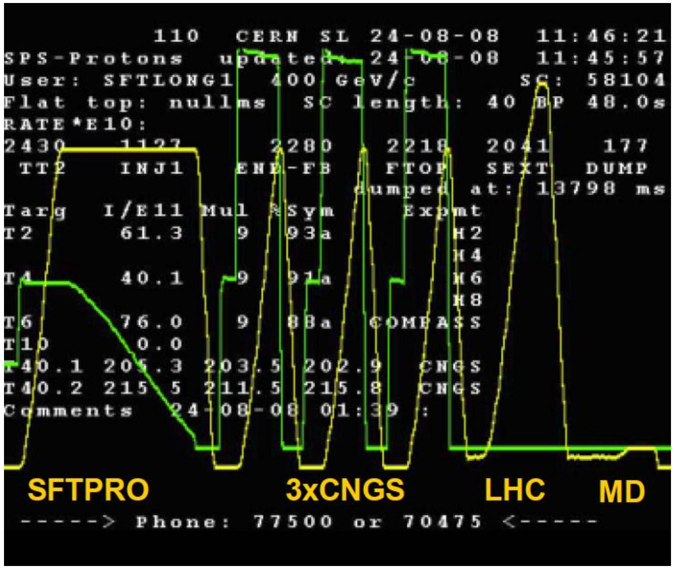




Fixed Target Physics

Just a few examples among many:

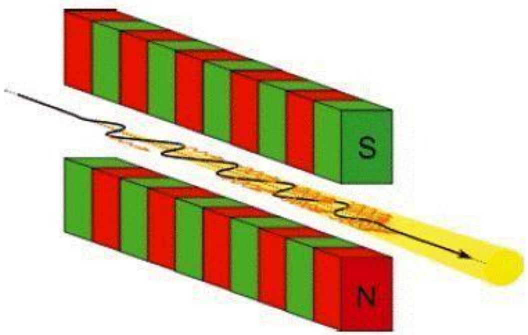
Test beam lines:
- Preferably long periods of low to intermediate intensity
- From single primary proton beam energy different types of particles are produced within a wide range of energies

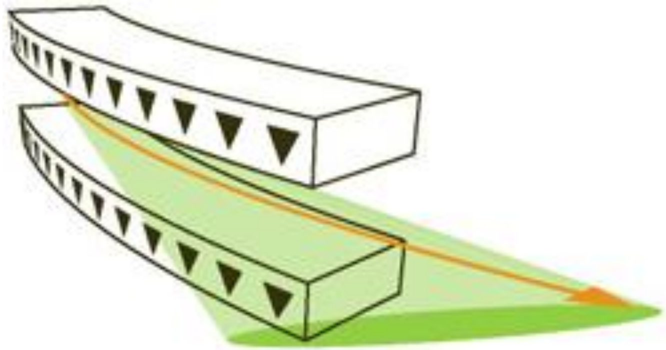


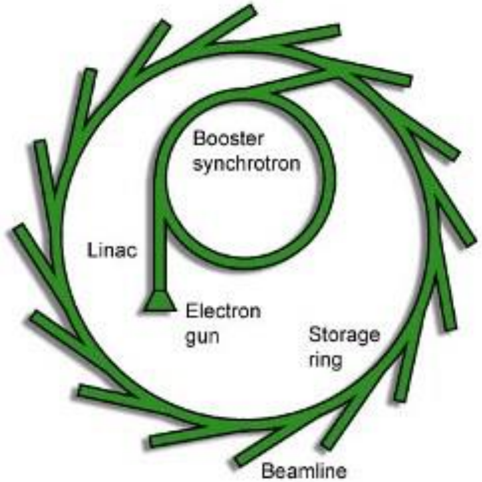
- The secondary particles are selected and distributed over several beam lines
- Uses often **resonant slow extraction** over several seconds

Synchrotron Light Sources

Just a few examples among many:







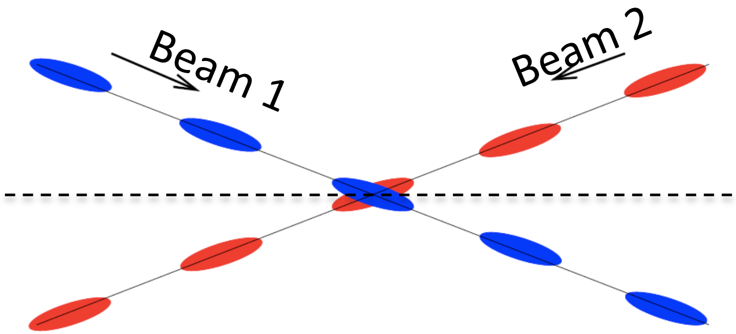
- Photon beam from stored (highly relativistic) electron beam
  - High electron beam intensity (Accelerator & Storage Ring)
  - Use of **undulators** to enhance photon emission
- Swiss Light Source (SLS) – Europe
- European Synchrotron Radiation Facility (ESRF) – Europe
- National Synchrotron Light Source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

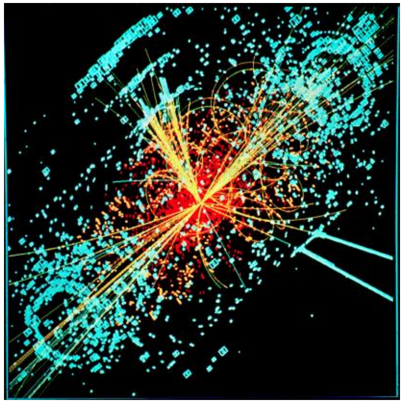
Collider Physics

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

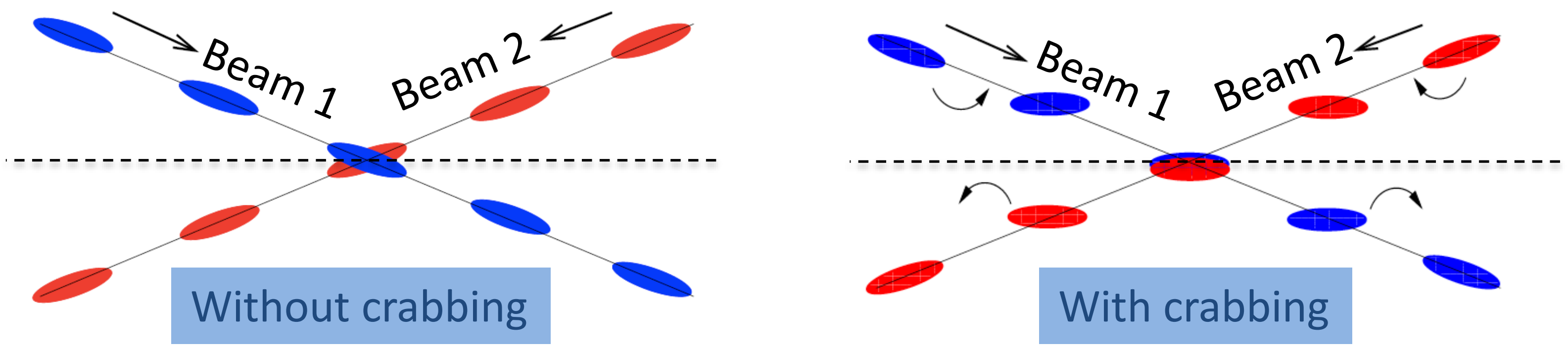
$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S$$

Reduce the β* (σ)

- Stronger focusing around the interaction points

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

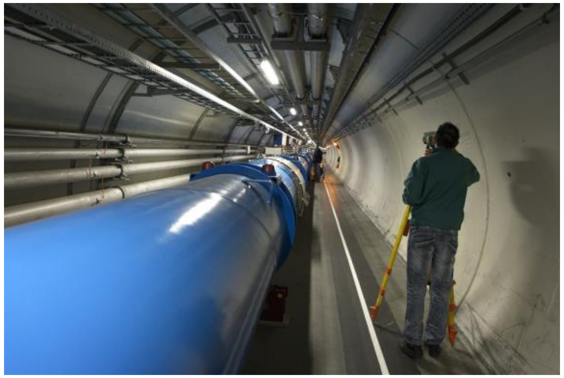
- Tilt the bunches to have more head-on collision effect



"We shall have no better conditions in the future if we are satisfied with all those which we have at present."

Thomas A. Edison
Inventor and businessman, 1874 – 1931

E. Lawrence who invented the cyclotron in 1929



The LHC Today…

……. much has changed since then….