

Introduction to Accelerators

Rende Steerenberg - CERN - Beams Department

CERN Accelerator School

Introduction to Accelerator Physics

31 August – 12 September 2014

Prague – Czech Republic

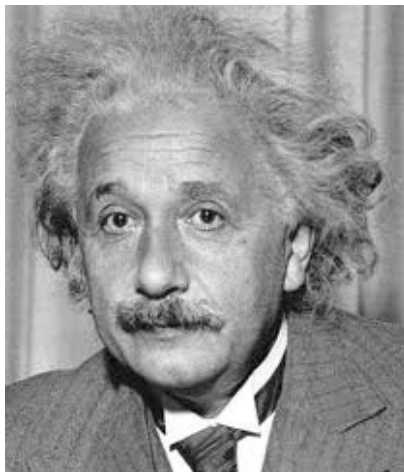
- Why Accelerators and Colliders ?
- A very Brief Historic Overview
- The Main Ingredients of an Accelerator

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

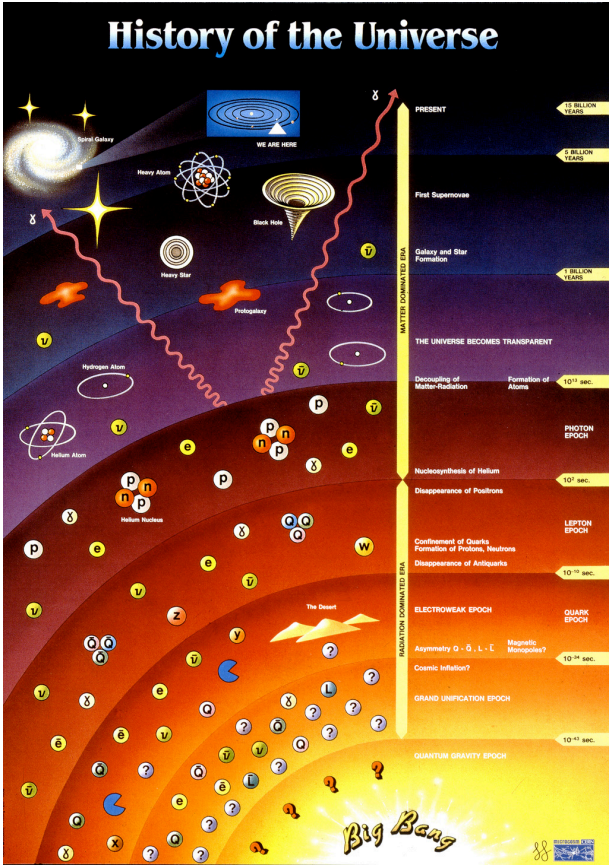
Matter versus Energy

$$E = m c^2$$

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



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

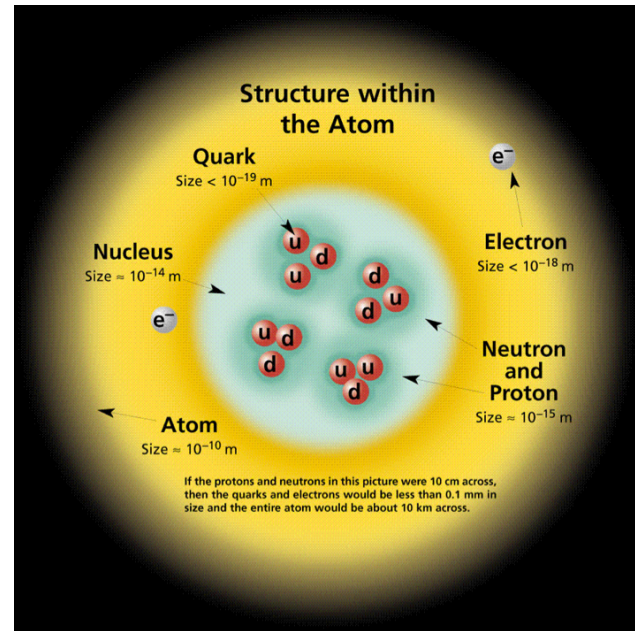


$$\lambda = \frac{hc}{E}$$

X-ray
 $\lambda = 0.01 \rightarrow 10 \text{ nm}$



Particle accelerators
 $\lambda < 0.01 \text{ nm}$



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 is used to produce secondary particles

Collider

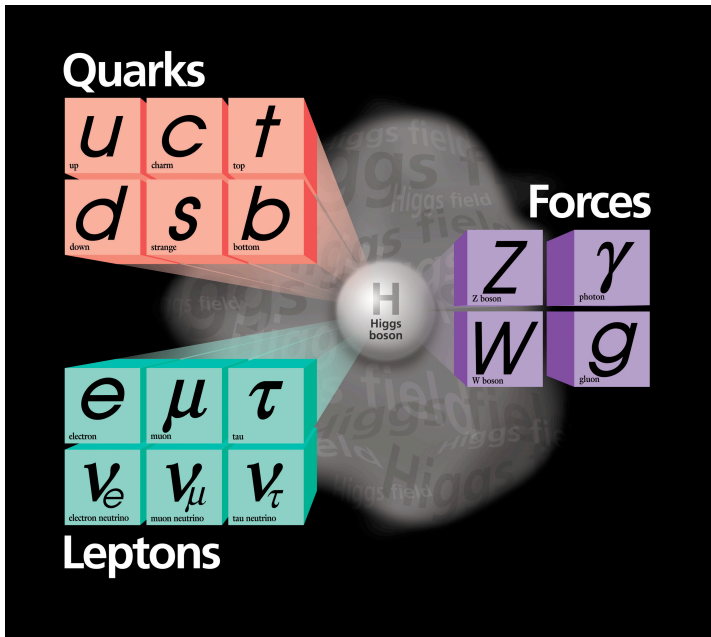


$$E = E_{beam1} + E_{beam2}$$

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

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



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

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

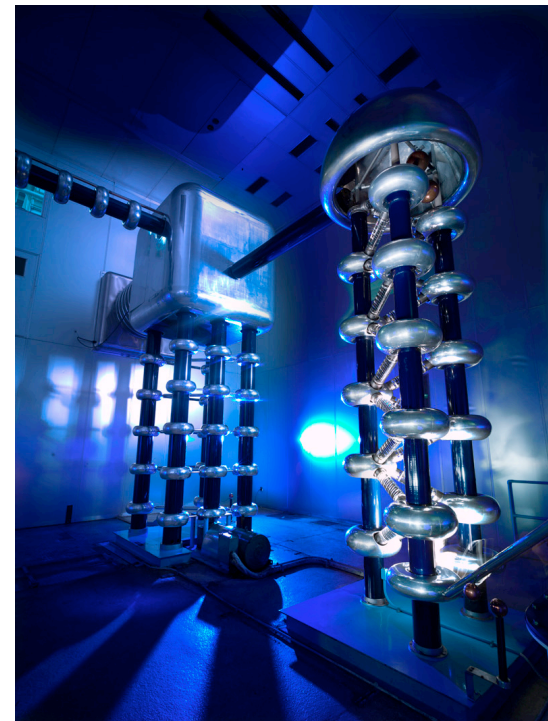
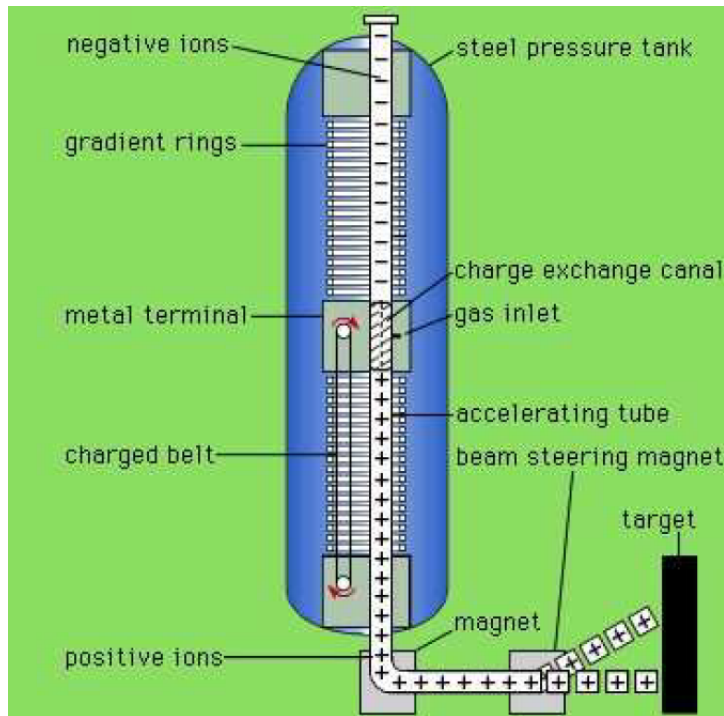
- Industrial applications: ~ 20'000*
- Medical applications: ~ 10'000*

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

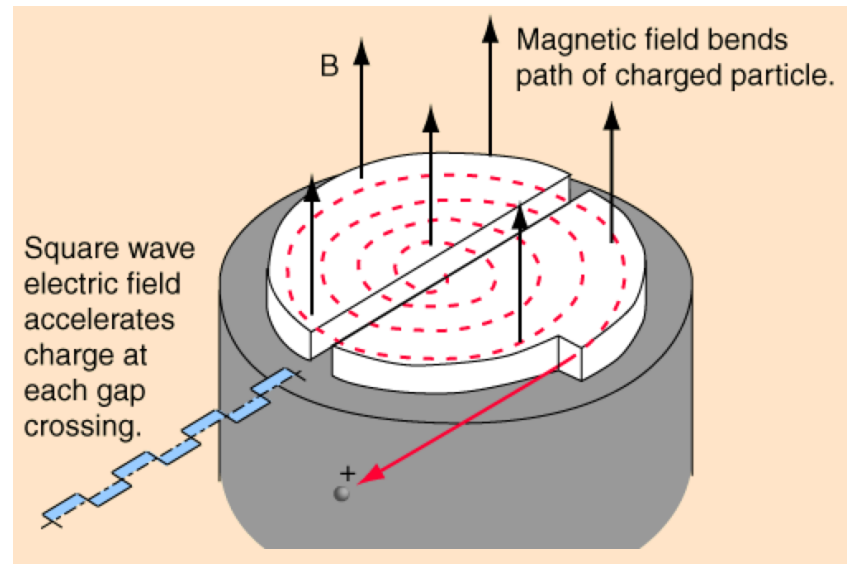
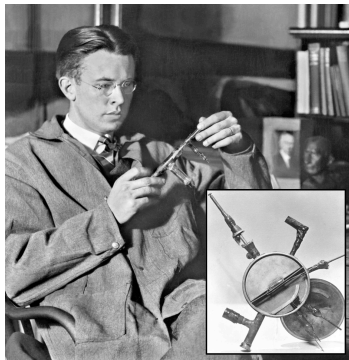
**Source: World Scientific Reviews of Accelerator Science and Technology
A.W. Chao*

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



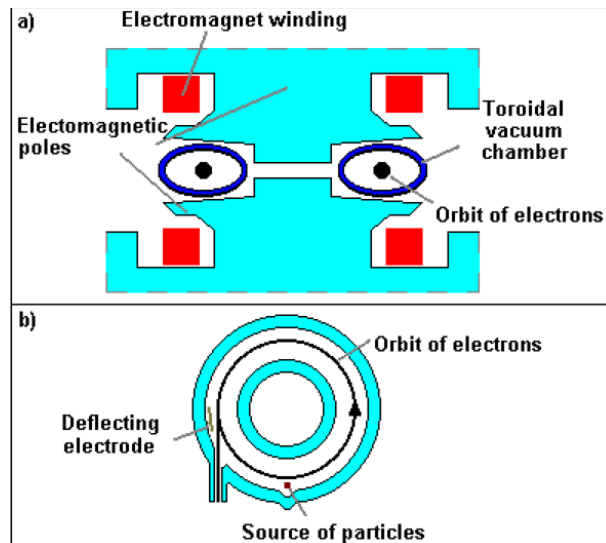
- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- Constant magnetic field
- Alternating voltage between the two D's
- Increasing particle orbit radius
- Development lead to the synchro-cyclotron to cope with the relativistic effects.

In 1939 Lawrence received the Noble prize for his work.

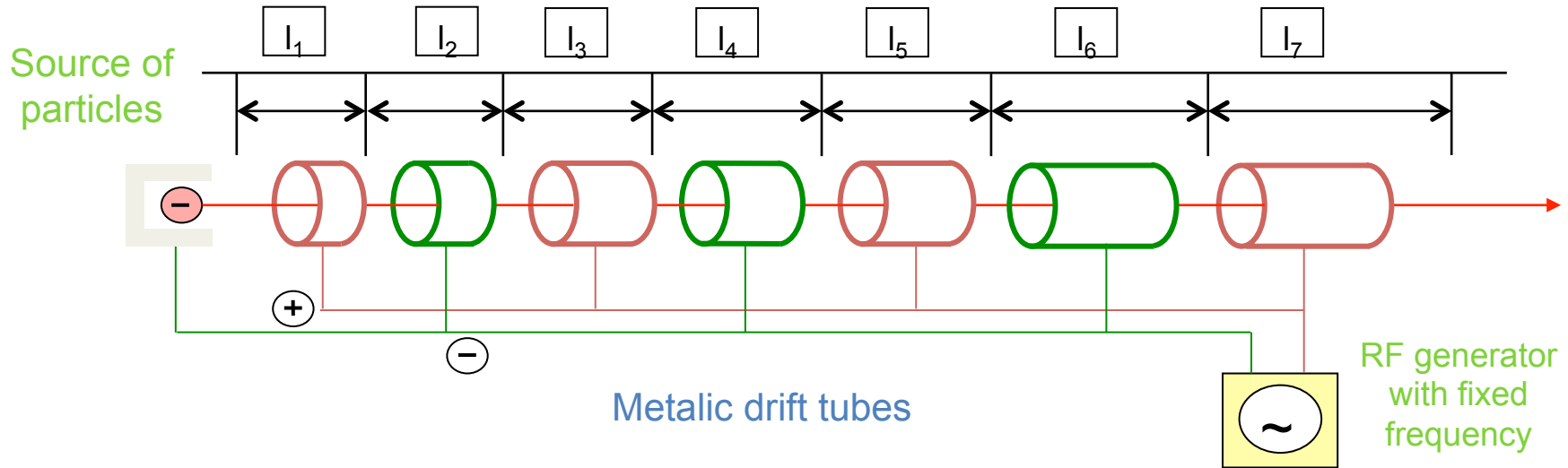


Betatron

- 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.



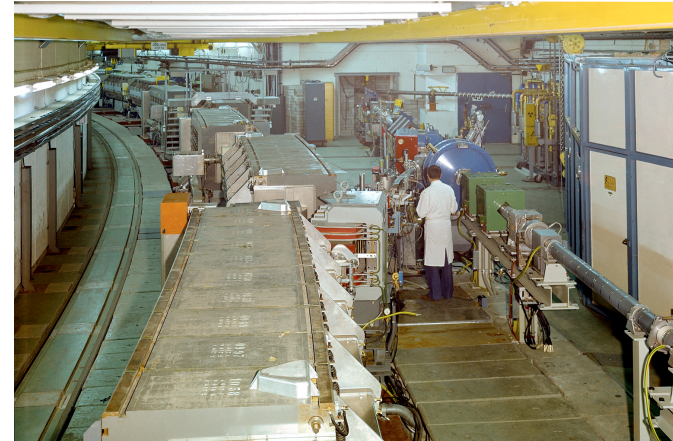
Linear Accelerator



- 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.

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

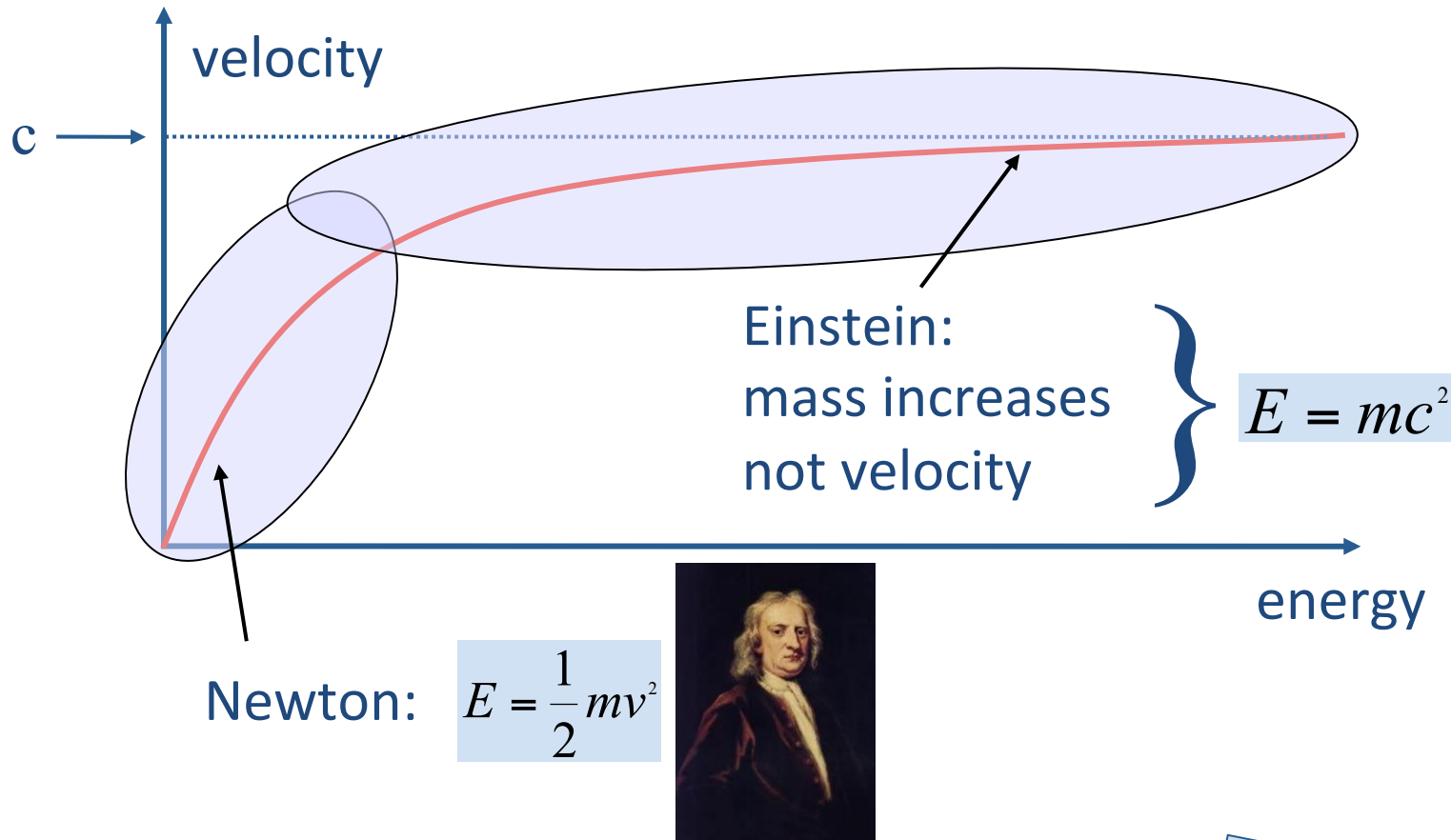
- 1959: CERN-PS and BNL-AGS
- Fixed radius for particle orbit
- Varying magnetic field and radio frequency
- Phase stability
- Important focusing of particle beams (Courant – Snyder)
- Providing beam for fixed target physics
- Paved the way to colliders



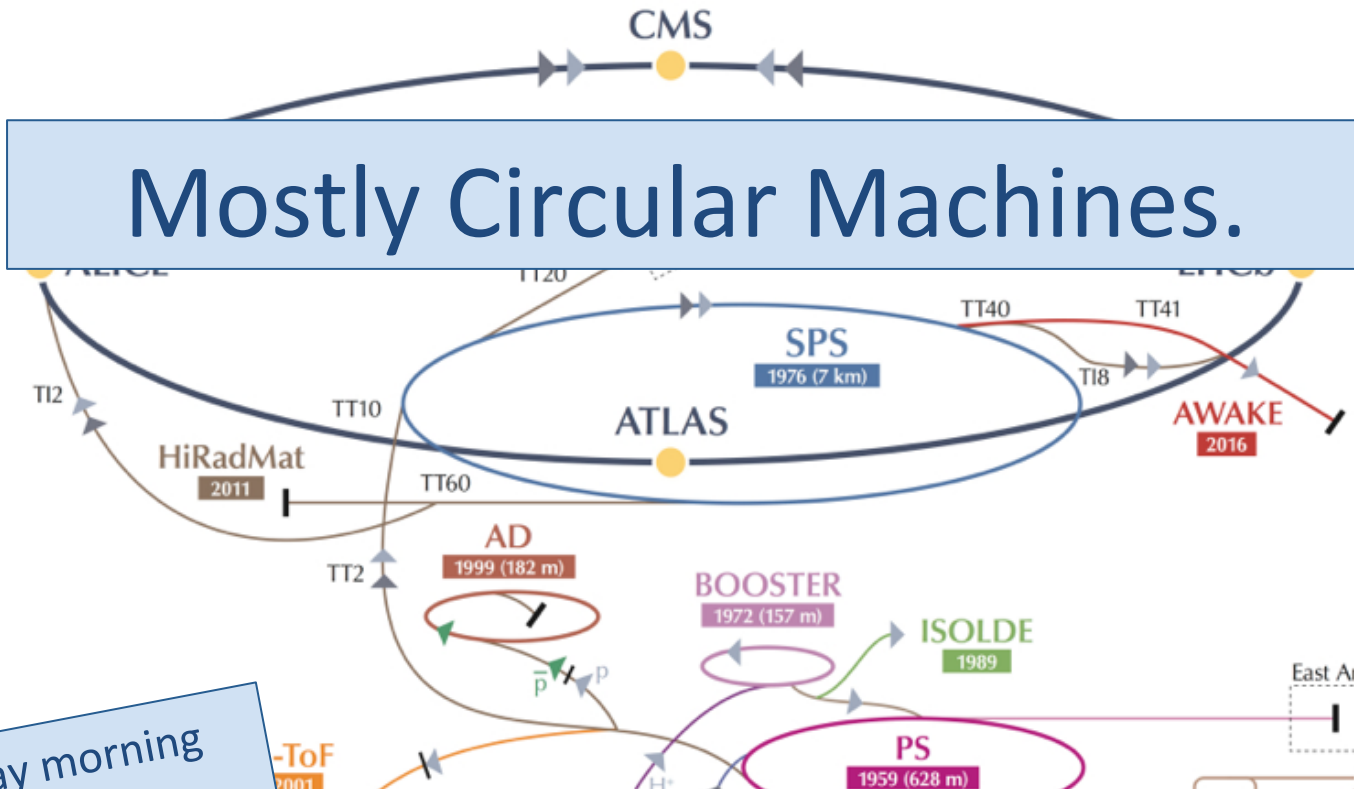
- Why Accelerators and Colliders ?
- A very Brief Historic Overview
- **The Main Ingredients of an Accelerator**

Towards Relativity

Introduction to Accelerators – CERN Accelerator School



“Relativity” by W. Herr This afternoon



Tuesday morning
next week

“Sources” by D. Faircloth
“LINACS” by A. Lombardi

Thursday afternoon
Next week

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

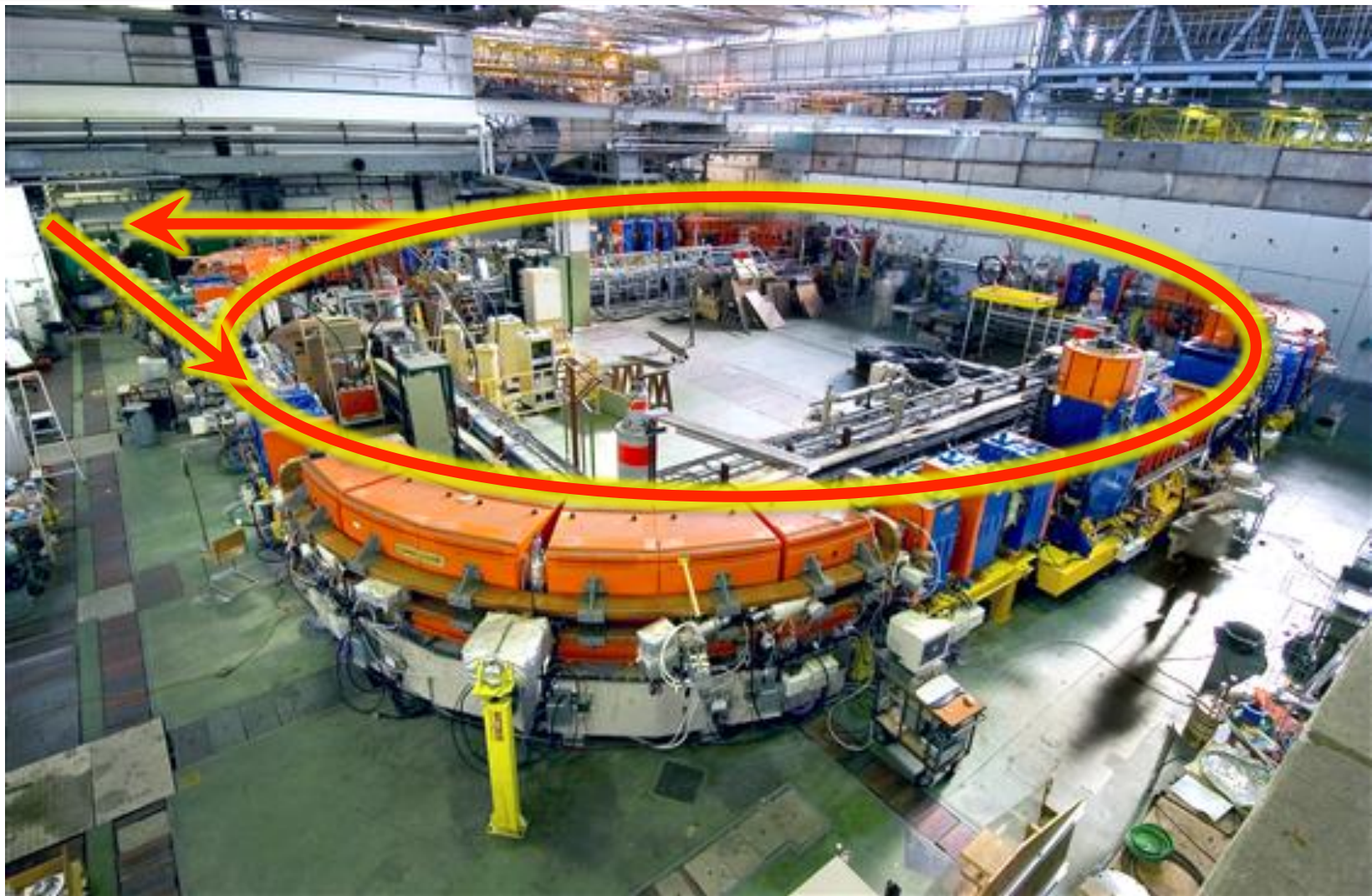
A Guided Tour

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.

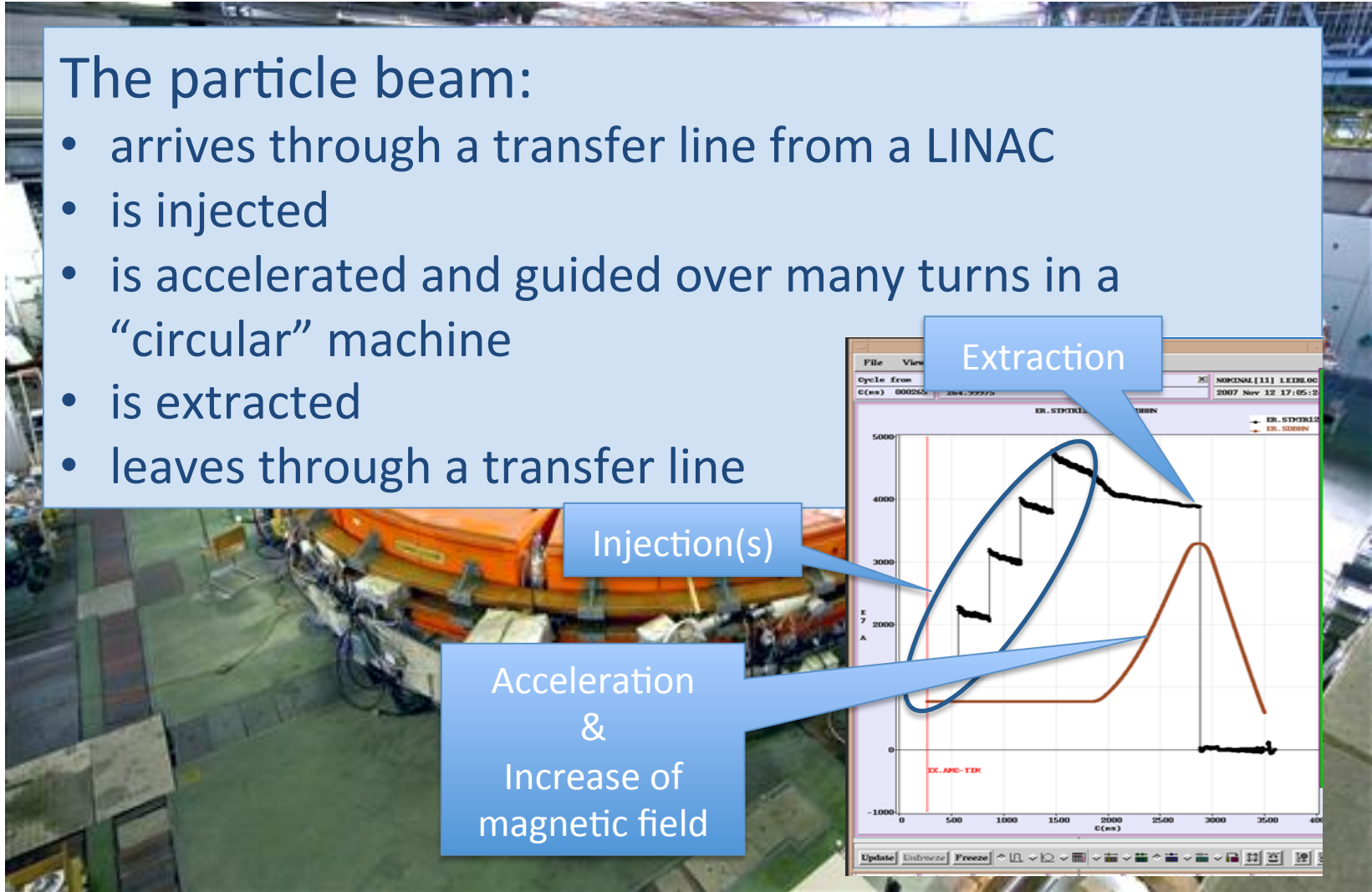
LEIR **Low Energy Ion Ring**



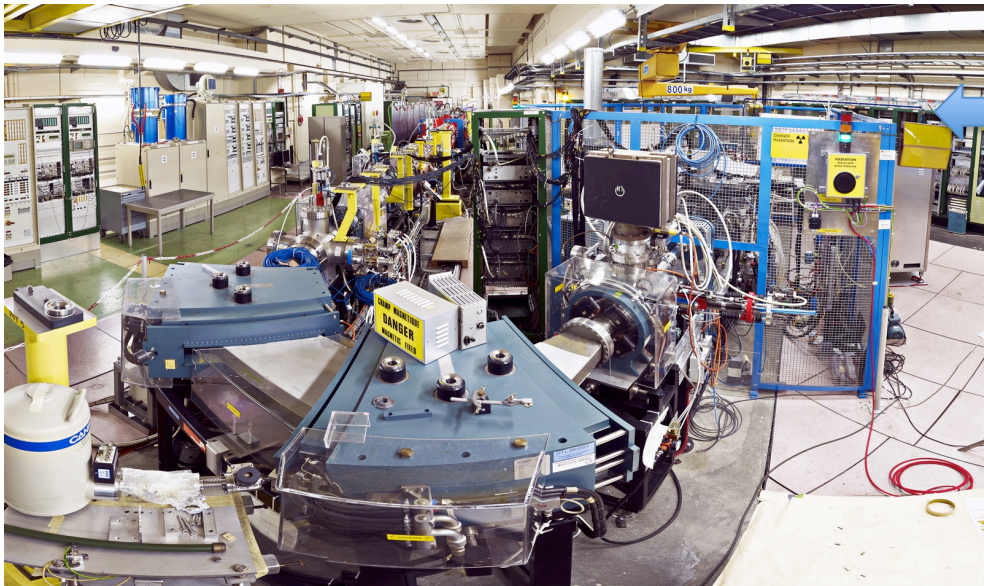
LEIR as an Example

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

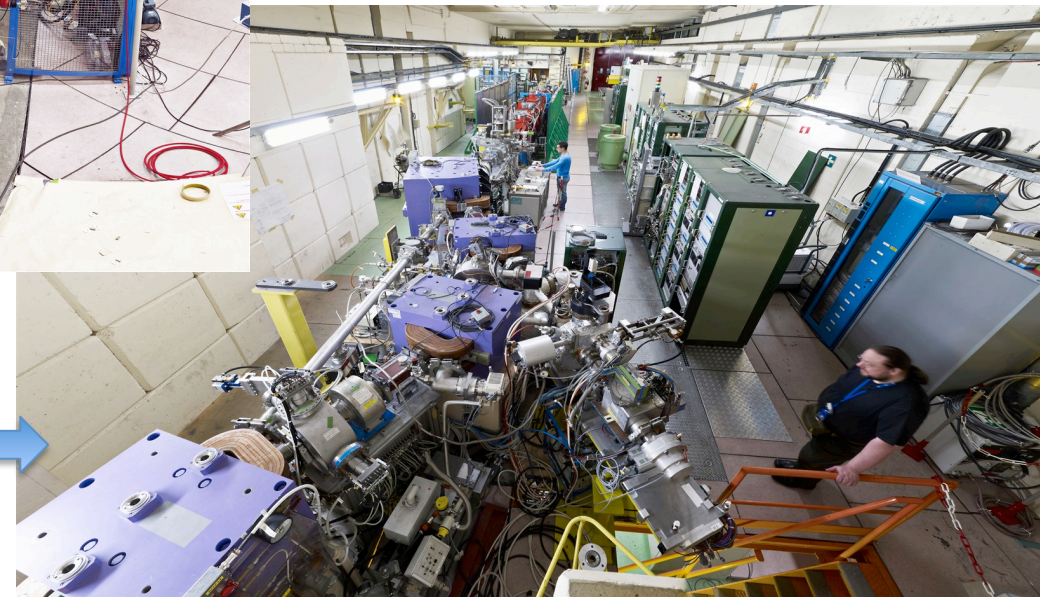


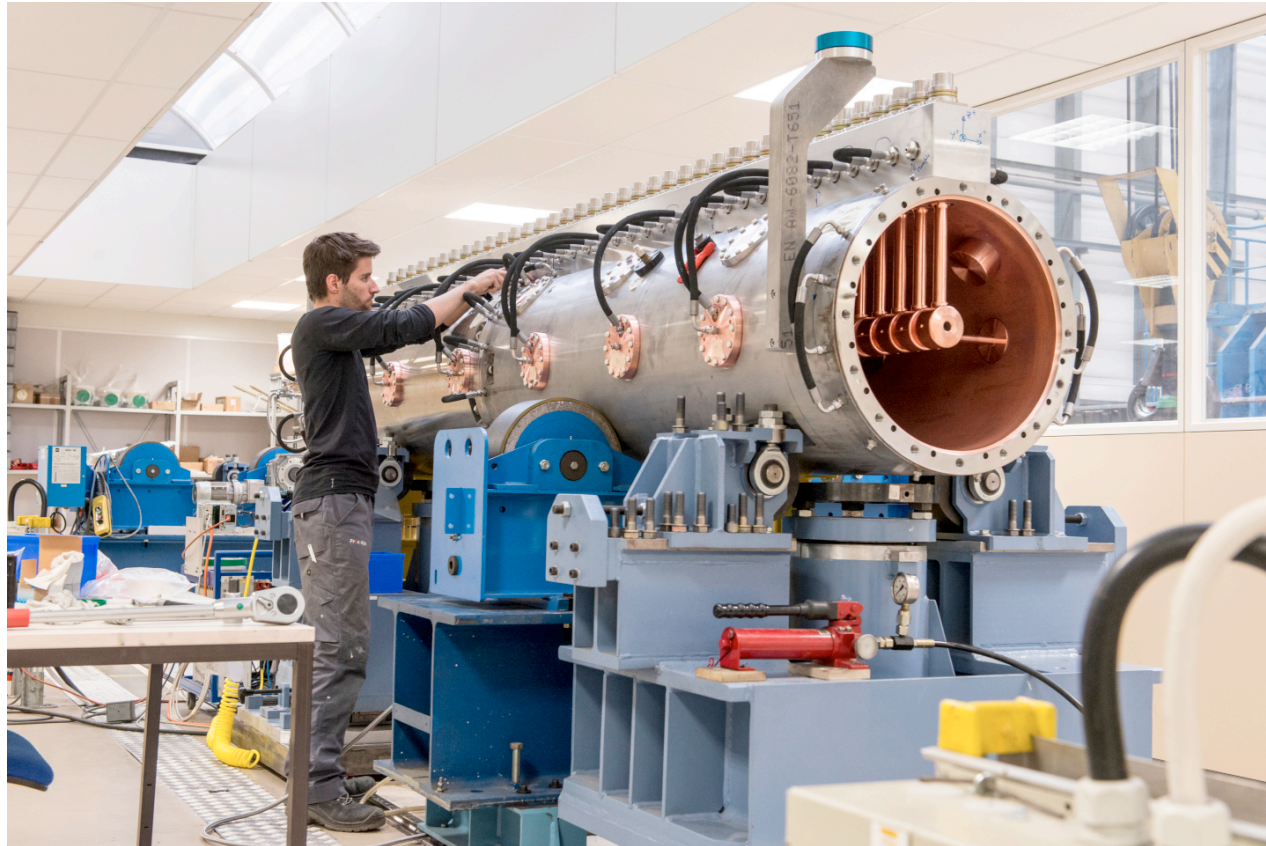
The CERN LINAC 3 provides different ion species to LEIR



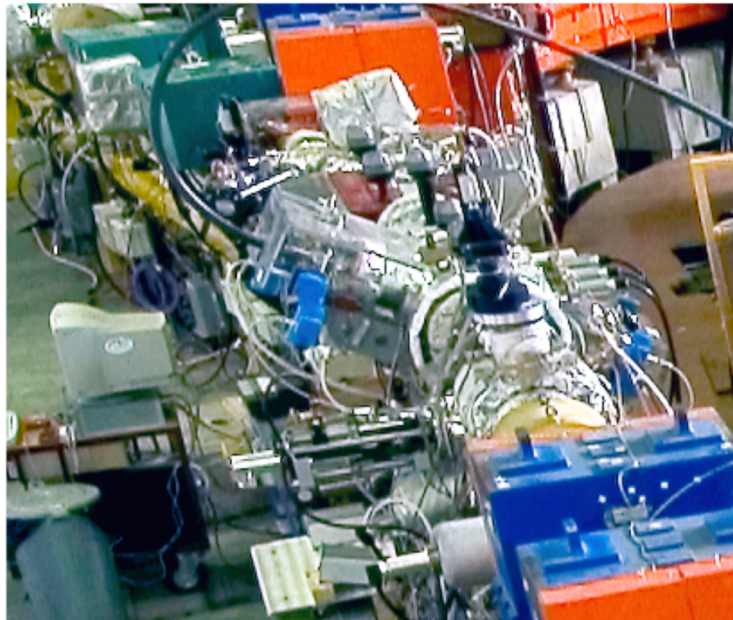
The ion source in the blue cage with the spectrometer in the front, follow by the LINAC behind

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



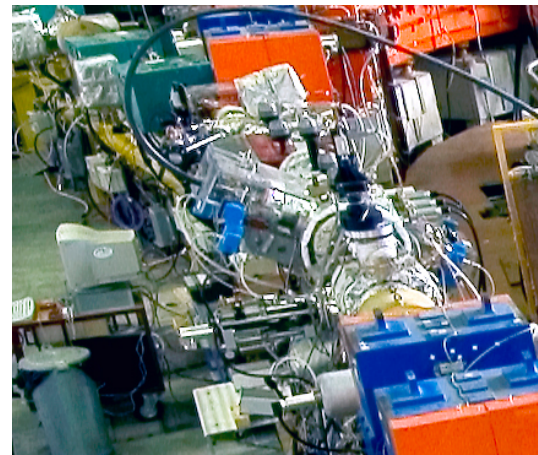
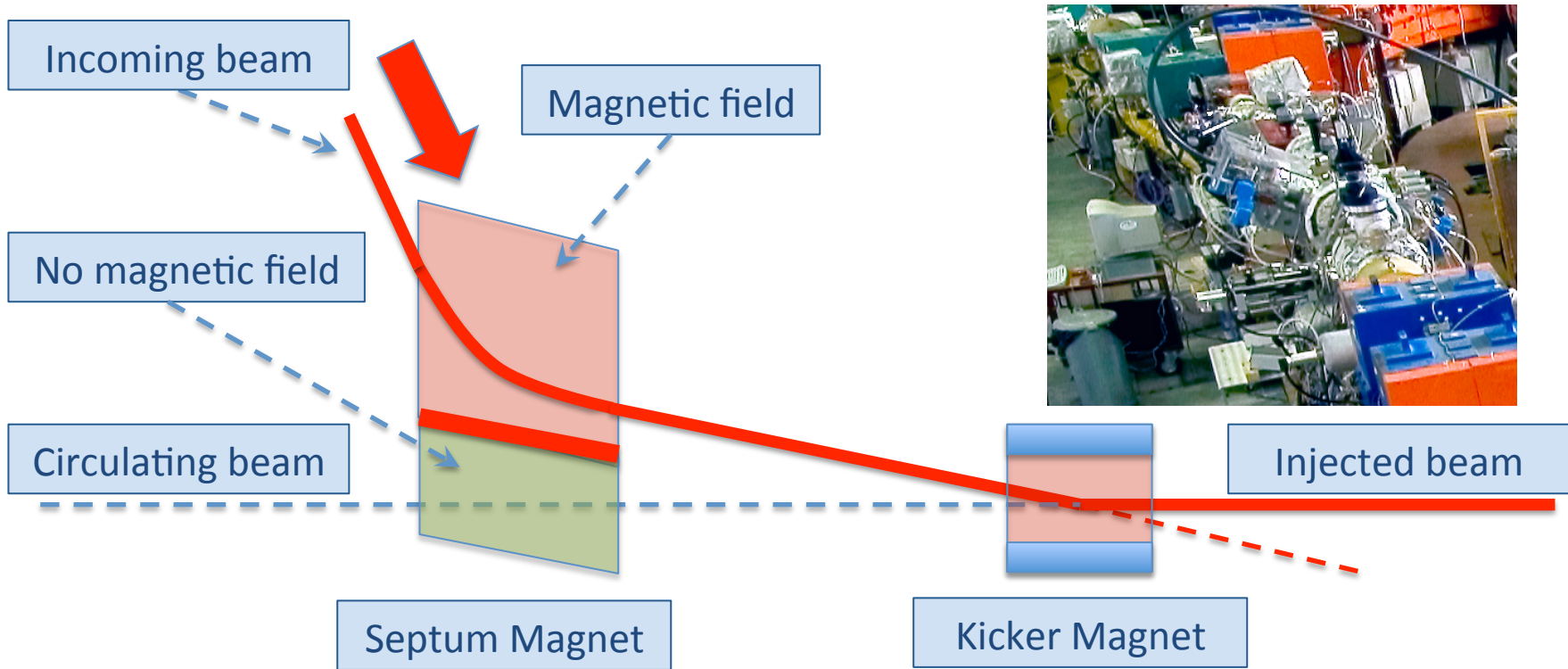


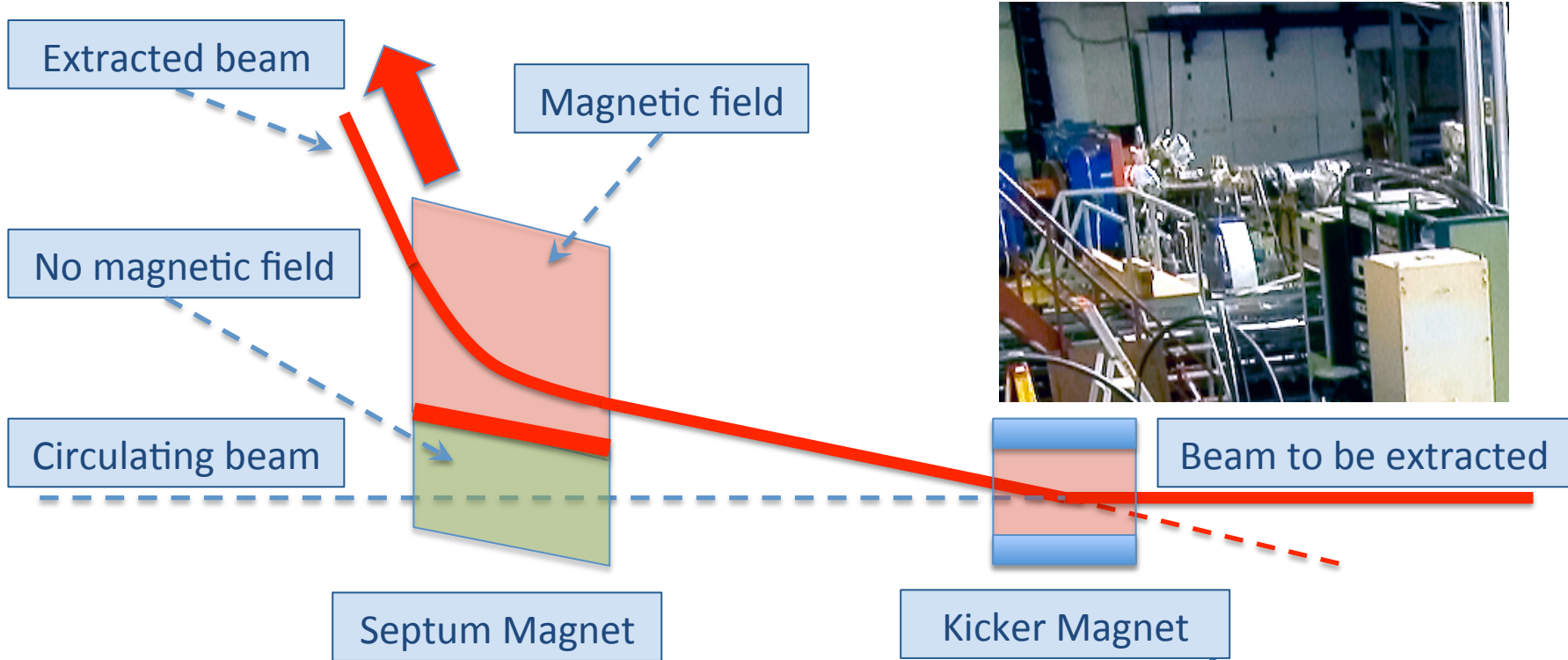
The CERN LINAC 4 drift tube



Injecting & Extracting Particles

Introduction to Accelerators – CERN Accelerator School

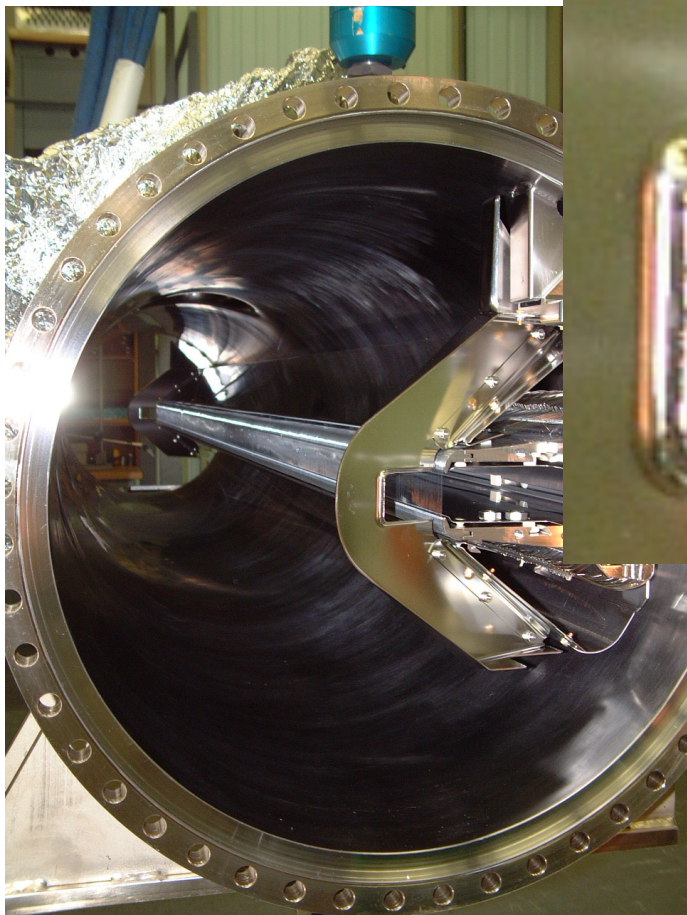




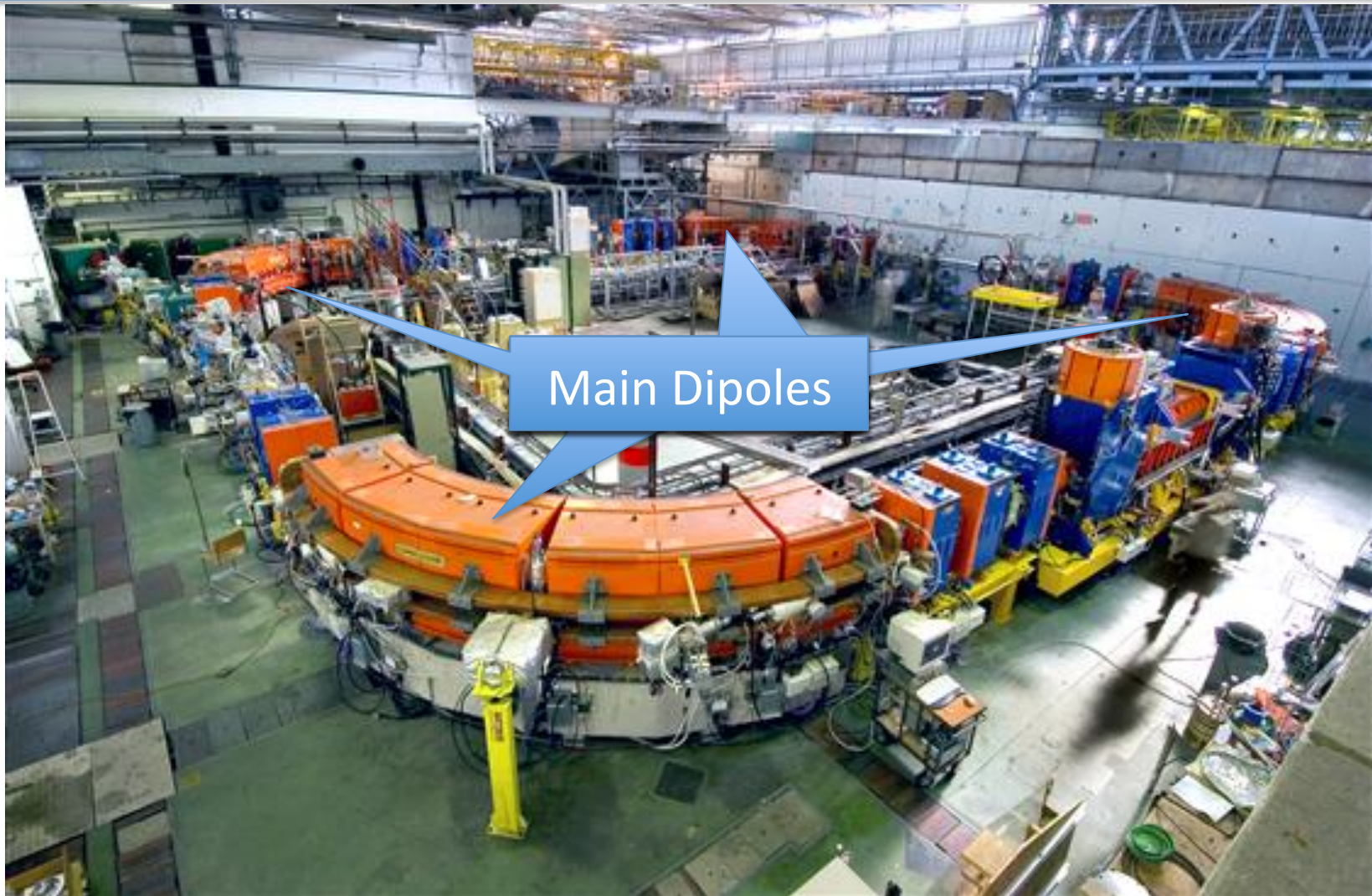
Beam to be extracted

Friday & Saturday afternoon

“Injection and Extraction” by W. Bartmann



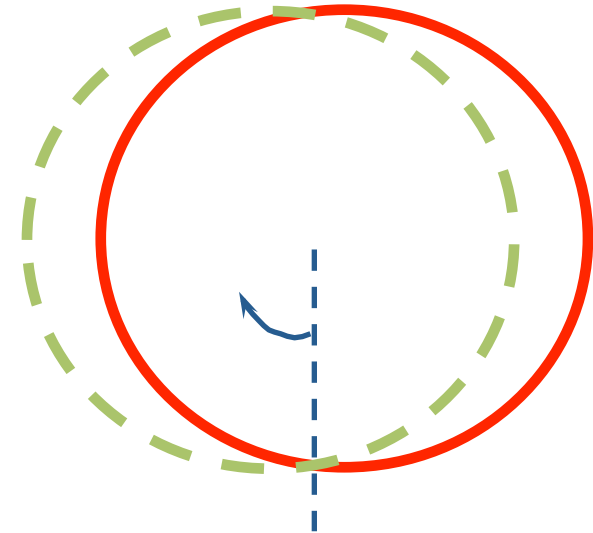
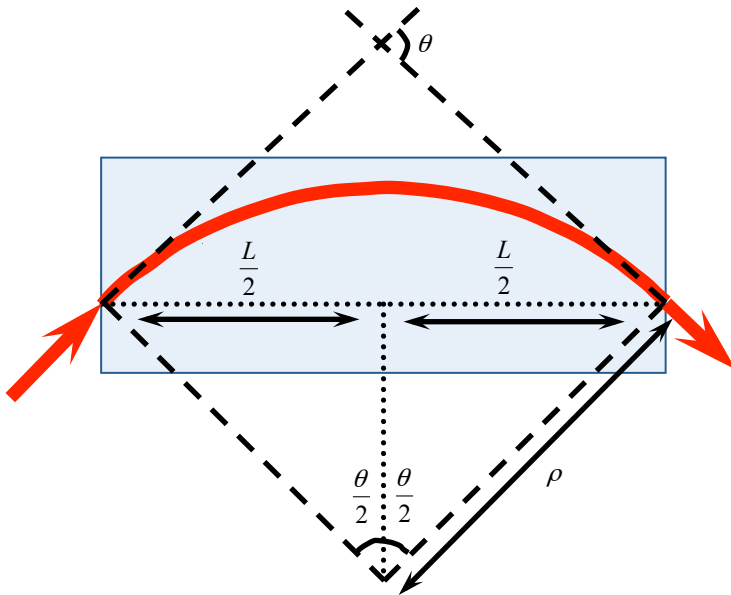
Make Particles Circulate



Charged Particles Deviated

Charged Particles are deviated in magnetic fields

Two charged Particles in a homogeneous magnetic field

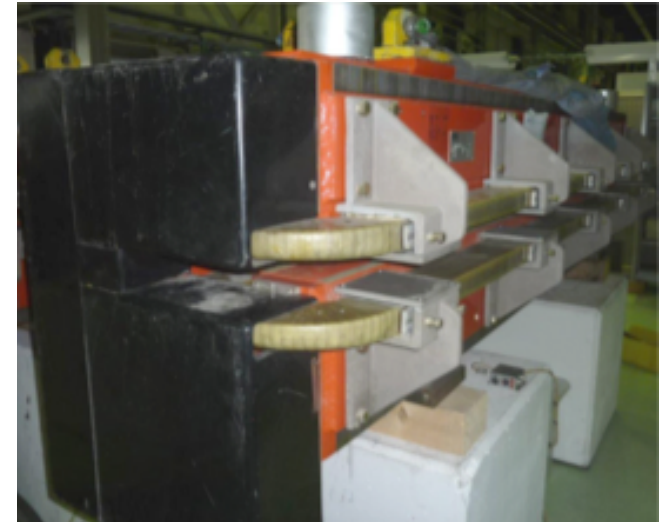
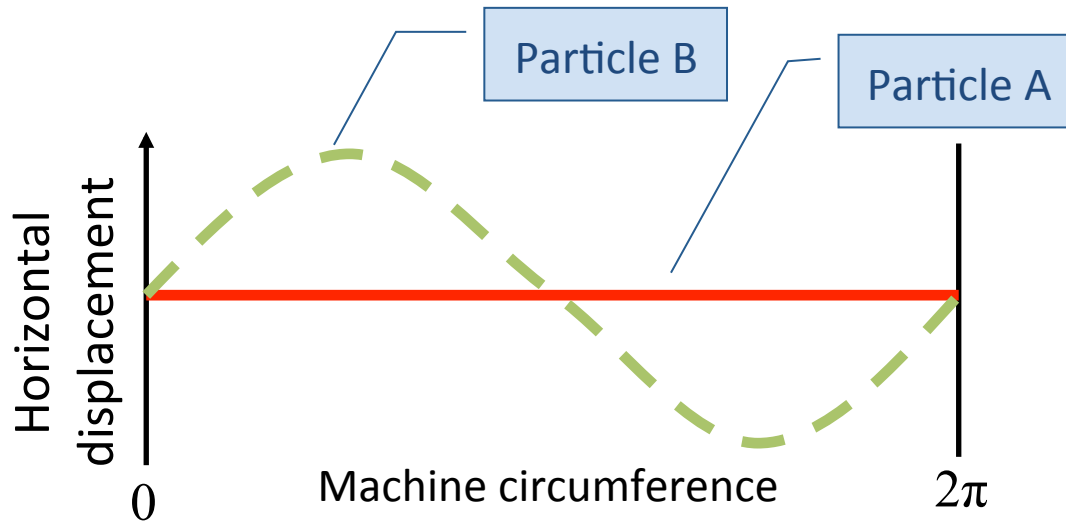


Lorentz force:

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

— Particle A
 - - - Particle B

Horizontal motion

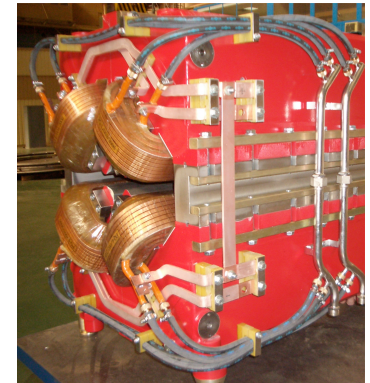
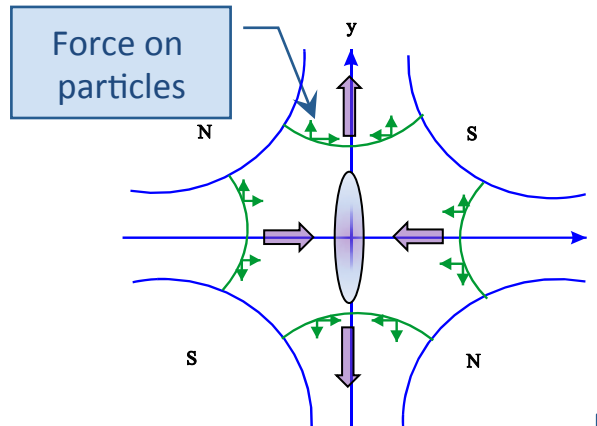
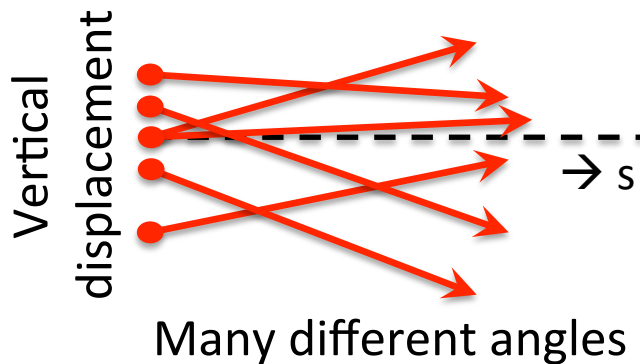


Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane

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

Many particles many initial conditions

Focusing particles, a bit like light



“Transverse Beam Dynamics” by B. Holzer

“Warm Magnets” by N. Marks

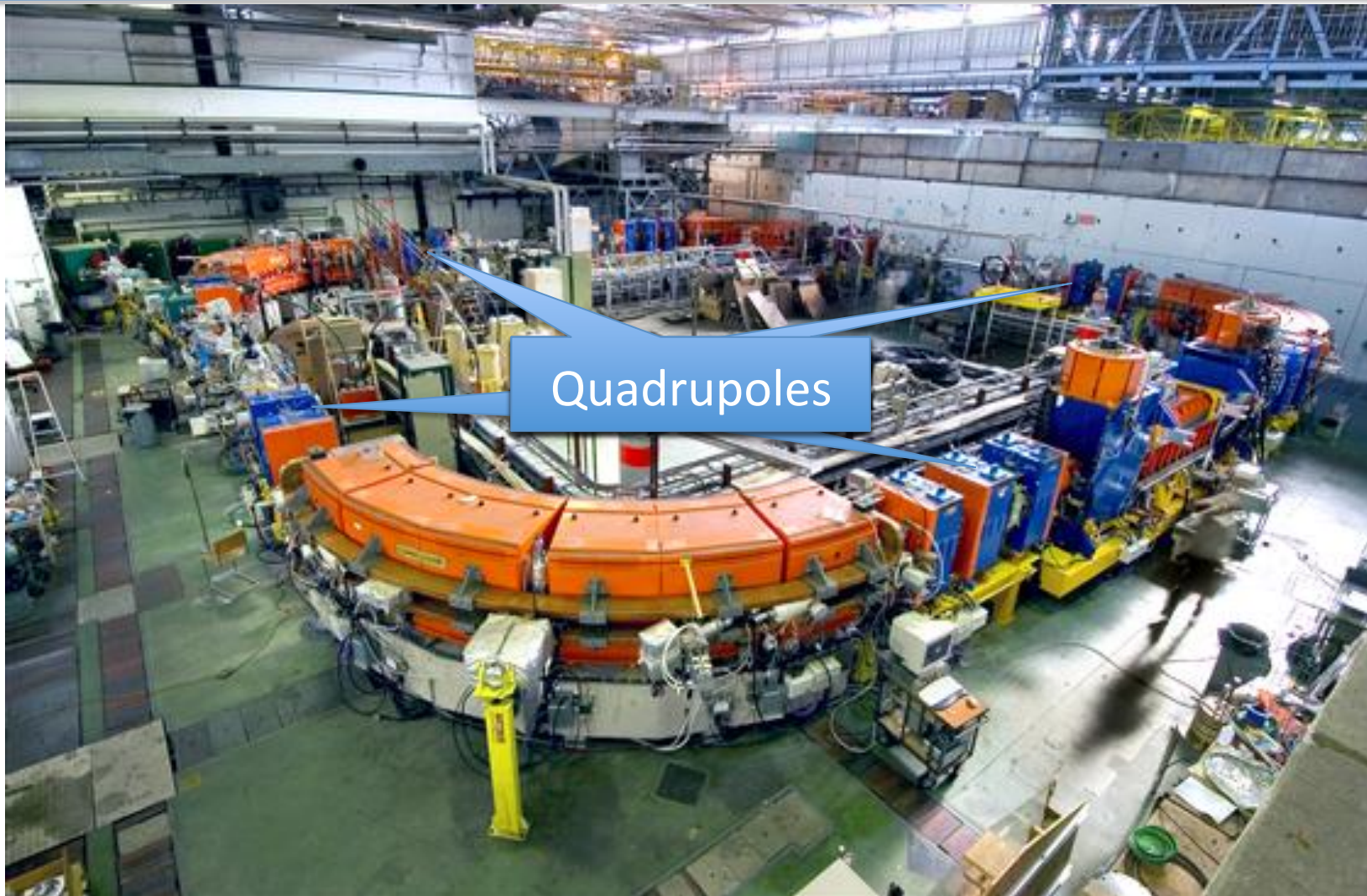
“Power Converters” by N. Marks

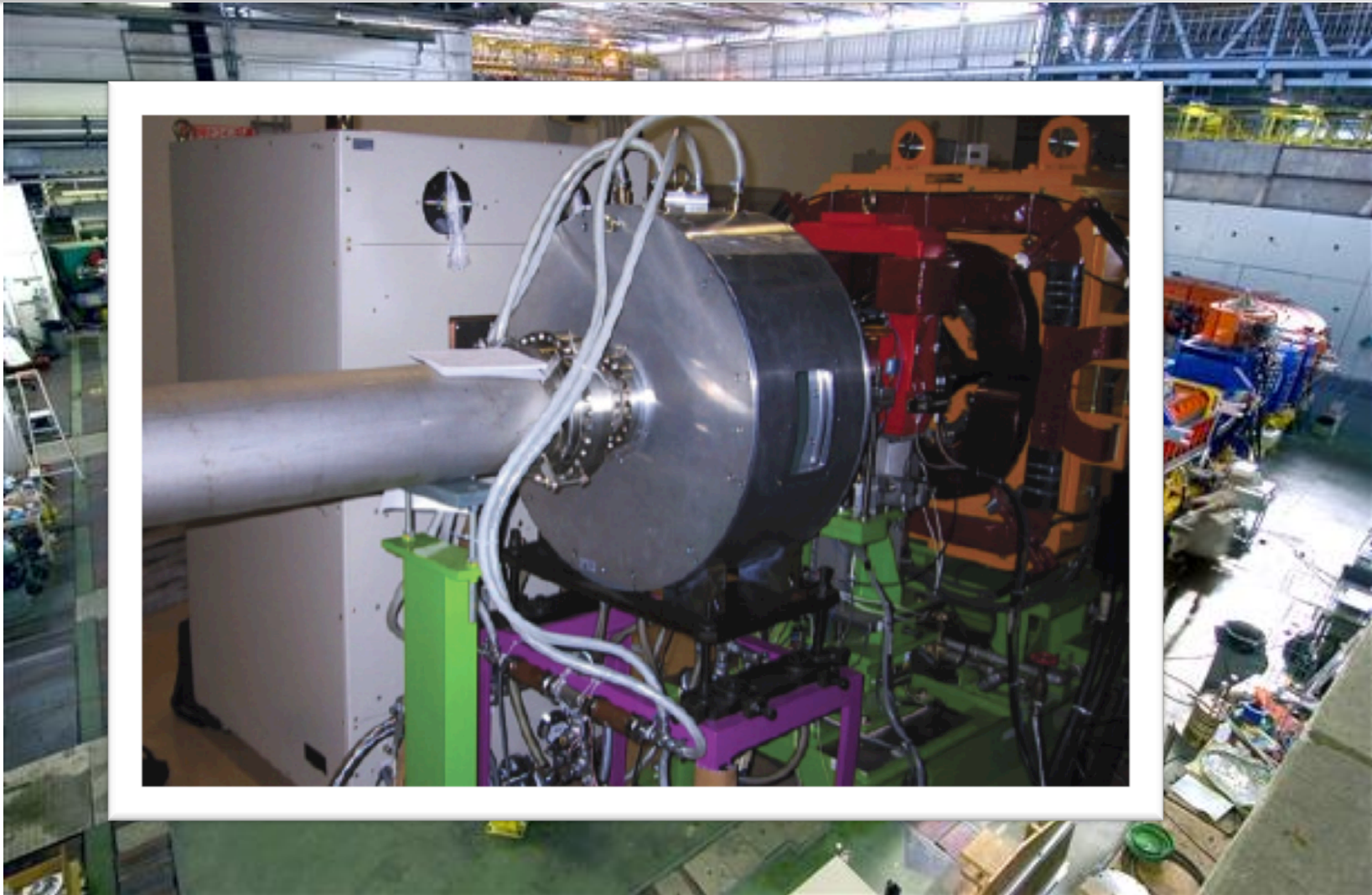
3 lectures on Tuesday & Wednesday

Tuesday & Wednesday morning

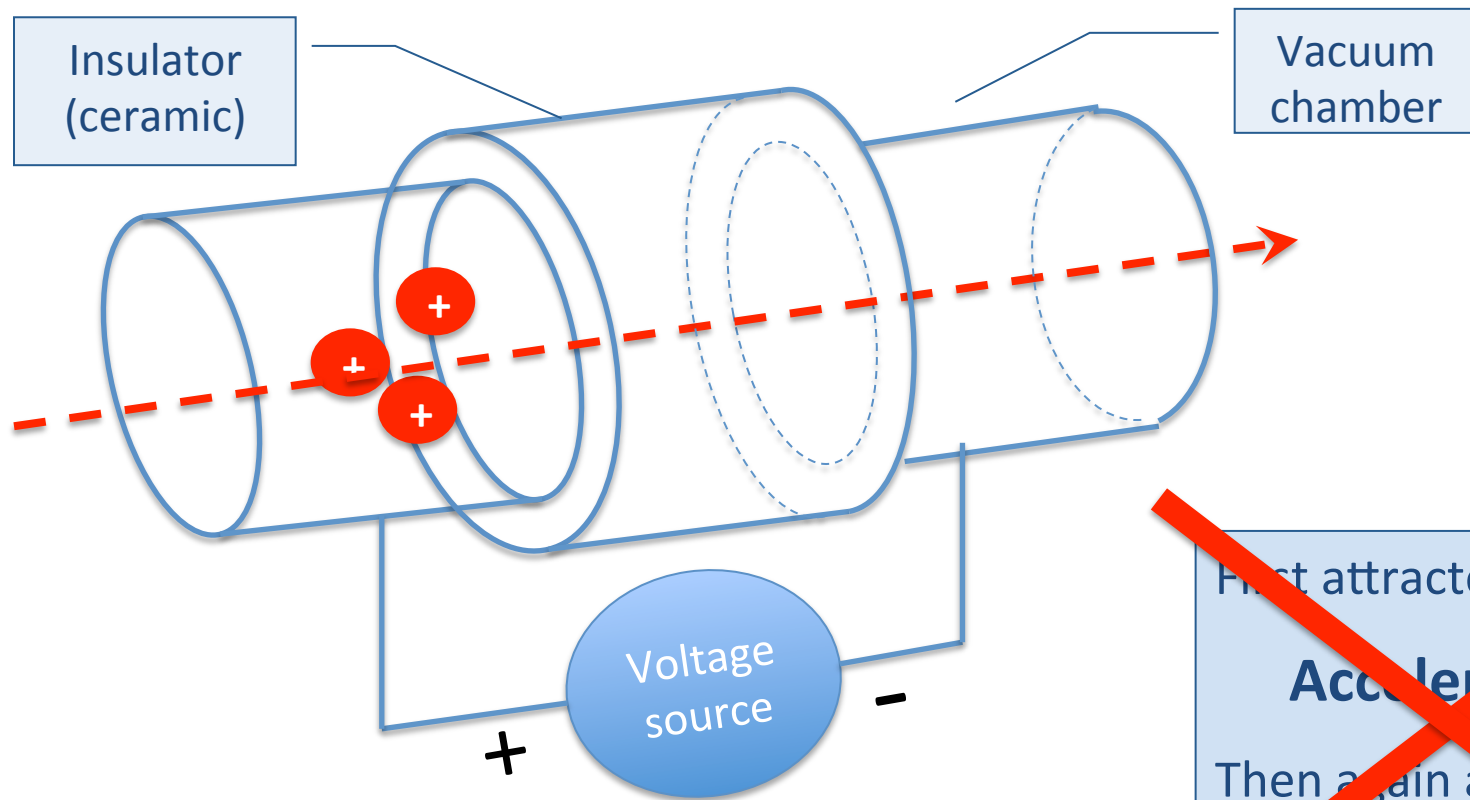
Thursday morning

Focusing the Particles





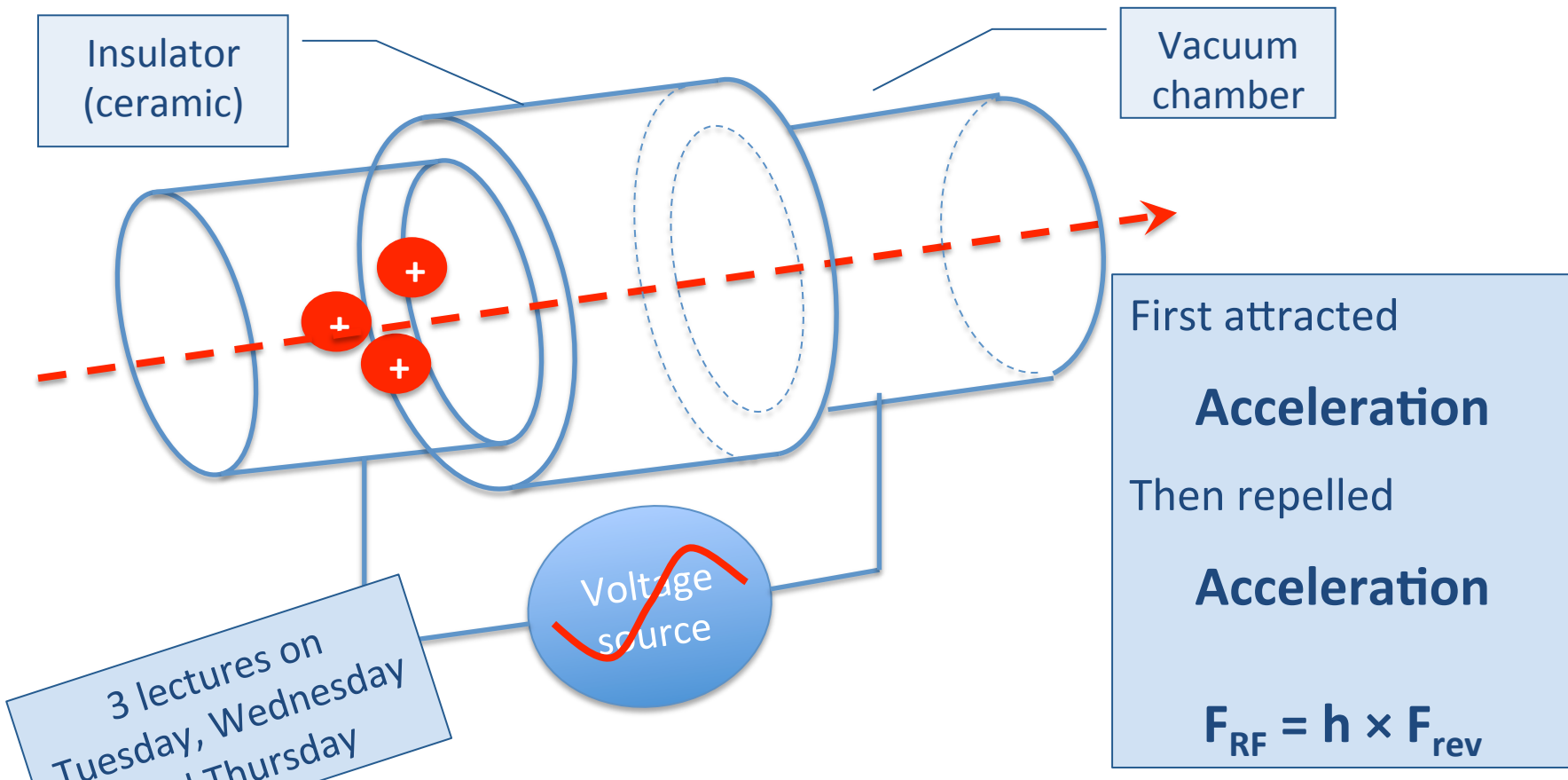
Accelerating Beams



Net result:
No Acceleration

~~First attracted
Acceleration
Then again attracted
Deceleration~~

Accelerating Beams

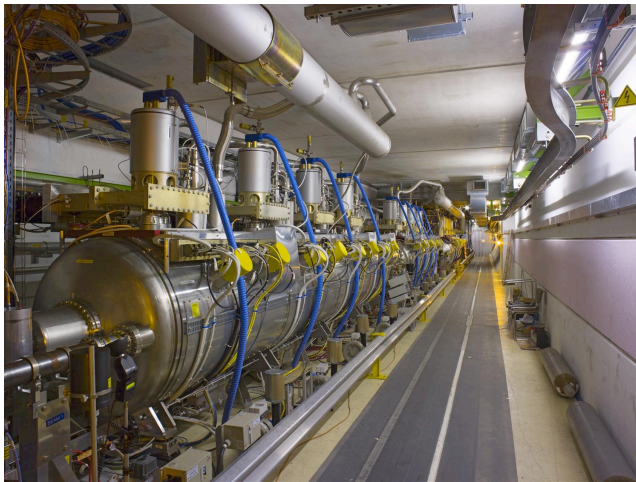


3 lectures on Tuesday, Wednesday and Thursday

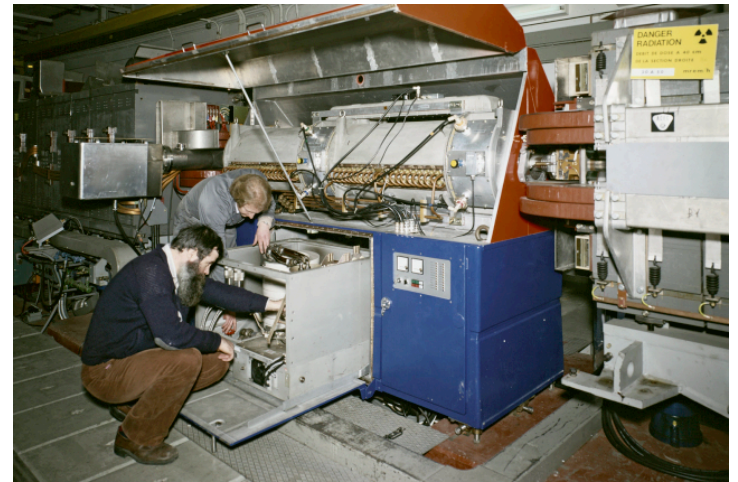
“Longitudinal Beam Dynamics” by F. Tecker
“RF Systems” by Erk Jensen

Monday & Tuesday next week

Fixed frequency cavities
(Superconducting) in the LHC



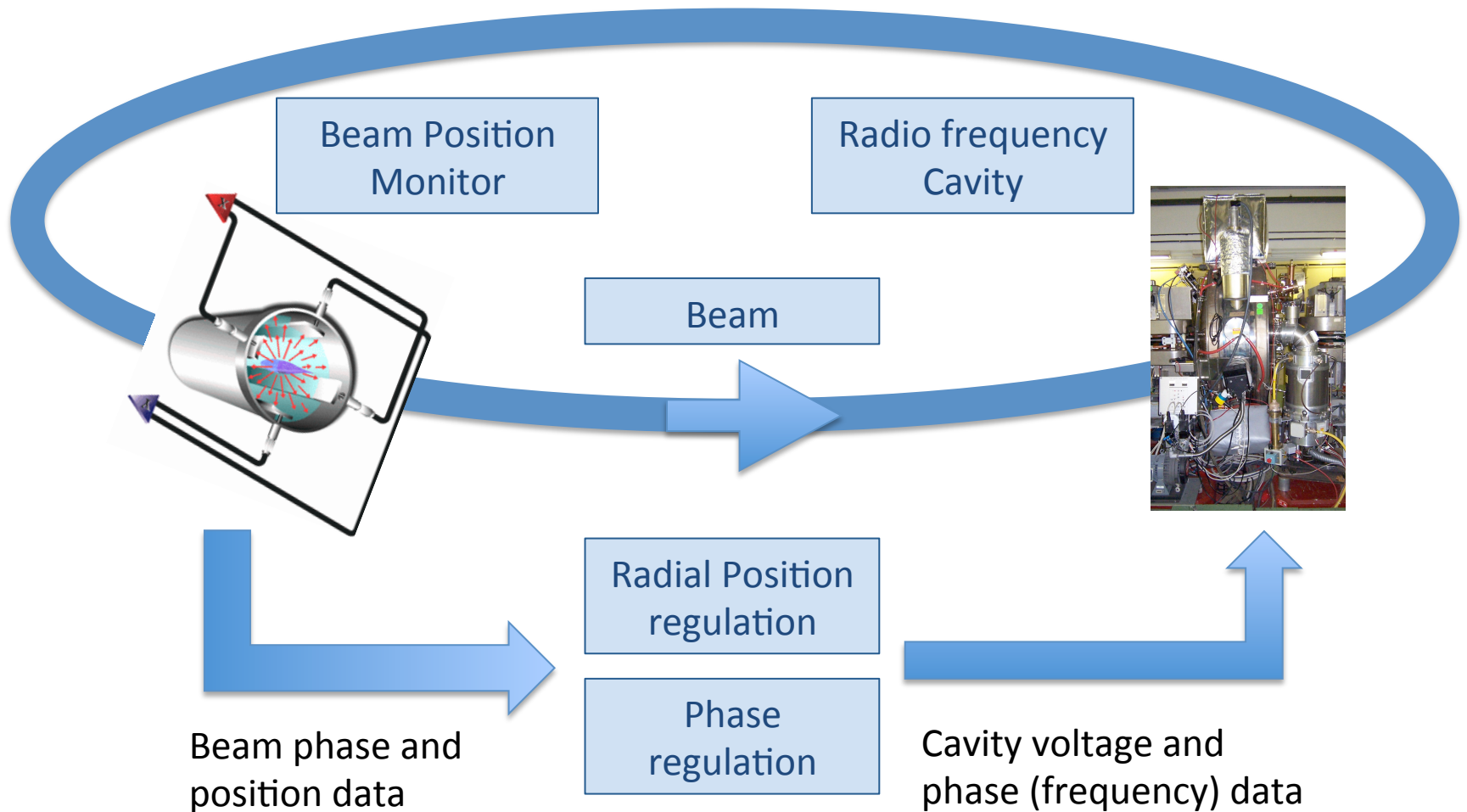
Variable frequency cavities (normal
conducting) in the CERN PS

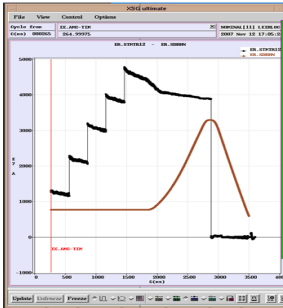


Radio frequency cavities are not only used to accelerate beams, but also to shape the beam:

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

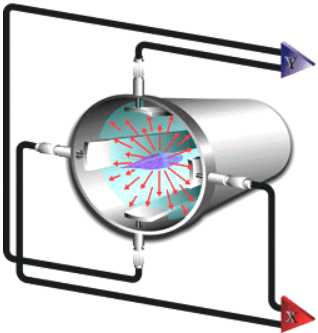
RF Beam Control



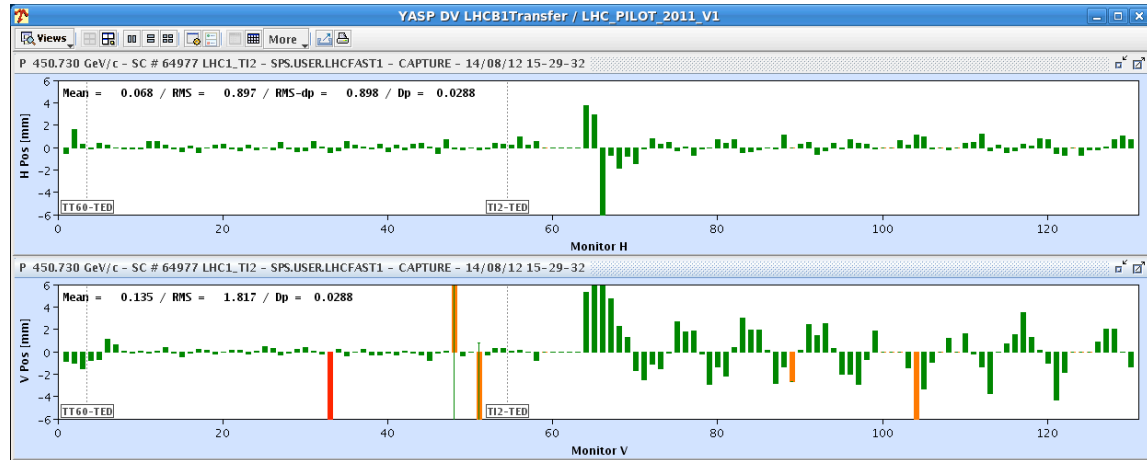


Beam intensity or current measurement:

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



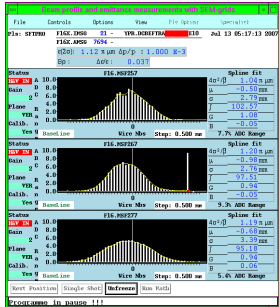
Beam position/orbit measurement:



Correcting orbit using automated beam steering

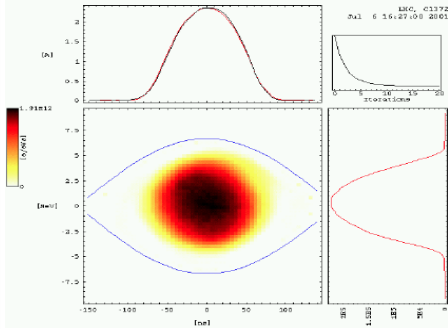
Measuring Beam Characteristics

Introduction to Accelerators – CERN Accelerator School



Transverse beam 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.....

Tuesday
afternoon

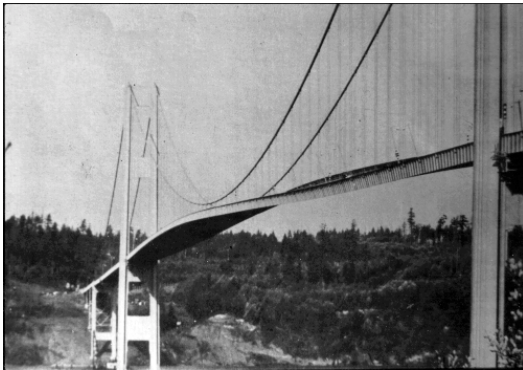
“Beam Instrumentation” by E Holzer
“Beam Diagnostics” by U. Raich

Wednesday
afternoon

Possible Limitations



Introduction to Accelerators – CERN Accelerator School



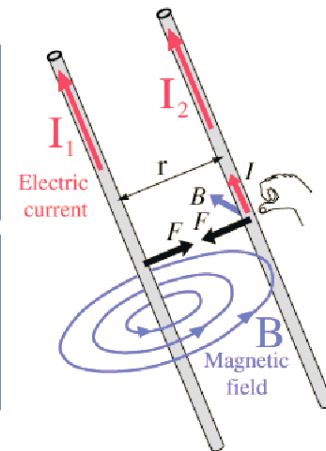
Machines and elements cannot be built and aligned with infinite precision

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



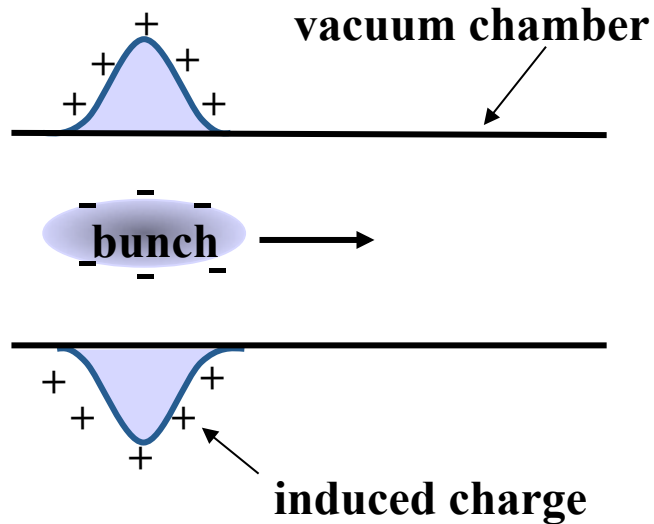
Neighbouring charges with the same polarity experience repelling forces

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

Monday & Thursday
next week

“Linear Imperfection” by R. Tomas
 “Space charge” by G. Franchetti
 “Collective effects” by G. Franchetti

Friday and Saturday
morning

Monday next week

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

Wednesday morning

“SC Magnets” by L. Bottura
“Machine Protection” by I. Strasik

Friday afternoon

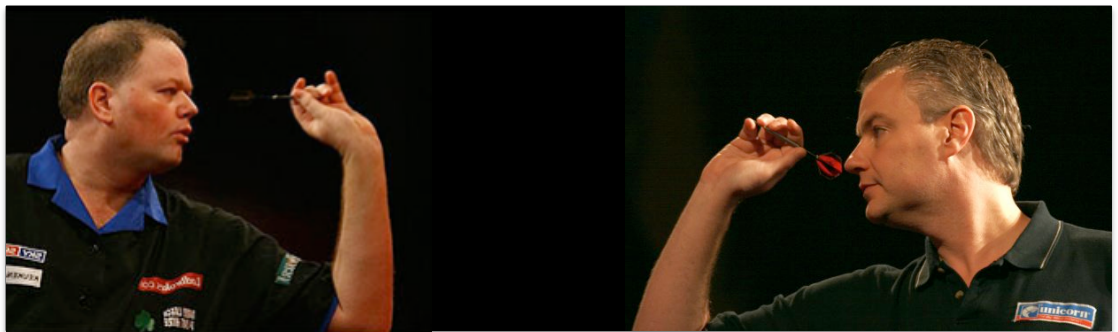
Figures of Merit in accelerators

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

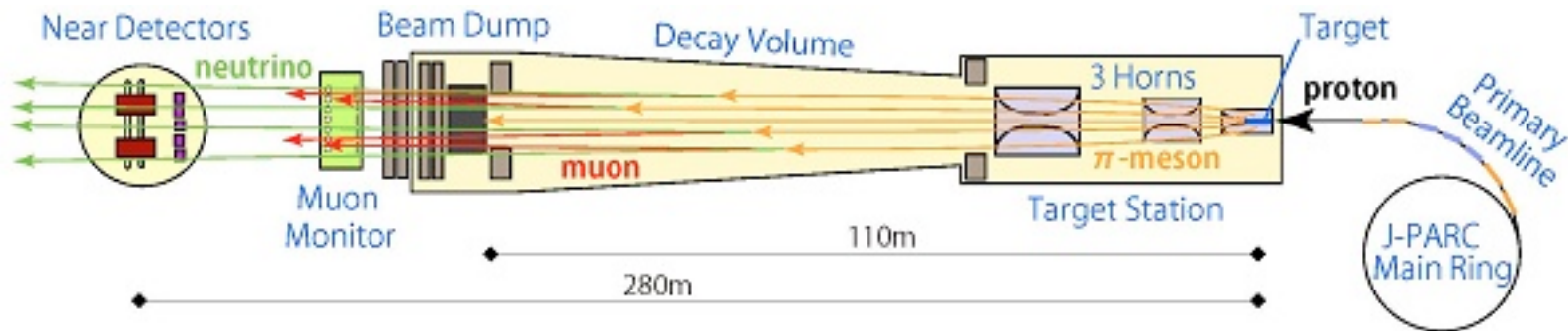
Fixed Target Physics:



Collider Physics:



Just a few examples among many:

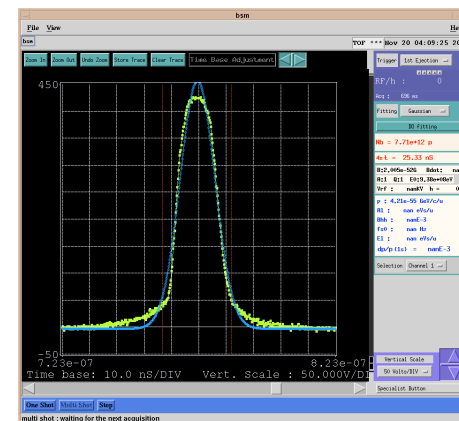
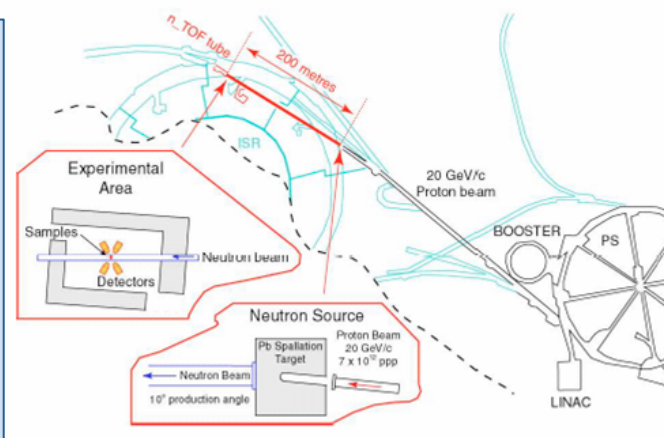


- Neutrino physics: high average beam power
 - High beam intensity with small beam size
 - High beam energy
 - High repetition rate
- J-PARC –Japan
- FermiLab - USA
- Previously CERN to CNGS – Europe

Just a few examples among many:

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

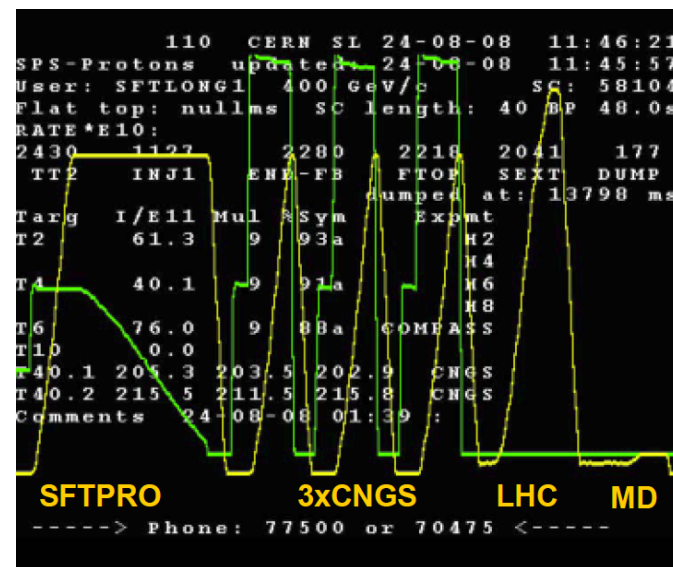
- Very short intense pulse of protons on a spallation target with a rather low repetition rate
- Large amount of neutrons produced in a wide range of energies (from a few MeV to several GeV)
- With the time of flight over 200 m the momentum of neutrons can be determined/selected



Just a few examples among many:

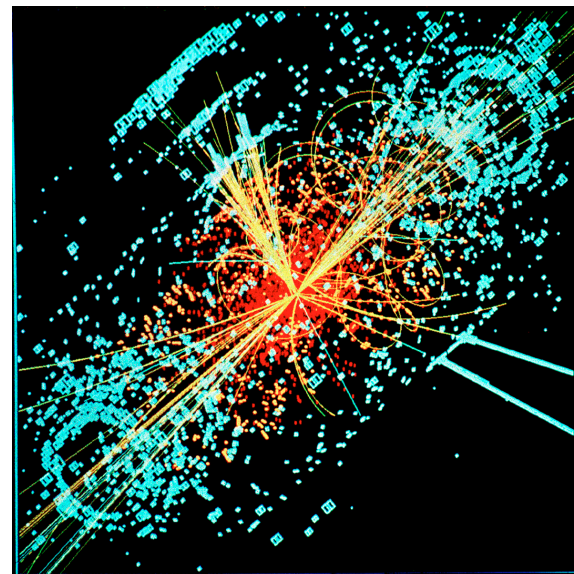
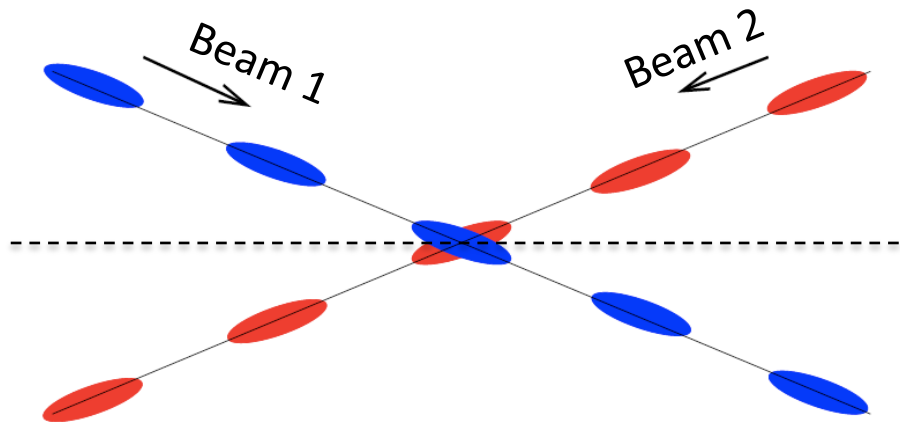
Test beam lines:

- 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



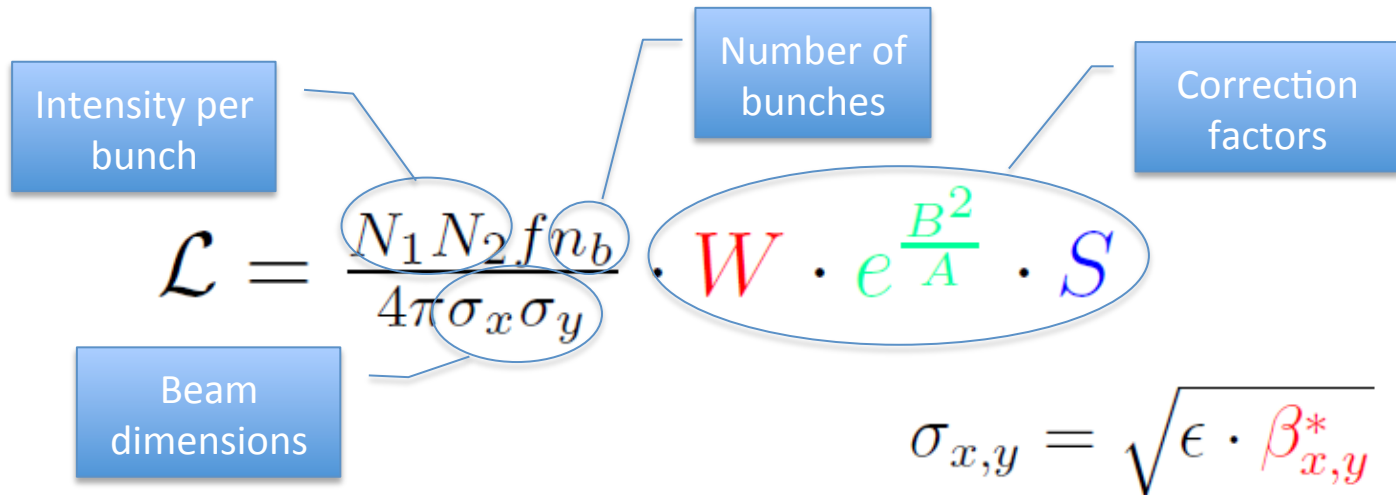
- The secondary particles are selected and distributed over several beam lines
- Uses often resonant slow extraction over several seconds

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)



Collider Luminosity

For collider physics the integrated luminosity is the figure of merit



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

Intensity per bunch

Beam dimensions

Number of bunches

Correction factors

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

- 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 2012 for ATLAS and CMS each 23.3 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

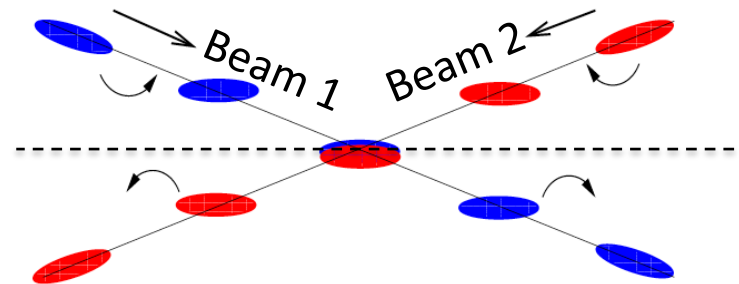
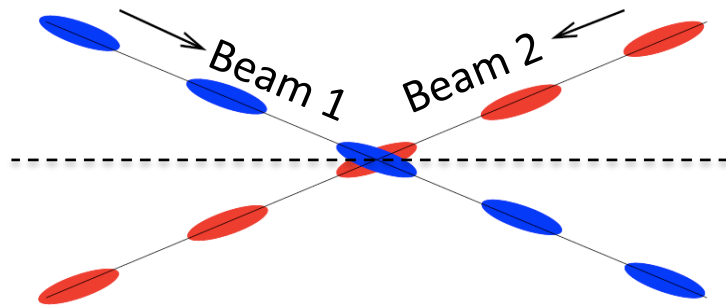
$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S$$

Reduce the β^* (σ)

- Stronger focusing around the interaction points

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

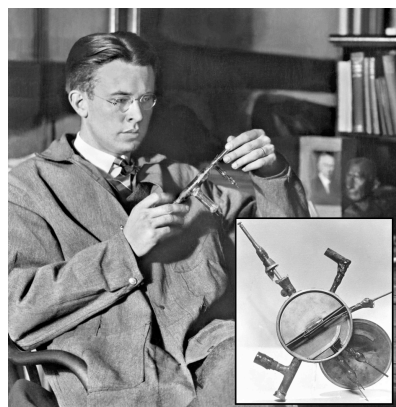
- Tilt the bunches to have more head-on collision effect



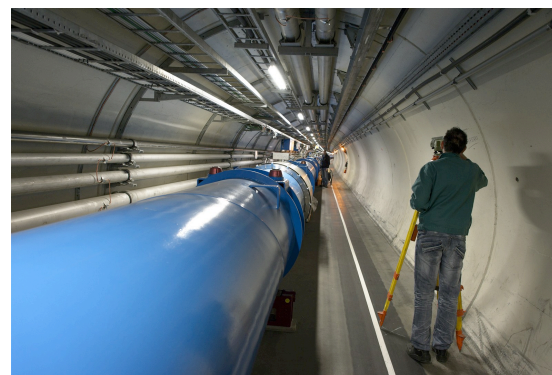
“We shall have no better conditions in the future if we are satisfied with all those which we have at present.”

Thomas A. Edison

Inventor and businessman, 1874 – 1931



E. Lawrence who invented the cyclotron in 1929



The LHC Today

..... much has changed since then....