Introduction to Accelerators

Rende Steerenberg - CERN - Beams Department

CERN Accelerator School
Introduction to Accelerator Physics
2 – 14 October 2016
Budapest – Hungary

The CERN Accelerator School

Contents

Introduction to Accelerators – CERN Accelerator School

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

The CERN Accelerator School

Introduction to Accelerators – CERN Accelerator School

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

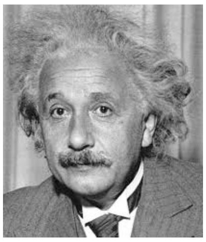
The CERN Accelerator School

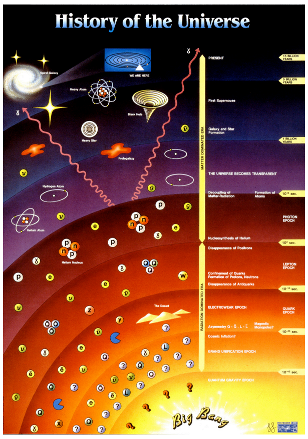
Matter versus Energy

Introduction to Accelerators – CERN Accelerator School

$E = m c^2$

During the Big Bang Energy was transformed in matter





In our accelerators we provide energy to the particle we accelerate.

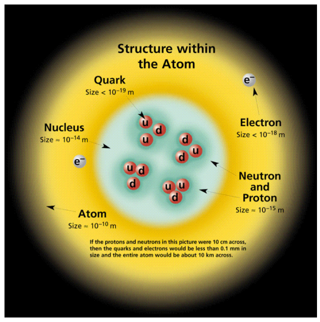
In the detectors we observe the matter

The CERN Accelerator School

Looking to smaller dimensions

Introduction to Accelerators – CERN Accelerator School

Visible light	X-ray	Particle accelerators
λ = 400 ➔ 700 nm	λ = 0.01 ➔ 10 nm	λ < 0.01 nm



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

Increasing the energy will reduce the wavelength

The CERN Accelerator School

Fixed Target vs. Colliders

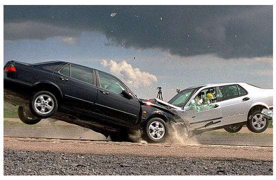
Introduction to Accelerators – CERN Accelerator School

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



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

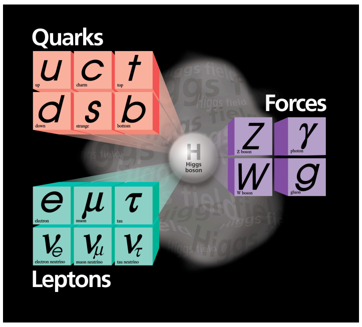
All energy will be available for particle production

The CERN Accelerator School

CERN

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

The CERN Accelerator School

CERN

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

Accelerators and Their Use

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

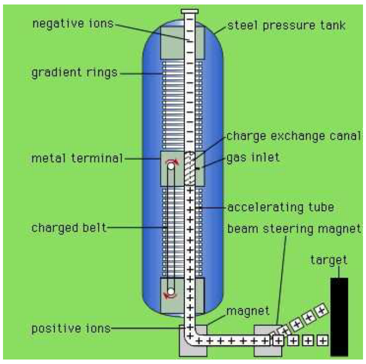
The **large majority** is used in **industry** and **medicine**
- Industrial applications: ~ 20'000*
- Medical applications: ~ 10'000*

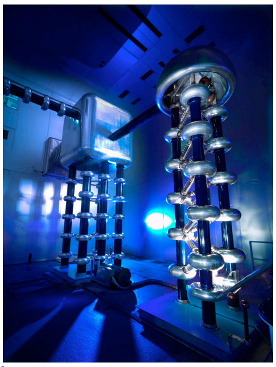
Les than a fraction of a percent is used for **research** and discovery science
- Cyclotrons
- FFAG
- Synchrotrons
- Synchrotron light sources (e-)
- Lin. & Circ. accelerators/Colliders

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





The CERN Accelerator School

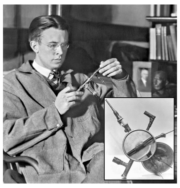
Cyclotron

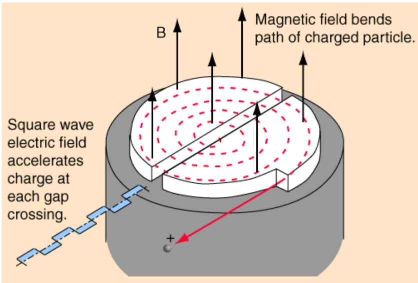
CERN

Introduction to Accelerators – CERN Accelerator School

- 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.





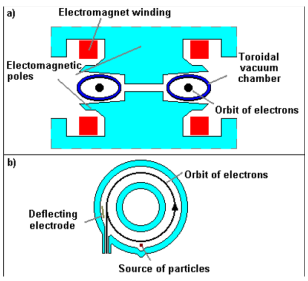
The CERN Accelerator School

Betatron

CERN

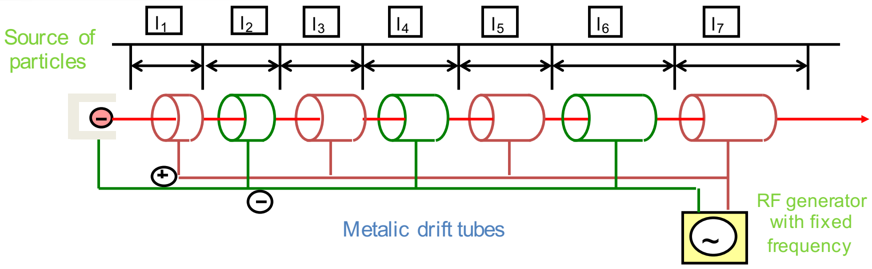
Introduction to Accelerators – CERN Accelerator School

- 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.



The CERN Accelerator School

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.

The CERN Accelerator School

Synchrotrons

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

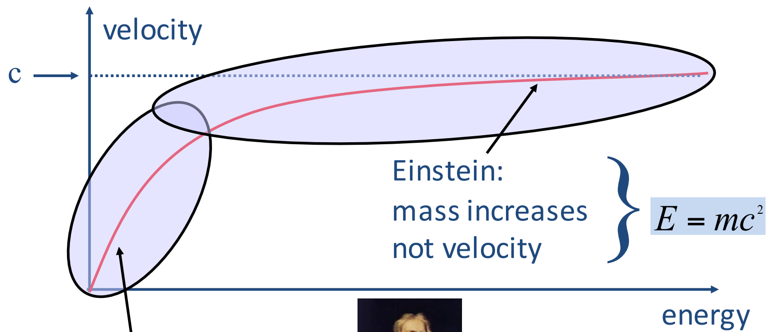
- 1959: CERN-PS and BNL-AGS
- Fixed radius for particle orbit
- Varying magnetic field and radio frequency
- Phase stability
- Important focusing of particle beams (Courant – Snyder)
- Providing beam for fixed target physics
- Paved the way to colliders

The CERN Accelerator School

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

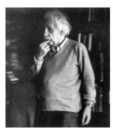
The CERN Accelerator School

Towards Relativity



Einstein:
mass increases
not velocity

$$E = mc^2$$



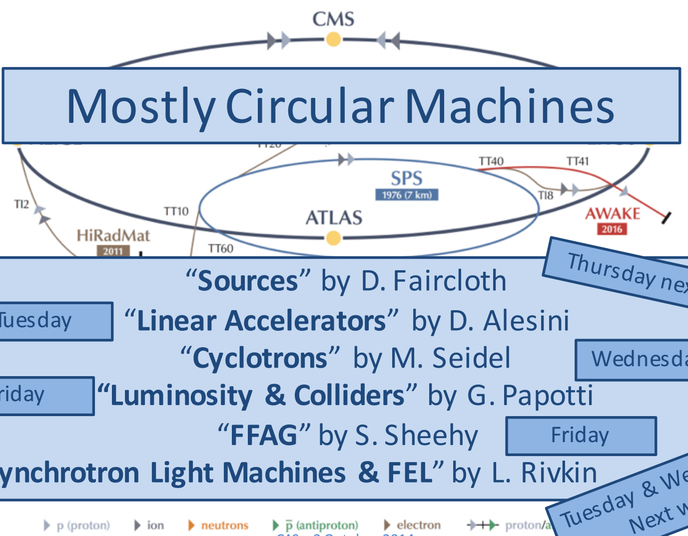
Newton: $E = \frac{1}{2}mv^2$

"**Relativity**" by W. Herr

This afternoon

The CERN Accelerator School

The CERN Accelerator Complex



Mostly Circular Machines

"**Sources**" by D. Faircloth — Thursday next week

Tuesday — "**Linear Accelerators**" by D. Alesini

"**Cyclotrons**" by M. Seidel — Wednesday

Friday — "**Luminosity & Colliders**" by G. Papotti

"**FFAG**" by S. Sheehy — Friday

"**Synchrotron Light Machines & FEL**" by L. Rivkin — Tuesday & Wednesday Next week

Introduction to Accelerators – CERN Accelerator School

Rende Steerenberg, CERN — CAS - 3 October 2014 Budapest - Hungary — 17

The CERN Accelerator School

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

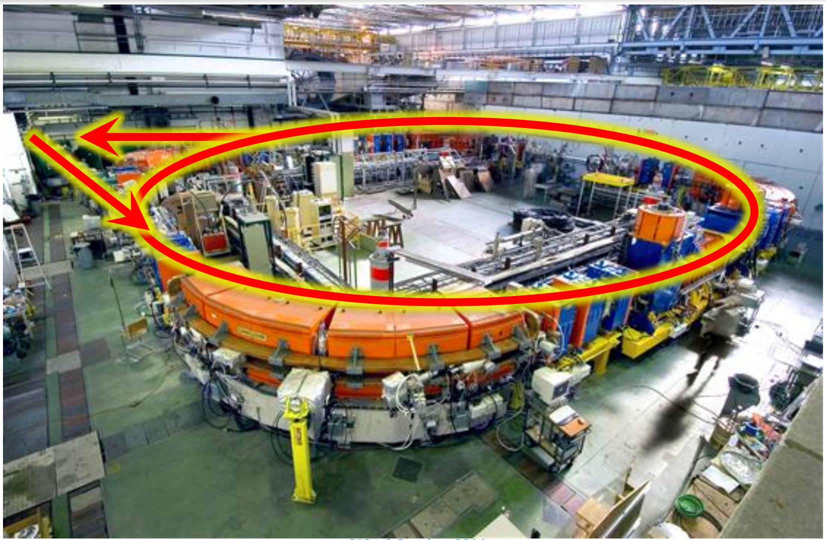
Low **E**nergy **I**on **R**ing

Introduction to Accelerators – CERN Accelerator School

Rende Steerenberg, CERN — CAS - 3 October 2014 Budapest - Hungary — 18

The CERN Accelerator School

CERN - LEIR as an Example



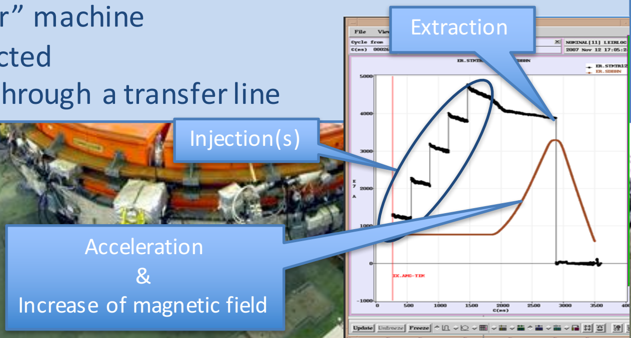
The CERN Accelerator School

LEIR as an Example

Introduction to Accelerators – CERN Accelerator School

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

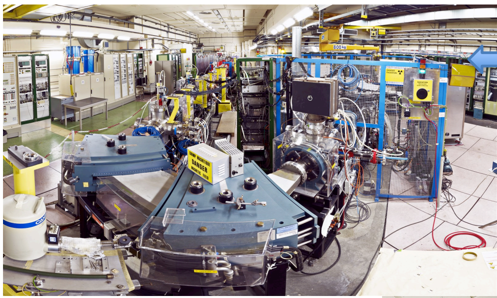


The CERN Accelerator School

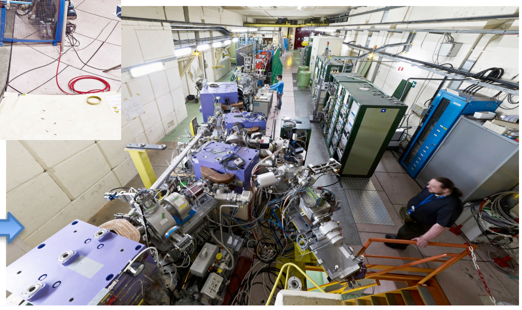
LINAC 3, injector of LEIR

Introduction to Accelerators – CERN Accelerator School

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

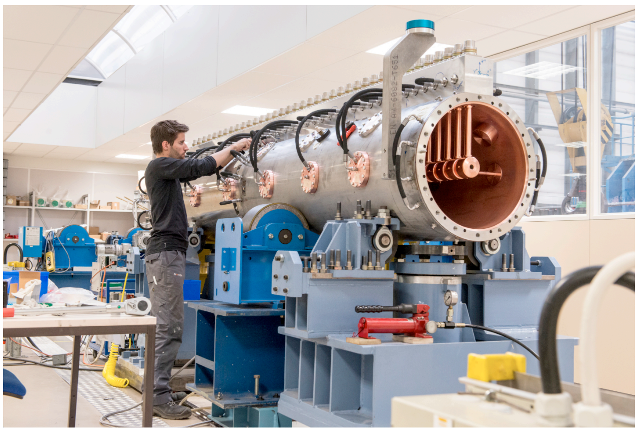


The downstream part of the LINAC with the accelerating structures (Alvarez) in the back of the image and transfer and measurement lines in the front

The CERN Accelerator School

LINAC Accelerating Structure

Introduction to Accelerators – CERN Accelerator School

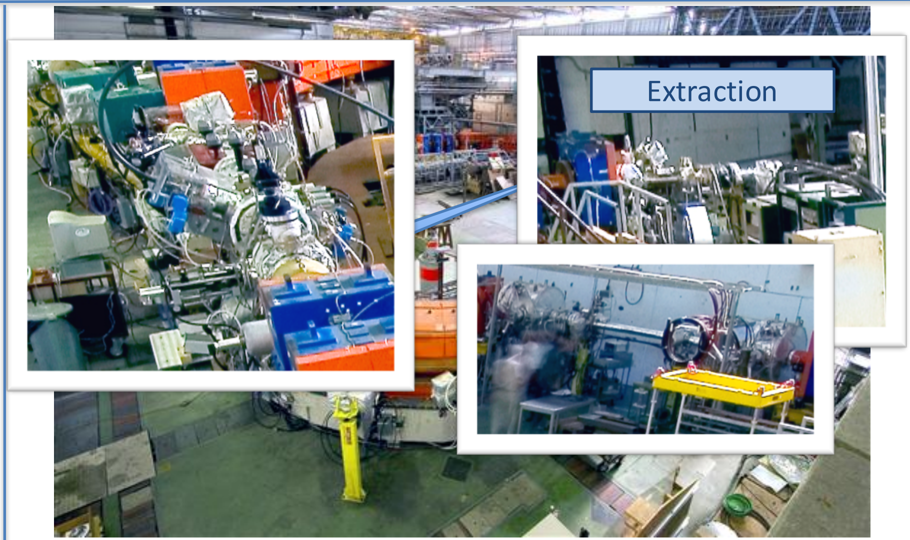


The CERN LINAC 4 drift tube

The CERN Accelerator School

Injecting & Extracting Particles

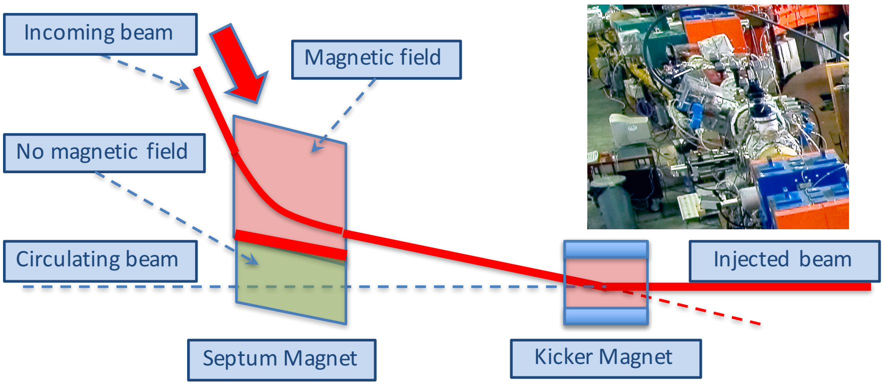
Introduction to Accelerators – CERN Accelerator School



The CERN Accelerator School

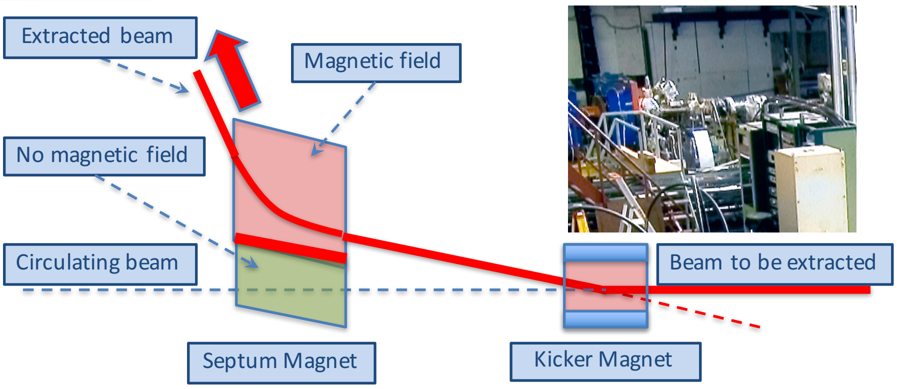
Injecting & Extracting Particles

Introduction to Accelerators – CERN Accelerator School



The CERN Accelerator School

Injecting & **Extracting** Particles



Wednesday next week

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

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

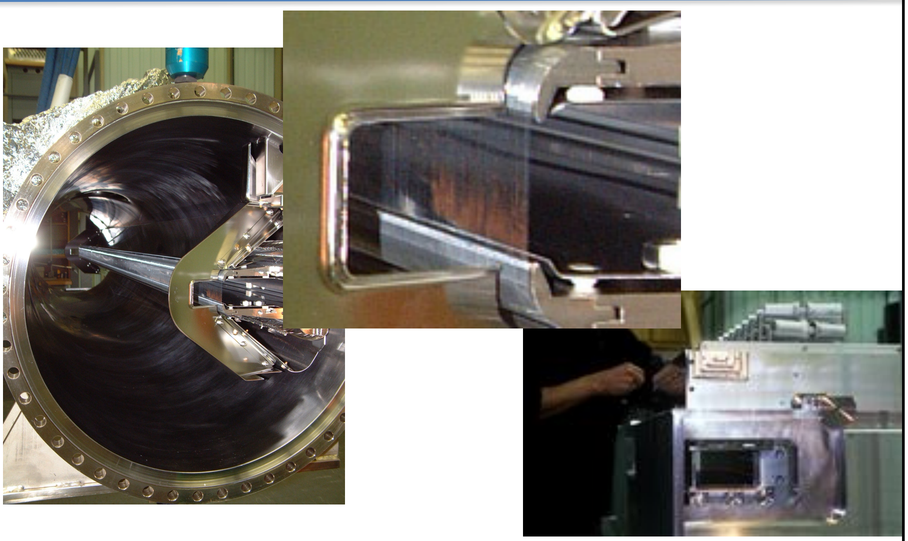
Thursday next week

Introduction to Accelerators – CERN Accelerator School

Rende Steerenberg, CERN — CAS - 3 October 2014 Budapest - Hungary — 25

The CERN Accelerator School

Septum and Kicker Magnets



Introduction to Accelerators – CERN Accelerator School

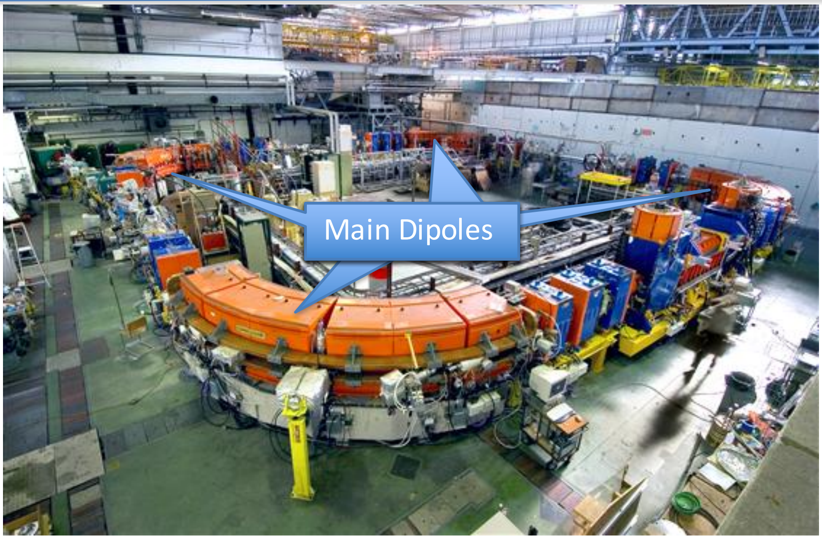
Rende Steerenberg, CERN — CAS - 3 October 2014 Budapest - Hungary — 26

The CERN Accelerator School

Make Particles Circulate

CERN

Introduction to Accelerators – CERN Accelerator School



Rende Steerenberg, CERN

CAS - 3 October 2014
Budapest - Hungary

27

The CERN Accelerator School

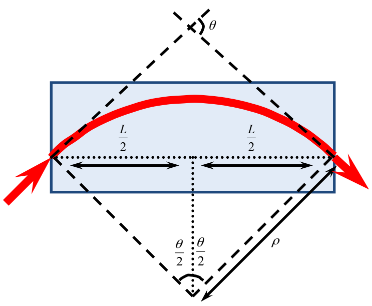
Charged Particles Deviated

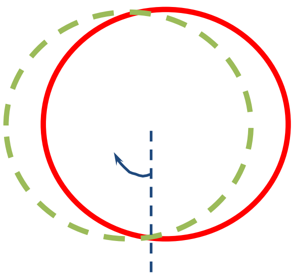
CERN

Introduction to Accelerators – CERN Accelerator School

Charged Particles are deviated in magnetic fields

Two charged Particles in a homogeneous magnetic field





Particle A

Particle B

Lorentz force:

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

Rende Steerenberg, CERN

CAS - 3 October 2014
Budapest - Hungary

28

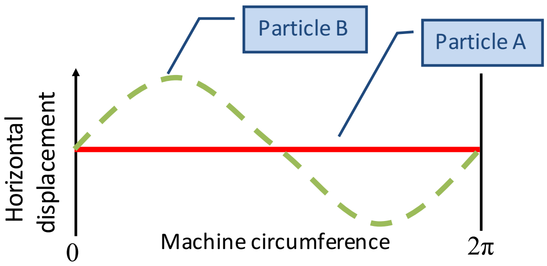
The CERN Accelerator School

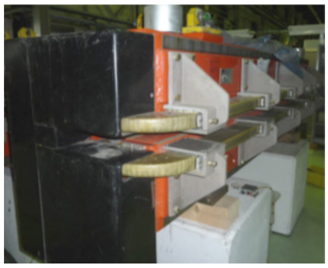
Oscillatory Motion of Particles

CERN

Introduction to Accelerators – CERN Accelerator School

Horizontal motion





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

The CERN Accelerator School

Oscillatory Motion of Particles

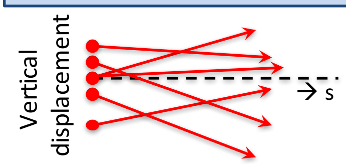
CERN

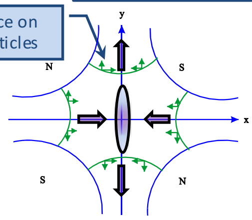
Introduction to Accelerators – CERN Accelerator School

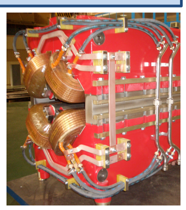
The horizontal motion seems to be "stable"…. What about the vertical plane ?

Many particles many initial conditions

Focusing particles, a bit like light







Tuesday & Wednesday

"**Transverse Beam Dynamics**" by B. Holzer

"**Warm Magnets**" by G. de Rijk

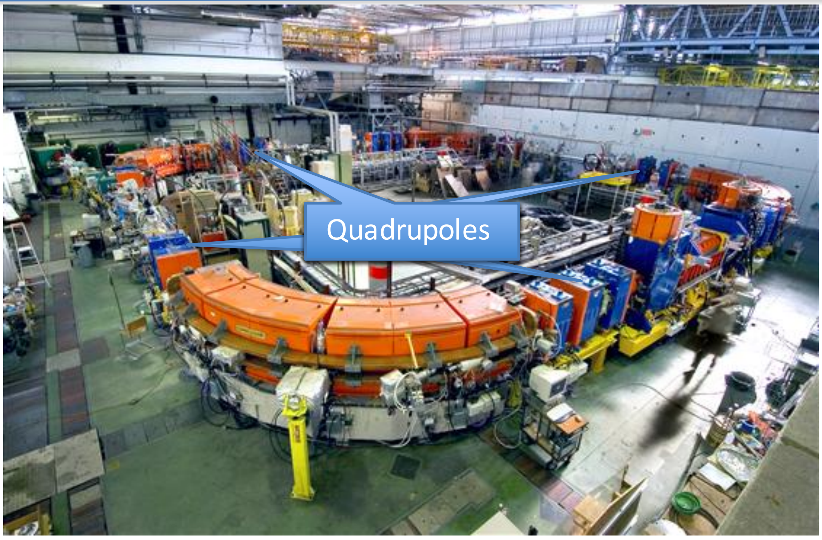
Friday

Saturday

"**Power Converters**" by J.-P. Burnet

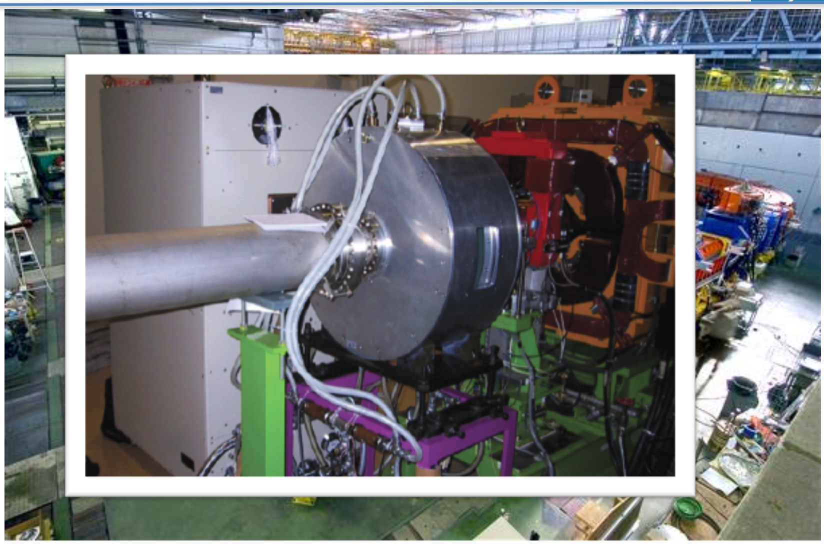
The CERN Accelerator School

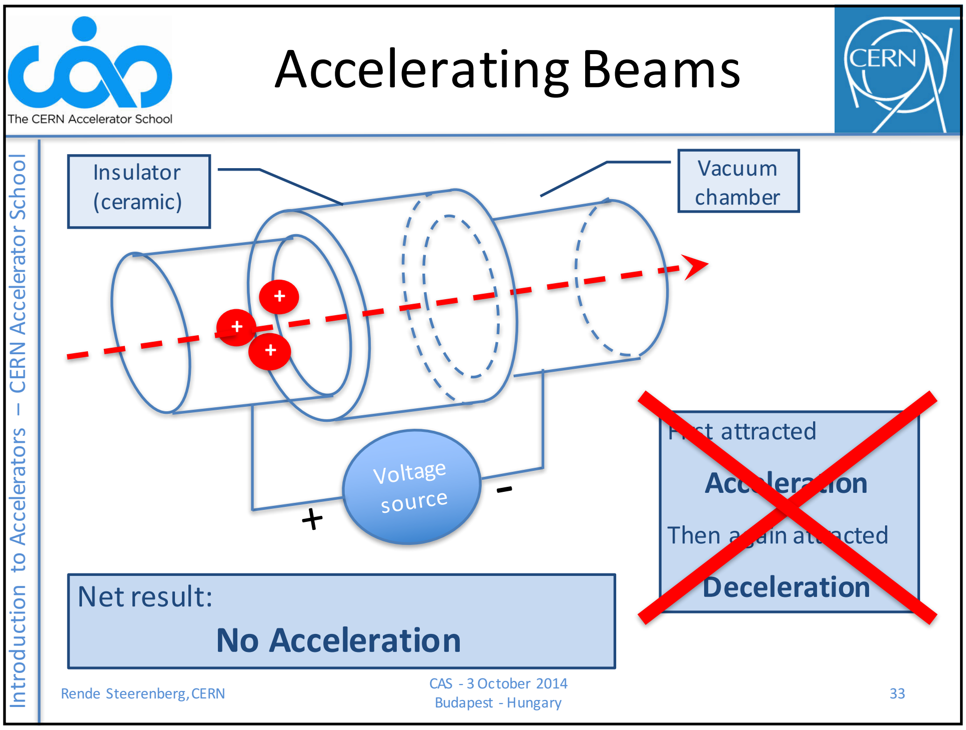
Focusing the Particles

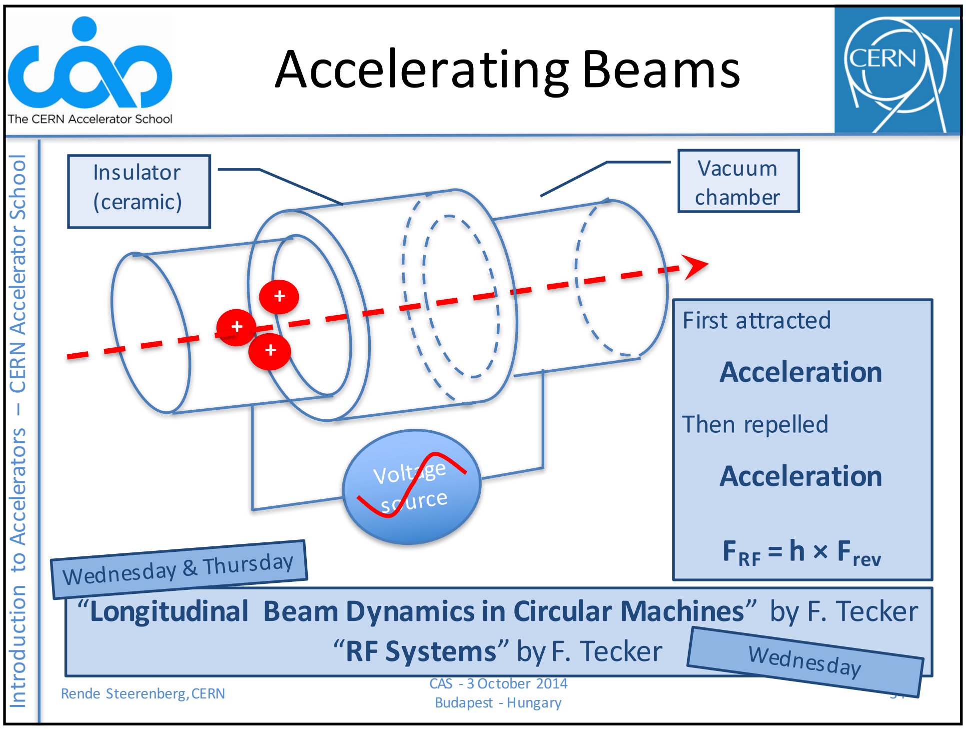


The CERN Accelerator School

Accelerating Particles



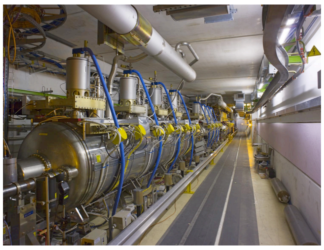

The CERN Accelerator School
Accelerating Beams
CERN
Introduction to Accelerators – CERN Accelerator School
Insulator (ceramic)
Vacuum chamber
Voltage source
+
-
+
t attracted
Then
Deceleration
Net result:
No Acceleration
Rende Steerenberg, CERN
CAS - 3 October 2014
Budapest - Hungary
33


The CERN Accelerator School
Accelerating Beams
CERN
Introduction to Accelerators – CERN Accelerator School
Insulator (ceramic)
Vacuum chamber
+
First attracted
Acceleration
Then repelled
Acceleration
$F_{RF} = h \times F_{rev}$
Wednesday & Thursday
"Longitudinal Beam Dynamics in Circular Machines" by F. Tecker
"RF Systems" by F. Tecker
Wednesday
Rende Steerenberg, CERN
CAS - 3 October 2014
Budapest - Hungary

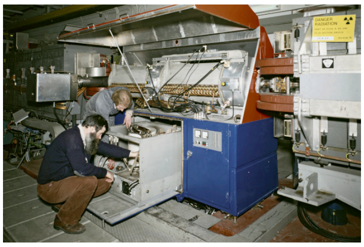
The CERN Accelerator School

Some RF Cavities and feedbacks

Fixed frequency cavities (Superconducting) in the LHC



Variable frequency cavities (normal conducting) in the CERN PS

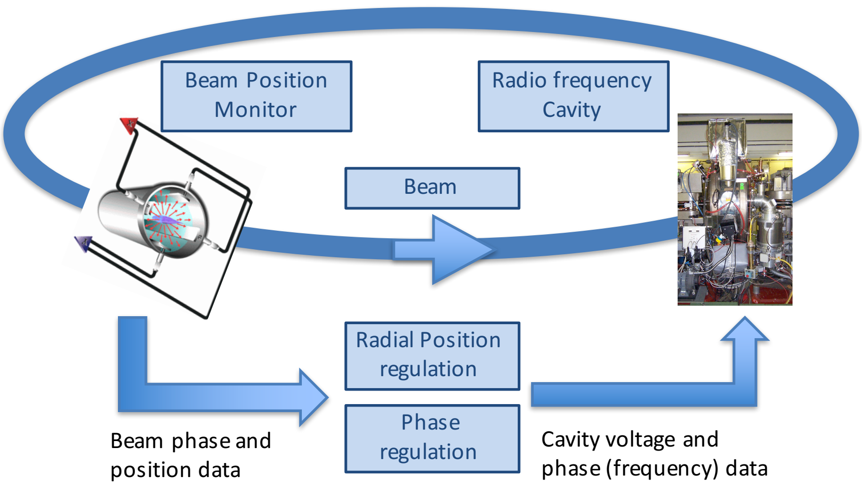


RF cavities are not only used to accelerate beams, but also to shape the beam:
- Longitudinal emittance
- Number of bunches
- Bunch spacing, shaping, etc.

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

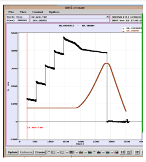
The CERN Accelerator School

RF Beam Control



Measuring Beam Characteristics

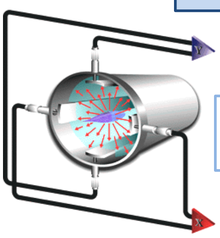
Introduction to Accelerators – CERN Accelerator School



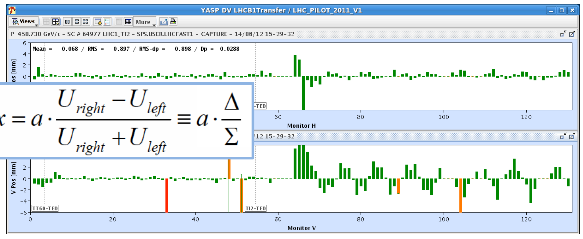
Beam intensity or current measurement:

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

Beam position/orbit measurement:



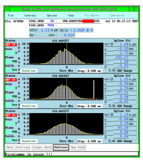
$$x = a \cdot \frac{U_{right} - U_{left}}{U_{right} + U_{left}} \equiv a \cdot \frac{\Delta}{\Sigma}$$



Correcting orbit using automated beam steering

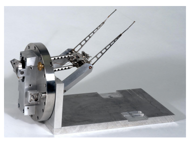
Measuring Beam Characteristics

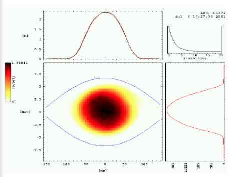
Introduction to Accelerators – CERN Accelerator School



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

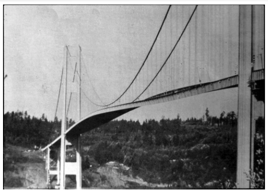
"**Beam Diagnostics**" by E. Holzer

Monday next week

Possible Limitations

The CERN Accelerator School

Introduction to Accelerators – CERN Accelerator School

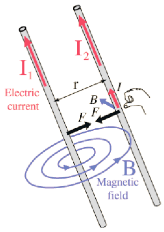


Machines and elements cannot be built and aligned with infinite precision

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**

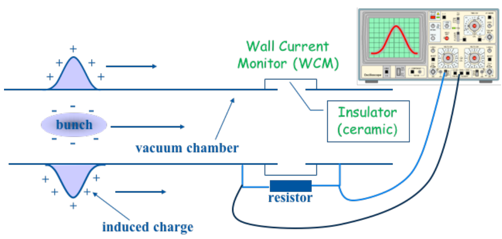


These effects can degrade beam quality and increase losses

Possible Limitations

The CERN Accelerator School

Introduction to Accelerators – CERN Accelerator School



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

The CERN Accelerator School

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

The CERN Accelerator School

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

The CERN Accelerator School

Figures of Merit in accelerators

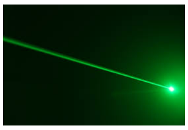
CERN

Introduction to Accelerators – CERN Accelerator School

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:

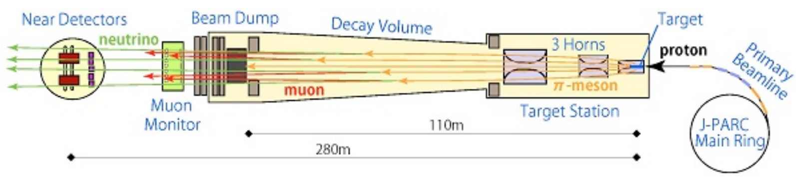
The CERN Accelerator School

Fixed Target Physics

CERN

Introduction to Accelerators – CERN Accelerator School

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

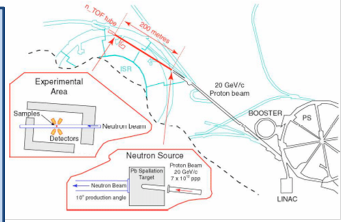
Fixed Target Physics

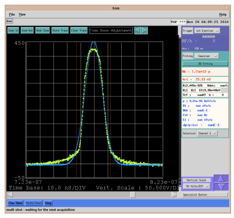
Introduction to Accelerators – CERN Accelerator School

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





Rende Steerenberg, CERN — CAS - 3 October 2014, Budapest - Hungary — 45

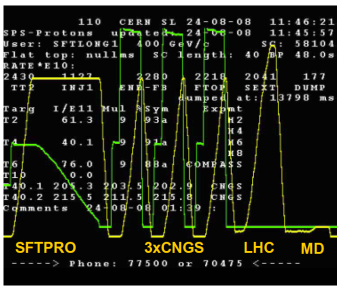
Fixed Target Physics

Introduction to Accelerators – CERN Accelerator School

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



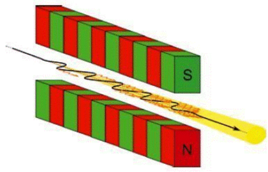
- The secondary particles are selected and distributed over several beam lines
- Uses often **resonant slow extraction** over several seconds

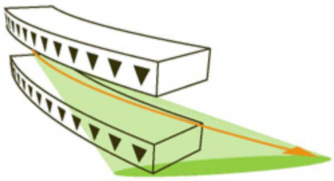
Rende Steerenberg, CERN — CAS - 3 October 2014, Budapest - Hungary — 46

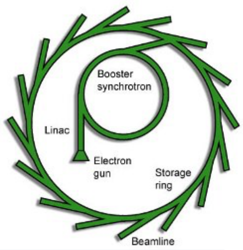
The CERN Accelerator School

Synchrotron Light Sources

Just a few examples among many:







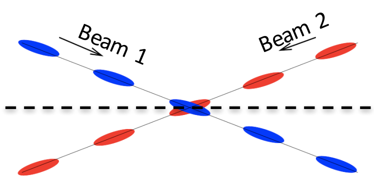
- Photon beam from stored (highly relativistic) electron beam
  - High electron beam intensity (Accelerator & Storage Ring)
  - Use of **undulators** to enhance photon emission
- Swiss Light Source (SLS) – Europe
- European Synchrotron Radiation Facility (ESRF) – Europe
- National Synchrotron Light Source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

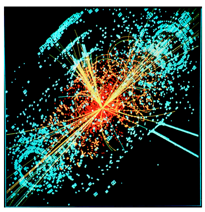
The CERN Accelerator School

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

The CERN Accelerator School

Introduction to Accelerators – CERN Accelerator School

For collider physics the integrated luminosity is the figure of merit

Intensity per bunch — Number of bunches — Correction factors — Beam dimensions

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

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

- The instantaneous luminosity is the amount of events per unit of surface per second [$cm^{-2}s^{-1}$]
- 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

The CERN Accelerator School

Introduction to Accelerators – CERN Accelerator School

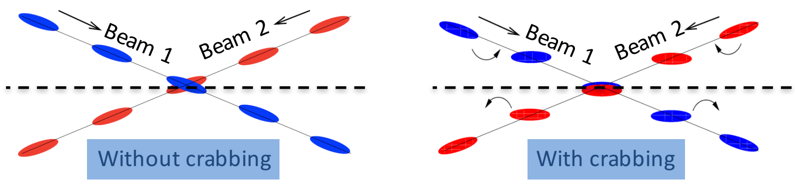
Increase the beam brightness from the injectors (N and σ)
- More particle in smaller beams (increase brightness)

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



The CERN Accelerator School

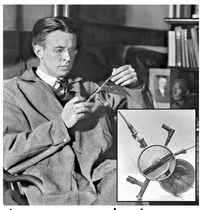
CERN

Introduction to Accelerators – CERN Accelerator School

"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….