Introduction to Accelerators

Rende Steerenberg - CERN - Beams Department

CERN **A**ccelerator **S**chool
Introduction to Accelerator Physics
31 August – 12 September 2014
Prague – Czech Republic

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Contents

Introduction to Accelerators – CERN Accelerator School

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Introduction to Accelerators – CERN Accelerator School

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

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Matter versus Energy

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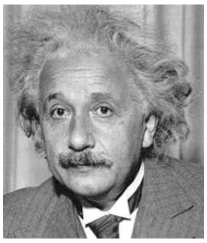
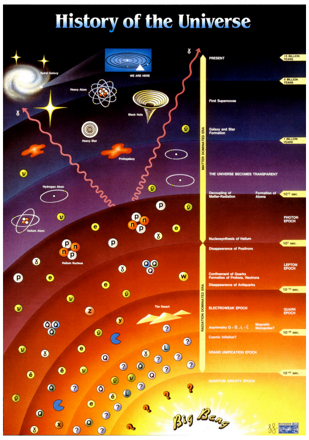
$E = m c^2$

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

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Looking to smaller dimensions

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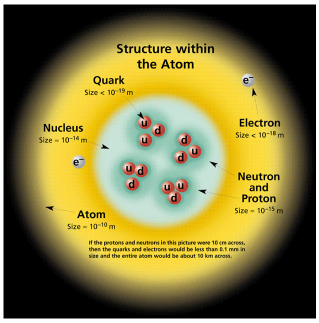
Visible light
λ = 400 ➔ 700 nm

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

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Fixed Target vs. Colliders

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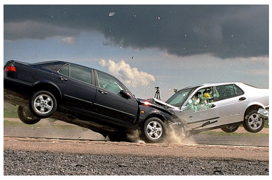
Fixed Target

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

Much of the energy is lost in the target and only part is used to produce secondary particles

Collider

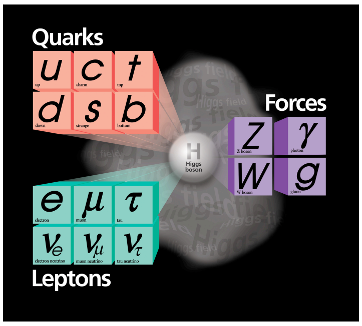


$$E = E_{beam1} + E_{beam2}$$

All energy will be available for particle production

The Aim

Verify 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

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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 procent 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

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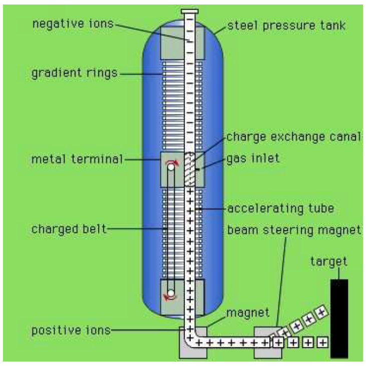
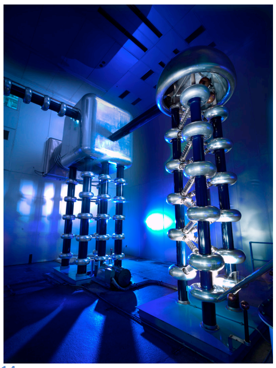
Cockroft & Walton / van de Graaff

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

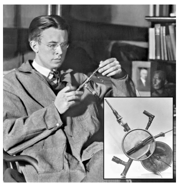


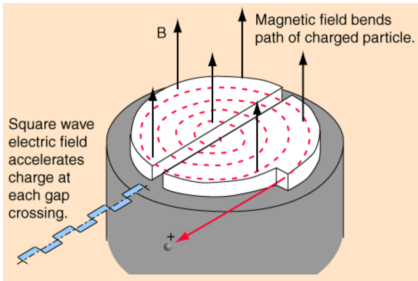


Cyclotron

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

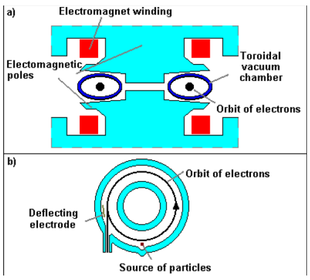
In 1939 Lawrence received the Noble prize for his work.





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.



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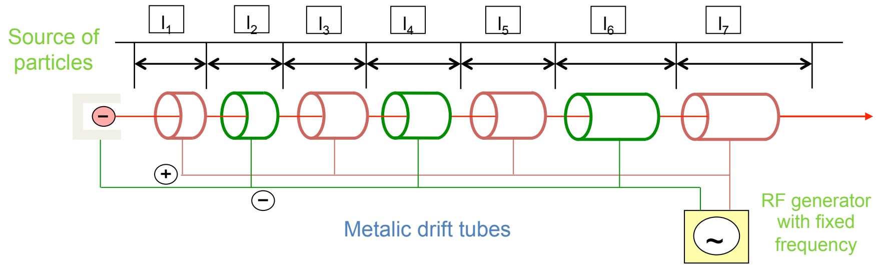
Linear Accelerator



- 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.

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Synchrotrons

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

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Towards Relativity

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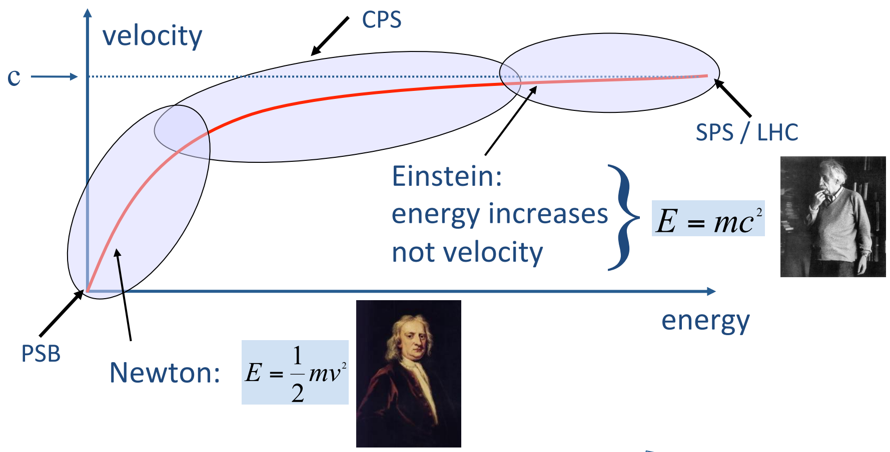

"**Relativity**" by Werner Herr

This afternoon

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The CERN Accelerator Complex

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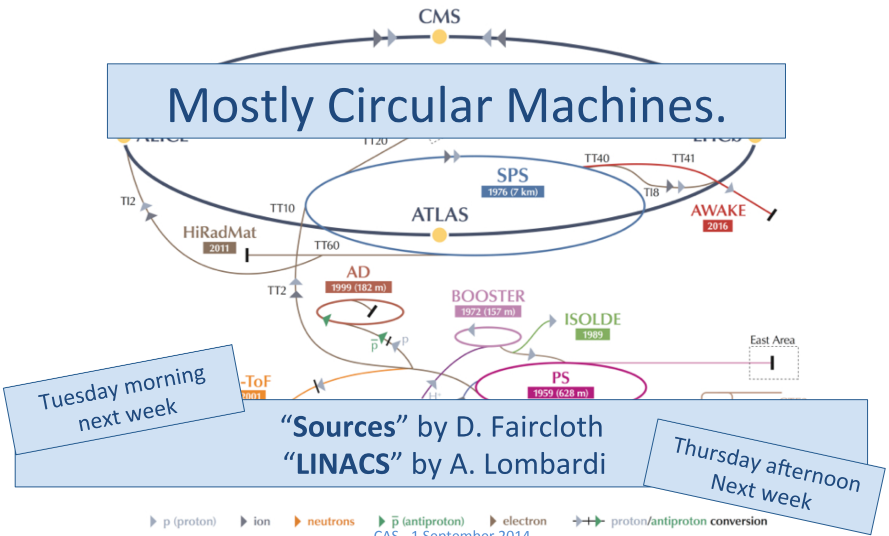

Mostly Circular Machines.

Tuesday morning next week

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

Thursday afternoon Next week

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A Guided Tour

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Lets have a look at a synchrotron:

- Identify the different 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

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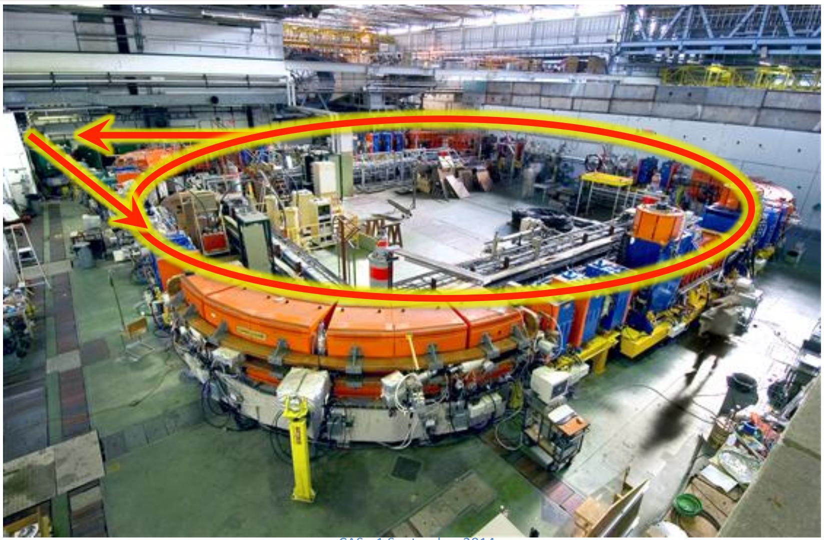
CERN - LEIR as an Example



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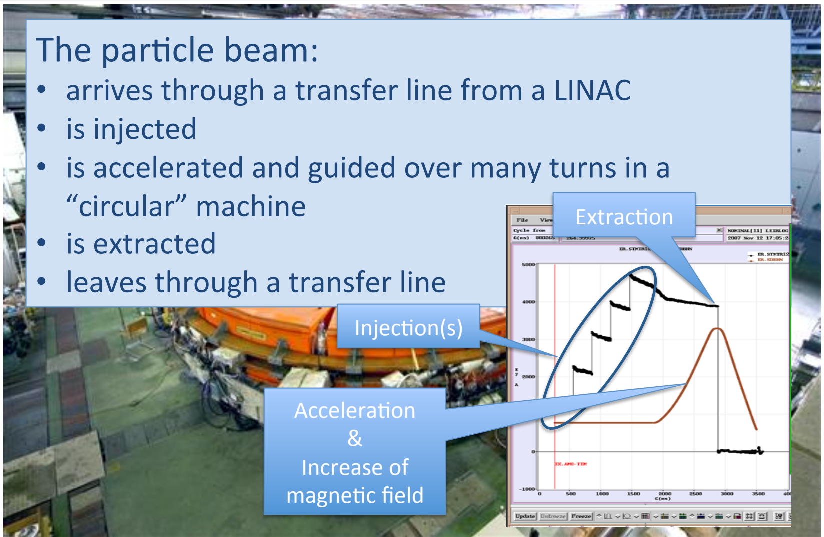
LEIR as an Example

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



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LINAC 3, injector of LEIR

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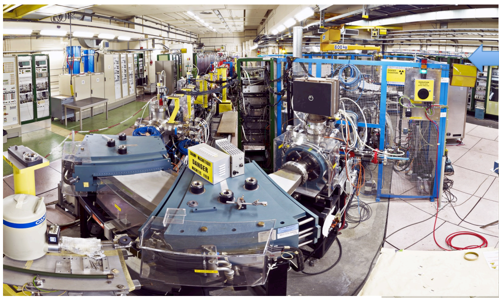
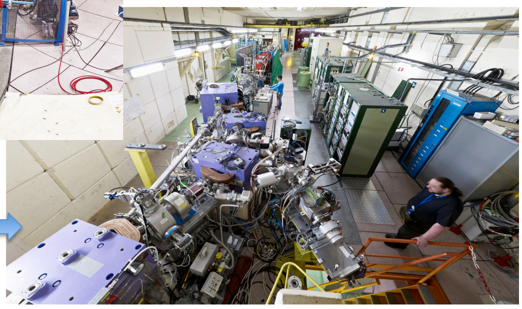
The CERN LINAC 3 provides different ion species



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

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LINAC Accelerating Structure

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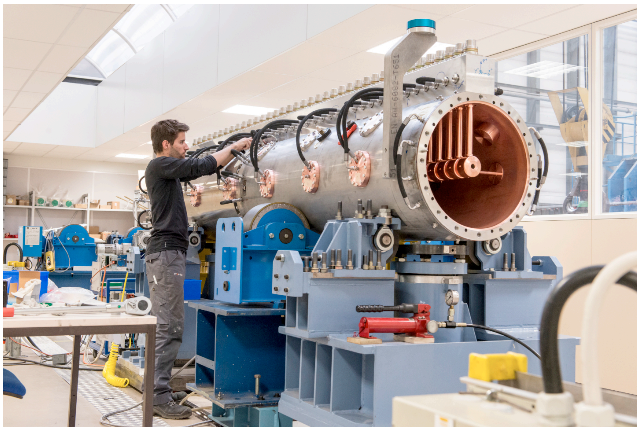

The CERN LINAC 4 drift tube

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Injecting & Extracting Particles

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Injecting & Extracting Particles

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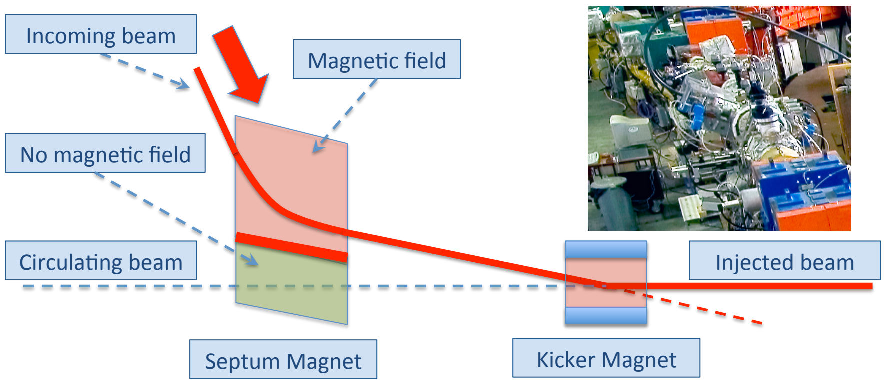

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Injecting & **Extracting** Particles

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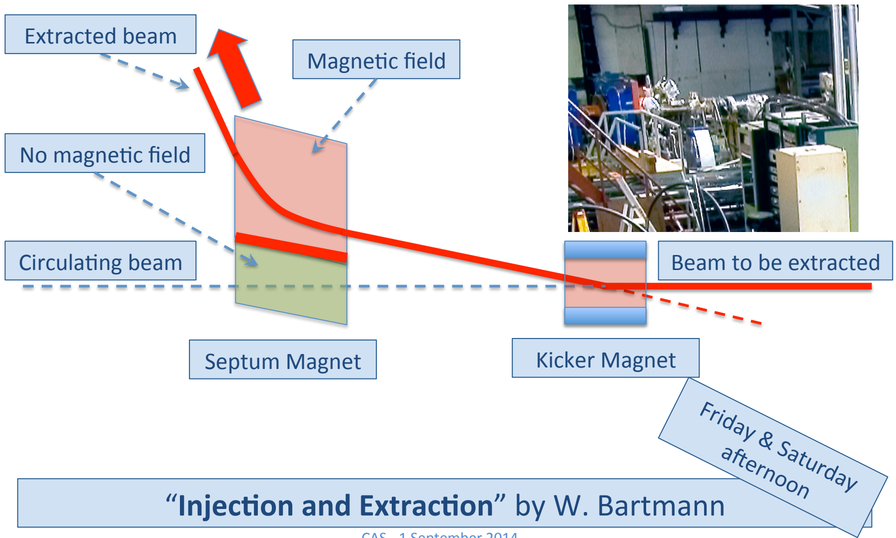

"**Injection and Extraction**" by W. Bartmann

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Septum and Kicker Magnets

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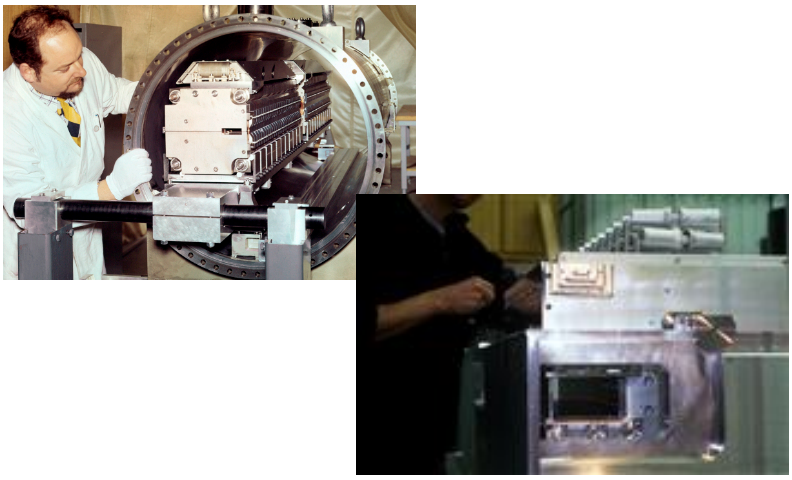

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Make Particles Circulate

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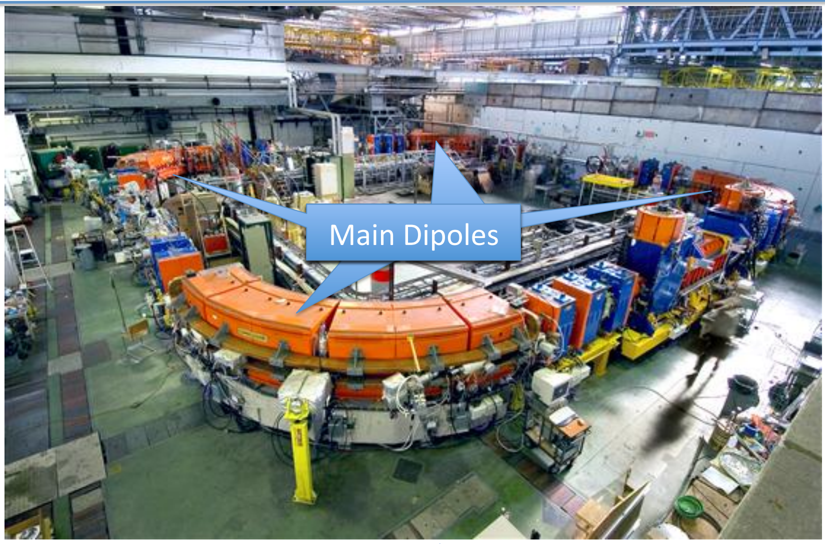

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Charged Particles Deviated

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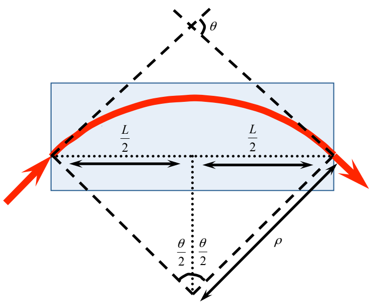
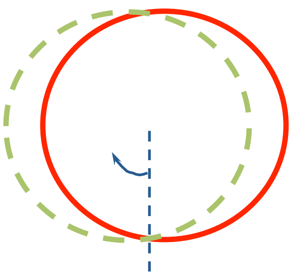
Charged Particles are deviated in magnetic fields



Lorentz force:

$$F = e\, v \times B$$

Two charged Particles in a homogeneous magnetic field



Particle A

Particle B

Oscillatory Motion of Particles

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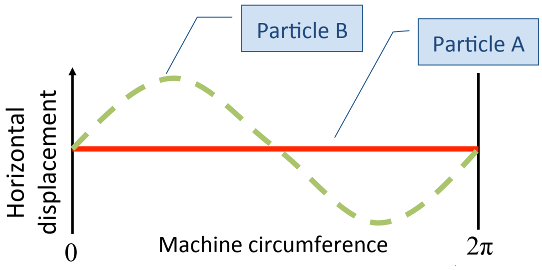
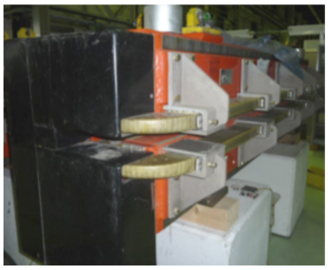
Horizontal motion





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

Oscillatory Motion of Particles

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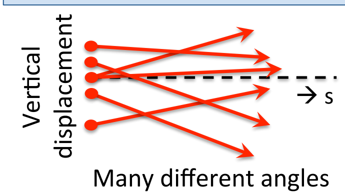
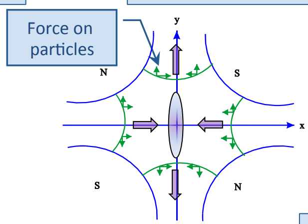
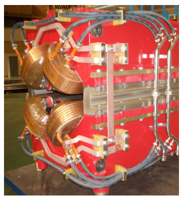
The horizontal motion seems to be “stable”…. What about the vertical plane ?

Many particles many initial conditions

Focusing particles, a bit like light







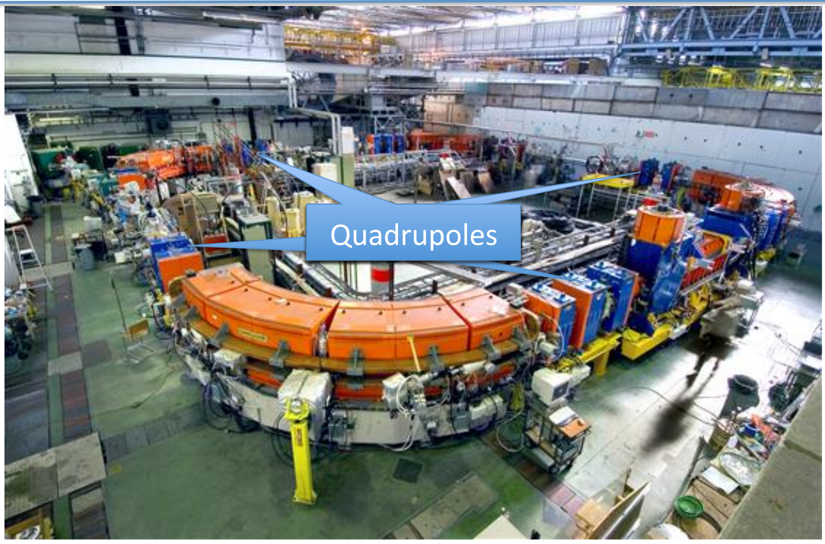
“**Transverse Beam Dynamics**” by B. Holzer
“**Warm Magnets**” by N. Marks
“**Power Converters**” by N. Marks

3 lectures on Tuesday & Wednesday

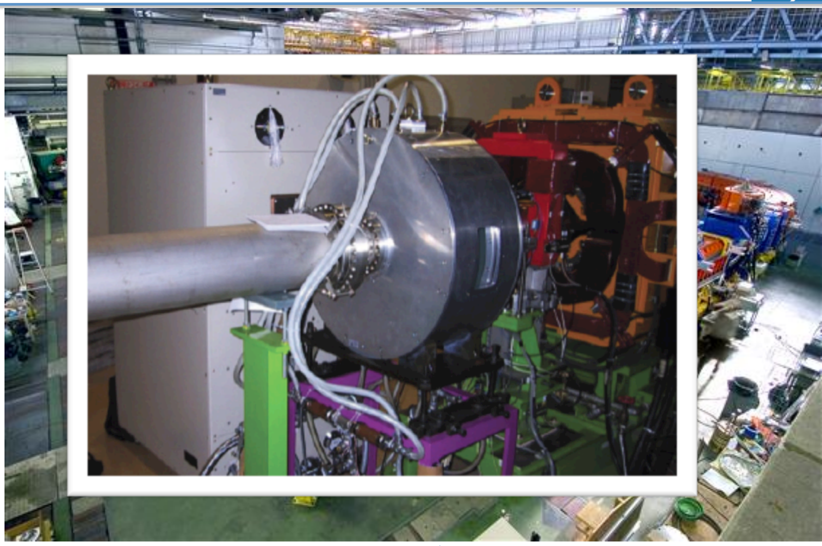
Tuesday & Wednesday morning

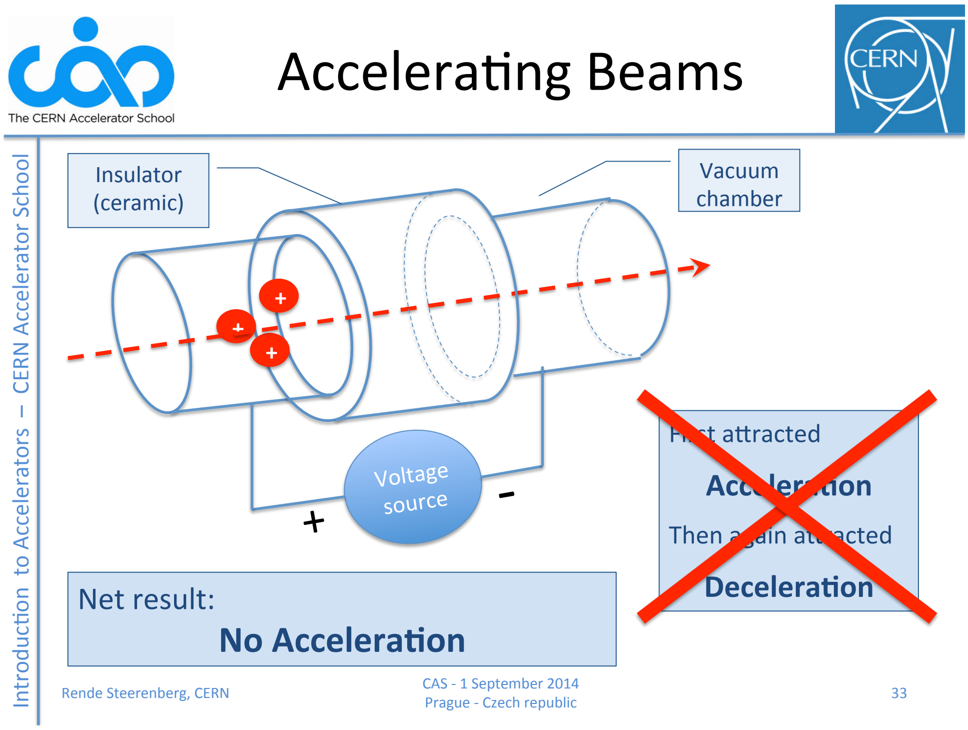
Thursday morning

Focusing the Particles



Accelerating Particles

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Accelerating Beams
CERN
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Insulator (ceramic)
Vacuum chamber
+
+
+
Voltage source
+
-
First attracted
Acceleration
Then again attracted
Deceleration
Net result:
No Acceleration
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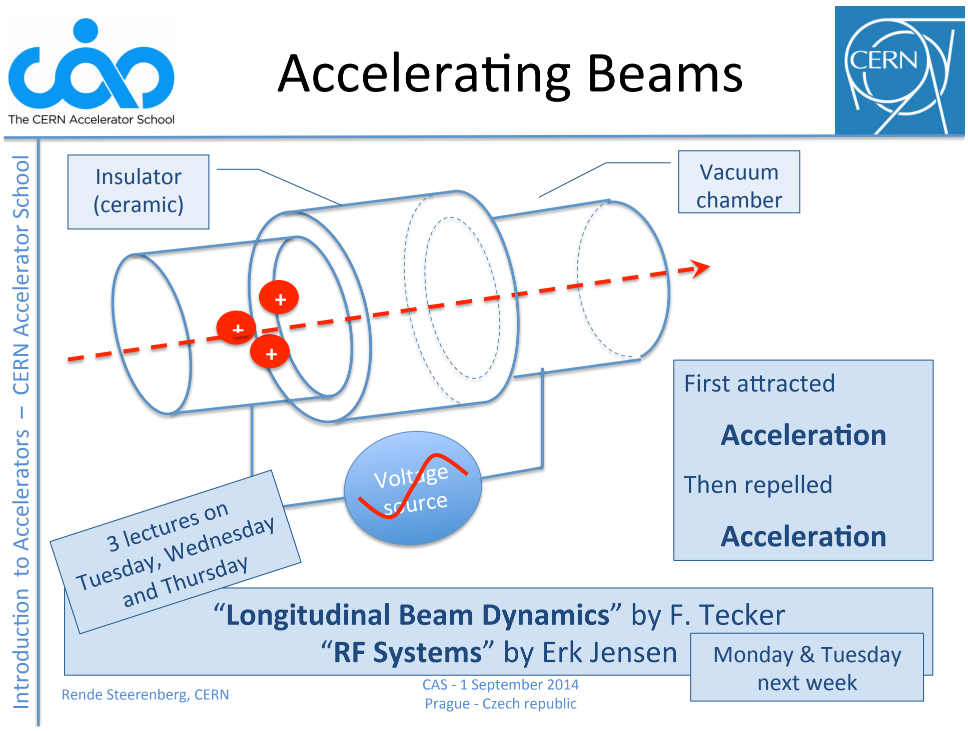
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Insulator (ceramic)
Vacuum chamber
+
+
+
Voltage source
First attracted
Acceleration
Then repelled
Acceleration
3 lectures on Tuesday, Wednesday and Thursday
"Longitudinal Beam Dynamics" by F. Tecker
"RF Systems" by Erk Jensen
Monday & Tuesday next week
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Some RF Cavities and feedbacks

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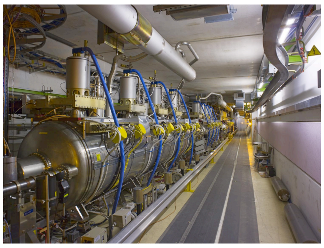
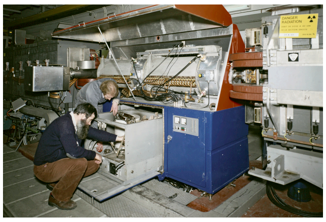


Fixed frequency cavities (SC) in the LHC



Variable frequency cavities (NC) in the PS

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RF Beam Control

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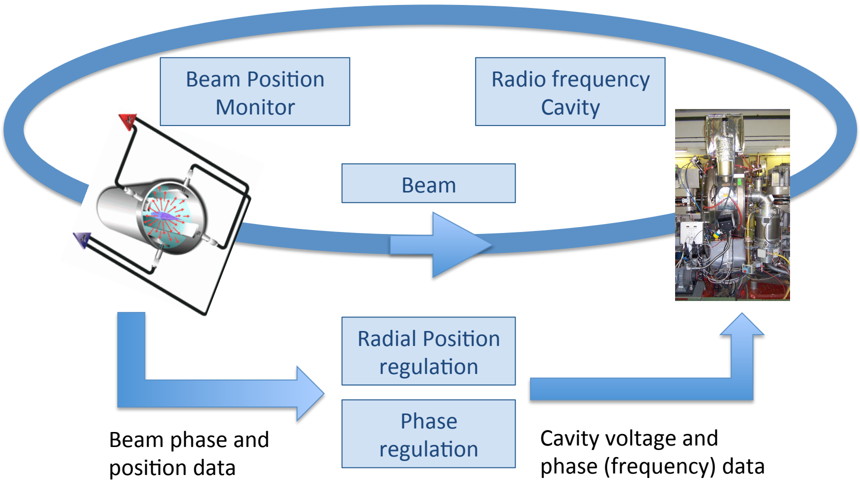

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Measuring Beam Characteristics

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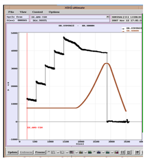
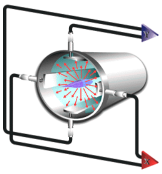
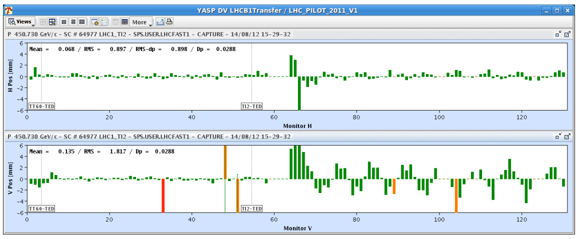


Beam intensity or current measurement:
- Working as classical transformer
- Beam act as primary winding



Beam position/orbit measurement:



Correcting orbit using automated beam steering

Measuring Beam Characteristics

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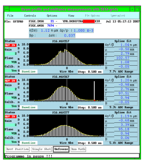
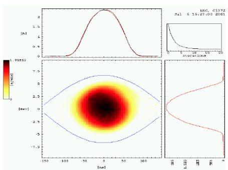


Transverse beam profile/size measurement:
- Secondary Emission Grids
- (Fast) Wire scanners



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

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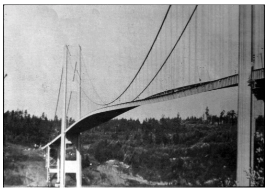
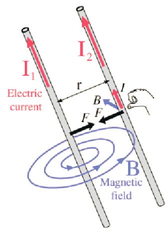
Possible Limitations



Machines and elements cannot be built and aligned with infinite perfection

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 effect can degrade beam quality and increase losses

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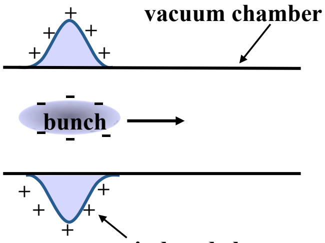

Coupled Bunch Instabilities

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

Monday & Thursday next week

"**Linear Imperfection**" by R. Tomas

Friday and Saturday morning

"**Space charge**" by G. Franchetti

Monday next week

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

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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

Wednesday morning

"**SC Magnets**" by L. Bottura
"**Machine Protection**" by I. Strasik

Friday afternoon

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QUESTIONS ?