Accelerators for Beginners

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CERN Accelerator School
Basic Accelerator Science & Technology at CERN
3 – 7 February 2014 – Chavannes de Bogis
Contents

• 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
Creating Matter from Energy

\[ E = m \cdot c^2 \]

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 created.
Looking to smaller dimensions

<table>
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<th>Visible light</th>
<th>X-ray</th>
<th>Particle accelerators</th>
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<tr>
<td>$\lambda = 400 \rightarrow 700 \text{ nm}$</td>
<td>$\lambda = 0.01 \rightarrow 10 \text{ nm}$</td>
<td>$\lambda &lt; 0.01 \text{ nm}$</td>
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Increasing the energy will reduce the wavelength

$$\lambda = \frac{\hbar c}{E}$$

- Visible light: $\lambda = 400 \rightarrow 700 \text{ nm}$
- X-ray: $\lambda = 0.01 \rightarrow 10 \text{ nm}$
- Particle accelerators: $\lambda < 0.01 \text{ nm}$
**Fixed Target vs. Colliders**

**Fixed Target**

\[ E \propto \sqrt{E_{\text{beam}}} \]

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

**Collider**

\[ E = E_{\text{beam1}} + E_{\text{beam2}} \]

All energy will be available for particle production
Verify the Standard Model

Search for physics beyond the Standard Model

“Standard Model and Beyond” by Paris Sphicas

This afternoon
• 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
Synchrotron light sources (e−)
Lin. & Circ. accelerators/Colliders

This lecture will concentrate on the CERN type machines of which the majority are

Synchrotrons

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

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• 1932: First accelerator – single passage 160 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.
• 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 used to deflect the particle for extraction.
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.
• 1959: CERN-PS and BNL-AGS
• Fixed radius for particle orbit
• Varying magnetic field and radio frequency
• Important focusing of particle beams
• Providing beam for fixed target physics
• Paved the way to colliders
• Why Accelerators and Colliders?

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• The Main Ingredients of an Accelerator
Towards Relativity

Einstein: energy increases not velocity

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

$E = mc^2$

“Relativity” by Werner Herr

This afternoon

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Mostly Circular Machines.

“Overview of the CERN Complex” by Reyes Alemany Fernandez
“Sources” by Richard Scrivens
“LINACS” by Maurizio Vretenar

In less than 1 hour

Wednesday morning

Thursday afternoon
LEIR as an Example
The particle beam:
• arrives through a transfer line
• is injected
• is accelerated over many turns in a “circular” machine
• is extracted
• leaves through a transfer line
Vacuum in a mostly **stainless steel vacuum chamber** is required to **avoid** the particles to **interact** with the **gas molecules**

Especially important for low energy particles and anti-matter particles
Injecting & Extracting Particles

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Injecting & Extracting Particles

- Incoming beam
- Magnetic field
- No magnetic field
- Circulating beam
- Septum Magnet
- Injected beam
- Kicker Magnet

Basics of Accelerator Science & Technology at CERN

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Injecting & Extracting Particles

- Extracted beam
- Magnetic field
- No magnetic field
- Circulating beam
- Septum Magnet
- Kicker Magnet
- Beam to be extracted

“Injection and Extraction” by Wolfgang Bartmann
“Beam Transfer” by Verena Kain
“Kickers and Septa” by Mike Barnes

Thursday morning
Make Particles Circulate

Main Dipoles
Charged Particles Deviated

Charged Particles are deviated in magnetic fields

Two charged Particles in a homogeneous magnetic field

Lorentz force:

$$F = e \nu \times B$$
Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane.
Oscillatory Motion of Particles

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

Many particles many initial conditions

Focusing particles, a bit like light

Vertical displacement

Many different angles

Vertically displaced

“Transverse Beam Dynamics” by Bernhard Holzer

“Magnets” by Paolo Fessia

“Power Converters” by Jean-Paul Burnet

3 lectures on Tuesday & Wednesday

Tuesday morning

Tuesday afternoon
Focusing the Particles

Quadrupoles
Accelerating Particles
Accelerating Beams

First attracted
Acceleration
Then again attracted
Deceleration

Net result:
No Acceleration

Voltage source
Insulator (ceramic)
Vacuum chamber

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Accelerating Beams

First attracted
Acceleration
Then repelled
Acceleration

“Longitudinal Beam Dynamics” by Frank Tecker
“RF Systems” by Erk Jensen

3 lectures on Tuesday & Wednesday

Vacuum chamber
Insulator (ceramic)
Voltage source
Beam intensity or current measurement

Transverse beam profile/size measurement

Longitudinal beam profile measurements

Measure the LHC luminosity, number of events per surface and time unit.

Any many more beam properties.....

“Beam Instrumentation” by Uli Raich,

Thursday afternoon
Possible Limitations

- Machines and elements cannot be built 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
- Moving particles create currents, These currents result in attracting or repelling magnetic fields

"Linear Imperfection" by Rogelio
"Collective effects" Giovanni Rumolo
"Colliders and Beam-Beam" by Tatiana Pieloni

Wednesday afternoon

Friday morning
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, require cryogenics

High stored beam energies require sophisticated machine protection systems

“Magnets” by Paolo Fessia
“Cryogenics” by Serge Claudet
“Machine Protection” by Jorg Wenninger
Everything must be made as simple as possible. But not simpler....

Albert Einstein