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E = m c^2

During the Big Bang Energy was transformed into matter.

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

In the detectors we observe the matter.

Rende Steerenberg, CERN
Looking to smaller dimensions

**Visible light**
\[ \lambda = 400 \rightarrow 700 \text{ nm} \]

**X-ray**
\[ \lambda = 0.01 \rightarrow 10 \text{ nm} \]

**Particle accelerators**
\[ \lambda < 0.01 \text{ nm} \]

Increasing the energy will reduce the wavelength

\[ \lambda = \frac{hc}{E} \]

Rende Steerenberg, CERN
Fixed Target vs. Colliders

Fixed Target

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

Collider

$$E \mu \sqrt{E_{\text{beam}}}$$

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

Search for physics beyond the Standard Model
Such as dark matter and dark energy

Discover the Higgs boson
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Today: ~ **30’000 accelerators** operational world-wide*

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

- Less 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

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- 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 used 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
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Towards Relativity

**Newton:**
\[ E = \frac{1}{2}mv^2 \]

**Einstein:**
\[ E = mc^2 \]

- Mass increases, not velocity
Mostly Circular Machines

"Sources" by D. Faircloth
"Linear Accelerators" by D. Alesini
"Cyclotrons" by M. Seidel
"Luminosity & Colliders" by G. Papotti
"FFAG" by S. Sheehy
"Synchrotron Light Machines & FEL" by L. Rivkin

Wednesday

Tuesday & Wednesday

Thursday next week

Tuesday

Friday
Let's 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
CERN - 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
Injecting & Extracting Particles

- Incoming beam
- Magnetic field
- No magnetic field
- Circulating beam
- Septum Magnet
- Injected beam
- Kicker Magnet
Injecting & **Extracting** Particles

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

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

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Rende Steerenberg, CERN

CAS - 3 October 2014
Budapest - Hungary
Septum and Kicker Magnets
Make Particles Circulate
Charged Particles are deviated in magnetic fields

Two charged Particles in a homogeneous magnetic field

Lorentz force:

$$ F = e(\vec{v} \times \vec{B}) $$
Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane → **Betatron Oscillations**
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 $\rightarrow s$

Many different angles

Force on particles

Tuesday & Wednesday

“Transverse Beam Dynamics” by B. Holzer

“Warm Magnets” by G. de Rijk

“Power Converters” by J.-P. Burnet

Friday

Saturday
Focusing the Particles

Quadrupoles
Accelerating Particles
Accelerating Beams

Net result:

No Acceleration

First attracted
Acceleration

Then again attracted
Deceleration
Accelerating Beams

First attracted

Acceleration

Then repelled

Acceleration

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

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

“RF Systems” by F. Tecker
Some RF Cavities andfeedbacks

Fixed frequency cavities (Superconducting) in the LHC
Variable frequency cavities (normalconducting) 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

Beam Position Monitor

Radio frequency Cavity

Beam

Radial Position regulation

Phase regulation

Beam phase and position data

Cavity voltage and phase (frequency) data
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

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

“SC Magnets” by G. de Rijk
“Beam Losses and Machine Protection” by I. Strasik
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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:**
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
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
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 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 $\rightarrow$ 2 separate rings
• Electron – Positron or Proton – Antiproton $\rightarrow$ single ring
For collider physics the integrated luminosity is the figure of merit

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

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

- 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 $\sigma$)
- More particle in smaller beams (increase brightness)

Increase number of bunches
- Higher harmonic RF systems

Reduce the $\beta^*$ ($\sigma$)
- 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

\[ \mathcal{L} = \frac{N_1 N_2 f n_b}{4 \pi \sigma_x \sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S \]
“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…..