Applications of Accelerators (1)

Particle colliders for High Energy Physics (HEP) experiments

- fix target experiments:

- two beams collision experiments:
Applications of Accelerators (1)

Particle colliders for **High Energy Physics (HEP)** experiments

- **fix target experiments:**
  - Particle
  - Target
  - Detector

Example: the **Large Hadron Collider (LHC)** at **CERN**

- Superconducting magnets (inside a cryostat)

Lake Geneva, Mont Blanc, Geneva

8.6 km
Applications of Accelerators (2)

Light sources for biology, physics, chemistry... experiments

- structural analysis of crystalline materials
- X-ray crystallography (of proteins)
- X-ray microscopy
- X-ray absorption (or emission) spectroscopy
- ...

Example: Doppel-Ring-Speicher (DORIS)
'double ring store' at DESY

built between 1969 and 1974
HEP exp. until 1983
synchrotron rad. since 1980
Applications of Accelerators (2)

X-ray crystallography

Ada Yonath
Leader of MPG Ribosome Structure Group at DESY
1986-2004
2009 Nobel Prize of Chemistry together with T. Steitz and V. Ramakrishnan

Example: Doppel-Ring-Speicher (DORIS) 'double ring store' at DESY

- **history**
  - built between 1969 and 1974
  - HEP exp. until 1983
  - synchrotron rad. since 1980

- **future**
  - synchrotron rad. until 2012
  - HEP exp. from 2012

accelerator control room
> About 120 accelerators for research in "nuclear and particle physics"
> About 70 electron storage rings and electron linear accelerators used as light sources (so-called 'synchrotron radiation sources')

> More than 7,000 accelerators for medicine
  radiotherapy (>7,500), radioisotope production (200)

> More than 18,000 industrial accelerators
  ion implantation (>9,000), electron cutting and welding (>4,000) …
Applications of Accelerators (3)

Medical applications

For radioisotope production
proton beam + stable isotope $\rightarrow$ transmutation radioactive isotope

For radiotherapy and radiosurgery:
• x-rays and gamma-rays
• ions (from protons to atoms with atomic number up to 18, Argon)
• neutrons

Applications of Accelerators (3)

Medical applications

For radioisotope production
For example:

$18$ MeV proton accelerator $\rightarrow$ target

Oxygen-18 (stable) (transmutation)

Fluorine-18 (half-life time = 110 min.)

97% of decays

Oxygen-18 + positron
Medical applications

For radioisotope production
For example:

\[ p \rightarrow \text{target} \]
\[ \text{Oxygen-18} \]
\[ \text{(transmutation)} \]

Fluorine-18 (half-life time = 110 min.)

\[
\begin{align*}
\text{Fluoroxyglucose (}^{18}\text{F)}
\end{align*}
\]
### Applications of Accelerators (4)

#### For industrial applications:

<table>
<thead>
<tr>
<th>Application</th>
<th>~</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion implantation</td>
<td>9500</td>
</tr>
<tr>
<td>Electron cutting and welding</td>
<td>4500</td>
</tr>
<tr>
<td>Electron beam and x-ray irradiators</td>
<td>2000</td>
</tr>
<tr>
<td>Ion beam analysis (including AMS)</td>
<td>200</td>
</tr>
<tr>
<td>Radioisotope production (including PET)</td>
<td>900</td>
</tr>
<tr>
<td>Nondestructive testing (including security)</td>
<td>650</td>
</tr>
<tr>
<td>Neutron generators (including sealed tubes)</td>
<td>1000</td>
</tr>
</tbody>
</table>

approx. numbers from 2007 (worldwide)

with energies up to 15 MeV

---

For industrial applications:

an example: electron beam welding

- acceleration up to 60-200 keV
- magnets as 'focusing lenses' as well as 'deflectors'
- up to 15 cm
- 'deep welding effect'
Many millions of television sets, oscilloscopes using CRTs (Cathode Ray Tube)

acceleration

magnets as ‘focusing lenses’ as well as ‘deflectors’
Geiger-Marsden experiment: the gold foil experiment (1909)

Thomson model of the atom (1904)

alpha particles

expected result

1 in 8000 reflected with $\theta > 90^\circ$

shooting with 1000 km/s, a few coming back!

Rutherford model of the atom (1911)
Acceleration with an electrostatic field

**Cockcroft-Walton generator**

(1932)

400 keV p → Lithium-7

\[ ^{4}\text{He} + ^{4}\text{He} + 17.35 \text{ MeV} \]

maximum voltage < 1 MV

→ **Van de Graaff generator**

maximum voltage ~ 25 MV

---

Acceleration with an electrostatic field

**Van der Graaff generator:**

invented in 1929

---
Acceleration with an electrostatic field

Tandem Van der Graaff accelerator

\[ V = 12 \text{ MV} \]

*beam*

\[ V = 0 \]

\[ V = 0 \]

Tandem = “two things placed one behind the other”

---

20 MV-Tandem

at Daresbury, UK

12 MV-Tandem Van de Graaff Accelerator

at MPI Heidelberg, GE
Limitation of electrostatic fields

breakdown

Replica of the Widerøe accelerator
Acceleration using Radio-Frequency (RF) generators

Widerøe (1928): apply acceleration voltage several times to particle beam

charged particle
RF-generator
metallic ‘hollow’ cylinders

half a period later:
Restrictions of RF

- particles travel in groups → called bunches
- bunches are travelling synchronous with RF cycles

\[ \Delta E \rightarrow \Delta \nu \]

Acceleration using Radio-Frequency (RF) generators

\[ \beta < 1 \]

\[ \gamma_p \cdot \frac{T_{RF}}{2} = \gamma_p \cdot \frac{\lambda_{RF}}{2c} = \beta_p \cdot \frac{\lambda_{RF}}{2} \]

original Wideröe drift-tube principle

relativistic \( \beta \)
Acceleration using Radio-Frequency (RF) generators

$\beta \approx 1$ (ultra relativistic particles)

Limitations of drift tube accelerators:

- only low freq. (<10 MHz) can be used

$$L_{\text{tube}} = \beta \frac{\lambda_{RF}}{2} = \beta \frac{c}{2f_{RF}} \rightarrow 30 \text{ m for } \beta=1 \text{ and } f=10 \text{ MHz}$$

- drift tubes are impracticable for ultra-relativistic particles ($\beta=1$)
- only for very low $\beta$ particles
**Resonant cavities**

Alvarez drift-tube (1946) structure:

![Diagram of resonant cavities](image)

**Examples**

**DESY proton linac (LINAC III)**

\[ E_{kin} = 50 \text{ MeV} \]

\[ \beta = 0.3 \]

**GSI Unilac**

(GSI: Heavy Ion Research Center)
Darmstadt, Germany

Protons/Ions

\[ E \approx 20 \text{ MeV per nucleon} \]

\[ \beta = 0.04 \ldots 0.2 \]
**Charges, currents and electromagnetic fields**

LC circuit (or resonant circuit) analogy:

**Widerøe drift-tube**

**Alvarez drift-tube**

A quarter of a period later:

A quarter of a period later:
Charges, currents and electromagnetic fields

half a period later:

\[ + \quad - \quad + \quad - \quad + \quad - \]

3 quarters of a period later:

\[ L \quad C \]

Resonant cavities

Alvarez drift-tube structure:

RF resonator

twice longer tubes

higher frequencies possible → shorter accelerator

preferred solution for ions and protons up to few hundred MeV

voltage between tubes

min. length of the tube

Pedro Castro | Introduction to Accelerators | 20th July 2011 | Page 38
Examples

inside a drift tube linac

Linac2 at CERN, 50 MeV

Acceleration using Radio-Frequency (RF) generators

original Widerøe drift-tube principle

RF-generator

first concept of the 'cyclotron' (1929) (from E. Lawrence)

drift-tube linac "rolled up"
**Acceleration using Radio-Frequency (RF) generators**

original Widerøe drift-tube principle

[Diagram of drift-tube linac]

first concept of the 'cyclotron' (1929) (from E. Lawrence)

drift-tube linac "rolled up"

---

**Cyclotron**

two 'hollow' metallic Dees

[Diagram of cyclotron]

RF-generator
\[ \overrightarrow{F} = \frac{d\overrightarrow{p}}{dt} = q \overrightarrow{v} \times \overrightarrow{B} \]

magnetic field

momentum charge velocity

of the particle

\[
\vec{B} \perp \vec{v} \quad \Rightarrow \quad F = q \, v \, B = \frac{m \, v^2}{R} \quad \Rightarrow \quad R = \frac{m \, v}{q \, B}
\]

time for one revolution:

\[
T = \frac{2\pi \, R}{v} = 2\pi \, \frac{m}{q \, B} = \text{const.}
\]

Cyclotron

... in a uniform constant magnetic field:

\[
T = 2\pi \, \frac{m}{q \, B} = \text{const.} \quad \text{(for non-relativistic velocities)}
\]

cyclotron frequency:

\[
\omega = \frac{2\pi}{T} = \frac{q}{m} \, B = \text{const.}
\]

\[
\Rightarrow \text{protons up to } 15 \text{ MeV} \quad (\beta = 0.1)
\]
Velocity as function of energy → $\beta$ as function of $\gamma$

Newton: \[ E_{\text{kin}} = \frac{1}{2}mv^2 \]

Einstein: \[ E = E_0 + E_{\text{kin}} = \gamma mc^2 = \frac{mc^2}{\sqrt{1 - \beta^2}} \]

\[
\beta = \frac{v}{c} \\
\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \\
\text{relativistic} \quad \gamma = 3 \\
\text{non-relativistic}
\]

Relativistic examples:
- 2.8 GeV proton
- 1.5 MeV electron

Cyclotron at Fermilab, Chicago IL, USA
Circular accelerators

Circular accelerators

injector

vacuum chamber

accelerating device

magnet

straight sections

\[ \vec{B} \perp \vec{v} \quad \rightarrow \quad F = q \, v \, B = \frac{m \, v^2}{R} \quad \Rightarrow \quad R = \frac{m \, v}{q \, B} \]

synchrotron: \( R \) is constant, 
\( \rightarrow \) increase \( B \) synchronously with \( E \) of particle

Low Energy Antiproton Ring (LEAR) at CERN
DESY (Deutsches Elektronen Synchrotron)

DESY: German electron synchrotron, 1964, 7.4 GeV

accelerator control room
Electromagnet

Permeability of iron = 300...10000 larger than air

Dipole magnet

Beam

Flux lines

Air gap

Fringing fields

Mean core length $l_c$

Cross-sectional area $A_c$

Magnetic core permeability $\mu_c$

Area $A_p$

Air gap permeability $\mu_{gap}$

Area $A_g$
Dipole magnet cross section

Max. $B \rightarrow$ max. current $\rightarrow$ large conductor cables

Power dissipated: $P = R \cdot I^2$

Dipole magnet cross section

water cooling channels
Dipole magnet cross section

Dipole magnet

- iron
- beam
- current loops
Dipole magnet cross section

C magnet + C magnet = H magnet

Dipole magnet cross section (another design)

force
beam
Dipole magnet cross section (another design)

Power dissipated: \[ P = R \cdot I^2 \]

Superconducting dipole magnets

LHC

HERA

Superconducting dipoles
Superconductivity

12.5 kA normal conducting cables

12.5 kA superconducting cable

Superconductivity

resistance $\rho$ vs. temperature $T$

- $T_c$: critical temperature
- $T_{cr}$: critical temperature (Tc)

$\rho = \begin{cases} 
\rho_0 & T < T_c \\
\rho_s & T > T_c 
\end{cases}$
Dipole field from 2 conductors

\[ J = \text{uniform current density} \]

Ampere’s law:
\[ \oint B \cdot ds = \mu_0 I \]

Current through the circle:
\[ B = \frac{\mu_0 J}{2} r \]

\[ B_x = \frac{\mu_0 J}{2} r \sin \theta \]
\[ B_y = \frac{\mu_0 J}{2} r \cos \theta \]
Dipole field from 2 conductors

The current density $J$ is uniform.

The magnetic field is given by:

$$B = \frac{\mu_0 J r}{2}$$

where:

$$B_x = -\frac{\mu_0 J}{2} r \sin \theta$$

$$B_y = \frac{\mu_0 J}{2} r \cos \theta$$

The expressions for $B_x$ and $B_y$ are:

$$B_x = \frac{\mu_0 J}{2} (-r_1 \sin \theta_1 + r_2 \sin \theta_2)$$

$$B_y = \frac{\mu_0 J}{2} (r_1 \cos \theta_1 - r_2 \cos \theta_2)$$

These expressions hold for the given geometry.
Dipole field from 2 conductors

From the principle to the reality...

15 mm x 2 mm
LHC cables

1 cable houses 36 strands

1 strand = 0.825 mm diameter houses 6300 filaments

Copper is the insulation material between two filaments
(around each filament: 0.5 µm Cu)

1 filament = 6 µm

Computed magnetic field

Computed magnetic flux map
LHC dipole coils in 3D
Superconducting dipole magnets

LHC dipole magnet interconnection:
Dipole antenna

Radiation of a dipole antenna

Radiation of an oscillating dipole

Radiation of a moving oscillating dipole

Lorentz-contraction
**Radiation of a oscillating dipole under relativistic conditions**

Dipole radiation: electron trajectory

- Lorentz-contraction
- Electron trajectory
- Electron trajectory

\[ v = 0.5c \]
\[ \gamma \approx 1.15 \]

\[ v = 0.9c \]
\[ \gamma \approx 2.3 \]

**DORIS:** \( \gamma = 8900 \)

**PETRA:** \( \gamma = 12000 \)

**Synchrotron radiation**

Power radiated by one electron in a dipole field:

\[ P = \frac{c q^2 \gamma^4}{6\pi \varepsilon_0 r^2} \]

\[ \gamma = \frac{E}{m_0 c^2} \]

\[ \frac{1}{r} = \frac{q B}{p} \]

Electron bunch

Dipole magnet

Synchrotron light

Electrons

 Vacuum permittivity
### Synchrotron radiation

Total energy loss after one full turn:

\[
\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0} \gamma^4 \Rightarrow \Delta E_{\text{turn}}[\text{GeV}] = 6.032 \times 10^{-18} \frac{\gamma^4}{r[\text{m}]}
\]

**HERA electron ring:**
- \( r = 580 \text{ m} \)
- \( E = 27.5 \text{ GeV} \)
- \( \gamma = 54000 \)
- \( \Delta E_{\text{turn}} = 87 \text{ MeV (0.3\%)} \)
- Need acceleration = 87 MV per turn

**HERA proton ring:**
- \( r = 580 \text{ m} \)
- \( E = 920 \text{ GeV} \)
- \( \gamma = 980 \)
- \( \Delta E_{\text{turn}} \approx 10 \text{ eV (10^{-9}\%)} \)
Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3 \varepsilon_0} \frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032 \times 10^{-18} \frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:

- \( r = 580 \text{ m} \)
- \( E = 27.5 \text{ GeV} \)
- \( \gamma = 54000 \)
- \( \Delta E_{\text{turn}} = 87 \text{ MeV (0.3%)} \)

HERA proton ring:

- \( r = 580 \text{ m} \)
- \( E = 920 \text{ GeV} \)
- \( \gamma = 980 \)

The limit is the max. dipole field = 5.5 Tesla

need acceleration = 87 MV per turn

LEP collider:

- \( r = 2800 \text{ m} \)
- \( E = 105 \text{ GeV} \)
- \( \gamma = 205000 \)
- \( \Delta E_{\text{turn}} \cong 4 \text{ GeV (4%)} \)

need 4 GV per turn!!
**Synchrotron radiation**

Total energy loss after one full turn:

\[
\Delta E_{\text{turn}} = \frac{q^2}{3\epsilon_0} \frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032 \times 10^{-18} \frac{\gamma^4}{r[\text{m}]}
\]

HERA electron ring:
- \( r = 580 \text{ m} \)
- \( E = 27.5 \text{ GeV} \)
- \( \gamma = 54000 \)
- \( \Delta E_{\text{turn}} = 87 \text{ MeV (0.3\%)} \)

LEP collider:
- \( r = 28 \text{ m} \)
- \( E = 5 \text{ TeV} \)
- \( \gamma = 290 \text{ 000} \)
- \( \Delta E_{\text{turn}} \simeq 4 \text{ GeV (4\%)} \)

need acceleration = 87 MV per turn  
need 4 GV per turn!!

**Project for a future e-e+ collider: ILC**

The International Linear Collider

Colliding beams with \( E = 500 \text{ GeV} \)

**e+e-LC lecture on Monday, by J. Timmermans**

more: [http://www.linearcollider.org/](http://www.linearcollider.org/)
Superconducting cavities for acceleration

- **International Linear Collider (ILC)**
  - e+e- LC lecture on Monday, by J. Timmermans (in project)

- **European X-ray Free-Electron Laser (XFEL)**
  - FELs lecture on Friday, by M. Dohlum (in construction)

- **Free-electron LASer in Hamburg (FLASH)**
  - (in operation)

RF cavity basics: the pill box cavity

![ Pill box cavity diagram ]
a quarter of a period later:

Alvarez drift-tube

RF cavity basics: the pill box cavity

a quarter of a period later:
**Pill box cavity: 3D visualisation of E and B**

![3D visualisation of E and B](image)

**Superconducting cavity used in FLASH and in XFEL**

Superconducting cavity used in FLASH (0.3 km) and in XFEL (3 km)

![Superconducting cavity](image)

- Pill box called ‘cell’
- RF input port called ‘input coupler’ or ‘power coupler’
- Higher Order Modes port (unwanted modes)
- RF input port called ‘input coupler’
**Accelerating field map**

Simulation of the fundamental mode: electric field lines

**Advantages of RF superconductivity**

![Resistance vs Temperature Graph]

- for DC currents!

- at radio-frequencies, there is a "microwave surface resistance" which typically is 5 orders of magnitude lower than R of copper
2nd law of Thermodynamics

“Heat cannot spontaneously flow from a colder location to a hotter location”

\[ \eta = \frac{T_H - T_C}{T_H} \]

Carnot efficiency:

\[ \eta_c = \frac{T_C}{T_H - T_C} \]

Applications:
- thermal power stations, cars, ...
- air conditioners, refrigerators, ...

Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

<table>
<thead>
<tr>
<th>Type of cavity</th>
<th>power dissipation at 2 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>superconducting cavity</td>
<td>1.5 W/m</td>
</tr>
<tr>
<td>normal conducting cavity</td>
<td>56 kW/m</td>
</tr>
</tbody>
</table>

Carnot efficiency:

\[ \eta_c = \frac{T}{300 - T} \]

\[ \eta_c \approx 0.007 \times \]

Applications:
- cryogenics efficiency 20-30%
- including RF generation efficiency (50%)

\[ >100 \text{ (electrical) power reduction factor} \]
Number of cavities: 8
Cavity length: 1.038 m
Operating frequency: 1.3 GHz
Operating temperature: 2 K
Accelerating Gradient: 23.35 MV/m

Cavities inside of a cryostat

Module installation in FLASH (2004)
Free-electron LASer in Hamburg (FLASH) ~300 m

accelerator control room

European X-Ray Free Electron Laser (XFEL)

3.4 km
First summing-up

Applications:
- HEP (example: LHC)
- light source (example: DORIS, Ribosome)
- medicine (example: PET)
- industry (example: electron beam welding)
- cathode ray tubes (example: TV)

Electrostatic accelerators:
- Cockcroft-Walton generator
- Tandem Van der Graaff accelerator

Radio-frequency accelerators:
- Widerøe drift-tube

Second summing-up

Linear accelerators:
- Alvarez drift-tube structure

Circular accelerators:
- Cyclotron, E. Lawrence
- Synchrotron

Dipole magnets:
- normal conducting dipoles
- superconducting dipoles
Third summing-up

Circular colliders (synchrotrons with $R=\text{const.}$):

- proton synchrotrons    dipole magnet
- electron synchrotrons  synchrotron radiation

Linear accelerators:

- International Linear Collider (ILC)
- European $X$-ray Free-Electron Laser (XFEL)
- Free-electron LASer in Hamburg (FLASH)

Based on S.C. cavities

Thank you for your attention

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