Low energy irradiation of material
Dose and beam power
Synchrotron light sources (ESRF)
The cone of synchrotron radiation
The spectrum
The scale of things
Diffraction
Lithography
Brightness
Spallation source
GSI – Ions Galore!
HYOGO (JPN)- Ion beam medical center
Energy amplifier
Inertial confinement
The development of accelerators
Need for higher energy
Center of mass v. Fixed target
Luminosity
CLIC
### Table II – Particle accelerator family worldwide
(items 2 to 6: lack of exact statistics, authors estimation only)

<table>
<thead>
<tr>
<th>Category of accelerators</th>
<th>Number in use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Energy Accelerators</strong></td>
<td>112</td>
</tr>
<tr>
<td><strong>BIOMEDICAL ACCELERATORS</strong></td>
<td></td>
</tr>
<tr>
<td>(2) Radiotherapy</td>
<td>&gt; 4000</td>
</tr>
<tr>
<td>(3) Research including Biomedical Research</td>
<td>800</td>
</tr>
<tr>
<td>(4) Medical Radioisotope Production</td>
<td>~ 200</td>
</tr>
<tr>
<td>(5) Accelerators in Industry</td>
<td>~ 1500</td>
</tr>
<tr>
<td>(6) Ion Implanters</td>
<td>&gt; 2000</td>
</tr>
<tr>
<td>(7) Surface Modification Centres and Research</td>
<td>~ 1000</td>
</tr>
<tr>
<td>(8) Synchrotron Radiation Sources</td>
<td>~ 50</td>
</tr>
</tbody>
</table>

Total in 1994: ~ 9962
TOTAL estimated for 1995: ~ 10,000
Dynamitron
Low energy irradiation of material

- Electrons are easy to produce, accelerate and shield
- Use an energy below the nuclear reaction threshold of 10 MeV. (7 MeV in some cases)

Stopping power $= \frac{dE}{dx} \approx 1.8$ MeV.cm$^{-2}$.g$^{-1}$

Maximum thickness $= \frac{1.5E}{(dE/dx)}$ g.cm$^{-2}$

$\approx 2.5$ g.cm$^{-2}$ for $E = 3$ MeV
Production line for sterilization
Dose and beam power

- A milliamp of particles, each losing 2 MeV, passing through a 1 cm cube of material will for one second will deposit a total energy of

\[ 10^{-3} \times 2 \times 10^6 = 2 \times 10^3 \text{ Joules} \]

- This corresponds to a (beam) power of 2 kW

- 1 Gy is 1 Joule per kilo and if the density of the cube is 1 this will be a dose of

\[ 10^{-3} \times 2 \times 10^3 = 2 \text{ Gy} \]

- This is not much and we need several kGy to disinfect material say 100 kW for 20 seconds

- The dose would be the same for a thin film but we can use a lower energy and reach a much higher dose – 250 kGy to polymerize film.
Methods of analysis by scattering
Spectrum from PIXE analysis

Fig.  

E.J.N.Wilson - Introduction to Accelerators III – Applications
Scanning a lorry for drugs
Synchrotron light sources (ESRF)
The cone of synchrotron radiation

- When an electron is bent in a circle it radiates synchrotron “light” along a tangent in a narrow cone (opening angle = $1/\gamma$)
The spectrum

- Spectrum is broad and looks the same when normalized to

\[ \xi = \omega/\omega_c = u/u_c \]

- Every quantity is normalized to the frequency of a characteristic quantum which is proportional to \( u_c \)

\[ u_c = \hbar \omega_c = \frac{3 \hbar c \gamma^3}{2 \rho} \]
The scale of things

1 angstrom = $10^{-10}$ m

= $12.4/E_{\text{photon}}$ [MeV]

\[
E_{\text{photon}} = 2218 \frac{E_{\text{beam}}^3}{r} \text{[GeV}^3\text{m}^{-1}] 
\]

<table>
<thead>
<tr>
<th></th>
<th>Energy [GeV]</th>
<th>Photon [keV]</th>
<th>$\lambda$ [Å]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BESSY-I</td>
<td>0.8</td>
<td>0.64</td>
<td>19.4</td>
<td>UV</td>
</tr>
<tr>
<td>HELIOS</td>
<td>0.7</td>
<td>1.5</td>
<td>8.5</td>
<td>UV</td>
</tr>
<tr>
<td>SRS</td>
<td>2.0</td>
<td>3.2</td>
<td>3.9</td>
<td>Hard X</td>
</tr>
<tr>
<td>ESRF</td>
<td>6.0</td>
<td>20.7</td>
<td>0.60</td>
<td>Hard X</td>
</tr>
<tr>
<td>LEP</td>
<td>50.0</td>
<td>88.5</td>
<td>0.14</td>
<td>Hard X</td>
</tr>
</tbody>
</table>

Fig.
Diffraction experiment (synch.rad)

Fig. 2 Practical implementation of X-ray lens

Fig. 3 Diffraction diagram from frog semitendinosus muscle
A very complex molecule

- RNA Polymerase – the structure that enables the code for each protein to be used to make each protein
Lithography in practice

Fig.

AC9.8.95_11(mask).pet
Brightness (importance of small emittance)

Brightness = \frac{d^4}{dxdzd\theta d\phi} = \frac{dF/d\theta}{2.36\sigma_x \cdot 2.36\sigma_z \cdot 2.36\sigma_\gamma}

where \( dF/d\theta \) is the vertically integrated flux

\( \sigma_\gamma \approx \frac{1}{2\gamma} \)

◆ Brightness is measured in:
photons/sec/mm\(^2\) / mr\(^2\) / 0.1% bandwidth

◆ Wigglers and undulators enhance this!
Average Beam Power: 2 x 5 MW

Average Neutron Flux : 3.1 x 10^{14} n/cm^2s

Pulse frequency = 16 2/3 Hz

Neutron pulse length = 2 Milliseconds

Mean Power = 5 MW

Target material = mercury

Max. Neutron flux = 1 x 10^{16} n/cm^2s

**Compare with ISIS**

Proton energy: 0.800 GeV

Protons per second: 2.5 x 10^{13} x 50 Hz = 1.3x10^{18}

Current = Charge/sec x 1.3x10^{15} x 1.6 x 10^{-19} = 0.2 mA

Mean Power = 0.2 mA x 800 MeV = 0.16 MW
High temperature superconductor

Crystal structure of the 90K YBa2Cu3O7 superconductor

HgBa2CuO4.Color-PICT
View along the SIS accelerator ring, which can accelerate the ions coming from the UNILAC to 90% of the speed of light.

**GSI accelerator facility**

- **High Charge Injector**
  - $E = 1.4$ MeV/nucleon
  - range: $\sim 10 \, \mu m$

- **UNILAC**
  - $E = 11.4$ MeV/nucleon
  - range: $\sim 100 \, \mu m$
  - incl. microprobe

- **SIS (cave A)**
  - $E = 1-2$ GeV/nucleon
  - range: $> 10$ cm

**Ions**: C..Au..Pb, U

- every 2-3 months
- for 2-3 days
Ion-beam surface treatment

Setup for surface treatment of artificial knee joint by low energy ion implantation. Collaboration Aesculap and Technical University Darmstadt
Membranes made with ion-beams

The damage produced by the heavy ions along the track in the material can be used to develop pores. With this technique tracks in many polymers, crystalline insulators, glasses, semi-conductors and recently amorphous metals are etcheable.

Etched ion tracks in polymer foil. The pore density is 10 million per cm$^2$. By ion track etching it is possible to produce membranes with track diameter from 10 nm up to 10 µm and densities from 1 to $10^9$ pores per cm$^2$. 
Quartz micro machining by control of ion track etch access

fluence = ions per area [ions / cm²]

1 ion/sample-single pore membrane
10⁶…10¹⁰ ions/cm²-etching
10⁹…10¹¹ ions/cm² -single track regime
10¹¹ 10¹⁴ ions/cm² -overlapping tracks
HYOGO (JPN)- Ion beam medical center

<table>
<thead>
<tr>
<th>Particle species</th>
<th>p, He and C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy for p and He [MeV/u]</td>
<td>70 - 230</td>
</tr>
<tr>
<td>Beam energy for C [MeV/u]</td>
<td>70 - 320</td>
</tr>
<tr>
<td>Beam spill length [ms]</td>
<td>400</td>
</tr>
<tr>
<td>Repetition rate for He and C [Hz]</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- Beam intensity is typically $10^{10}$ ppp
- The tumor is “painted “ with beam
- Depth modulation = energy loss absorber
- Slow extraction must be ripple free.
Depth in tissue

Fig.

X-rays deposit more radiation in healthy tissue.
Lawrence’s Cyclotron

Fig.
# Isotopes for PET

## PET Production Table

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Nuclear Reaction</th>
<th>Chemical Form</th>
<th>Beam Current</th>
<th>Irradiation Time</th>
<th>Yield mCi</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-11</td>
<td>$^{14}\text{N(p,a)}^{11}\text{C}$</td>
<td>CO$_2$</td>
<td>50 µA</td>
<td>30 min</td>
<td>3000</td>
</tr>
<tr>
<td>N-13</td>
<td>$^{16}\text{O(p,a)}^{13}\text{N}$</td>
<td>NH$_3$</td>
<td>30 µA</td>
<td>30 min</td>
<td>450</td>
</tr>
<tr>
<td>O-15</td>
<td>$^{14}\text{N(d,n)}^{15}\text{O}$</td>
<td>O$_2$</td>
<td>50 µA</td>
<td>6 min</td>
<td>1200</td>
</tr>
<tr>
<td>F-18</td>
<td>$^{18}\text{O(p,n)}^{18}\text{F}$</td>
<td>HF</td>
<td>30 µA</td>
<td>60 min</td>
<td>1000</td>
</tr>
</tbody>
</table>
Energy amplifier
Inertial confinement

Fig.

E.J.N.Wilson - Introduction to Accelerators III – Applications

Slide 31
The history of accelerators

Fig.
Need for Accelerators

Why do we need accelerators? (2)

Resolution of "Matter" Microscopes:

Wavelength of Particles (Photon, Electron, Proton, ...): (de Broglie, 1923)

\[ \lambda = \frac{h}{p} \]  

\[ (\approx 1.2 \text{ fm} / p \ [\text{GeV/c}]) \]

The higher the momentum, the shorter the wavelength, the better the resolution

Energy to Matter:

Einstein (1905):

\[ E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma m_0 c^2 \]

Higher energy means we can produce more massive particles

When particles approach the speed of light, they get more massive, but not faster.
Center of mass v. Fixed target

\( W = \text{Energy available in center-of-mass for making new particles} \)

For fixed target:

\[ E_{c.m.} \approx \sqrt{2m_T E_B} \]

... and we rapidly run out of money trying to gain a factor 10 in c.m. energy

But a storage ring, colliding two beams, gives:

\[ E_{c.m.} \approx 2 E_B \]

Problem: Smaller probability that accelerated particles collide .... "Luminosity" of a collider

\[ L = N_1 N_2 \frac{1}{A} \frac{\beta c}{2 \pi R} \approx 10^{29} \ldots 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]
Imagine a blue particle colliding with a beam of cross section area - $A$

**Probability** of collision is $\frac{\sigma}{A} \cdot N$

For $N$ particles in both beams $\frac{\sigma}{A} \cdot N^2$

Suppose they meet $f$ times per second at the revolution frequency

$$f_{rev} = \frac{\beta c}{2 \pi R}$$

**Event rate**

$$\frac{f_{rev} N^2}{A} \cdot \sigma$$

Make big

e.g. $10^{-25}$

Make small

**Luminosity**

$\approx 10^{30}$ to $10^{34}$ [cm$^{-2}$ s$^{-1}$]
CLIC SCHEME

Fig.

E.J.N.Wilson - Introduction to Accelerators III – Applications

Slide 36
Summary of lecture:
III – Applications – E. Wilson

- Low energy irradiation of material
- Dose and beam power
- Synchrotron light sources (ESRF)
- The cone of synchrotron radiation
- The spectrum
- The scale of things
- Diffraction
  - Lithography
- Brightness
- Spallation source
- GSI – Ions Galore!
- HYOGO (JPN)- Ion beam medical center
- Energy amplifier
- Inertial confinement
- The development of accelerators
- Need for higher energy
- Center of mass v. Fixed target
- Luminosity
- CLIC