KE produced by accelerators system is limited by regulation to
- 10 MeV for direct electron irradiation
- 5 or 7.5 MeV for indirect irradiation using X-rays
E-beam Typical Installation

- Key elements
  - Accelerator system
  - Scanning system
  - Material handling system
  - Others
    - Vacuum & cooling subsystems
    - Shielding
    - Safety system
X-ray facility
Accelerator system
Bean scanning system
Material handling
Key concepts and parameters

- Dose uniformity and utilization efficiency for e-beams
- Dose uniformity and utilization efficiency for X-rays
- Dose and dose rate estimation
- Throughput estimates for electrons and X-rays
Dose uniformity and utilization efficiency for e-beams

- When energetic electrons pass through matter they lose energy via Coulomb interaction with atomic and molecular electrons and nuclei.

- Radiation shower – primary electrons produce
  - Secondary electrons, tertiary, so on.
Energy deposition profile

- 10 MeV electron normally incident onto the surface of water absorber
- Absorbed dose at a particular depth can be calculated as

\[ D(x) = E_{ab} I'' \times t \]
Example

- \( I'' = 10^{-6} \text{ amp/cm}^2 \) incident at surface
- \( t = 1 \text{ s} \)

\[
D[kGy] = E_{ab} I'' t \\
= \frac{1.85 \text{MeV cm}^2}{g} \times 10^{-6} \frac{A}{cm^2} \times 1s \\
= 1.85 \times 10^6 \text{ eV cm}^2 \frac{g}{cm^2} \times 10^{-6} \frac{A}{cm^2} \times 1s \\
= 1.85 \text{ eV cm}^2 \frac{g}{cm^2} \times \frac{A}{cm^2} \times 1s \times \frac{1C}{1A \times 1s} \times \frac{1.6022 \times 10^{-19} J}{1eV} \times \frac{1}{1.6022 \times 10^{-19} C} \\
D = 1.85 \text{ kJ/kg}
\]
Depth-dose profile

- For water [1 g/cm³]
- Can be extended to other absorbers with different densities
  \[\text{Depth} = \rho \times x \text{[kg/cm}^2\text{]}\]
- For 0.5 g/cm³ the MSP would have the same max (2.5 MeV-cm²/g], but it would occur at 5.5 cm
$D_{\text{min}}$ and $D_{\text{max}}$

- Electron energy deposition is not constant
- Position in product will receive the minimum dose and another the maximum
- Dose uniformity ratio

$$DUR = \frac{D_{\text{max}}}{D_{\text{min}}}$$
Dose uniformity ratio

- At 2.75 cm (maximum $E_{ab}$)
  - $D_{max}/D_{min} = 1.35$
  - $= 2.5/1.85$
- It remains constant up to
  - $A = 3.8 \text{ g/cm}^2$
- Beyond this depth, the minimum dose decreases and the ratio increases
Dose-depth curve for water-10MeV

\[ MSP = 1.84 + 0.25d \quad 0 < d < 2.5 \]
\[ MSP = 2.48 \exp[-0.27(d - 2.75)^{2.7}] \quad 2.5 < d < 6.5 \]
\[ MSP[MeV \cdot cm^2 / g] \]
DUR – water – 10 MeV

\[ DUR = \frac{2.84}{E} \]
DUR – water – 10 MeV

\[ \text{DUR} = \frac{2.84}{E} \]

Useful energy that is absorbed by the product
Maximum efficiency

- **Minimum dose:**
  - $A = 1.85 \text{ MeV-cm}^2/\text{g}$

- **Optimum depth:**
  - $B = 3.75 \text{ g/cm}^2$

- **Max.Eff.**
  - $= A \times B = 7 \text{ MeV}$

- **For 10 MeV electrons**
  - Maximum efficiency is 70%
Useful measure of the electron penetration power

Optimum depth \([g/cm^2]\) = 0.4 \(E [MeV]\) - 0.2
10 MeV electrons in water

- The entrance (surface) dose is 100%.
- The various ranges are identified as:
  - \( r_{\text{max}} \) = the depth at which the maximum dose occurs,
  - \( r_{\text{opt}} \) = the depth at which the dose equals the entrance dose,
  - \( r_{50} \) is the depth at which the dose equals half of the maximum dose
  - \( r_{33} \) is the depth at which the dose equals a third of the maximum dose.

For the example, \( E_{\text{mean}} \) is calculated to be 10.6 MeV for \( r_{50} = 4.53 \) cm (of water).
A typical dose distribution along the scan direction for an electron irradiator.
For 1-side e-beam irradiation

- Normalizing the surface dose to 100%,
  - the maximum dose $D_{\text{max}}$ of 130% occurs at a depth $r_{\text{max}} = 2.8$ cm,
  - the entrance dose equals the exit dose at $r_{\text{opt}} = 4.0$ cm.
- For a process load of thickness between 2.8 and 4.0 cm,
  - the DUR is constant with a value of about 1.3.
- If the process can allow a uniformity ratio of 2,
  - the maximum useful thickness of the process load is $r_{50} = 4.5$ cm
  - the exit dose equals half of the maximum dose.
For 1-side e-beam irradiation

- If a uniformity ratio of 3 is acceptable, the
  - maximum allowable thickness can be as much as \( r_{33} = 4.8 \text{ cm} \)
  - the exit dose equals a third of the maximum dose
- A steep increase in the DUR is observed as soon as the thickness exceeds the optimal range \( r_{\text{opt}} \).
- It approaches infinity when the maximum range of the electrons (about 6.5 cm for 10 MeV) is exceeded;
  - any product behind that range remains untreated.
- Two sided irradiation can overcome this restriction and extend the processable thickness
Depth–dose distributions for 10 MeV electrons for two sided irradiation

Each curve refers to the dose distribution for one sided irradiation; dashed curve, irradiation from top side; solid curve, irradiation from bottom side.
2-sided e-beam irradiation

- The position of \( D_{\text{max}} \) will be somewhere midway between the two outside planes, along two lines parallel to the motion of the product and about halfway between the top and bottom surfaces.

- \( D_{\text{min}} \) will be found along lines parallel to the direction of motion of the product either through the side edges at the top and bottom of the process load or in the midplane at the side edges.
Depth–dose distributions for 10 MeV electrons in varying thicknesses (widths) of water

**Thickness = 6 cm**
**DUR = 2.7**
Depth–dose distributions for 10 MeV electrons in varying thicknesses (widths) of water

Thickness = 8.5 cm
DUR = 1.35
Depth–dose distributions for 10 MeV electrons in varying thicknesses (widths) of water

Thickness = 10 cm
DUR = 5.4
Single-sided Irradiation
Min-Max & Energy Efficiency

- Mono-energetic beams
- Normally incident 10 MeV electrons
- The integral under the curve gives a total absorbed energy of 9.61 MeV/electrons
  - 46 keV is deposited in a 3-mil exit window
- **Goal**: a minimum dose to be delivered to all portions of product
  - Too much dose in any portion of product: *energy wasted and quality deterioration*
Utilization efficiency – Single-sided

- $d_{\text{max}} = \text{maximum thickness @ minimum required dose}$
- Optimum depth thickness in water

$$d_{\text{opt}}[cm] = 0.4E[MeV] - 0.2$$

$d_{\text{opt}} \equiv \text{at the max throughput efficiency}$

$$E_{ab}[MeV \cdot cm^2 / g] = 1.84 + 0.25d, \quad 0 < d < 2.5$$

$$= 2.48 \exp[-0.27(d - 2.75)^{2.7}]$$

$$\eta_u = \frac{d}{d_{\text{max}}}$$

$$d_{\text{max}} = \frac{E}{\rho E_{ab\text{min}}}$$

$$E_{ab\text{min}} = \min[E_{ab}(0), E_{ab}(d_r)]$$
DUR and Efficiency

\[ DUR = \frac{2.84}{E} \]

\[ Eff = \frac{d}{d_{\text{max}}} \]

\[ d_{\text{max}} = \frac{10\text{MeV}}{E(0)} \quad 0 \leq d \leq d_r \]

\[ d_{\text{max}} = \frac{10\text{MeV}}{E(d)} \quad d > d_r \]

DUR vs. Depth [g/cm²] graph

Throughput efficiency
Example of calculation – 10 MeV in water

<table>
<thead>
<tr>
<th>Thick [cm]</th>
<th>Eab [MeV-cm²/g]</th>
<th>max/min</th>
<th>d/dmax</th>
<th>dmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>1.84</td>
<td>1.00</td>
<td>0.00</td>
<td>5.43</td>
</tr>
<tr>
<td>0.50</td>
<td>1.97</td>
<td>1.07</td>
<td>0.10</td>
<td>5.09</td>
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<td>1.00</td>
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<td>1.14</td>
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<td>0.33</td>
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<td>0.77</td>
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<tr>
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<tr>
<td>5.00</td>
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<td>11.24</td>
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</tbody>
</table>

C1 = column 1
C2 = ...

C5 = 10 Mev/C2
C4 = C1/C5
C3 = C2/E_{abmin} until E_{abmax}
then E_{abmax}/E_{abmin}
then E_{abmax}/C2
Optimum depth thickness in water

\[ d_{\text{opt}}[cm] = 0.9E[MeV] - 0.4 \]

\( d_{\text{opt}} \) = at the max throughput efficiency

\( T = \) product thickness

\( x = \) depth into product measured from either surface

\( E_{ab}(x) = \) single-sided energy deposition

\[ E_{ab} = E_{ab}(x) + E(T - x) \]

\[ \eta_u = \frac{T}{d_{\text{max}}} \]

\[ d_{\text{max}} = \frac{2E}{\rho E_{ab \text{min}}} \]

\[ E_{ab \text{min}} = \min[E_{ab}(0), E_{ab}(d_r)] \]
For X-rays

- The energy deposition for X-rays decrease exponentially with time.
- For mono-energetic X-ray beam of intensity $I$, the decrease in intensity in passing through a material of thickness $s$ is:

$$I = I_o e^{-\mu s}$$

- $I$ is the intensity at the surface.
- $\mu$ is the Linear Attenuation coefficient.
X-ray Utilization efficiency

- Single sided X-ray

\[ \eta_u = (\mu_m \rho d) \exp(-\mu_m \rho d) \]

- Mass absorption coefficient
- X-rays flux \( F_o \)
- Conveyor direction
- \( d \)
Double-sided X-ray

- It is never used because the max:min ratio is very poor $\sim 2.72$
- Single-sided X-ray treatment is used when the product is rotated for a second pass or the product makes a single pass through two X-ray beams

![Diagram of X-ray setup with conveyor direction and X-rays flux $F_0$]
Dose distribution for double sided X-ray

\[
D(s) = \mu F_o \left[ e^{-\mu \rho s} + e^{-\mu \rho (d-s)} \right]
\]

\[
D_{\text{max}} = \mu F_o (1 + e^{-\mu \rho d})
\]

\[
D_{\text{min}} (s = d / 2) = 2 \mu F_o e^{-\mu \rho d / 2}
\]

\[
D_{\text{max}} / D_{\text{min}} = 0.5 \left[ 1 + e^{-\mu \rho d} \right] e^{\mu \rho d / 2}
\]

\[
\eta_u = \mu \rho d e^{-\mu \rho d / 2}
\]
Dose & Dose rate estimation

Electron beams
Dose & Dose rate estimation

- **Electron beams**
  
  \[ D(d) = E_{abs}(d) I_A t / A \]

  \[ A / t = \nu w \]

  \[ D(d) = E_{abs}(d) I_A / (\nu w) \]

  \[ \dot{D} = D / t_p = D \nu / W_b \]

  \[ D_s[kGy] = @ surface = 1.8 \times 10^6 I_A / (\nu w) \]

  \[ \dot{D}_s[kGy/s] = 1.8 \times 10^6 I_A / (\nu W_b) \]

- **W_b = e-beam width [cm], A[cm^2], t[s], w[cm],
  \nu[cm/s], I_A [amp]**
Example

- **Scan with,** \( w = 100 \text{ cm}; \) **conveyor speed** \( v = 10 \text{ cm/s} \)
- **Calculate the front surface dose delivered by a** 10MeV and 1mA beam

\[
D[kGy] = \frac{E_{ab}(d)I_A}{ww} \\
= \frac{1.85MeV - cm^2}{g} \times 10^{-3} \frac{A}{cm^2} \times \frac{1}{(1000cm^2 / s)} \\
= 1.85 \times 10^6 eV \frac{cm^2}{g} \times 10^{-6} \frac{A}{cm^2} \times 1s \\
= 1.85eV \frac{cm^2}{g} \times \frac{A}{cm^2} \times 1s \times \frac{1C}{1A \times s} \times \frac{1.6022 \times 10^{-19} J}{1eV} \times \frac{1}{1.6022 \times 10^{-19} C} \\
D = 1.85kJ / kg
\]
Dose & Dose rate estimation

- X-ray systems
- It more difficult to estimate because angular dependence of X-ray produced in the converter target
- The total electron beam energy \( (Q_{beam}) \) incident on the converter is multiplied by the X-ray efficiency
Dose & Dose rate estimation

$$\eta_c = E(\text{MeV}) / 60$$

For 5 MeV, $\eta_c = 0.08$

$$Q_{x-ray} = 0.08Q_{beam} = 0.08Pt$$

$$F_o = Q_{x-ray} / A = 0.08P/(vw)$$

$$D = \mu_m F = 0.08[\mu_m P/(vw)]$$

$$D_s = 2.7P/(vw)$$

Power e-beam incident onto the converter
Throughput Estimates

\[ M_p (kg / s) = \eta_t P(kW) / D_{\text{min}} (kGy) \]

\( \eta_t = \) throughput efficiency

\( \approx 0.45 \) for electrons

\( \approx 0.03 \) for X-rays at 5 MeV

\( \approx 0.045 \) for X-rays at 7.5 MeV

\( M_p = \) mass throughput of product [kg/s]

\( D_{\text{min}} = \) minimum dose [kGy]
Throughput rates versus e-beam power
Technology choices

**Product characteristics**
- irradiation goal
- Safety
- disinfestations
- fresh/frozen
- radiation response
- density
- packaging
- throughput
  peak/average

**Process requirements**
- min. required dose
- Max:Min ratio
- mass thickness
- Max/variation
- power
- Max/average
- mass thickness
- local regulations

**Technology selection**
- e-beam/X-ray
- Kinetic energy
- System power
- material handling
- single-/double-sided
- absorbers?
- refrigeration
- ozone removal
- shielding
## Yearly costs

- Costs estimates for food irradiation facilities
- \[$K\]
- Based on 2000 hours of production per year

### Fixed costs

<table>
<thead>
<tr>
<th>Capital costs</th>
<th>15 kW</th>
<th>150 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator</td>
<td>1176</td>
<td>2176</td>
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<tr>
<td>Installation</td>
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<tr>
<td>Shielding</td>
<td>353</td>
<td>653</td>
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<tr>
<td>Material handling</td>
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<td>250</td>
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<tr>
<td>Building</td>
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<td>2800</td>
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<tr>
<td>Engineering</td>
<td>340</td>
<td>370</td>
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<tr>
<td><strong>Total capital costs</strong></td>
<td>5302</td>
<td>6962</td>
</tr>
</tbody>
</table>

| Total investment      | 619   | 813    |
| Labor                 | 300   | 300    |
| Maintainance          | 71    | 121    |
| **Total fixed costs** | 991   | 1235   |

### Variable costs

<table>
<thead>
<tr>
<th>Cost</th>
<th>15 kW</th>
<th>150 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>19</td>
<td>192</td>
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<tr>
<td>Labor</td>
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<td>121</td>
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<tr>
<td><strong>Total variable costs</strong></td>
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<td>453</td>
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**TOTAL YEARLY COSTS**

<table>
<thead>
<tr>
<th></th>
<th>15 kW</th>
<th>150 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1221</td>
<td>$1688</td>
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<tr>
<td>Cost element</td>
<td>Formula/Description</td>
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<tr>
<td>---------------------------------</td>
<td>----------------------------------------------------------</td>
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<tr>
<td>Accelerator – LINAC [$K]</td>
<td>$= 10^3 \log(P[kW])$</td>
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</tr>
<tr>
<td>Installation [$K]</td>
<td>$= 20%$ accelerator</td>
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</tr>
<tr>
<td>Shielding [$K]</td>
<td>$= 30%$ accelerator</td>
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<tr>
<td>Material handling system [$K]</td>
<td>$= 250$</td>
<td></td>
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<tr>
<td>Building [$K]</td>
<td>$= 2800$</td>
<td></td>
</tr>
<tr>
<td>Engineering [$K]</td>
<td>$= 10%$ (shield + material-handling + building)</td>
<td></td>
</tr>
<tr>
<td><strong>Total Capital [$K], TC</strong></td>
<td>$= 3350 + 1660 \log(P[kW])$</td>
<td></td>
</tr>
<tr>
<td>Investment expense [$K], I</td>
<td>$= 0.117 \times TC$</td>
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</tr>
<tr>
<td>Labor [$K], L</td>
<td>$= 300$</td>
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<tr>
<td>Maintenance [$K], M</td>
<td>$= 5%$ (accelerator + material-handling)</td>
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<tr>
<td><strong>Total Fixed Costs [$K], TFC</strong></td>
<td>$= I + L + M$</td>
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</tr>
<tr>
<td>Electricity [$K], E</td>
<td>$= 6.4 \times 10^{-4} P[kW] \times U \text{[hr]}$; $U=\text{prod.hr/year}$</td>
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</tr>
<tr>
<td>Labor [$K], L2</td>
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<tr>
<td>Maintenance [$K], M2</td>
<td>$= 5%$ (accelerator + material-handling)</td>
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<tr>
<td><strong>Total variable costs [$K], TV</strong></td>
<td>$= E + L2 + M2$</td>
<td></td>
</tr>
<tr>
<td><strong>Total Yearly Costs [$K]</strong></td>
<td>$= TFC + TV$</td>
<td></td>
</tr>
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</table>