Hospital Cyclotrons: Radiation Safety Aspects

Matthew Griffiths
Isotope Production.

Positron decay is a way for an atom with too many protons to get to a more relaxed state.

Fluorine 18
excess Proton

Oxygen 18
Neutron, Neutrino,
Positron and Gamma rays

Production: Take a stable target atom and add a proton.
Cyclotron

Electric potentials accelerate ions. Magnetic fields cause ions to travel in circles.
Electric potentials accelerate ions. Magnetic fields cause ions to travel in circles.
Cyclotron

Not a Nuclear Reactor.

Needs no radioactive fuel.

Does not produce radioactive waste or emissions.

An electrical device that can be turned off.

(Very big brother to a TV set)

Requires a small amount of a stable material as a target.

Produces a small volume of a highly specific radioactive product.

Does not become radioactive.
CYCLOTRONS
Cyclotron subsystems

- Magnet system
- RF system
- Ion source system
- Extraction system
- Diagnostic system
- Vacuum system
- Control System
- Target system
- Cooling system
Cyclotron subsystems

- Extraction system
- Magnet pole
- RF system (Dee’s)
- Ion source
- Vacuum system
- Targets

Courtesy of GE Medical systems
Beam acceleration

Courtesy of GE Medical systems
Cyclotron Radiation Source Terms:

- Proton acceleration

  Lost protons
  (40% due to electron loss)
  \((p,x) + \gamma\) with vacuum chamber
  \(x = \) neutrons duterons tritons alphas

- Electrons after stripper foil

  \(x\) rays

- Carbon (stripper) foils

  Electrons up to 20 MeV
Cyclotron Radiation Source Terms:

- **Bombardment**
  
  \[(p,n) + \gamma \text{ from target material}\]
  
  \[(p,x) + \gamma \text{ from target body + collimators}\]
  
  \[x = \text{neutrons duterons tritons alphas}\]

  ejected high energy neutrons \((n, \gamma)\) with surrounding material
### Cyclotron Radiation Source Terms:

<table>
<thead>
<tr>
<th>Proton attenuation</th>
<th>µA</th>
<th>no./s</th>
<th>MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Lost H- with a range of energies</td>
<td>32</td>
<td>2.0x10(^{14})</td>
<td>0-16.5</td>
</tr>
<tr>
<td>• Protons leaving the acceleration</td>
<td>48</td>
<td>3.0x10(^{14})</td>
<td>16.5</td>
</tr>
<tr>
<td>• Tantalum collimator losses</td>
<td>8</td>
<td>5.0x10(^{13})</td>
<td>16.5</td>
</tr>
<tr>
<td>• Foil 20µm, He 30mm, Foil 50µm</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Havar (Co 42.5%, Cr 20%, Mn 1.6%, Mo 2%, Ni 13%, W 2.8%, Fe 18.1%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• (^{18})O (5% (^{16})O)</td>
<td>40</td>
<td>2.5x10(^{14})</td>
<td>15</td>
</tr>
<tr>
<td>• Some will impact on back of target (silver)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \text{H}_3^{18}\text{O} \) target for \(^{18}\text{F} \) 40 µA of 15 MeV protons (GE PET trace)
## Cyclotron Radiation Source Terms:

- **Proton interactions**

### E_{av} [MeV]

<table>
<thead>
<tr>
<th>Material</th>
<th>Proton flux [1/s]</th>
<th>Neutrons</th>
<th>Deutrons</th>
<th>Tritons</th>
<th>Alfa</th>
<th>Gamma</th>
<th>E_{av} [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (p,x)</td>
<td>4.0E+13</td>
<td>2.8E+09</td>
<td>6.3E+07</td>
<td>0.0E+00</td>
<td>2.8E+10</td>
<td>6.1E+10</td>
<td>2.45</td>
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<tr>
<td>Si (p,x)</td>
<td>1.5E+14</td>
<td>2.8E+09</td>
<td>1.0E+09</td>
<td>2.1E+06</td>
<td>2.1E+09</td>
<td>2.3E+11</td>
<td>2.02</td>
</tr>
<tr>
<td>Cu (p,x)</td>
<td>1.0E+13</td>
<td>3.6E+09</td>
<td>4.7E+06</td>
<td>5.2E+04</td>
<td>1.1E+09</td>
<td>1.5E+10</td>
<td>1.96</td>
</tr>
<tr>
<td>Ta (p,x)</td>
<td>5.0E+13</td>
<td>1.0E+11</td>
<td>3.3E+07</td>
<td>2.4E+06</td>
<td>7.0E+07</td>
<td>2.2E+11</td>
<td>1.38</td>
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<tr>
<td>Havar (p,x)</td>
<td>2.5E+14</td>
<td>2.8E+11</td>
<td>2.4E+09</td>
<td>1.9E+08</td>
<td>4.4E+09</td>
<td>4.4E+11</td>
<td>2.29</td>
</tr>
<tr>
<td>H_{2}^{18}O (p,x)</td>
<td>2.5E+14</td>
<td>3.2E+11</td>
<td>3.2E+09</td>
<td>0.0E+00</td>
<td>6.4E+11</td>
<td>2.2E+12</td>
<td>1.93</td>
</tr>
<tr>
<td>H_{2}^{16}O (p,x)</td>
<td>2.5E+14</td>
<td>0.0E+00</td>
<td>1.2E+06</td>
<td>0.0E+00</td>
<td>4.2E+10</td>
<td>3.2E+11</td>
<td></td>
</tr>
<tr>
<td>^{14}N_2 (p,x)</td>
<td>2.5E+14</td>
<td>1.1E+10</td>
<td>2.1E+10</td>
<td>0.0E+00</td>
<td>2.6E+11</td>
<td>1.3E+12</td>
<td>3.40</td>
</tr>
<tr>
<td>Al dummy</td>
<td>2.5E+14</td>
<td>1.3E+11</td>
<td>8.6E+09</td>
<td>0.0E+00</td>
<td>6.3E+11</td>
<td>2.3E+12</td>
<td>2.92</td>
</tr>
</tbody>
</table>

**Yields [particles/s]**

- 7.13E+11 total
- 1.41E+11 forward
- 5.72E+11 isotropic

**Neutron energy**

- H$_{2}^{18}$O target
- 40 µA, 15 MeV protons
- (GE PET trace)
**Gamma source terms**
(energy per second)
prompt gamma from $(p,x)$ and $(n,\gamma)$ reactions

<table>
<thead>
<tr>
<th>Material</th>
<th>$(p,x)$ [MeV/s]</th>
<th>$(n,g)$ [MeV/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta</td>
<td>1.7E+11</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>6.5E+11</td>
<td>1.0E+10</td>
</tr>
<tr>
<td>Pb</td>
<td></td>
<td>6.6E+09</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td>6.9E+11</td>
</tr>
<tr>
<td>Cu + Others</td>
<td>2.4E+10</td>
<td>1.7E+10</td>
</tr>
<tr>
<td>Al</td>
<td>1.5E+11</td>
<td>5.8E+11</td>
</tr>
<tr>
<td>Fe + SS</td>
<td></td>
<td>3.5E+12</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td>2.0E+09</td>
</tr>
<tr>
<td>H$_2$O + Oil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Havar</td>
<td>6.2E+11</td>
<td></td>
</tr>
<tr>
<td>Target - H$_2^{18}$O</td>
<td>3.8E+12</td>
<td></td>
</tr>
<tr>
<td>Target - H$_2^{16}$O</td>
<td>1.9E+12</td>
<td></td>
</tr>
<tr>
<td>Target - $^{14}$N$_2$</td>
<td>3.9E+12</td>
<td></td>
</tr>
<tr>
<td>Target - Dummy (Al)</td>
<td>6.6E+12</td>
<td></td>
</tr>
</tbody>
</table>
Net dose rate

- **Gamma:** Sieverts per hour

- **Neutron:** tens of Sieverts per hour

QLD design criteria 1 $\mu$Sv/hr
Reducing the radiation to safe levels

- Attenuation
- Minimize + localize the neutron interactions 
  \((n,\gamma)\) \((n,2n)\) \((n,\alpha)\)

Two basic choices
- Self shielded cyclotron
- Cyclotron vault
Self Shielded

Shielding encases cyclotron

- Moderate the neutrons.
  Polyethylene water wax
- Absorb neutrons with min activation and $\gamma$ rays.
  Boron
- Attenuate $\gamma$ rays
  Lead Concrete

- Still may require thick walls 50-300 mm
PETTrace

- Polyethene (3 %B)
- Lead shields
- Water tanks (3.5% B)
- Target
- Fe yoke
- Windings

47 000 kgs
GE PETtrace

- Water tanks (3.5% B)
- Lead shields
- Polyethene (3% B)
- Target
- Vacuum chamber
- Polyethene (0% B)
- Fe yoke
- Aux. Equipment (homogenised)
- Concrete floor

RBWH Nuclear Medicine
IBA

2 x 45,000 kgs

EBCO

60,000 kgs
Cyclotron Vault

Place cyclotron in shielded enclosure

- Use bulk material to attenuate Neutron and Gamma dose.
  Usually concrete, 1.6 - 2.0 m
  Can use additives to increase neutron capture

- Access via either a maze or a door (plug)
Partially underground vault
Bunker Doors
Maze entrance

3700 mm 5 gauss line

3800 mm
Cyclotron vault

vs

Self shield
Vault vs Self Shield

**Vault**
- future growth, beam lines
- maintenance access
- may cost less
- site specific radiation calcs (neutrons)

**Self Shield**
- limited additional targets
- limited maintenance access
- known radiation source
- smaller in height
Limited Local Shielding + Light Vault
PETtrace isodose curves

Gamma micro Sv/hr
40 mA dual beam O18 T1 + T4
PETtrace isodose curves

Neutron micro Sv/hr
40 mA dual beam O18 T1
Minitrace placed with in an existing building with additional 300 mm precast concrete walls.

Gamma

Neutron
Radiation Attenuation and Vaults

- **Prompt Gammas are easy.**
  Find source terms and effective energy and look up the attenuation values in references.

- **Neutrons are not easy.**
  The nature of, and likelihood of interaction depends on energy and material. Cross section for scatter and capture are energy dependent.
Neutrons

- Fast neutrons are elastically scattered losing energy. They do not get absorbed much. H-rich compounds are good moderators.
- Thermal neutrons have lost most of their energy and are elastically scattered until they are absorbed.
- Thermal neutrons in air are often described as a neutron gas and to a degree will diffuse like a gas.
- Elements with large capture cross sections act as neutrons sinks.
Neutron capture

- Generally a \( (n,\gamma) \) reaction.
  The \( \gamma \) rays are not trivial.
  - Boron \approx 0.3\,\text{MeV}
  - Hydrogen \approx 2\,\text{MeV}
  - Iron \approx 7\,\text{MeV}

These become a diffuse gamma source wherever the neutron stops, for instance partly through the vault wall,

Adding to the complexity of the gamma shielding.
Neutron Attenuation / Dose Calculation

- **Empirical** (for some materials) requires knowledge (assumptions) of neutron flux, energy and concrete density.

- **Monte Carlo simulation of cyclotron in vault.** Requires knowledge of neutron source terms, energy distribution and relative elemental composition of cyclotron and vault.
Empirical

NCRP Report No. 51 - Radiation Protection Design Guideline for 0.1 to 100 MeV Particle Accelerator Facilities

Dose, including gamma from (n,g) reactions in concrete rem cm\(^2\) per unit neutron fluence
Monte Carlo

- Source neutron terms, energy and direction.
- Geometry of vault.
- Elemental composition of surrounding material e.g., cyclotron steel, concrete, target material, etc.
- Cross section at various energies for elements.
- Run simulation to see the evolution of gamma and neutron dose.

GE PET trace simulation dose in 20 cm slabs for typical F18 run.
Monte Carlo

PETtrace: Neutron Dose Rate vs Concrete Shield
Reference case: No extra shielding

PETtrace: Gamma Dose Rate vs Concrete Shield
Reference case: No extra shielding

H₂¹⁸O target
40 µA, 15 MeV protons
(GE PET trace)
Monte Carlo

- Your vault will not be the same dimensions as the published simulation
- It is too hard to redo it yourself
- The composition of the concrete will not be the same.
Shielded or vault:

Get as much information as possible

Use a Semi Empirical approach.

1) Apply judicial fudge factors to the data you have, then add at least an extra 1/2 value.
2) Make sure at least two approaches produce a shielding value within the same order of magnitude.
3) Check with other installations
Consequences of stopping all those neutrons?

Activation.

After capturing a neutron the atom may not be stable

O^{18}_8 \rightarrow (p,n) \rightarrow F^{18}_9

Typical but not only
reaction also (n,2n),
(n,α) etc

X_y \rightarrow (n,γ) \rightarrow \text{β-} \rightarrow ?

X_{y+1}^{z+1} \ 1/2 \text{ life ?}

1/2 \text{ life ?}
Activation occurs everywhere

Air

\[
\text{N}14 \rightarrow \text{N}15 \rightarrow \text{N}16 \rightarrow \text{O}16 \\
(n,\gamma) \quad (n,\gamma) \quad (\beta-) \\
stable \quad stable \quad 7 \text{ sec } 1/2 \text{ life} \\
\]

6 MeV gamma ray

2 MeV beta

Negative pressure around cyclotron
slow passage up stack.
**Activation after production**

*Induced activity in the cyclotron*

A cocktail of radioactive isotopes will be formed in the cyclotron with a range of cross-sections and half-lives.

After a weekend most of low energy gamma radiation has decayed.

After isotope production, wait for at least two hours before entering the cyclotron room or opening shields. mSv per hour

Maintenance: a radiation measurement to see if work is appropriate. Plan the work. Prepare tools if needed. Stop and re assess if not going to plan.
Maintenance

Protective measures

- Electronic dosimeter at all times
- Gloves
- Lab coat
- Plastic safety glasses, protection from β’s
- Use of shielding where appropriate
- Long tweezers and tongs
- Treat all components as hot, waste store.
- Do not mill or sand materials
Target Maintenance

- Helium/Water cooling circuitry
- Target foils
- Seal
- Rear flange
- Water container made of silver
- Helium cooling flange
- Beam

Courtesy of GE Medical Systems

RBWH Nuclear Medicine
Long Term Activation: Protons

• Most cyclotron components are not exposed to proton beam.

• Notable exception are the Havar target foils.
  Co 42.5%, Cr 20%, Mn 1.6%, Mo 2%, Ni 13%, W 2.8%, Fe 18.1%

• and the Collimators
## Long Term Activation: Protons

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Activity [Bq]</th>
<th>Main components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al26</td>
<td>717 ky</td>
<td>1.3E+03</td>
<td>Silica, Alumina</td>
</tr>
<tr>
<td>V49</td>
<td>330 d</td>
<td>1.4E+08</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Cr51</td>
<td>27.7 d</td>
<td>3.8E+07</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Mn52</td>
<td>5.51 d</td>
<td>2.2E+08</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Mn53</td>
<td>3.74 My</td>
<td>4.5E+03</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Mn54</td>
<td>312.3 d</td>
<td>2.5E+09</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Fe55</td>
<td>2.73 y</td>
<td>7.9E+07</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Co56</td>
<td>77.27 d</td>
<td>7.2E+09</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Co57</td>
<td>271.74 d</td>
<td>2.5E+08</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Co58</td>
<td>70.86 d</td>
<td>1.8E+08</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Ni57</td>
<td>6.077 d</td>
<td>1.4E+06</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Ni59</td>
<td>76 ky</td>
<td>4.4E+06</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Ni63</td>
<td>100.1 y</td>
<td>7.6E+04</td>
<td>Havar foil</td>
</tr>
<tr>
<td>Zn65</td>
<td>244.26 d</td>
<td>3.4E+08</td>
<td>Copper</td>
</tr>
<tr>
<td>Ta179</td>
<td>1.82 y</td>
<td>4.7E+05</td>
<td>Ta Collimator</td>
</tr>
<tr>
<td>W181</td>
<td>121.2 d</td>
<td>1.7E+10</td>
<td>Ta Collimator</td>
</tr>
</tbody>
</table>

20 years of operation, 20% utilisation followed by a 30 day decay period
Long Term Activation: Neutrons

- Most cyclotron components are selected to have low activation profiles and or short 1/2 life products.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Activity [Bq]</th>
<th>Main components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr51</td>
<td>27.7 d</td>
<td>2.5E+07</td>
<td>Aux. Equipment</td>
</tr>
<tr>
<td>Mn54</td>
<td>312.3 d</td>
<td>4.8E+07</td>
<td>Acc. Cell, Iron yoke</td>
</tr>
<tr>
<td>Fe55</td>
<td>2.73 y</td>
<td>5.4E+08</td>
<td>Acc. Cell, Iron yoke</td>
</tr>
<tr>
<td>Fe59</td>
<td>45.1 d</td>
<td>1.3E+07</td>
<td>Acc. Cell, Iron yoke</td>
</tr>
<tr>
<td>Co58</td>
<td>70.86 d</td>
<td>1.1E+07</td>
<td>Aux. Equipment</td>
</tr>
<tr>
<td>Co60</td>
<td>5.27 y</td>
<td>9.8E+07</td>
<td>Aux. Equip., Iron yoke</td>
</tr>
<tr>
<td>Ni59</td>
<td>76 ky</td>
<td>1.6E+04</td>
<td>Aux. Equipment</td>
</tr>
<tr>
<td>Ni63</td>
<td>100.1 y</td>
<td>3.7E+06</td>
<td>Aux. Equipment</td>
</tr>
<tr>
<td>Ag108m</td>
<td>418 y</td>
<td>7.9E+05</td>
<td>Target holder (Ag)</td>
</tr>
<tr>
<td>Ag110m</td>
<td>249.9 d</td>
<td>7.2E+07</td>
<td>Target holder (Ag)</td>
</tr>
</tbody>
</table>

Un-shielded PET trace

20 years of operation, 20% utilisation followed by a 30 day decay period
## Long Term Activation: Neutrons

### Shielded PETtrace

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Activity [Bq]</th>
<th>Main components</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3</td>
<td>12.33 y</td>
<td>7.8E+07</td>
<td>Concrete floor</td>
</tr>
<tr>
<td>Be10</td>
<td>1.6 My</td>
<td>8.0E+01</td>
<td>Polyethylene (3% B)</td>
</tr>
<tr>
<td>C14</td>
<td>5730 y</td>
<td>1.5E+03</td>
<td>Concrete floor</td>
</tr>
<tr>
<td>Ca41</td>
<td>103 ky</td>
<td>2.0E+04</td>
<td>Concrete floor</td>
</tr>
<tr>
<td>Cr51</td>
<td>27.7 d</td>
<td>2.0E+07</td>
<td>Aux. Equipment</td>
</tr>
<tr>
<td>Mn54</td>
<td>312.3 d</td>
<td>3.7E+07</td>
<td>Acc. Cell, Iron yoke</td>
</tr>
<tr>
<td>Fe55</td>
<td>2.73 y</td>
<td>4.3E+08</td>
<td>Acc. Cell, Iron yoke</td>
</tr>
<tr>
<td>Fe59</td>
<td>45.1 d</td>
<td>1.0E+07</td>
<td>Acc. Cell, Iron yoke</td>
</tr>
<tr>
<td>Co58</td>
<td>70.86 d</td>
<td>8.8E+06</td>
<td>Aux. Equipment</td>
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<tr>
<td>Co60</td>
<td>5.27 y</td>
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</tr>
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<td>Ni59</td>
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</tr>
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<td>Aux. Equipment</td>
</tr>
<tr>
<td>Ag108m</td>
<td>418 y</td>
<td>6.1E+05</td>
<td>Target holder (Ag)</td>
</tr>
<tr>
<td>Ag110m</td>
<td>249.9 d</td>
<td>5.6E+07</td>
<td>Target holder (Ag)</td>
</tr>
<tr>
<td>Eu152</td>
<td>13.32 y</td>
<td>2.3E+06</td>
<td>Concrete floor</td>
</tr>
<tr>
<td>Eu154</td>
<td>8.6 y</td>
<td>2.1E+05</td>
<td>Concrete floor</td>
</tr>
</tbody>
</table>

20 years of operation, 20% utilisation followed by a 30 day decay period
# Long Term Activation: Neutrons

**Un Shielded PETtrace Vault Walls**

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Specific activity [Bq/kg]</th>
<th>Total [Bq]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-20cm</td>
<td>20-40cm</td>
</tr>
<tr>
<td>Co60</td>
<td>3.1E+03</td>
<td>1.0E+03</td>
</tr>
<tr>
<td>Cs134</td>
<td>5.0E+02</td>
<td>1.1E+02</td>
</tr>
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<td><strong>8.5E+04</strong></td>
<td><strong>3.1E+04</strong></td>
</tr>
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</table>

20 years of operation, 20% utilisation followed by a 30 day decay period
Planning for decommissioning at installation

- Long term activation in cyclotron
  - (organise storage in advance)
- Long term activation of self shield
  - (organise storage in advance)
- Long term activation of floor
  - Limestone mix in sacrificial topping over slab
- Vault walls / ceiling
  - Limestone mix in sacrificial topping over slab
  - and or neutron moderators absorbers around targets
Production

• **Products**
  – small volumes of material
  – well shielded in trenches / ducts running to hot cells
  – typically 50 mm of lead

• **Chemistry in Hot cells**
Production

- 2/3 of cyclotron problems are due to blockages, leaks, faulty valves, clogged filters and material getting where it shouldn’t.
Continuous monitoring + logging

- Gamma in vault or near self shield
- Gamma outside vault
- Stack monitoring
- Air concentration
- Gamma in hot lab.

- Periodic Gamma + Neutron surveys