F-18 production with the TOP linac injector
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Abstract
ENEA and ISS (Italian National Institute of Health), are collaborating to develop a dedicated proton medical accelerator, TOP (Oncological Therapy with Protons) linac, consisting of a sequence of three pulsed linear accelerators. The 7 MeV injector can be used in three operating modes: Protontherapy and Radiobiology Mode—injecting low current proton beam into the TOP linac accelerating sections; Radioisotope Mode—generating an intense proton beam (8–10 mA, 50–100 μs, 30–100 Hz) to produce the positron-emitting radionuclide F\textsubscript{18} for PET analyses. In the high current mode, at the exit of the injector the beam is guided through a magnetic quadrupoles channel to a target composed by a thin chamber (0.5 mm thick and 1 in. diameter) containing water enriched with O\textsubscript{18}. Production yield as well as total activity similar to these achieved with higher energy cyclotrons have been obtained. Environmental doses measured give indications on the shielding required for operation under current radioprotection regulations. Improvements are foreseen to optimize the production yield, the useful beam current and to better characterize gamma and neutron dose rates in the different operational modes.

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vaporization of the water with the consequent decreasing of the production yield.

3. Beam line, target and measuring device

The beam line for the high current beam, after the injector, goes straight to the target. At the moment two quadrupole lens are used to shape and homogenize the beam, space is allowed to insert other magnetic elements to achieve a better flatness of the beam intensity.

The target used has been designed by AccSys. It is composed by a 25.4 mm in diameter and 0.35 mm deep cavity filled with $^{18}$O enriched water. The entrance window is a 0.025 mm thick titanium foil that is supported by a 3 mm thick grid of copper bonded to stainless steel. The transmission of the grid is 58% (see Fig. 3). The energy loss through the titanium foil is 0.5 MeV. The proton beam enters the water at 6.5 MeV ($dE/dx = 65$ MeV/cm) and leaves the water cavity at 3.0 MeV with a residual effective cross-section very small.

The total target volume is 350 ml, with 200 ml being potentially exposed to the beam. The grid and the body of the cavity are cooled (see Fig. 4) with a closed chilled water circuit. The target is pressurized with argon to 20 bar. The enriched water is loaded in the cavity through an automatic system using small diameter tubing and pressurized with argon. At the EOB the argon pressure is used to force the $^{18}$F-water solution directly into a well-lodged proportional chamber PET-radionuclide activity calibrator [3], whose remote monitor allows the registration of the activity collected and its follow-up with time.

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### Table 1: TOP linac injector characteristics

<table>
<thead>
<tr>
<th>Mode</th>
<th>F-mode</th>
<th>P-mode</th>
<th>R-mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, MeV</td>
<td>7</td>
<td>7</td>
<td>3–7</td>
</tr>
<tr>
<td>Pulse current, mA</td>
<td>8–10</td>
<td>0.001–0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Pulse duration, µs</td>
<td>50–100</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Pulse rep frequency, Hz</td>
<td>50–100</td>
<td>250</td>
<td>100</td>
</tr>
</tbody>
</table>

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Fig. 1. View of test bunker installation: injector final section, transport line and target area.

Fig. 2. Beam energy dependence of the cross-section for $(p,n)$ production of $^{18}$F from $^{18}$O (adapted from [2]).

Fig. 3. V Grid and target.

Fig. 4. Target assembled at the irradiation position, out of the shielding with cooling and loading circuits.
4. Preliminary tests of low-energy $^{18}$F production

The theoretical saturated yield for $^{18}$F for 6.5 MeV proton beam is $\approx 2.96 \text{ GBq/µA} (\approx 80 \text{ mCi/µA})$ that with irradiation time of approximately 2 h (one one-half life) means $\approx 1.5 \text{ GBq/µA} (\approx 40 \text{ mCi/µA})$. Taking into account the enrichment of the water ($< 100\%$) and the non-complete recovering of the irradiated sample an effective production yield between 80% and 90% of the theoretical value can be achieved. A proton beam delivered by the 7 MeV injector with 60 µA on the target and then 35 µA on the water could produce more than 37 GBq (1 Ci) at the EOB of 2 h that is the usual production of cyclotrons used for in-house production in hospitals.

Numerous production tests at 7 MeV with partially $^{18}$O enriched water (4.5–95%), average on water currents of 25–35 µA and irradiation times between 15 min and 2 h, produced F-18 yields in the range of 65–80% of the theoretical values. The identification of the radionuclide was done through the decay curve (see Fig. 5) Typical test results are reported in Table 2.

Current on the target was limited by a non-optimized beam tuning resulting in beam loss along the transport line and a non-uniform intensity distribution.

![Fig. 5. Decay of the product of irradiation test reported in row 4 of Table 2 showing its compatibility with $^{18}$F production.](image)

![Fig. 6. Radiation levels (mRem/h) in different operating conditions: Circled: 7 MeV, 6 mA, 180 Hz, without shielding added; Squared: protontherapy, low current, 250 Hz with added shielding; N (neutrons) and X (gamma) in F-mode with target shielded with water tank.](image)

<table>
<thead>
<tr>
<th>Rep rate (Hz)</th>
<th>Current out or target current</th>
<th>Water current (µA)</th>
<th>Irradiation time (min)</th>
<th>O-18 enrichment</th>
<th>Predicted activity (mCi)</th>
<th>Predicted effective activity (mCi)</th>
<th>Achieved activity (mCi)</th>
<th>% of theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>58.21</td>
<td>33.59</td>
<td>15</td>
<td>4.94%</td>
<td>11.97</td>
<td>9.58</td>
<td>8.62</td>
<td>72%</td>
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<tr>
<td>60</td>
<td>43.25</td>
<td>24.95</td>
<td>120</td>
<td>95.00%</td>
<td>1006.2</td>
<td>804.93</td>
<td>762.00</td>
<td>76%</td>
</tr>
<tr>
<td>60</td>
<td>44.06</td>
<td>25.42</td>
<td>15</td>
<td>4.94%</td>
<td>9.06</td>
<td>7.25</td>
<td>6.71</td>
<td>74%</td>
</tr>
<tr>
<td>60</td>
<td>44.06</td>
<td>25.42</td>
<td>120</td>
<td>95.00%</td>
<td>1025.15</td>
<td>820.12</td>
<td>763.16</td>
<td>74%</td>
</tr>
</tbody>
</table>
In any case the results are not too different from what it is expected to achieve and there are still many tools to use to reach the desired solution.

Environmental dose rates, with injector functioning in its different modes of operation, were measured during the factory injector acceptance test. The measurements are reported in Fig. 6. Several considerations can be drawn on the shielding needed during operating conditions to comply with radiation protection regulations. More extensive measurements are planned in Frascati.

References