# A NON LINEAR TRANSPORT LINE FOR THE OPTIMIZATION OF F18 PRODUCTION BY THE TOP LINAC INJECTOR

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*Abstract*

The injector of the TOP Linac (Oncological Therapy with Protons), under development by ENEA and ISS consists in a 7 MeV, 425 MHz RFQ+DTL (AccSys Model PL-7). It is actually in operation at ENEA-Frascati laboratories for the production of the positron-emitting radionuclide F18 for PET analyses by an intense proton beam (8 – 10 mA, 50 – 100 μs, 30 – 100 Hz). At the exit of the injector, the beam is guided through a magnetic channel to a target composed by a thin chamber (0.35 mm thick and 1 inch diameter) containing water enriched with O18. Two techniques aimed to flatten the proton beam distribution and so optimize the radioisotope production are compared: a spot scanning system and the use of a non-linear magnet system including octupoles.

In the paper the details of the beam dynamic study and the first measurements results are presented.

## THE TOP LINAC INJECTOR

ENEA and ISS (Italian National Institute of Health) are developing a dedicated proton medical accelerator, the TOP (Oncological Therapy with Protons) Linac [1] designed to be installed in a medium size hospital in the Rome area. It consists in a sequence of three pulsed accelerators. The injector is a 7 MeV AccSys Model PL-7 system modified to meet the TOP requirements . It will be used in two different working modes: Fluorine-18 production (F-Mode) and Protontherapy beam injection (P-mode). In table 1 the typical beam characteristics are reported for each mode. In the high current mode, at the exit of the injector the beam is guided through a channel including two magnetic quadrupoles to a target composed by a thin chamber containing water enriched with O-18.
The injector has been temporarily installed in a test bunker at ENEA Frascati laboratories (see Fig. 1) where beam characterization measurements and F18 production tests are underway.

Table 1: TOP linac injector characteristics

| | F-mode | P-mode |
|---|---|---|
| Energy, MeV | 7 | 7 |
| Pulse current, mA | 8-10 | 0.001-0.03 |
| Pulse duration, μs | 50-100 | 7 |
| Pulse rep. freq., Hz | 50-100 | 250 |

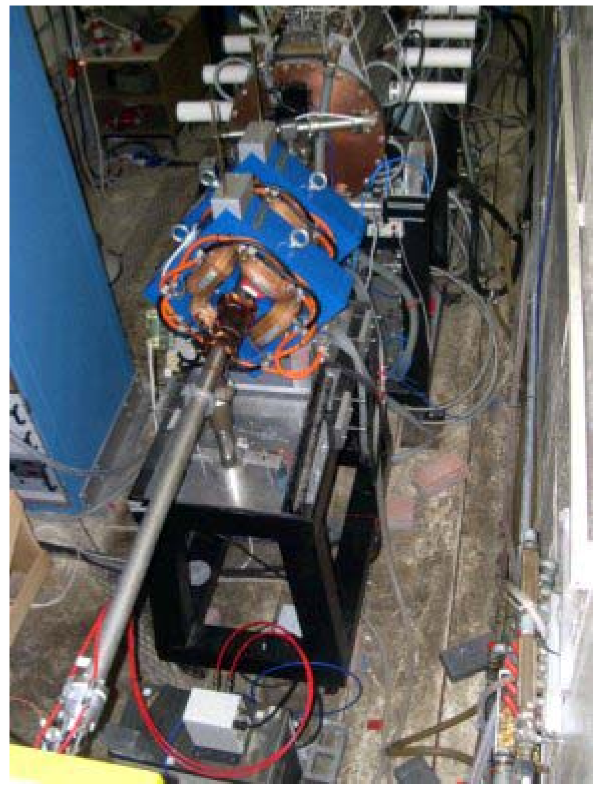


Figure 1: Inside the bunker: injector final section, transport line and target area.

### *Preliminary Tests of F18 Production*

The target used for F18 production (AccSys design and realization) is composed by a 25.4 mm in diameter and 0.35 mm deep cavity filled with O-18 water. The entrance window is a 0.025 mm thick titanium foil supported by a 3 mm thick grid of copper bonded to stainless steel. The transmission of the grid is 55%. Numerous production tests at 7 MeV with partially O-18 enriched water (4.5%-95%), at average on water currents of 25-35 μA and irradiation times between 15 min and 2 hours have been done. The best achieved activity value was 762 mCi in 2 hours with 25-35 μA on target and a O-18 water enrichment of 95%. The total F-18 production is the product of the yield (ranging from 45 to 70 mCi/uA, depending on the operating condition of the target) and of to total current delivered to the water. This is limited by the peaked shape of the beam intensity distribution of the spot and by the maximum tolerable value of beam density current on target of 35 $\mu A/cm^2$. The goal activity with a pulsed current of 10 mA at accelerator maximum ratings (pulse duration=100 μsec, repetition frequency=100 Hz) is 1Ci/h. In order to increase the production yield we have to increase the intensity that implies that uniform irradiation of the target is necessary.

## BEAM DISTRIBUTION

The beam current transmitted through the 38 mm internal diameter beam line (2 m long) and the final beam profile have been measured in order to find the quadrupoles setting giving the more suitable beam distribution on the target for F-18 production. The best choice is indeed a compromise between two requirements: the need to reduce the beam losses (small final beam size) and the need to reduce the peak current density and the consequent temperature increase on target (large final beam size). The losses are recorded on a 28 mm diameter beam position monitor at the end of the beam pipe. The measurements have been done using a 3 mA pulse current at a pulse length of 80 μsec and a repetition frequency of 30 Hz.

### *Blue Cellophane Measurements*

The final beam distribution has been measured by analyzing the intensity profile of the beam spot on a blue cellophane placed at the end of the beam transport line. A large number of measurements has been done for different quadrupole settings and different irradiation times of the cellophane. The main problems of this technique derive from the risk of cellophane destruction, when the beam spot is very small and concentrated and from the cellophane saturation effect for long irradiation time.

When the saturation effects are reduced, shorting the cellophane exposure times, a triangular shape appears. This has been compared (fig. 2) with a very good agreement, to the computed horizontal and vertical distributions, starting from the beam description at the linac output, as given from AccSys.

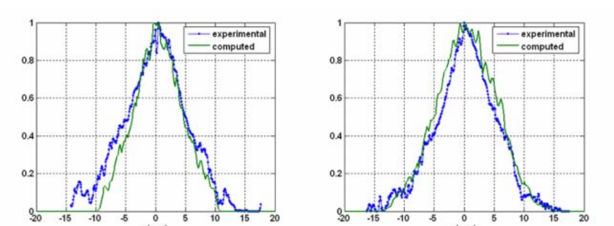



Figure 2: Comparison between measured and computed horizontal and vertical distributions.

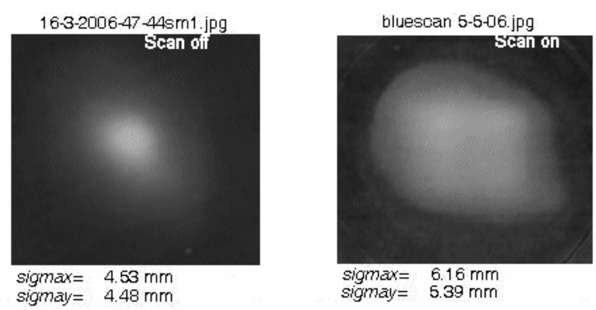
In order to reduce the losses level below a few percent it is necessary to get on target σ values of about 4.5-5 mm. In these conditions the peak current density at a current beam pulse of 3 mA extrapolated at the maximum ratings parameters is between 15 and 18 $\mu A/cm^2$. This means that the maximum allowable peak current density on target of 35 $\mu A/cm^2$ is compatible with maximum operating currents of 6-7 mA. This prevents to operate the accelerator at its maximum pulse current, with consequent reduction of the F-18 production efficiency.

In order to overcome this limit we decided to test on our system the techniques described below with the aim of transforming the peaked triangular distribution into a nearly uniform distribution.

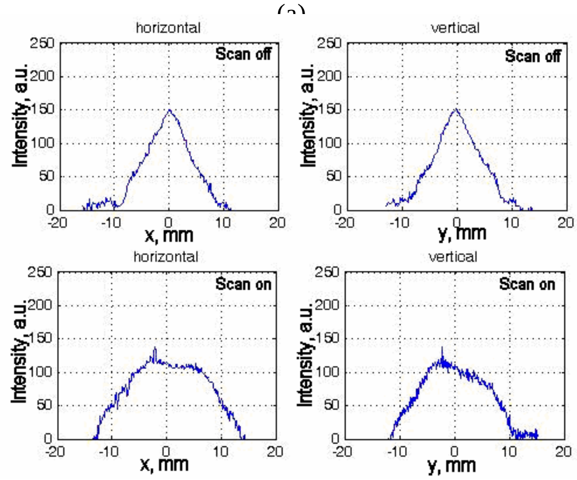
## BEAM DISTRIBUTION FLATTENING TECHNIQUES

### *Spot Scanning*

The spot scanning technique consists in moving magnetically the beam spot in horizontal and vertical directions in order to cover uniformly the target area by means of a four-poles scanning magnet. The pole length is 120 mm and the maximum current is 2 Amp. corresponding to a magnetic field of 180 gauss. The horizontal scan is driven by a fast (T~0.8 secs) square wave and the vertical scan by a slow (T~5.3 secs) sinusoidal wave. The magnet is placed at a distance to target of 1100 mm, just after the second quadrupole, where the beam is large in horizontal plane and the horizontal deflection acts only on the central portion of the beam. A beam distribution with a quasi-square pattern core (on blue cellophane, with 1 mA pulse, 30 Hz, 6 sec irradiation) obtained with a field of 130 Gauss and a deflection of 4.4 mm compared with the beam distribution with spot scanning off is shown in figure 3.




(a)




(b)

Figure 4: Measured beam spot (a) and distribution (b) on target with spot scanning off and on.

The FWHM is increased from 10-11 mm to 16-18 mm. This system is very promising to increase the EOB activity. For a routinely operation it requires safety interlocks to avoid that any fail, during an irradiation, would cause beam overheating the target in one position.

### *Distribution Shaping by Octupoles*

The principle of the method is to use a magnetic optics including two octupoles, that sequentially fold the horizontal and vertical tails of the beam profile back onto the core, in order to achieve a nearly-rectangular beam distribution. The beam folding in each plane is carried out in two stages: first the nonlinear magnetic fields fold the beam phase-ellipse in x' (or y') space and then when the beam drifts in a long field-free region the beam ellipse shears in x (or y) space, causing the tails in the transverse profile to fold back onto the core of the beam. This folding is done sequentially in the x-x' and y-y'space.

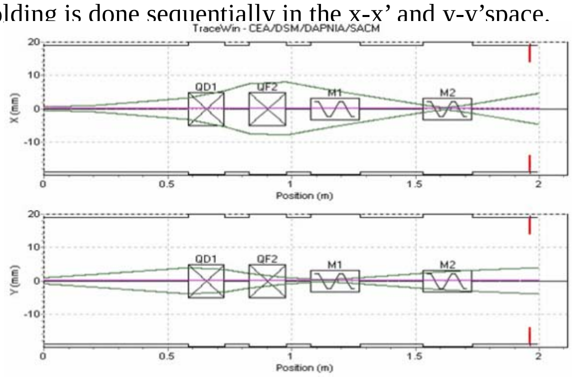



Figure 4: X-Y RMS envelope vs z. The two octupoles are labelled M1 and M2.

The beamline including these non-linear elements has been optimized by the TRACEWIN/PARTRAN code [2]. The non-linear lenses dedicated to the horizontal distribution flatness (and, respectively, the vertical one) are located approximately at a waist of the vertical motion (respectively the horizontal), that allows to act on one plane so minimizing effects on the other plane (see figure 4). Figures 5 and 6 show respectively the computed beam distribution on target with the octupoles on and off.

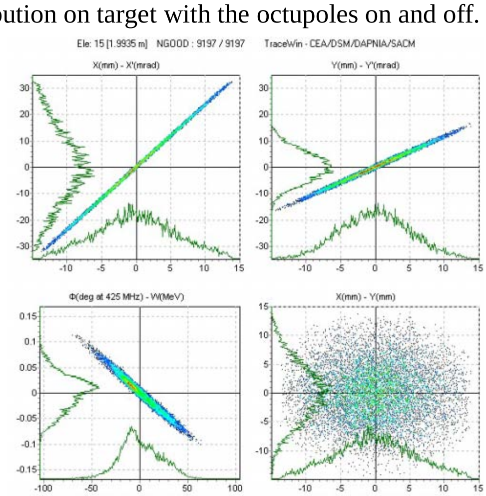



Figure 5: Computed beam on target phase spaces and distributions with octupoles off.

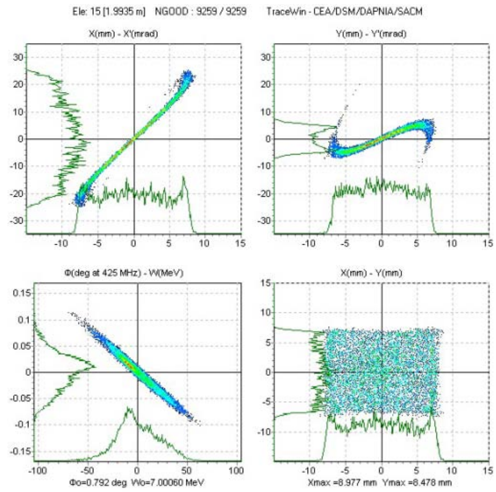



Figure 6: Computed beam on target phase spaces and distributions with octupoles on.

We designed the two octupoles by using the POISSON code and committed their machining to an external workshop. The main characteristics are reported in table 2 and the photo in figure 7 shows one of the two octupoles ready for the installation on the TOP injector beam line.

Table 2: Main octupoles parameters

| **Parameter** | **Value** |
|---|---|
| Maximum tip field | 5000 gauss |
| Ampere turns for the max. tip field | 2140 Amp-turns |
| Internal radius | 19 mm |
| Effective length | 200 mm |

Figure 7: One of the two octupoles to be installed on the TOP linac injector line.

## REFERENCES

[1] C. Cianfarani et al. "Status of the TOP linac project", Proceedings of ACCAPP05 Conf. (29 Aug.-1 Sept. 2005, Venice, Italy), NIMA562, 2006, 1060-1063

[2] R. Duperrier, N. Pichoff, D. Uriot, in Proceedings of the International Conference Computational Science 2002, Amsterdam,(Springer-Verlag, Berlin, 2002).