PROGRESS IN THE DEVELOPMENT OF THE TOP LINAC

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Abstract

The TOP Linac (Oncological Therapy with Protons), under development by ENEA and ISS is a sequence of three pulsed (5 µsec, 300 Hz) linear accelerators: a 7 MeV, 425 MHz RFQ+DTL (AccSys Model PL-7), a 7-65 MeV, 2998 MHz Side Coupled Drift Tube Linac (SCDTL) and a 65-200 MeV, variable energy 2998 MHz Side Coupled Linac (SCL). The first SCDTL module is composed by 11 DTL tanks coupled by 10 side cavities. The tanks has modified to overcome vacuum leakage that occurred during brazing, and now the module has been completed, and is about to be ready to be tested with protons. The 7 MeV injector will be installed in September at the ENEA Frascati laboratories for preliminary test, before being transferred to a large oncologycal hospital in Rome (Istituto Regina Elena or Ospedale S. Andrea).

INTRODUCTION

Protontherapy is nowadays a reality in the oncologycal radiotherapy and several accelerators are being developed worldwide for this application, but they are mainly cyclotrons and synchrotrons while the accelerator described in this paper is the only linac. The reasons why walking this unusual road are: the modularity of the construction, as the linac can be expanded in at least 3 steps, each of them able to be operated for a specific task, the compactness, as the linac extends in the area used by beam transport lines in other types of machine, and the flexibility, as a fully 3D scanning irradiation with energy, current and position variable on a pulse-to pulse basis is possible.

Moreover, the use of 3 GHz accelerating structures in a large part of the machine makes the use of the facility closer to the electron conventional radiotherapy accelerators as to time structure, maintenance and dosimetry.

The TOP (Terapia Oncologica con Protoni) Linac [1] is a proton medical linac designed to produce at least the following beams (fig. 1):

- a 7 MeV, 700 W beam for F-18 radioisotope production;
- a 65 MeV, 10nA (average) beam for proton eye therapy;
- a 100-200 MeV, 10 nA (average) beam for deep seated tumours proton therapy.

The linac is composed of a 7 MeV 425 MHz injector, a 7-65 MeV 3 GHz linac booster, named SCDTL (Side Copled Drift Tube Linac) from the accelerating structure name, a second 65-200 MeV 3 GHz linac booster named SCL, and the various beam lines to the application rooms. The time structure is pulsed with typical hundreds of Hz rep rate and a few µs pulses. The fully 3-D scanning irradiation of deep seated tumours requires a beam whose position, energy and pulse charge can be varied on a pulse-to pulse basis, that is energy between 130 and 200 MeV, pulse current between 0.1 and 10 µA (a factor 100) and pulse duration between 1 and 5 µs pulses at 100-250 Hz repetition frequency.

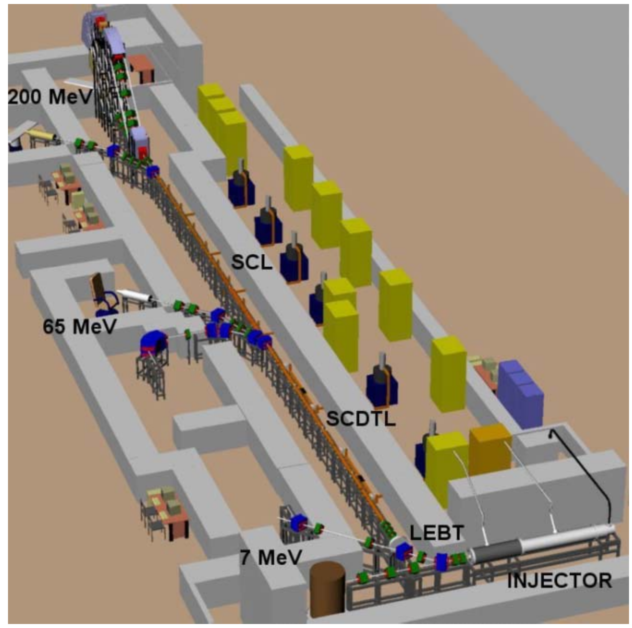

Figure 1: TOP Linac design layout.

The design [2] was developed by ENEA in collaboration with CERN, INFN and TERA and it was approved by ISS (National Institute of Health) and funded in 1997 but only with about 4.5 M€ against the 22 M€ estimated for the high technology devices of the facility. Despite this, construction started within a cooperation agreement between ENEA and ISS and installation was agreed to be done in Rome at a large Oncologycal Hospital. Up to now unfortunately no additional funding has been available so that work is carried on at ENEA Frascati laboratories, where a proper temporary site was set up for the first machine tests, up to 20 MeV. Interest for the installation has been evidenced by S. Andrea Hospital in Rome.

THE 7 MEV LINAC INJECTOR

The injector linac was bought from AccSys Inc., USA. It is a PL-7 model modified to meet the TOP requirements [3]. It is actually installed in a test bunker at Frascati and scheduled to be put in operation in September. It will be used for three main purposes: Fluorine-18 production (F-Mode, high current), Protontherapy beam injection and radiobiology experiments (P-mode, low current). In the high-current mode the pulse current will be 8 mA for 60 µs and 60-100 Hz rep. rate. In the low-current mode the pulse current will be variable between 1 and 30 μA for 7 μs and up to 250 Hz rep. rate.

The injector linac is composed of a pulsed 30 keV duoplasmatron proton source a 3 MeV RFQ and a 4 MeV DTL. The total length is 4.6 m. The source is followed by a single einzel lens and a water-cooled current limiting aperture that can be inserted by remote control to reduce the linac current by a factor of 100 for operation in the proton therapy mode. The two main 425 MHz RF amplifiers, one for RFQ and the other for DTL are based on a parallel arrangement of twelve EIMAC YU176 tubes. The injector was successfully tested at factory [4]. In protontherapy mode up to 300 Hz (maximum flat top pulse length of 2 μs), and steadily at 250 Hz with flat top of 7 μs. It is possible to vary the pulse current by a factor more than 100 acting on the ion source arc voltage, gas pressure and magnet current, on the Einzel lens voltage combined with the limiting aperture. Another factor of 4-5 can be obtained by an appropriate phasing of injection line cavities.

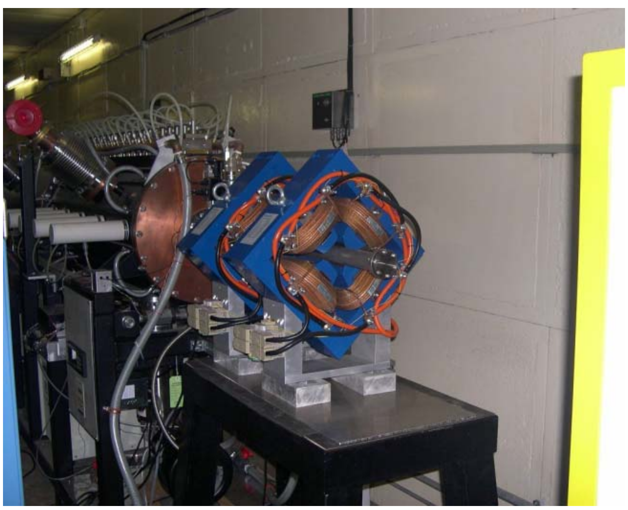

Figure 2: PL-7 Injector linac at CR Frascati.

As to the F-mode, numerous radioisotope production tests at 7 MeV confirmed the possibility of F-18 production rate of about 1 Ci for 2 h irradiation time. In the test arrangement at CR Frascati (fig.2) in a 1-m wall thickness bunker, a couple of quadrupoles has been installed to size the beam on F-18 target, which will be placed inside a polyethylene-lead beam dump.

7 MEV LEBT

In the reference layout of the TOP linac (fig. 1), after the 7 MeV injector 2 quadrupoles are placed, and then the high current beam can go straight to the radioisotope production (shaped by using other quadrupoles and eventually octupoles to flatten the beam distribution on target) while the low current beam is transferred, through the LEBT to the following accelerating sections. The LEBT is composed by a 90° achromatic bend system to preserve the horizontal emittance, and a sequence of two RF cavities and four quadrupoles to adapt the total beam phase space to the SCDTL acceptance. The longitudinal matching is obtained by allowing the bunch to lengthen to much more than one 2998 MHz RF period, under the velocity spread, and then by using two RF cavities, the first (425 MHz, 65 KV) reducing the beam energy spread and the second (2998 MHz, 16 KV) for re-bunching at 2998 MHz to increase the beam capture in the SCDTL. An aluminium model of the 425 MHz cavity, has been built. The 3 GHz prebuncher has been realized (fig. 3).

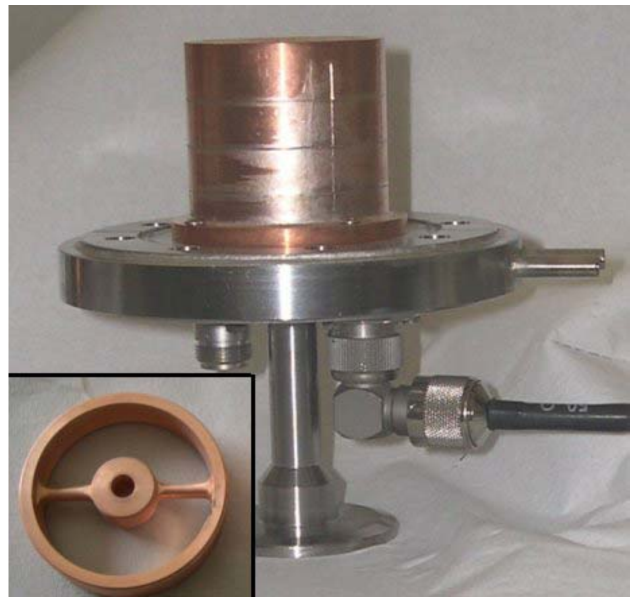

Figure 3: 3GHz prebunching cavity. In the frame the drift tube-stem. Cooling is achieved by contact with CF flange.

It is a three-gap cavity with slanted noses drift tubes each supported by a couple of 4 mm diameter stems. It is bolted to a cooled CF flange where also the connectors to RF input and pick-up loops are placed. The geometry is a compromise between efficiency due to transit time factor (larger gaps) and multipactoring suppression (shorter gaps) at the given voltage. In fig. 4 the measured field on axis is shown. The Superfish Qo value increased, as usual by 25% is 5500. First measurements indicate a similar value. In this condition, 20 kV require 750 W of RF power.

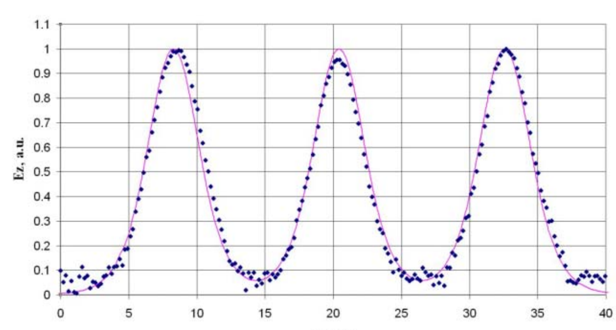

Figure 4: 3GHz prebunching cavity field on the axis: dots are measurements, continuous line is Superfish output.

SCDTL 7-65 MEV

The Intermediate energy (7-65 MeV) part of the TOP Linac is a 3 GHz linac booster bases on the SCDTL (Side Coupled Drift Tube Linac) accelerating structure, that was developed to satisfy the requirement of a high shunt impedance in the low-beta part of the TOP Linac. According to the original design the SCDTL tanks are grouped in seven modules of similar length (around 1.4 m each): the first three boost the energy to 30 MeV and the other four to 65 MeV. A total RF power of 7.5 MW is required, that should be given by two klystrons. An alternative scheme switching at 30 MeV to the easier structure SCL (Side Coupled Linac), tolerating the RF power increase (about 10 MW) due to the lower shunt impedance of SCL at these energies.

The SCDTL structure has been described in several papers [1, 3]. It consists of short DTL tanks coupled together by side cavities. The DTLs are short tanks, each having 5 to 7 cells of $\beta\lambda$ length, and the side cavity extends in a space left free on the axis for the accommodation of a very short (3 cm long, 2 cm o.d., 6 mm i.d.) PMQ (Permanent Magnet Quadrupole) for transverse focusing.

All tanks and coupling cavities of the first module (7-13.4 MeV, 1.32 m long, 11 DTL tanks, 5 cells per tank) were built. All the intermediate brazing steps were performed but for the final braze. The whole structure was bolted and measured on RF bench [1]. With the structure correctly tuned at the proper frequency the electric field was adjusted with tuning screws in the coupling cells to obtain the axial distribution uniform within ±2% among the 11 average tank fields and ±5% among the 55 cells fields. Unfortunately, vacuum leakage occurred during the intermediate brazing steps in about 40% of the tanks. The reason was that cooling channels were obtained by a complicated manufacture of the stem/drift tube assembly as described in a previous paper [5], and some brazing alloys re-melted and opened a leak just on the drift tube. As this was not recoverable, major modifications were introduced in the stem/drift tube manufacture of all the tanks. The final shape is shown in fig. 5 on the right.

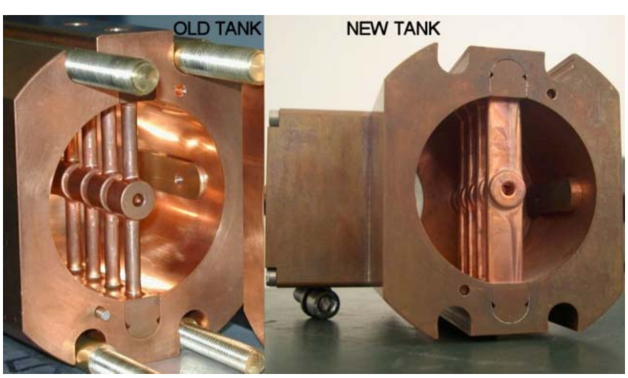

Figure 5: SCDTL tank: old stem (Left), new stem (right).

The stem and drift tube are machined from a solid piece and two parallel 1.5 mm diameter holes are drilled trough the 60 mm long rectangular stem with smoothed edges, for the coolant flow. Each stem is then TIG welded to the tank outer surface to provide for vacuum/coolant tightness, while thin channels are drilled at the inner surface of the tank body and filled with brazing alloy that will melt during final braze and will provide the correct electric contact between surfaces. Due to some manufacture delay, not all tanks are ready; the ones already manufactured have been measured and are within the frequency specifications. The structure is expected to be completed within this year.

Passing from the old to the new structure one of the prices to pay is that shunt impedance lowers by 12%. Due to the however high shunt impedance, this increment does not seem harmful, and the structure is much safer and we are confident that this task will be carried out without other problems.

SCL 65-200 MEV

The development of the final part of the TOP Linac has been left to a second priority. It will be based on conventional SCL structure at 3 GHz, suitably graded to follow the particle velocity. A prototype of a similar structure was built in 2002 by the TERA group [6]. Also in this case the cavities are grouped in tanks and connected by bridge couplers. Several klystrons are foreseen to manage the peak Required RF peak power is in the range of 30 MW and the total length is about 12 m.

CONCLUSIONS

The temporary site (a 20 m long bunker) in ENEA Frascati Laboratory is now available, and the injector has been installed and will be put in operation in September. Almost all the components of the 7 MeV LEBT are ready. Within a few months the first module of the SCDTL structure will be completed, and if the cold test are passed, a beam line will be arranged to test it with the 7 MeV protons from injector. Any future development is subjected to the definitive funding of the total project.

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