THE TOP - ISS LINEAR ACCELERATOR: A HIGH FREQUENCY PROTON LINAC FOR THERAPY[1]

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Abstract

The Italian National Institute of Health (Istituto Superiore di Sanità, ISS), has recently (Dec. 1995) decided the construction of a proton linac for its TOP (Terapia Oncologica con Protoni) project. It is close to the Compact High Frequency Linac, envisaged by the TERA foundation for proton therapy. The TOP linac will be composed of a 428.3 MHz 7 MeV RFQ+DTL injector followed by a 7-70 MeV section of the innovative 3 GHz SCDTL structure and a 70-200 MeV variable energy SCL 3 GHz structure. This machine, whose construction will begin in 1996, will be the first linear accelerator dedicated to proton therapy, and the first 3 GHz proton linac ever built. In this paper the accelerator design and the construction schedule will be described.

1 THE TOP PROJECT

The Italian Hadrontherapy project, leaded by Prof. Amaldi, started in 1993 with the aim of designing and building a big centre named CNAO [1] for proton and ion therapy, connected to a distributed network of smaller protontherapy centres equipped with so-called compact accelerators. An analysis of the type of accelerator particularly suited to this application and to be built in Italy was carried on in the years 1994-1995. It showed two possibilities (among four studied), both of them widely innovative in the accelerator field: a very compact superconducting cyclotron and a high frequency linear accelerator.

In the meantime the Italian National Institute of Health (ISS) got approved a project on the "development of the use of protons in oncologycal therapy", shortly TOP (Terapia Oncologica con Protoni) which foresaw the construction of a compact proton accelerator prototype. The study on the accelerators was examined by the ISS which approved in Dec. 1995 the construction of the linac. In the study, the cost of the linac without gantry and bunker was estimated less than 9 MKLit, if designed and built by Institutions and Universities. The ISS project up to now has been partly funded, (this making more evident the choice for a machine that can grow in energy and performances with the money flux) and the first actions will regard acquisition of the injector, SCDTL design and bunker construction. A number of official collaborations between ISS and other institutions like ENEA, is being set up, to use at the best all Italian competencies for the TOP project.

2 LAYOUT OF THE TOP - ISS PROTON LINAC

Fig.1 shows the layout of the TOP linac without the gantry system.

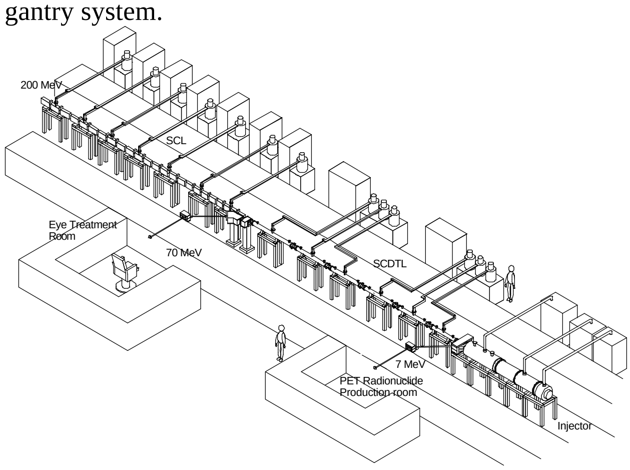

***Figure 1**. Layout of the TOP - ISS proton linac*

The linac is composed of four main parts: the injector, the SCDTL, the SCL, the beam delivery system. In fig.1 the various parts are connected straight, the total length is about 25 m, and this is the best layout both from the point of view of acceleration, and of the ISS site, but other schemes were investigated, like a 180° bend (in vertical or horizontal plane) to compact the accelerator.

The general concept at the basis of the design is to use, as much as possible, a frequency as high as 3 GHz, although this is quite unusual for protons. Most proton linacs operate with intense beams and must therefore have large apertures, which is incompatible with very high frequencies, but for tumour treatments, however, very weak intensities are required (the average beam currents are only about 10 nA), and therefore the 3 GHz technology is applicable. This technology is very well known in radiotherapy divisions of hospitals and tends to reduce drastically the costs and the size of the proton accelerator. At this end we introduced a novel structure (SCDTL) which permits to extend the use of the 3 GHz technology even to beam energies of only 5 MeV.

[1] Work supported by INFN-Ater Project

ISS program plans to build an accelerator working not only for radiotherapy. Accordingly, the layout presented here is for three main uses: protontherapy, PET radioisotope production and radiobiology studies. Switching the beam to the last two applications poses some problems to the layout, that can anyway be overcome.

The intrinsic pulsed nature of the linac suggests strongly the use of active scanning system. Moreover the last part (70-200 MeV) has been designed to produce a continuously variable energy beam, thus promoting a xyz scanning. This requires a pulse repetition rate as high as possible (≥400 Hz) to irradiate a single pixel at least twice during a 1 min treatment, and a precise control (2-3 % in a relative intensity range of 50-100) of the dose rate of the single pulse. This must be achieved in the source control.

3 INJECTOR

TERA collaboration [2] studied a 5 MeV 750 MHz multisection resonantly coupled RFQ for injecting in SCDTL, that remains a reference point for the TOP linac. However now, as said, the injector has to serve three purposes: protontherapy, radiobiology and PET radionuclide production. The first two are low current applications, while the third high. The beam will go straight for the protontherapy and will be bent by a "switching magnet" to a separate room for the other applications. The injector (table 1) will operate at a subharmonic of 2.998 GHz, the higher, the best, but at present only the 7th (428.3 MHz) seem able to provide enough current for PET; if only for protontherapy, the frequency could be raised to 750 MHz.

Table 1: Main Injector Parameters

	Proton therapy	PET	Radio-biology
Energy, MeV	7	7	≤ 7
Max. Ave. Current, µA	0.1	100	0.001
Rep Frequency, Hz	400	100	10 - 400
Pulse Duration, µs	5	100	5
RF Frequency, MHz	428.3/750	428.3	428.3

The energy has been fixed to 7 MeV for a compromise between costs and the possibility of producing PET radioisotopes: this can happen at 100 µA level average currents, available without difficulties. Only the switching magnet ON will allow the control system to set the high-current mode. From first contacts with US firms, the 428 MHz injector will be composed by a proton source, a RFQ and a DTL for a total length of about 4.5 m. It will be able to change pulse-by-pulse the current in the low-current mode, assuring the required precision and dynamics.

The 750 MHz RFQ studied by TERA was completely matched to the SCDTL acceptance, having a normalised transverse emittance of 0.2π mm mrad and a longitudinal emittance of 0.15 π deg MeV with the phase space ellipse having semi-axis of 5 deg (20 3-GHz-deg) and 0.03 MeV. In ISS case while the transverse emittance can be almost the same, the longitudinal emittance has been evaluated having semi-axis of 80 3-GHz-deg and 0.06 MeV at the SCDTL entrance, including the bunch lengthening due to a 30 cm drift between injector and SCDTL needed to place the switching magnet.

4 SCDTL STRUCTURE (7-70 MEV)

The SCDTL [3] (Side Coupled Drift Tube Linac) structure is described in details in another paper of this Conference [4]. It is on the same development line of other high frequency intermediate energy structures for protons[5]. It consists of short DTL tanks coupled together by side coupling cavities and each one followed by a 3 cm long permanent magnet quadrupole for focusing. This structure has been chosen due to its better shunt impedance for β<0.4 (energies below 85 MeV) with respect to a standard SCL. The output energy has been chosen as 70 MeV, because this is the energy required to cure eye melanomas and therefore a 70 MeV beam will be transported to the corresponding treatment rooms.

The tanks are grouped in independently powered six modules with output energies of 16, 25, 36, 46, 57, 70 MeV. Modules are composed of an odd number of tanks, are shorter than 2 m, and require less than 1.3 MW RF peak power. At the moment, we plan to use six 1.5 MW klystrons powered by only two high voltage modulators, but fed each one by an single solid state amplifier.

Table 2: Main SCDTL parameters

Frequency (MHz)	2998
Input-Output Energy(MeV)	7 - 70
Length (m)	11
# of modules	6
# of tanks per module	15, 9, 9, 7, 7, 7
# of cells/tank	5, 6, 7
Intertank space (βλ/2)	7, 5, 3
Bore hole radius (mm)	2, 2.5, 3
Average Field (MV/m) (Eo)	12
Effective Accelerating Field (MV/m) (EoT)	8.5
Average Energy Gain (MeV/m)*	5.7
PMQs gradients (T/m)	200-150
Max. Kilpatrick Factor	1.6
Peak Power (MW) (25% margin included)	8

* includes dead space for PMQs

The dynamics simulations show no growth in the transverse emittance (0.2 π mm mrad). The longitudinal phase acceptance is 40° RF and the longitudinal emittance is 0.6 deg MeV, being the semi-axis 0.13 MeV and 4.4 ° RF. The current needed for protontherapy was fixed to be lower than 20 nA, that already takes into account the losses in a passive distribution system. This corresponds to a 5 µs pulse current of about 10 µA at a rep. rate of 400 Hz. Dynamics calculations indicate a SCDTL 100% capture up to 5 pC charge/bunch at 3 GHz. The corresponding maximum pulse current for a 428 MHz injector is more than 2 mA much larger than the required 10 μA. As a note, a nine-fold value current could be obtained if the matching to the injector were optimised for high current.

An accurate error study in the SCDTL showed that some care must be given to the alignment tolerance on the PMQs, especially in the first section of the SCDTL, which has a bore radius of 2 mm and accelerates the beam from 7 to 16 MeV. The alignment tolerances on the quadrupoles are ± 0.05 mm. Opening up the bore in this section to 2.5 mm does not help because the beam cannot be allowed to stray relatively far off axis. Some first PMQs (20 mm o.d., 6 mm i.d., 200 T/m) are in construction at ASTER Ent. (USA) and an alignment bench will be set up. Moreover, diagnostics between modules is foreseen. Anyway the final PMQs alignment will not be done to a perfectly straight line but to a smooth curve fitted to the centres of all the PMQs. The electric field tolerances seem to be reachable: ± 2% for the electric field amplitude and ± 3° RF in phase.

5 SCL STRUCTURE (70-200 MeV)

A magnet will bend the beam at 70 MeV to the eye treatment room. At magnet OFF, the beam will go straight in the SCL, a beta-graded structure providing the acceleration to 200 MeV. The structure will be grouped in seven independently powered modules (5 MW klystrons), the lower-energy 3 ones composed of 4 tanks and the higher-energy 4 ones composed of 3 tanks. The tanks are connected inside a single module by bridge couplers; between tanks PMQs are placed. Switching on/off the single modules gives a stepwise energy variation. The fine energy variation is achieved by amplitude variation in the last module still under power; this method gives a pretty smooth energy variation with a small energy spread (0.4% - 0.2%) in the range above 130 MeV (last four modules).

Table 2: Main SCL parameters

Frequency (MHz)	2998
Input Energy (MeV)	70
Output Energy (MeV)	200
Length (m)	11
# of modules	7
# of tanks (total)	24
# of cells/tank	17
Intertank spacing (βλ/2)	3
Bore hole radius (mm)	3
Average Accelerating Field (MV/m) (Eo)	15.5
Effective Accelerating Field (MV/m) (EoT)	13.5
PMQs gradients (T/m)	117-88
Average Energy Gain (MeV/m)	11.8
Max. Kilpatrick Factor	1.8
Peak Power (MW) (15% margin included)	26

Also in the SCL the dynamics simulations show no particle losses and no growth in the transverse emittance (0.2 π mm mrad). The longitudinal emittance is still 0.6 deg MeV, with the semi-axis equal to 0.2 MeV and 3° RF.

Error study showed that also here the most severe error is the quadrupole displacement, but tolerance is larger, ± 0.1 mm in which case there is 90 % probability that less than 1% of the beam is loss, which is fully satisfactory. The SCL electric field tolerances are ± 2% for the electric field amplitude and ± 3° RF in phase.

6 BEAM DELIVERY

One of the advantages of this high frequency linac is the small beam emittance (< 0.25 π mm mrad) which allows the use of a lightweight gantry (about 16 tons compared to 90 tons gantry used in Loma Linda) and small transport elements. The gantry, already proposed for CNAO synchrotron, is compact in the longitudinal dimension (5.5 m) but not in radial (10.4 m dia.). Anyway, a study of other unconventional systems tending to reduce costs, dimensions and complications of present built gantry and nozzle systems (CIGNUS) [6] is under way in the Hadrontherapy collaboration for the use both in CNAO synchrotron and in the protontherapy centres that should be equipped with as much as possible compact gantries.

7 CONCLUSIONS

The proton linac in course of development for the Italian National Institute of Health (ISS) has been briefly described. The design was originated under the Hadrontherapy Collaboration, but then was adapted to the requests of ISS. The ISS funds will be used this year and next to buy the injector linac, to built and to test a prototype of the first module of SCDTL, and to complete the machine design.

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