BEAM INJECTION STUDY OF THE TOP LINAC USING AN ACCSYS MODEL PL-7 LINAC

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ABSTRACT

A new scheme has been developed for injection of the 7 MeV proton beam from an AccSys Model PL-7 linac (RFQ + DTL) into the 2998 MHz TOP (Therapy Oncological Protons) 200 MeV linac (SCDTL + SCL). Unlike previous versions, this new design eliminates the requirement to synchronize the rf frequencies of the two accelerators and therefore eliminates the need to phase lock them. The injector linac rf frequency will not be fixed at the seventh subharmonic (428.3 MHz) of the 2998 MHz SCDTL frequency but will be at the standard Model PL-7 frequency of 425 MHz. As a result of this large frequency difference, the beam injected in the SCDTL can be treated as a d.c. beam, with two cavities (one at 425 MHz and one at 2998 MHz) used to optimise the particle capture. In this study, the longitudinal and transverse matching have been optimised for efficient injection to reduce the beam losses between the two accelerators and the consequent material activation. This paper presents the beam dynamics design results.

1. INTRODUCTION

ENEA, in collaboration with ISS (National Institute of Health), is developing a proton accelerator dedicated to medical applications, the Terapia Oncologica con Protoni (TOP) Linac. It will be a pulsed (5 μs, 300 Hz) proton accelerator composed of a sequence of three linear accelerators[1]: a *7 MeV, 425 MHz Injector linac*, a *7 - 65 MeV, 2998 MHz linac* for which a new type of 2998 MHz accelerating structure, the Side Coupled Drift Tube Linac (SCDTL) has been patented, and a *65 – 200 MeV, variable energy 2998 MHz Side Coupled Linac (SCL).* The SCDTL output will be used for proton treatment of ocular melanoma and for radiobiology studies and the SCL output will be dedicated to proton treatment of deep seated tumours.

The injector linac will be used in three modes:

- injecting particles into the TOP Linac accelerating sections **(PROTON THERAPY MODE - P mode)**;
- generating an intense proton beam to produce the positron-emitting radionuclide ^{18}F for PET analyses **(^{18}F - PRODUCTION MODE - F mode)**; and
- generating a low intensity, variable energy beam for radiobiology and material analysis studies **(RADIOBIOLOGY MODE - R mode)**.

The technical specifications for these three operating modes are listed in Table 1.

Table 1 : Operating modes of the TOP injector linac

P – MODE	
Energy	≥ 7 MeV
Pulse duration (flat-top)	7 μsec
Pulse current (adjustable)	3 – 30 μA
Pulse-to-pulse current setting	10 - 100 %
Repetition frequency (variable)	50 - 300 Hz
Norm. transverse emittance (90% of the beam)	≤ 0.6 π mm mrad
Energy spread (90% of beam)	≤ ±100 keV
F – MODE	
Energy	≥ 7 MeV
Average current	≥ 70 μA
^{18}F production - (120 min run)	1 Ci EOB
Norm. transverse emittance (90% of the beam)	≤ 1 π mm mrad
Energy Spread (90% of beam)	≤ ±150 keV
R – MODE	
Energy (variable)	3-7 MeV
Beam current	P-mode values

An AccSys Model PL-7 system modified to meet the TOP linac requirements has been purchased as the injector linac. The order was placed in December 1999 and the unit will be delivered to Italy by December 2000.

2. THE TOP LINAC INJECTOR

The standard AccSys Model PL-7 consists of a pulsed 30 keV duoplasmatron proton source, a low energy beam transport (LEBT) consisting of a single einzel lens, a 3 MeV, 2.3 m long RFQ and a 0-4 MeV, 1.6 m long variable energy DTL. Both of the accelerating structures operate at a frequency of 425 MHz.

Normal operation of the Model PL-7 is with a pulsed beam current of 10-15 mA. Low current operation (P and R-modes) is implemented to meet the TOP linac requirements by insertion of a water-cooled current limiting aperture before the RFQ to limit the beam current injected into the linac. The ion source output can be varied from 1-2 mA up to 15 mA using the arc voltage, gas pressure and magnet current, and the einzel lens voltage is used to rapidly vary the current through the aperture by another factor of 10-20. A programmable, pulsed high voltage power supply allows pulse-to-pulse variation of the beam current through the aperture. The system interlocks do not permit operation of the injector in the P-mode without the aperture inserted.

2.1 Beam dynamics in the injector

The beam dynamics calculations in the injector linac were performed with PARMULT and PARMILA using 100,000 macroparticles in the input beam. The low current aperture is 1.59 cm long, with the aperture bore tapered from 0.78 mm to 0.47 mm diameter. The normalized transverse emittance and energy spread (90% of the beam) calculated at the output of the DTL are listed in Table 2 for several output beam currents. The mismatch induced by current variation in the low-current mode does not appreciably degrade the beam quality.

Table 2. Computed emittances and energy spread at DTL output

Input I (mA)	DTL I (μA)	V_{lens} (kV)	ε_x π mm mrad	ε_y π mm mrad	ΔE (keV)
1	1.2	~20.0	0.066	0.058	90.8
1	3.1	~23.0	0.068	0.071	85.4
5	6.2	~25.0	0.302	0.283	81.2
10	9.9	~23.0	0.58	0.55	80.8
10	15.5	~25.0	0.62	0.51	82.2
10	21	~26.0	0.55	0.54	84.0
10	26.2	~26.8	0.53	0.57	78.7
10	30.1	~27.0	0.52	0.56	79.2
16.5	15250	~28.5	0.5	0.58	60.5

3. INJECTION SCHEME

In an earlier proposed injection scheme[1], the Model PL-7 was to be operated at 428.3 MHz (the 7th subharmonic of 2998 MHz) to match the phase of every bunch entering the SCDTL. This scheme required the phase stability of the injector linac to be ±2° at 428.3 MHz so that the maximum allowable RF phase jitter at 2998 MHz would be ±14°.

This constraint has been overcome by adopting a different injection scheme. By allowing the bunch from the Model PL-7 to lengthen to much more than one 2998-MHz RF period in the transport line, synchronous operation is no longer needed. This simplifies the RF system and drops the requirement of changing the operating frequency of the Model PL-7. The decrease in capture efficiency is recovered by utilizing two cavities for longitudinal matching into the SCDTL.

3.1 Longitudinal matching into the SCDTL

The 2998 MHz SCDTL structure has been previously described[1,2] and its present status is reported at this conference[3]. The SCDTL longitudinal phase and energy acceptance is about 60° and ±100 keV respectively. The longitudinal area occupied by the beam at the injector output is not matched to the SCDTL acceptance, because the bunch length is 120° at 2998 MHz. For this reason, in the case where the two RF systems are phase locked and the two accelerators are closely coupled, longitudinal dynamics calculations show that the capture would only be 44%. If a phase shift occurs, the capture decreases (to zero for 100° phase shift) because the injected beam is shorter than one 2998-MHz wavelength. Moreover, a drift space between the injector and the SCDTL is required for a switching magnet to bend the beam into the beamline for the other applications. This causes an increase in the bunch length due to the velocity spread that in turn lowers the capture efficiency even more. After only 1.5 m, the efficiency drops to 15% but remains constant at longer drifts because the bunch is longer than one 2998-MHz RF period. If the two accelerators are not phase locked, two RF cavities can be used to recover the capture efficiency: the first operating synchronously with the injector at 425 MHz and the second operating synchronously with the SCDTL at 2998 MHz. The first cavity reduces the energy spread of the injector beam after a drift space and is designated the Energy Spread Compression (ESC) cavity. The second is a prebuncher because it receives practically a continuous beam (that is a bunch much longer than one wavelength) which is re-bunched at 2998 MHz to increase the beam capture in the SCDTL.

3.2 Transverse matching

The injection line design is shown in figure 1. The beam is either bent by a magnet for radioisotope production or proceeds straight for injection into the SCDTL. The quadrupoles required for focusing the beam and transversely matching it to the SCDTL are shown. The TRACE3D transport elements are listed in Table 3.

The transport line parameters were optimized for the input Twiss parameters of a 9.9 μA output beam current from the DTL and the calculations were then repeated for the injector output conditions corresponding to 3-30 μA. These calculations show that this design is suitable for the entire P-mode operating current range.

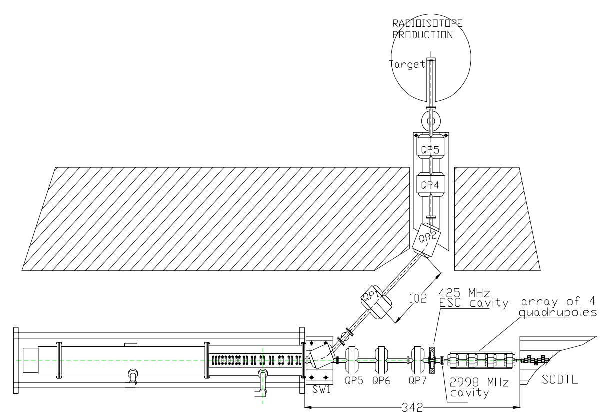

Fig. 1. TOP injection line.

All quadrupoles have a magnetic length of 10 cm, and a gradient lower than 30 T/m.

The calculated beam envelope shows that the beam has a maximum diameter of 30 mm in the first part of the channel (up to the ESC cavity) and 20 mm in the second part. This beam size reduction allows smaller dimensions for the quadrupoles.

3.3 Beam dynamics results

After TRACE3D optimization, the beam dynamics were computed in the transport line by PARMELA and in the SCDTL by LINAC[4]. Figure 2 shows the beam longitudinal phase space plots at several positions.

It should be noted that the 15 cm length of the drift after the prebuncher cavity allows a moderate gap voltage (21.5 kV) to be used in the cavity. Keeping this voltage low is very important in reducing the emittance increase due to the different transverse kicks received by the particles in the bunch as they travel through the cavity at different RF phases, since these kicks are proportional to the cavity voltage. For a comparison, the same longitudinal bunching is achieved with a gap voltage of 100 kV and a 30 cm drift but the emittance at the SCDTL input doubles.

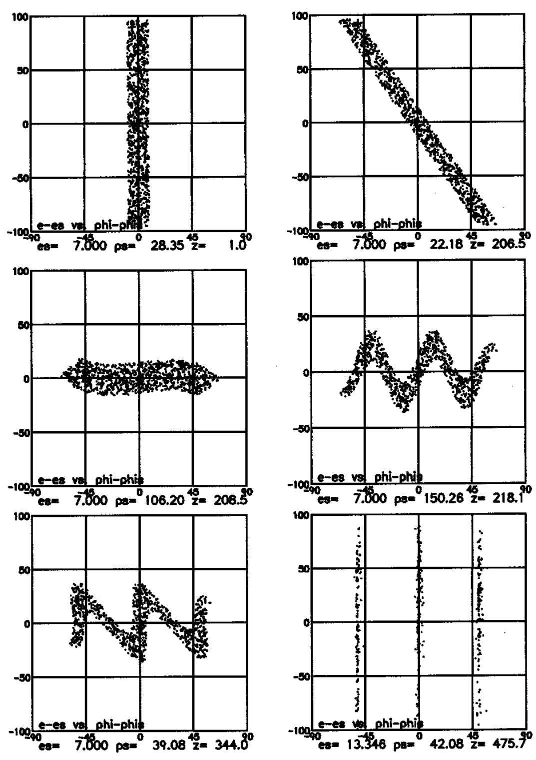

Fig. 2: Beam evolution in the transport line (phase is in 425 MHz degrees): a) at 1 cm after the injector; b) at ESC input; c) at the ESC output; d) at the prebuncher output; e) at input to first SCDTL module; f) at the output of first SCDTL module.

To calculate the real SCDTL particle capture the phase between the two RF systems (425 MHz and 2998 MHz) has been varied. The average capture when both cavities are operating is 39%. The calculation was repeated with the same quadrupole settings if one or both cavities are switched off. The results are shown in fig. 3: it can be observed that when the ESC cavity is on and the prebuncher is off the capture is slightly higher than in the case when the ESC cavity is off and the prebuncher is on. In this second case in order to reach a capture of 17% it is necessary to double the electric field amplitude in the prebuncher cavity.

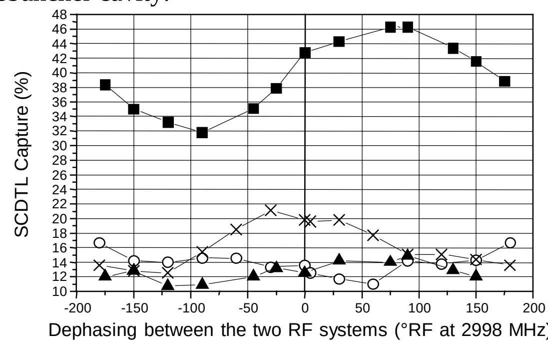

Figure 3 SCDTL Capture versus the phase between the two RF systems: ■ ESC on, PB on, ○ ESC off, PB off , × ESC on, PB on, ▲ ESC off, PB on

In addition, the combined use of the two cavities in the transport channel was explored as a way to change the beam current on a pulse-to-pulse basis. In fact, by correctly de-phasing the cavities, it is possible to vary the beam current by almost an order of magnitude. Calculations show that the beam current can be varied in two ways: by varying the phase between the ESC cavity and injector and/or by varying the phase between prebuncher and the SCDTL (figure 4).

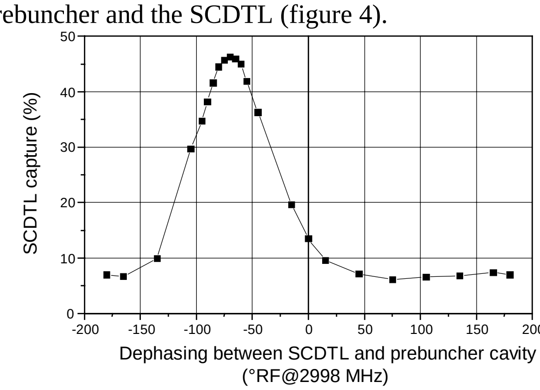

Fig. 4: SCDTL capture as a function of the phase between prebuncher cavity and SCDTL.

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[3] L. Picardi et al. “The first module of the 2998 MHz Side Coupled Drift Tube Linac (SCDTL): numerical studies of RF properties and cold tests results”, these Proceedings.

[4] LINAC-Beam dynamics computer code provided by the author K. R. Crandall (Los Alamos)