HYBRID SCHEMES FOR THE POST-ACCELERATION OF LASER GENERATED PROTONS

C. Ronsivalle, L. Picardi, ENEA C.R. Frascati, Frascati (Roma), Italy,
P. Antici, A. Mostacci, M. Migliorati, L.Palumbo, Sapienza University of Rome, Roma and LNF-INFN, Frascati (Roma), Italy,
D. Alesini, LNF-INFN, Frascati (Roma), Italy

Abstract

Protons generated by the irradiation of a thin metal foil by a high-intensity short-pulse laser have shown to posses interesting characteristics in terms of energy, emittance, current and pulse duration. They might therefore become in the next future a competitive source to conventional proton sources. Previous theoretical and numerical studies already demonstrated the possibility of an efficient coupling between laser-plasma acceleration of protons with traditional RF based beam-line accelerator techniques. This hybrid proton accelerator would therefore benefit from the good properties of the laser-based source and from the flexibility and know-how of beam handling as given from RF based accelerator structure. The proton beam parameters of the source have been obtained from published laser interaction experimental results and are given as input to the numerical study by conventional accelerator design tools. In this paper we discuss recent results in the optimization and design of the such hybrid schemes in the context of proton accelerators for medical treatments.

INTRODUCTION

High-current collimated multi-MeV beams of protons can be generated by back-irradiating thin solid foils with ultraintense (>10^{18} W/cm^2) short laser pulse (30 fs–10 ps). This technique, generating currently protons with the best characteristics in terms of energy , number and laminarity, is called target sheath normal acceleration (TNSA) technique. First experimental results using these proton beams and focusing and energy-selecting them with an ultrafast laser triggered microlens [1] have led to protons characteristics as those reported in Table 1 [2].

Table 1: parameters of the laser generated proton beam using an ultrafast laser-triggered microlens

Parameter	Value
Energy	7.0±0.1 MeV
RMS unnormalized emittance	0.18 mm-mrad
RMS Spot size $\sigma_x=\sigma_y$	20 µm
RMS divergence $\sigma_x'=\sigma_y'$	9 mrad
Number of protons	2 10^9
Charge	320 pC

Laser-based particle acceleration has the advantage of being more compact than traditional accelerators, however, at the moment, the quality of laser-produced beams is not comparable to that using standard RF acceleration for most of the relevant applications, e.g. in the medical field.

A possible way to overcome these difficulties is adopting hybrid schemes where the laser generated protons are further on accelerated and controlled by conventional accelerator structures which adapt the beam in order to fulfil the demanding parameters of different applications. In this paper we discuss the post-acceleration of laser generated protons with state of the art medical LINAC structures.

The post-acceleration of laser-generated proton beams by using conventional linear accelerators has already been discussed and studied numerically [2,3]. In particular numerical studies [2] demonstrated the possibility to accelerate experimentally-measured laser-generated protons from 7 to 14 MeV with a more than 6 meters long 350 MHz drift tube LINAC (DTL). However the allowed injected proton charge was limited by the large emittance growth the beam was undergoing when accelerated.

We propose an optimized design of a compact hybrid acceleration scheme coupling a laser-generated beam to a high frequency (3 GHz) SCDTL (Side Coupled DTL) structure [4] developed in the context of accelerators for protontherapy up to current used in combination with a conventional injector.

POST-ACCELERATION SCHEME

Despite of the very high quality of the laser-generated protons (see Table 1), the large beam divergence angle makes the transport from the source to the accelerator and the focusing within very difficult. Moreover, it enhances chromatics effects, also in absence of space charge.

As to the transport from the source to the booster, the use of a solenoid collimation results preferable respect to the quadrupole collimation [5,6] due to the reduced chromatics effects in the symmetric solenoid focusing system that suppresses large beam transverse deviations. The possibility of using a single pulsed solenoid has been demonstrated in the PHELIX experiment at GSI [7] where a 2.5 MeV laser-generated proton beam has been successfully collimated by a 8 T solenoid field by using a pulsed-power device. Such a device is able to give a magnetic strength up to 16 T sufficient to parallelize 10 MeV protons.

In this paper we have studied a compact post-acceleration scheme consisting in a short focusing system based on a solenoid with the edge placed 17 mm away from the target (likewise in the PHELIX experiment) with the same characteristics of the PHELIX solenoid (length of 7 cm with an aperture diameter of 4.4 cm) followed by a 2998 MHz SCDTL structure placed at 11.7 cm from the solenoid exit boosting the beam from 7 to 15.5 MeV.

The accelerating structure consists of a sequence of short DTL tanks coupled by side coupling cavities with 30 mm long Permanent Magnet Quadrupoles (PMQs) placed in the inter-tanks spaces arranged in a FODO scheme. The original design of this structure, invented to accelerate with high efficiency low beta - low current beams for protontherapy applications injected by a conventional injector at lower frequency, has been revised in order to benefit of the excellent quality of the laser-generated proton beam. The SCDTL structure considered in the present study, whose parameters are summarized in Table 2, has been optimized by the DESIGN code [8].

Table 2: SCDTL structure parameters

Parameter	**Value**
Number of modules	2
Number of tanks/module	11
Number of cells/tank	4
Inter-tank distance	4.5 $\beta\lambda$ in module #1, 4.5 $\beta\lambda$-3.5 $\beta\lambda$ in module #2
Bore radius	2 mm in module #1, 2.5 mm in the module #2
Total length	2.59 m
Average electric field, E_0	11.3 MV/m
Acc. electric field, E_0T	between 7 and 7.75 MV/m
Synchronous phase, φ_s	-30°
Maximum PMQ gradient	220 T/m
RF power for the structure	<1.5 MW

BEAM DYNAMICS SIMULATIONS

The beam dynamics in the post acceleration scheme up to the SCDTL output have been studied with the TSTEP code [9] including space charge effects. The proton source has been modelled by assigning randomly the coordinates of 3 10^5 macroparticles according to the beam parameters reported in Table 1.

The solenoid is modelled as an ideal lens, this means that only the chromatics effects are taken into account, whilst geometric aberrations are not included. The electric fields in the SCDTL are assigned as field maps created by the SUPERFISH code used to design the SCDTL cells starting from the data set found with the DESIGN code.

"Space charge off" calculations

The computed evolution of the horizontal end vertical envelopes and the increase of the reference particle energy in conditions of space charge off are shown in Fig. 1. Due to the large beam divergence, the beam size rapidly increases in the leading drift where the solenoid provides to collimate (slightly focusing) the round beam at the entrance of the SCDTL. The transverse size of the beam is then controlled by the FODO lattice.

The lengthening effect of the bunch (due to the energy-spread in the 20.4 cm long leading drift) is reported in Fig. 2 which shows the longitudinal phase space in three points, namely at the input of the beamline, at the SCDTL input and at SCDTL output. The computed transmission in these conditions is 95.52%, with a rms normalized emittance less than 0.1 mm-mrad. The 81% of the output beam has an energy in the 15.52±0.30 MeV range.

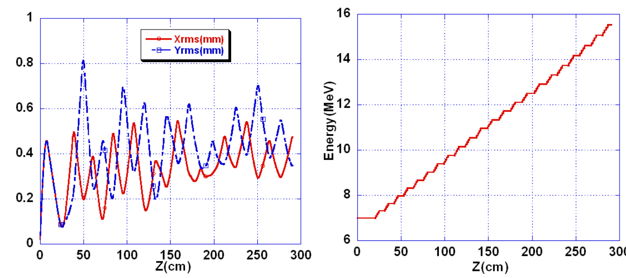

Figure 1: Horizontal and vertical envelopes (left picture) and energy of the reference particle (right picture) along the propagation axis z.

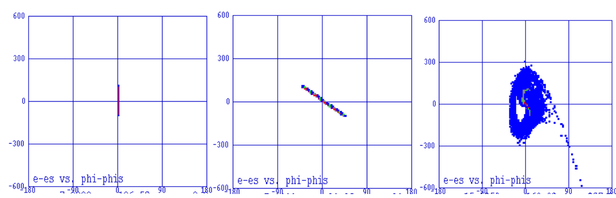

Figure 2: Longitudinal phase space at the initial point (left plot), at the SCDTL input (middle plot) and at SCDTL output (right plot).

The maximum current transportable with this scheme has been evaluated by varying the input current and switching on the space charge in the TSTEP simulations.

Due to space charge, the bunch length and energy spread at the entrance of SCDTL are strongly increased with respect to the case without space charge (middle plot in Fig.2) as it is shown in Fig.3 for an input current of 50 mA; consequently the transmission decreases.

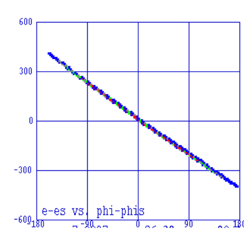

Figure 3 : Longitudinal phase space at the SCDTL input for an input current of 50 mA.

Figure 4 shows the beam current transmission and the final rms normalized emittance versus the input current: the emittance saturates to a value around 0.22 mm-mrad due to the strong reduction of the transmission for input currents larger than 400 mA. The total output current (red bars in Fig. 5) increases with the input current in the range in which the increase of the input current compensates the decrease of the transmission (0-200 mA). The maximum output current is obtained in the range 150-200 mA and reaches a value of about 36mA. The blue bars in fig. 5 indicate the amount of the transmitted current within a window of 0.6 MeV centred around the energy where the particle density is at its maximum: this fraction has been named as "useful current", being the selected energy window sufficiently small for direct applications at the end of the LINAC or for a further acceleration. The maximum value of the useful current is around 13 mA corresponding to about the 36% of the total output current. The number of "unwanted" particles that increase the total output rms emittance and energy spread could be eventually reduced by increasing the focusing in the SCDTL module in order to overfocus the low energy particles, pushing them out of the transverse acceptance of the accelerator.

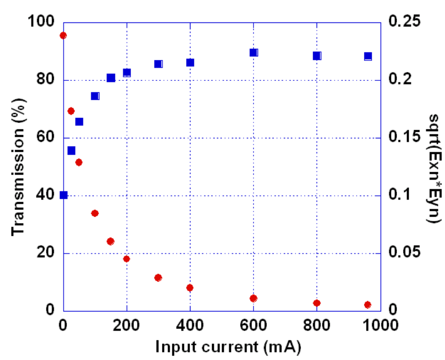

Figure 4: Transmission (red points), output normalized emittance (blue points) versus the input current.

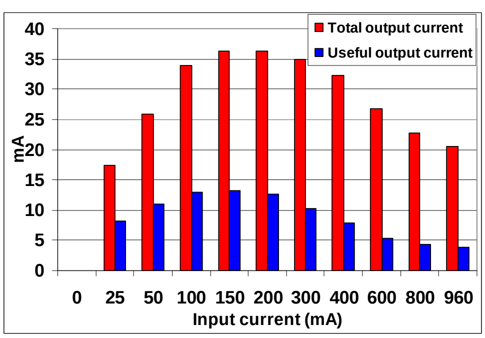

Figure 5: Total output current (red) and useful output current (blue) versus the input current.

The limit in the maximum accelerated useful current in this scheme is given by the strong growth of energy spread and bunch length in the leading drift. Some calculations performed with a reduction of 10 cm in the distance between the output edge of the solenoid and the input of the SCDTL show that the value of the useful current could be doubled in these conditions. Figure 6 comparing the normalized output energy spectra in these two cases for 100 mA of input current shows the sensible increase of the ratio between useful and total current at the end of the LINAC obtainable shortening the drift.

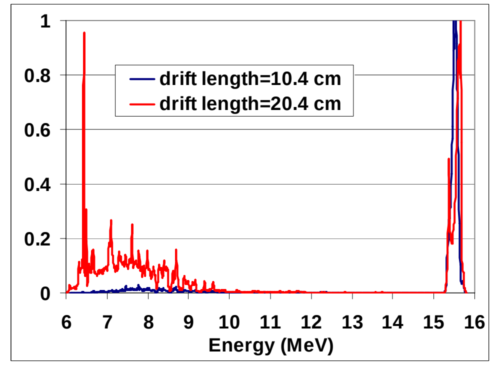

Figure 6: Normalized energy spectrum for 100 mA input current and two different lengths of the leading drift.

CONCLUSIONS

The results of the preliminary study presented here demonstrate that it is possible to couple laser generated protons to a high frequency LINAC in a compact acceleration hybrid scheme.

Future experiments can profit of the novel generation of 300 TW class lasers (e.g. FLAME at the LIFE facility at Frascati [10]) which can reach 10 Hz repetition rate. Assuming that the proton characteristics are comparable to the one given in Table 1, our study shows that a current between 13 and 26 mA (depending on the leading drift length) can be usefully accelerated up to 15.5 MeV in roughly 3 m. A 10 Hz laser repetition rate corresponds to an average current of 43-86 pA of protons that could be used to perform radiobiology experiments (requiring average current around 1-10 pA).

Unfortunately these values are still too low for medical applications such as protontherapy where average current of few nA are required.

A possible improvement surely will concern the reduction of the longitudinal mismatching between the laser proton beam and the LINAC. In order to increase the capture a system of longitudinal matching to be placed between the solenoid and the SCDTL structure is under study: it consists in a "bunch rotation" cavity at 500 MHz compensating the energy spread followed by a harmonic pre-buncher and a set of quadrupoles.

REFERENCES

[1] T. Toncian et al., Science 312, 410, (2006).
[2] P. Antici et al., Jour. Appl. Phys. 104, 124901 (2008).
[3] T. Cowan, E. Colby, AIP Conf. Proc. 647, 135(2002).
[4] L. Picardi et al., "Struttura SCDTL", Patent n. RM95-A000564. See also L. Picardi et al., Proc. of EPAC 06, p.2313 (2006).
[5] M. Schollmeier et al., PRL 101, 055004 (2008).
[6] I. Hoffmann et al. , HIAT09 (2009), http://www.lnl.infn.it/~HIAT09/papers/oral.html
[7] V. Bagnaud et al., Appl. Phys B, DOI 10.1007/ s00340-009-3855-7 (2009).
[8] K. Crandall, DESIGN code, private communication.
[9] L. Young, private communication.
[10] http://www.lnf.infn.it/acceleratori/life