MATCHING A LASER DRIVEN PROTON INJECTOR TO A CH – DRIFT TUBE LINACS

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Abstract

Experimental results and theoretical predictions in laser acceleration of protons achieved energies of ten to several tens of MeV. The LIGHT project (Laser Ion Generation, Handling and Transport) is proposed to use the PHELIX laser accelerated protons and to provide transport, focusing and injection into a conventional accelerator. This study demonstrates transport and focusing of laser-accelerated 10 MeV protons by a pulsed 18 T magnetic solenoid. The effect of co-moving electrons on the beam dynamics is investigated. The unique features of the proton distribution like small emittances and high yield of the order of 10^{13} protons per shot open new research area. The possibility of creating laser based injectors for ion accelerators is addressed. With respect to transit energies, direct matching into DTL's seems adequate. The bunch injection into a proposed CH- structure is under investigation at IAP Frankfurt. Options and simulation tools are presented.

INTRODUCTION

The generation of protons from intense laser-plasma interactions with solid targets is well established [1-6]. Recent developments in laser technology have allowed to achieve focused intensities of up to 10^{21} W/cm^2. Under these conditions, intense protons are accelerated normally from the rear surface of the solid target at electrostatic fields in the order of 10^{12} V/m [3-4]. This acceleration scheme is known as Target Normal Sheath Acceleration (TNSA) [4]. In contrast to conventional accelerators, the laser generated proton bunch can achieve considerably higher peak currents at beam energies of ten to several tens of MeV [1-6] when compared to state of the art injectors like RFQ's. An important topic for a further acceleration of the laser generated proton bunch is the matching into the acceptance of the succeeding RF accelerator. Several projects are proposed in this field, LIGHT is one of them [7,8]. It aims at injecting these protons into a conventional accelerator structures. Due to the available energies, drift tube linacs are the most adequate choice. H-type drift tube accelerators [9-10] seem well suited to accept beam bunches like generated by lasers. A <u>C</u>rossbar <u>H</u>-type (CH) structure is suggested because of its high acceleration gradient, β- range, mechanical robustness, and high shunt impedance [9-10] at the relevant injection energies. The motivation for such a combination is to deliver single beam bunches with quite small emittance values and at extremely high particle number per bunch.

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Laser-proton acceleration offers unique features like very high acceleration gradients of the order TV/m, small longitudinal and transverse emittances as well as a high yield of particles (10^{12} - 10^{13} protons) per shot [1-6]. The results from PHELIX laser experiments and from simulations performed by the Warp code [5-6,11], show that there are some restrictions with respect to a post acceleration of the generated bunches.

At PHELIX protons with energies up to 30 MeV and a total yield of 10^{13} protons were observed [5,12]. The proton spectrum is characterized by a large divergence (± 23° at 10 MeV). This divergence decreases with increasing energy down to ± 8° at 29 MeV [5,12].

This work is focused on matching laser-accelerated protons into a CH-DTL. The paper is divided into two parts; the first one is about the tracking of the proton bunch, including the co-moving electrons, through the magnetic solenoid using the LASIN code developed at IAP Frankfurt. The second part is about the beam dynamics simulations along the CH- accelerating structure using LORASR code [13].

MAGNETIC SOLENOID

In order to capture the laser-accelerated protons, a pulsed magnetic solenoid was chosen [6,12]. For the reference energy 10 MeV, a pulsed solenoid coil with 33 turns, 44 mm aperture and 72 mm length is used at field level up to 18 T (see Ref.12).

In reality, the proton bunch is expected to be space charge neutralized to a high degree behind the target foil in the absence of magnetic field. The input parameters of the initial distributions for the protons and electrons are chosen according to the simulated and measured data at PHELIX [14].

In the simulations, the proton and electron bunches expand isothermally in the first 10 ps. After that, they have convenient dimensions for the simulation with LASIN. Due to the fringing field of the solenoid in the target region, the electrons are transversally captured while the protons, on contrary, can expand (see Fig. 1). Because of that, the proton density decreases while the electron density stays almost unchanged. This leads to a negative on axis potential reaching about -40 kV (Fig. 2). The effect of the captured electrons on the proton beam profile is quite significantly: In Fig. 3, it can be seen that, the central part of protons ($|x| < 500$ μm) is strongly focused.
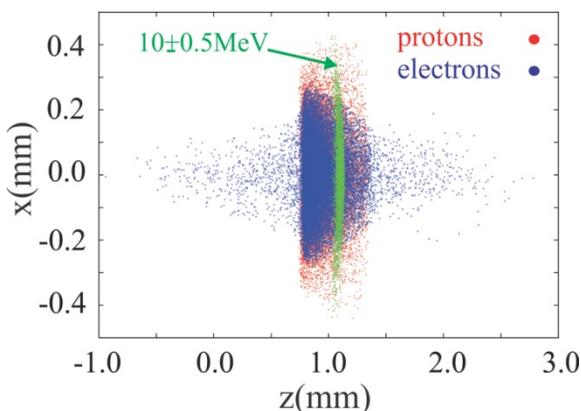
Figure 1: The proton and electron bunched in z-x plane after 25 ps after the generation in the fringing fields.
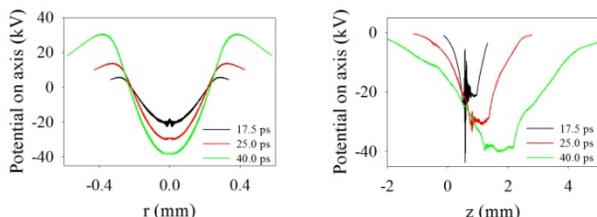
Figure 2: Potential curves in longitudinal (left) and transversal (right) directions at different positions along z.
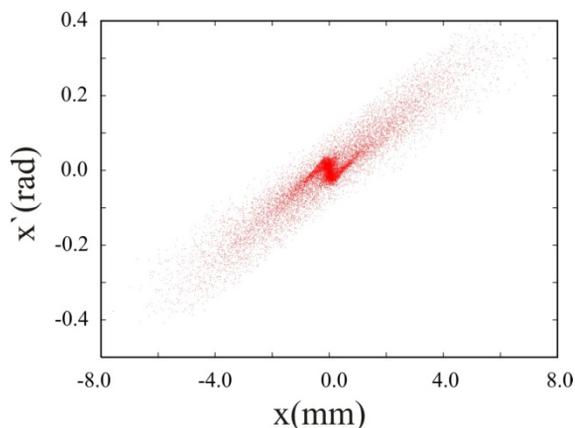
Figure 3: The x-x' phase space projection of the transported proton spectrum at 460 ps (2 cm after the target).

The peaked transversal proton distribution, with about 30% of all macroparticles (core) is concentrated within a radius of 500 μm. The resulting distribution in Fig.3 is transported along the remaining length of the solenoid and an additional drift of 6 cm (Fig. 4). The inner core expands along the drift after the solenoid (x'_{max} = 15 mrad), while the rest distribution is almost located within the "focused beam" quadrants.

DEDICATED CH - DTL

With respect to matching and injection studies, an advanced CH- linac is proposed (Fig.5). This design consists of four CH- cavities operating at 325 MHz, to accelerate the bunch from 10 – 40 MeV. The accelerating gradient per cavity varies from 9 – 12 MV/m.

The proton bunch fraction within an energy band of 10 MeV ± 0.5 MeV as marked in Fig.4 is selected out for further acceleration.
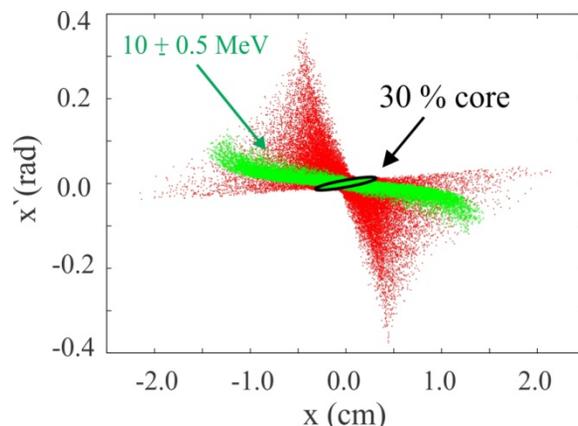
Figure 4: x-x' distribution for the proton bunch (10 ± 5 MeV) after solenoid and 6 cm drift (Red). Green marked area corresponds to the energy of interest (10 ± 0.5 MeV).

Due to the shape of protons in phase space behind the target, where part of protons is focused and the other part is defocused as shown in Fig. 6, it was not possible to match the whole distribution into the CH-DTL. Consequently, 70% of the total number of the protons is effectively fitted into the acceptance of the CH-DTL (see Fig. 6).
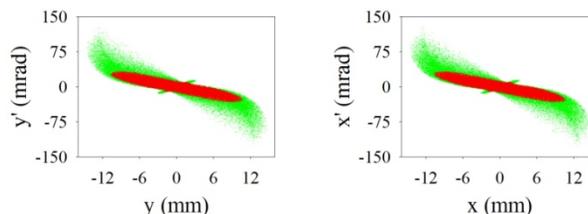
Figure 6: The cutted distributions in x-x' (left) and y-y' (right) that are fitted into the acceptance of the CH-structure. The green one shows the whole proton distribution of energy 10 MeV ± 0.5 MeV, while the red one shows the accepted distributions.

The beam parameters for the accepted bunch are summarized in Table 1, all particles were effectively accelerated through the whole structure to the exit.

Table 1: Normalized RMS-Emittance Values for the Input and Output Distribution for the Accepted Bunch

Emittance	Input	Output
Transverse	x: 2.89	3.41 mm mrad
	y: 2.89	3.08 mm mrad
Longitudinal	5.34	8.43 keV ns

A normalized relative rms- emittance growth up to a factor 3 in longitudinal plane and less than 20% in transverse planes was reached.
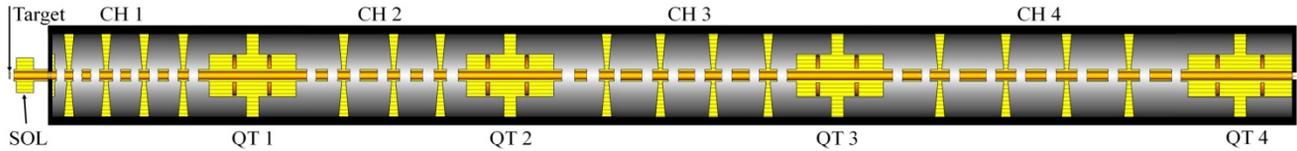
Figure 5: 3D view on the new CH- DTL consisting of four RF- cavities separated by triplet quadrupole which is suggested for the laser generated protons.

The transverse and longitudinal 90, 99 and 100 % beam envelopes can be seen in Fig.7. The magnetic field gradients of the quadrupoles are ranging up to 50.8 T/m, allowing a loss free transport of the selected input distribution.
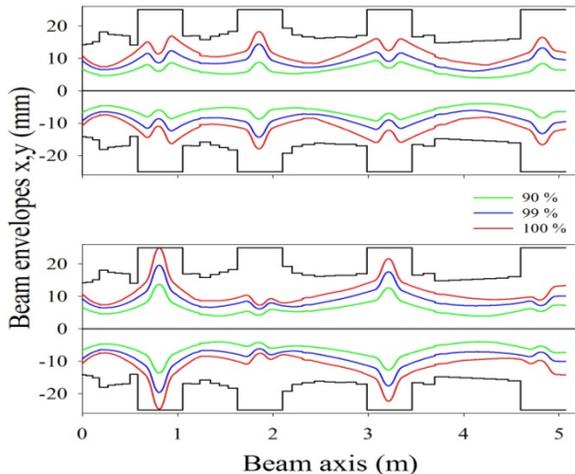
Figure 7: Transverse 90%, 99% and 100% beam envelopes starting at 6 cm from the end edge of the solenoid.

The particle distributions at the entrance and exit in transverse and longitudinal planes are shown in Fig.8 for 250000 macroparticles.
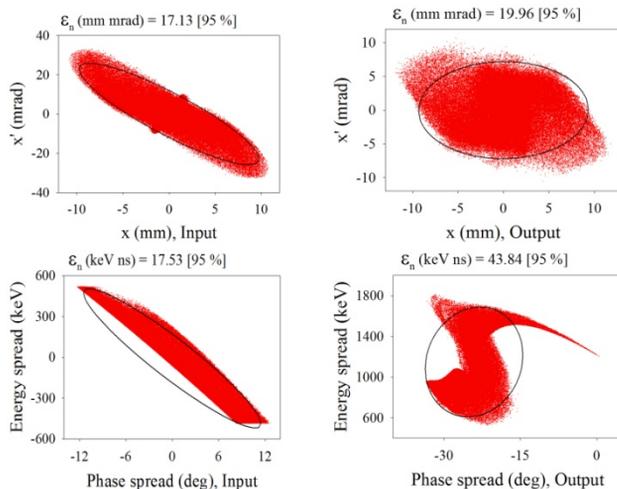
Figure 8: Transversal (up) and longitudinal (down) particle distribution at entrance (6 cm from the end of the solenoid) and exit of the CH-DTL structure.

CONCLUSION AND OUTLOOK

Matching a laser generated intense proton bunch into a conventional rf linac seems very attractive. For the reference energy of 10 MeV, the number of protons within the energy band $\pm$ 0.5 MeV is exceeding 10^{10}. The bunch transport through the pulsed solenoid with full space charge and including the co-moving electrons was investigated. The effect of the captured electrons on the proton beam profile is quite significant. The peaked transversal proton distribution, with about 30% of all macroparticles (core) is concentrated within a radius of 500 μm at a position 2 cm behind the target.

The main task of this work is to find the matching tools between the laser-accelerated protons at the target position and at the injection point into an rf linac (CH-structure for example). With respect to the proton bunch parameters, a new CH design was designed at IAP-Frankfurt. Further optimization and development is needed in order to improve the proposed accelerator scheme. This concept will lead towards intense single proton bunch acceleration far above particle numbers reached so far by conventional accelerator techniques.

REFERENCES

[1] E. L. Clark et al., Phys. Rev. Lett. 84, 670 (2000).

[2] R. A. Snavely et al., Phy. Rev. Lett. 85, 2945 (2000).

[3] T. E. Cowan et al., Phys. Rev. Lett, 92, 204801 (2004).

[4] H. Schwoerer et al., Nature 439, 445 (2006).

[5] V. Bagnoud et al., App. Phys. B 100, 100 (2010).

[6] K. Harres et al., Phys. Plasmas 17, 023107 (2010).

[7] https://www.gsi.de/documents/DOC-2010-Nov-36-1.pdf.

[8] S. Yarameshiv et al., Proceeding of IPAC11, San Sebastián, Spain, MOODB03 (2011).

[9] U. Ratzinger and R. Tiede, Nucl. Instrum. and Methods Phys. Res., Sec. A 415, 229 (1998).

[10] U. Ratzinger et al., Proceeding of LINAC06, Knoxville, Tennessee, USA, TH1004, P. 526 (2006).

[11] F. Nürnberg et al., Journal of Physics: Conference Series 244, 022052 (2010).

[12] A. Almomani et al., Proceeding of IPAC10, Kyoto, Japan, THPD035, p.4355 (2010).

[13] R. Tiede et al., Proceeding of EPAC06, Edinburgh, Scotland, WEPCH118, p. 2194 (2006).

[14] F. Nürnberg "Laser-Accelerated Proton Beams as a New Particle source", PhD Thesis, Technische Universität Darmstadt (2010).