# MATCHING THE LASER GENERATED P- BUNCH INTO A CH-DTL*

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### *Abstract*

The concept of laser acceleration of protons by Target Normal Sheath Acceleration TNSA from thin foils could be used to produce a high intensity proton bunch. This proton bunch could be injected into a linac at energies of ten to several tens of MeV. A CH- structure is suggested as the linac structure because of its high gradient. The motivation for such a combination is to deliver single beam bunches with quite small emittance values of extremely high particle number - in order of $10^{10}$ protons per bunch. Optimum emittance values for the linac injection are compared with the available laser generated beam parameters. Options and simulation tools for beam matching by a pulsed magnetic solenoid and CH-structure using LASIN and LORASR codes are presented.

## INTRODUCTION

The generation of proton beams from intense laser-plasma interactions with solid targets has been well studied [1-4]. In modern lasers like PHELIX, one can achieve focused intensities approaching $10^{20}$ W/cm$^2$ . Under these conditions, intense protons are accelerated normally from the rear surface of the target by a quasistatic electric fields of order TV/m [1,3,4]. This process is called Target Normal Sheath Acceleration (TNSA). 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 when compared to state of the art injectors like RFQ's [1,4-6]. The important topic for a further acceleration of the laser generated bunch is the matching into the acceptance of an RF accelerator stage. With respect to the high space charge forces and the transit energy range, only drift tube linacs seem adequate for this purpose. A cross Bar H-type (CH- structure) is suggested as the linac structure because of its high acceleration gradient, mechanical robustness, and high shunt impedance [5-7]. Laser-proton acceleration has demonstrated unique features like: an extremely small longitudinal and transverse emittance due to short time pulses (ps- range, not yet measured) and small source spot (few tens of μm) as well as a high yield of particles ($10^{12}$ - $10^{13}$ protons per shot) [1,3,5] . In PHELIX experiments, a 170 TW laser beam of about 700 fs duration was focused by a copper parabola mirror on a beam spot of 12×17 μm (FWHM) which means the intensity was approximately $4\times10^{19}$ W/cm$^2$. The spectrum of TNSA proton energies was up to 30 MeV, within the total yield of $1.5\times10^{13}$ protons over all energies (Figure 1) [1]. For the reference energy of 10 MeV, the yield within ± 0.5 MeV was exceeded $10^{10}$ protons. To compare this number with the conventional currents, the sum current of these bunches would add up to 500 mA beam current if every bucket would be filled with that proton number. Proton spectra are characterized by a large divergence (23° half angle for energies around 10 MeV). This divergence was found to decrease with increasing energy down to 8° half angel for 29 MeV [1,3].

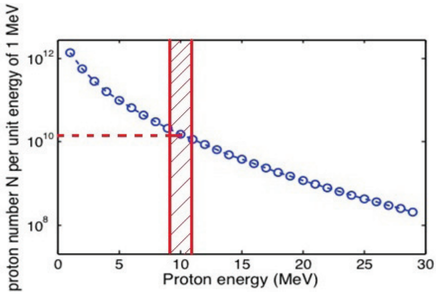

Figure 1: Dependance of differential particle yield on energy for PHELIX experiment.

## PULSED MAGNETIC SOLENOID

In order to catch the protons around 10 MeV, a pulsed solenoid of 33 circular windings with an inner diameter of 44 mm, an outer diameter of 76 mm and a total length of 72 mm could be used with field strength theoretically up to 20 T (Figure 2). The distance between target and coil entrance was set to 15 mm and corresponds to the performed experiments. A 3D-PIC code LASIN (LASer INjection), which was developed at IAP- Frankfurt, is used for multi-particle tracking through the solenoidal magnetic field and its fringing fields. The magnetic components are calculated by a Biot-Savart solver from the known current distribution in every time step.

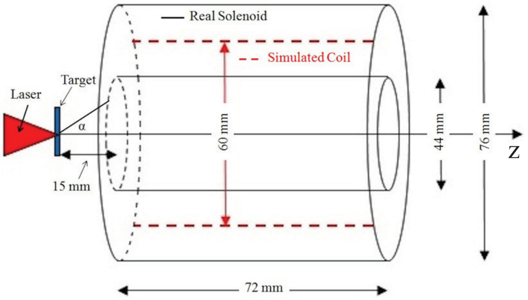

Figure 2: The pulsed magnetic solenoid and its parameter.

### *Chromatic and Geometric Aberration*

In order to estimate the chromatic and geometric effects for the pulsed magnetic solenoid, the beam dynamics simulations with KV- input distribution were performed for a beam with different input transverse divergence (α: ± 45 mrad, ± 90 mrad and ± 180 mrad) together with

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different momentum spreads up to ± 10%, and at negligible space charge conditions. The chromatic emittance for a given solenoid and spot radius obeys a scaling

$$\varepsilon \propto \alpha^2 \, \Delta p / p \tag{1}$$

where α is the opening angle and Δp/p is the momentum spread [1].

The magnetic field level 200 mm behind the target is below 1% of the maximum. The resulting emittance at that position depends on the initial beam divergence as well as on the momentum spread. The influence of both effects can be seen by Figures 3, where three cases for the beam divergence are plotted. The predicted linear behavior is confirmed between 1% and 10% momentum spread (Figure 3a). At vanishing momentum spread the relative rms emittance growth caused by beam divergence and corresponding non-paraxial solenoid optics can be seen from Figure 3b. In Figure 3b, the ratios of the output to the input rms emittances, at the same momentum spread, are different for different input divergence. This difference in the ratio is due to the geometric effect.

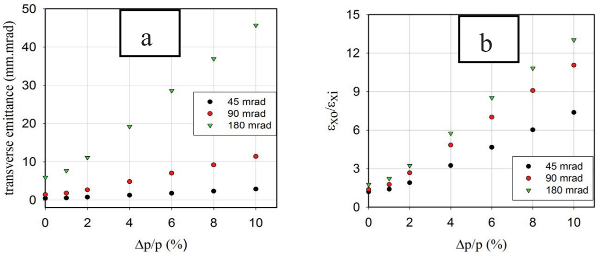

Figure 3: (a) Output rms- emittance in x-x' versus Δp/p (b) output to input rms- emittance ratio in x-x' versus Δp/p at different opening angles.

The LASIN includes non-paraxial effects, which leads to an s- shaped distortion of the output distribution even for a mono- energetic beam (Figure 4).

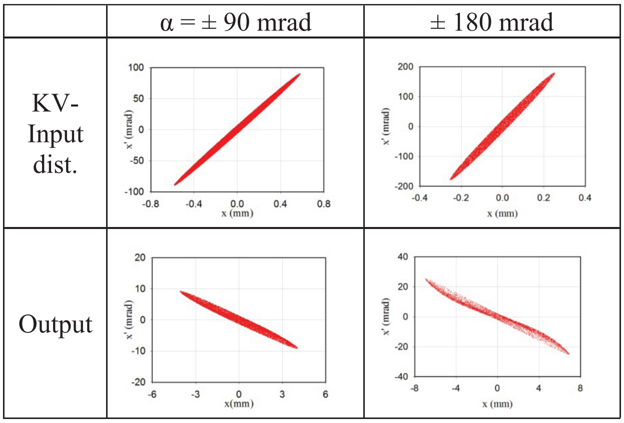

Figure 4: Input and output distributions in x-x' for different full opening angles with Δp/p = 0%.

This effect (s- shaped) which is dominant for large divergence more than small one is considered as geometric aberration. The geometric aberration effect will add additional increase in the effective emittance. To clarify the chromatic effect, the input and output phase space distributions x-x' are plotted for three different momentum spreads with ± 90 mrad input divergence (Figure 5). In Figure 5, the effective enlargement in output distribution is proportional to momentum spreads which is in agreement with the theory (equation 1).

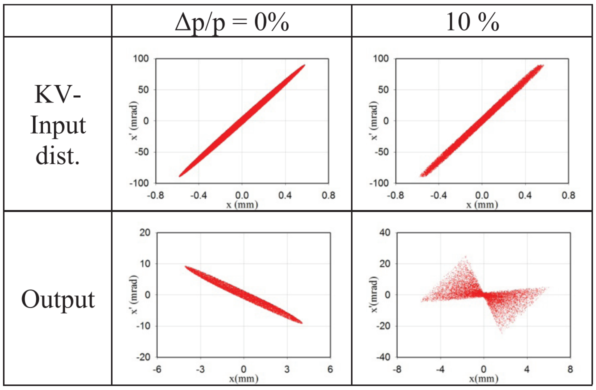

Figure 5: Input and output distributions in x-x' for different Δp/p with ± 90 mrad opening angle.

## MATCHING INTO THE CH- DTL

With respect to laser accelerated beams, the capability of a CH- structure for high currents (500 mA) has been investigated, and a new design was suggested at IAP-Frankfurt (Figure 6). The purpose of this design is to match the beam parameters of laser accelerated bunches and of CH- cavities.

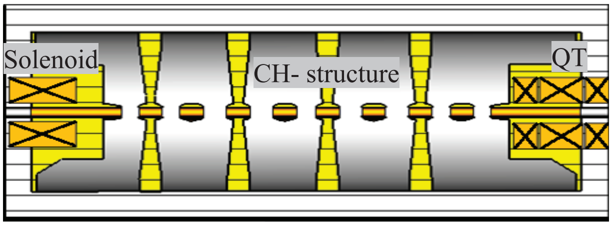

Figure 6: 3D view into the new design starting with the solenoid then followed by CH- structure.

This design with 9 gaps in 1.22 m in total will be operated at 325 MHz. It will accelerate the protons from 10.0 to 17.4 MeV. The beam parameters at 500 mA are summarized in table 1. The simulations on the acceleration of heavily space charge dominated beams with matched emittance values for a maximum beam current for longitudinal and transverse beam dynamics were performed by the LORASR code [8].

**Table 1:** Matched rms- emittance values.

| Beam Current | Emittance | Input | Output |
|---|---|---|---|
| 500 mA | $\varepsilon_{tr}$ | 0.33 | 0.53 mm-mrad |
| | $\varepsilon_{long}$ | 3.22 | 4.08 keV-ns |

The envelopes resulting from $10^5$ particles run can be seen in Figure 7, the transmission was 100%. The magnetic field gradients of the quadrupoles are ranging up to 65 T/m and up to 18 T for 72 mm solenoid. The particle distributions at the entrance and exit are shown in Figure 8. The water bag distribution was used as the input distribution.

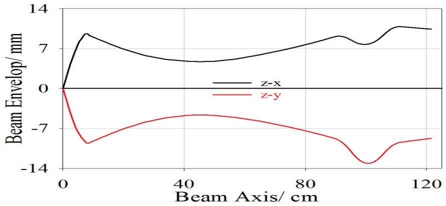

Figure 7: Transverse 95 % beam envelopes.

The rms emittance growth is less than 30% for longitudinal plane and less than 65% for transverse planes.

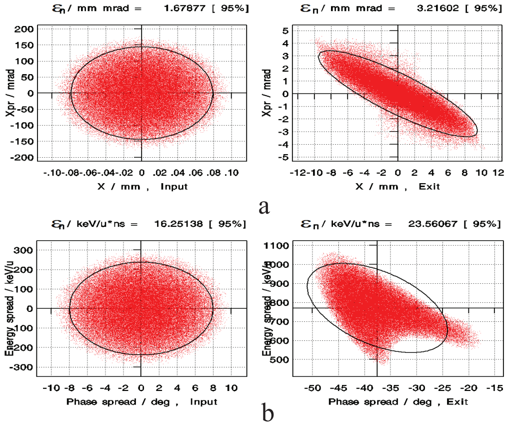

Figure 8: Transverse (a) and longitudinal (b) particle dist. at entrance and exit of the design at 500 mA beam current with water bag input distribution.

### *Emittance Growth Problem*

The proton bunch that is laser generated might have a length below 1ps (below 0.1 degree spread in phase space). The predicted rms values for longitudinal and transverse emittance are quite small ($\varepsilon_{long}$ = 0.02 keV-ns and $\varepsilon_{tr.}$ = 0.1 mm-mrad) originally. For such small emittance values, one will face a problem in the emittance growth through the solenoid and the CH- structure, especially in longitudinal plane which may show a factor of 100 (Figure 9).

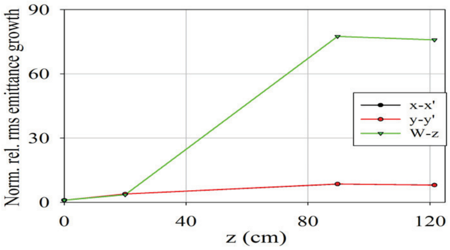

Figure 9: rms- emittance growth through the design due to original value from laser beam.

The particle distribution at entrance and exit in transverse and longitudinal planes are shown in Figure 10. Here one can see the effect of small input emittance values on the particle dist. especially on longitudinal plane. However, in the second case the output norm. emittance is still considerably smaller than in the "matched case", while the transmission was again 100%.

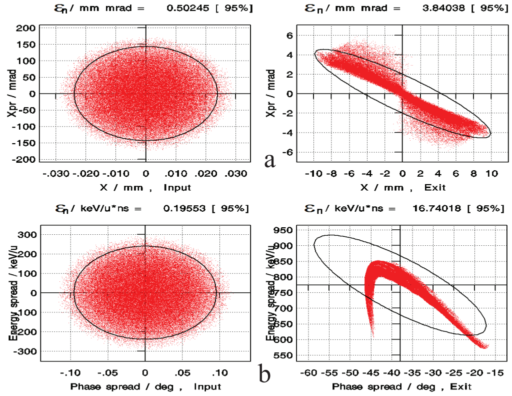

Figure 10: Transverse (a) and longitudinal (b) particle dist. at entrance and exit of design for the predicted norm. emittance with a water bag input distribution. Norm. emittance numbers refer to the plotted ellipses.

## CONCLUSION AND OUTLOOK

The capability of CH- structure for high current was investigated up to 500 mA. This means that, one can use the CH as a linac structure for the protons generated by laser. One main task of this work is to find the matching tools between the laser driven spot at the starting point and injection into the cavity which not only means to shape the emittance areas but also to give them reasonable absolute numbers. Because of that the coupled CH prototype cavity for the FAIR project which is under construction at IAP- Frankfurt might be used for first laser generated proton beam injection into a DTL.

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