CHROMATIC, GEOMETRIC AND SPACE CHARGE EFFECTS ON LASER ACCELERATED PROTONS FOCUSED BY A SOLENOID*

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Abstract

We studied numerically emittance and transmission effects by chromatic and geometric aberrations, with and without space charge, for a proton beam behind a solenoid in the laser proton experiment LIGHT at GSI. The TraceWin code was employed using a field map for the solenoid and an initial distribution with exponential energy dependence close to the experiment. The results show a strong effect of chromatic and a relatively weak one of geometric aberrations as well as dependence of proton transmission on distance from the solenoid. The chromatic effect has an energy filtering property due to the finite radius beam pipe. Furthermore, a relatively modest dependence of transmission on space charge is found for p production intensity below 10^{11}.

INTRODUCTION

The new acceleration technique of ion beams generation by laser interaction with thin metallic foils differs from that generated in conventional accelerators due to extremely small longitudinal and transverse emittances, large energy spread and angular divergence, high yields of ions per bunch (typically 10^{11} or more particles per shot) and short duration [1-3]. These properties of laser accelerated ions will be investigated in the upcoming "Laser Ion Generation Handling and Transport" (LIGHT) project at GSI [4]. The main goal is to explore properties of generated proton beams, their collection, transport, de-bunching and possibly post-acceleration in conventional accelerator structures, both experimentally and theoretically.

The Z6 experimental area at GSI is equipped with a unique high power laser system of Petawatt-class, PHELIX (Petawatt High Energy Laser for Ion eXperiments). It is connected with a newly set up vacuum compressor and off-axis parabola mirror to recompress pulses to high energy with pulse duration 500 fs and focusing onto a beam spot on the front surface of a metallic target to reach 10^{19} W/cm^2 [5]. As a result of this interaction, a beam of energetic electrons is generated and propagates through the target, with a dense sheath of electrons formed on the rear side. The resulting quasi-static electric field is of the order 10^{12} V/m ionizing all atoms in the surface layer and accelerating them. This process is called Target Normal Sheath Acceleration (TNSA) [2].

In a first experiment at GSI the measured proton energy spectrum showed an exponentially decreasing spectrum up to 30 MeV, with a total yield of 1.5×10^{13} protons over all energies and a spatial angle of typically 25^0. In order to collect this beam a pulsed solenoid with field strength up to 5.7 Tesla for a reference energy of 10 MeV (108 circular windings with an inner diameter of 40.5 mm, outer diameter of 90 mm and total length of 150 mm) is placed at about 130 mm behind the target (see Fig. 1 – note that in our work we are not studying the planned diaphragm and RF cavity). The LIGHT project is discussed in more detail in Ref [4].

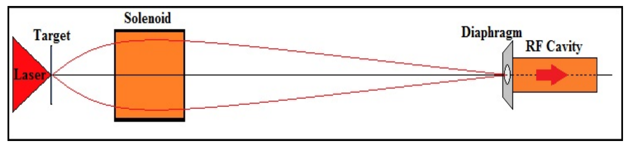

Figure 1: Scheme of the LIGHT project elements from source to bunch rotation RF cavity.

TraceWin Code

The TraceWin code has been developed in CEA [6]. It can be used for study the tracking of 2D and 3D ion or electron beams. TraceWin is a particle in cell code with envelope option, which can be used for different elements of linac structures.

In TraceWin tracking of the ion beams through standard magnetic elements (hard-edge solenoid) gives only the 2nd order chromatic effect, and to investigate the 3rd order geometric effect TraceWin is loaded with a FIELD_MAP command to implement the magnetostatic field map, which was computed separately by using a MATLAB program. The total length of solenoid field map is 400 mm.

NUMERICAL RESULTS

Two distributions were performed to calculate the chromatic, geometric and space charge effects.

The TraceWin standard input distribution (6 dimensional ellipse uniform distributions) was employed, with different input transverse divergence (Ω = 25, 50, 75, and 100 mrad) together with different energy spreads up to 10%. The other distribution is an exponential one generated by a Matlab program, which is similar to that measured in PHELIX experiments. The proton spectrum is running from 3-30 MeV with a maximum initial divergence up to 150 mrad was used. Both distributions are for a beam originating from a source spot size of 12.5 μm with 1 ps pulse duration and are modelled using 10^6 simulation particles.

Chromatic and Geometric Effects

The chromatic and geometric effects can be estimated by using the standard input distribution, ignoring the

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space charge effect. The chromatic emittance for a given solenoid and spot radius with varying input transverse divergence obeys the scaling law:

$$\varepsilon_{ch} = \alpha_c \Omega^2 \frac{\Delta E}{E} \qquad (1)$$

Here α_c is the chromatic constant for a given geometry, Ω the opening angle and $\Delta E/E$ the energy spread [7].

The resulting emittance, at 2 meter focal distance from center of solenoid, depends on energy spread and initial beam divergence. Figure 2, shows both aberration effects on the resulting emittance. In left figure a linear behaviour is shown between 4% and 10 % energy spread caused by chromatic effect, and for small energy spread a non-linear behaviour appears caused by geometrical aberration.

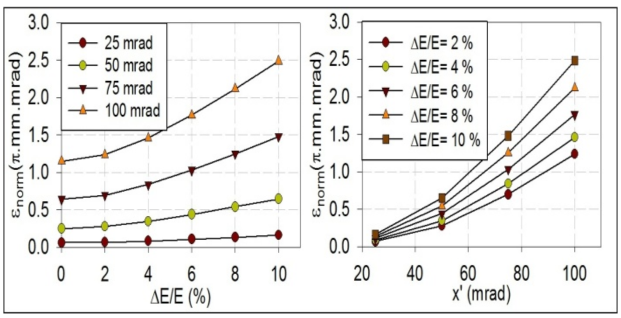

Figure 2: Output rms-emittance in x-x' versus energy spread at different opening angle (left), and versus opening angle at different energy spread (right).

The resulting emittances at the same energy spread (right figure) equally show the nonlinear trend due to the geometrical effect.

To study the correlation between the geometric and chromatic aberration, two different cases of energy spread were taken with $\Delta E/E$ = 0.01% and 5% (Figure 3). The curve of vanishing energy spread 0.01% represent a purely geometric effect of emittance growth, while the lower curve is the geometrical effect for the case 5% after subtracting the chromatic effect calculated from the hard-edge solenoid model. This means that geometric aberration is affected by chromatic aberration, so they are correlated and not additive.

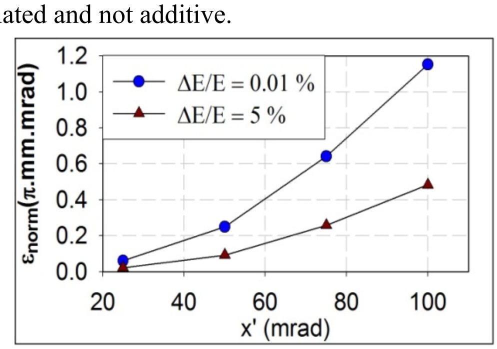

Figure 3: Transverse rms emittance vs. opening angle (x') for $\Delta E/E$=0.01% and 5% after subtracting the chromatic emittance effect.

The distribution in the focal spot for ΔE/E = 5% due to both effects is shown in figure 4. The tracking through solenoid hard edge element gives a pure chromatic aberration (left figure). An additional s-shape geometric aberration in the focal spot resulted with solenoid field map (right figure).

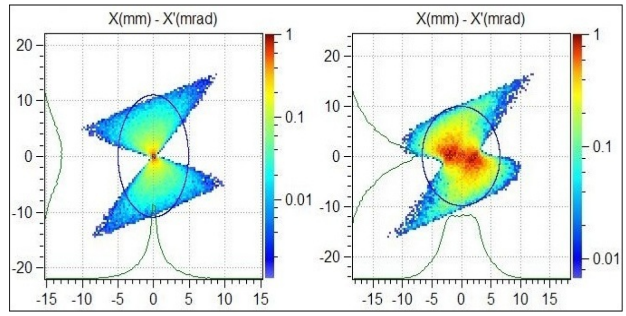

Figure 4: Only chromatic (left), and combined with geometric (right) effects in x-x' phase space.

In order to study the transverse emittance growth and particle loss along the focusing channel and subsequent drift space (20 mm radius), the tracking of exponential distribution in solenoid field map model was investigated (Figure 5). The plots indicate an increase of emittance inside solenoid field map region and continuous decreasing in the subsequent drift (Figure 5.a), due to large energy spread that causes continuous loss of particles through beam pipe (Figure 5.b).

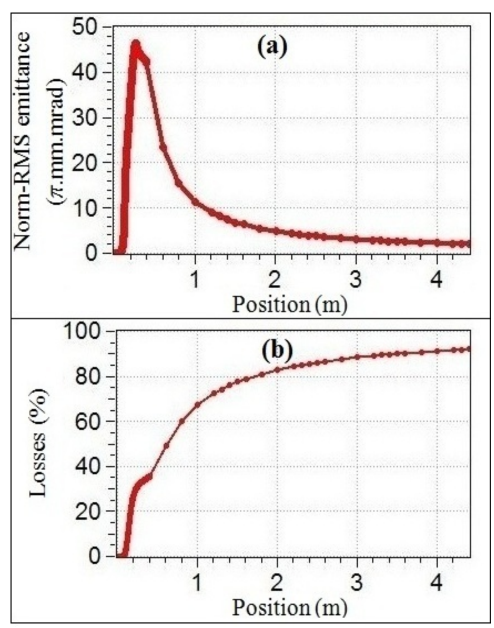

Figure 5: (a) Norm-rms transverse emittance and (b) losses particles for exponential distribution with solenoid field map.

Transmission at Different Focal Lengths

The solenoid field map is adjusted to create different focal lengths at distances 2 and 4 meter, and for the exponential distribution.

The proton transmission (relative to initial number of 10^6 simulation particles) is analysed to study the surviving energy spectrum and transmission of protons through the beam pipe of 20 mm radius (Figure 6).

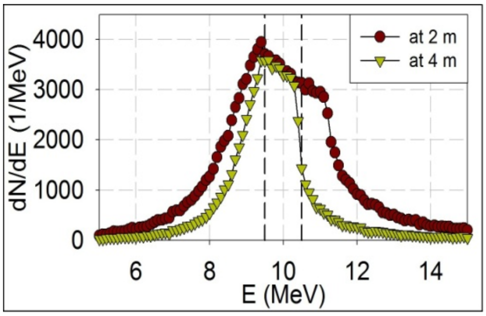

Figure 6: Energy spectra at two different focal distances.

We find that the width of the energy spectrum is controlled by the energy filtering property of the finite radius beam pipe in combination with the chromatic effect of the solenoid. Note that the spectral width reduction progresses with distance and the transmission of protons, within the energy band 10±0.5 MeV, is 3.7% after 2 meter and 3.4% after 4 meter drift length.

For full investigation, the dependence of the transmission on the adjusted magnetic field and at different distances was studied (Figure 7).

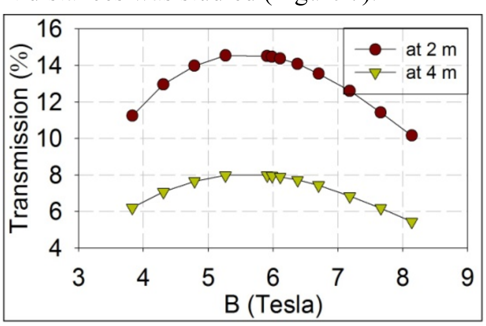

Figure 7: Transmission at two different focal distances versus magnetic field.

Space Charge Effect

In the early stage of the TNSA, the high intensity proton beam is neutralized by the co-moving electrons [2]. De-neutralization and resulting space charge effects appear when the beam enters the solenoid magnetic field region. Electrons start gyrating at small gyro-radius and about part of the electrons may get reflected by the magnetic mirror effect [8].

In this work, we also study the dependence of the total transmission of protons (at 2 meter distance) on the total particle number produced at the source. For simplicity, we suppose the beam neutraliation is completely destroyed and the full space charge effect starts in the first step of the solenoid field region. This early de-neutraliation might overestimat e the space charge effect. Results for the exponential initial distribution show an effective decrease of transmission starting after 10^{10} protons with a modest effect up to 10^{11} protons (Figure 8).

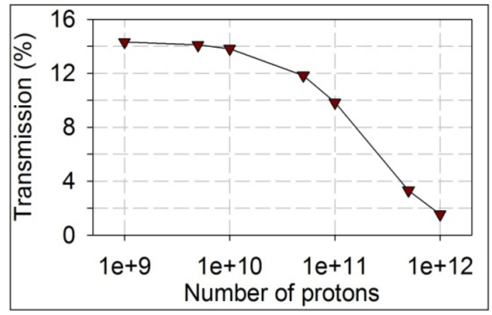

Figure 8: Transmission at 2 meter for different initial number of particles.

CONCLUSION AND OUTLOOK

We find a correlation between chromatic and geometric effects. Geometric aberration is not so important in transmission of particles, because the final transmission at 2 m was 8.02% with solenoid hard edge (only chromatic aberration effect) and 7.88% with solenoid field map (including geometric aberration). The shape of energy spectrum for the transmitted protons shows dependence on focal distance and indicates the role of aperture as energy filter, which will be used in further studies to control the energy width into the RF cavity by a dedicated diaphragm. Determination of the beam neutralization distance is beyond the framework of this study and requires different simulation tools.

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