BEAM DYNAMICS SIMULATIONS FOR THE LASER PROTON INJECTOR TRANSPORT LINE*

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Abstract

The DYNAMION code was implemented to perform beam dynamics simulations for different possible transport lines for a proton beam with an energy of 10 MeV, coming from a high intensity laser ion source. It was intended to check the chromaticity and space charge effects taking into account high order aberrations. The investigations were performed for a solenoidal focusing and alternatively for a quadrupole channel applying different beam parameters (energy spread, transverse divergence, beam current) as well as different layouts of the transport line. The beam evolution along the transport line, the emittance growth and the beam transmission were analyzed and compared. Finally, the influence of an rf - buncher, required to match the proton beam to the following accelerating structure, was investigated.

INTRODUCTION

The recent development in the field of "laser acceleration of protons and ions" has initiated several investigations of this concept of a innovative and compact accelerator. The currently known beam parameters do not allow for a realistic detailed study. But a simulation of proton collimation and transport, based on output data from the PHELIX experiment [1], already give a useful hint, especially chromatic and geometric aberrations of the first collimator as an interface between the production target and the adjacent accelerator structure are of particular importance [2].

The advanced multiparticle code DYNAMION [3], dedicated to the beam dynamics simulations in linacs, was created in 1992 in the Institute of Theoretical and Experimental Physics (ITEP, Moscow) and developed in a long-term collaboration of GSI Helmholtzzentrum fuer Schwerionenforschung (Darmstadt) and ITEP. Due to the most common form of 3D particle motion equation and detailed description of the external electromagnetic field, the non-linear effects and high order aberrations are included in this code automatically. The space charge calculations in the DYNAMION code are based on the particle-particle interactions, including a dedicated routine to avoid artificial collisions of particles. Numerous comparisons of the calculated results with measured data have proved the reliability of DYNAMION simulations for convenient linacs [4-8]. For this reason the DYNAMION code is used to perform beam dynamics investigations for the laser proton injector beam transport line. For special tasks, as the very early expansion phase of the proton cloud, simulations with a recent DYNAMION version were carried out introducing estimated beam parameters, based on numerical and experimental data. The simulations for the zero current case attract a particular interest as the most optimistic case. Addition of any diversifications of the input beam parameters leads to emittance growth.

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BEAM LINE LAYOUT

Calculations were done for quadrupole (Q-line) and solenoidal (S-lines) channels varying the input beam parameters (Fig. 1).

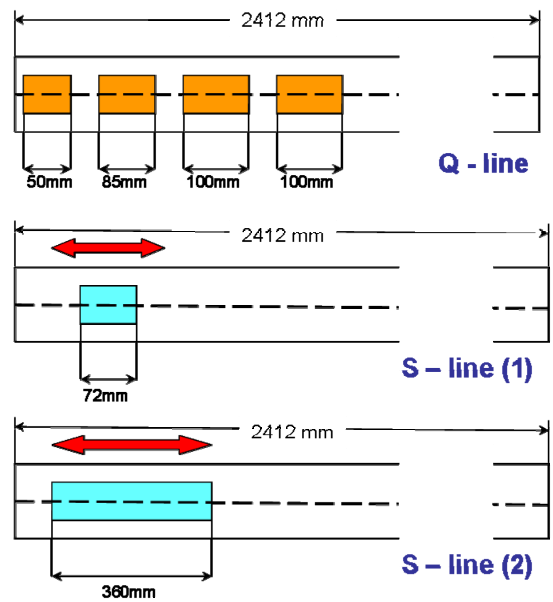

Figure 1: Layout of the beam transport line with quadrupole or solenoidal focusing.

For this set of simulations the following beam parameters were fixed:
- energy 10 MeV;
- transverse size ± 0.03 mm;
- transverse divergence ± 43 mrad, ±86 mrad;
- total unnormalized emittance $\varepsilon_x = \varepsilon_y = 1.25$ mm·mrad, 2.5 mm·mrad;
- phase spread $\Delta\varphi = \pm 0.75°$ (related to 108 MHz);
- energy spread $0\% \le \Delta W/W \le 6\%$;
- current $0 \text{ mA} \le I \le 50$ mA;
- Gaussian particle distribution, truncated at 2σ.

Q-line Layout

The position of the 4 quadrupoles and their gradients (optimized by TRACE 3D code) are fixed; maximum magnetic field in quadrupoles is 1.2 T; «open» aperture of the quadrupoles in order to study high order aberrations and space charge effects without particle losses. The total length of the line is 2412 mm.

S-line Layout

The length of the solenoid is 72 mm (S-line 1) and 360 mm (S-line 2); aperture radius of the solenoid is 30 mm; solenoid is placed on the distance 15 mm from the ion source; total length of the line is the same. The short solenoid has been designed by the "Institut fuer Strahlenphysik" and constructed by the "Institut fuer Hochfeld-Magnetlabor in Dresden". The solenoidal field was calculated with the assumption of its axi-symmetrical structure [9]. A mapping of the magnetic field was introduced into the DYNAMION (Fig. 2).

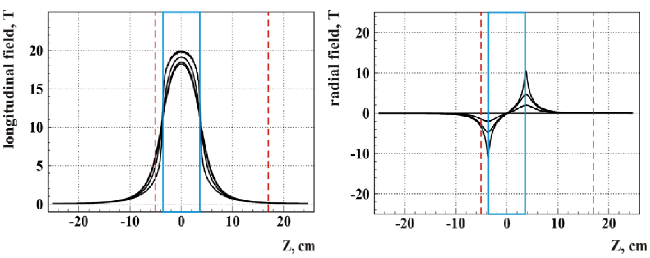

Figure 2: Longitudinal and radial fields of the short solenoid (S-line 1).

The blue box represents the geometrical size of the solenoid. For the simulations of the particle motion the magnetic field mapping is cut at the source position from the left side and at 1% of maximum field on the right side (marked by red dashed lines).

The beam dynamics simulations, neglecting space charge effects, for the quadrupole transport line show a much higher emittance growth, than for the solenoidal one (Fig. 3).

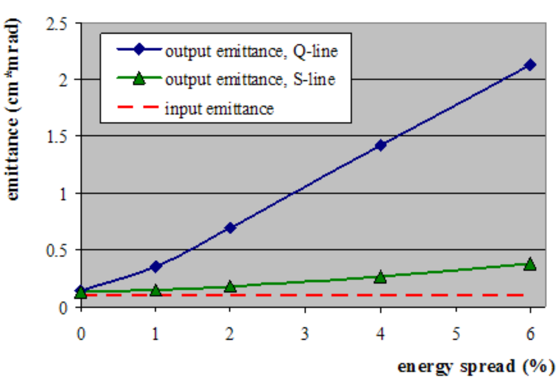

Figure 3: Total transverse emittance for S-line and Q-line (I=0mA).

The non-paraxial effect and the chromatic aberrations are weaker for the solenoid due to the symmetric solenoid focusing strength, suppressing large transverse deviation of the beam. Results of calculations including space charge effects are qualitatively the same. Therefore in the next simulations we restrict ourselves on the S-lines [2].

DETAILED STUDY OF THE S-LINE LAYOUT

Short Solenoid

In the simulations along the S-line (1) the beam size is remarkable smaller than the aperture of the solenoid. Therefore the distance to the ion source is prolonged to avoid propagation of the proton-electron cloud under influence of the strong magnetic field. Consequently the solenoidal field is decreased in order to provide for a slightly focused beam. Distance between an ion source and solenoid was varied from 15 mm to 120 mm.

Long Solenoid

For the S-line (2), a five times longer solenoid (360 mm) was considered. The displacement from the ion source as well, as 3D field mapping were the same as for the short solenoid. The field-factor was varied from 19% to 14% of maximum field (24 T) for the distance between ion source and solenoid of 15 - 120 mm.

The emittance growth as function of the distance for the short and for the long solenoid is shown on Fig. 4.

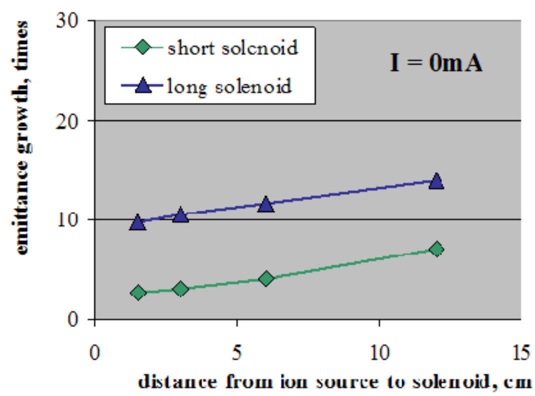

Figure 4: Emittance growth for S-line (1) and S-line (2).

A longer distance leads to an increased beam spot at the solenoid entrance. Obviously, the aberrations and chromaticity effects are stronger (and non-linear) for particles with increased distance to the axis, leading to higher emittance growth.

Additionally, at the output of the long solenoid the transverse beam spot is significantly larger. This leads to an even higher emittance growth (up to a factor of 3). The correlation between beam size at the end of the solenoid and emittance growth is demonstrated in Fig. 5.

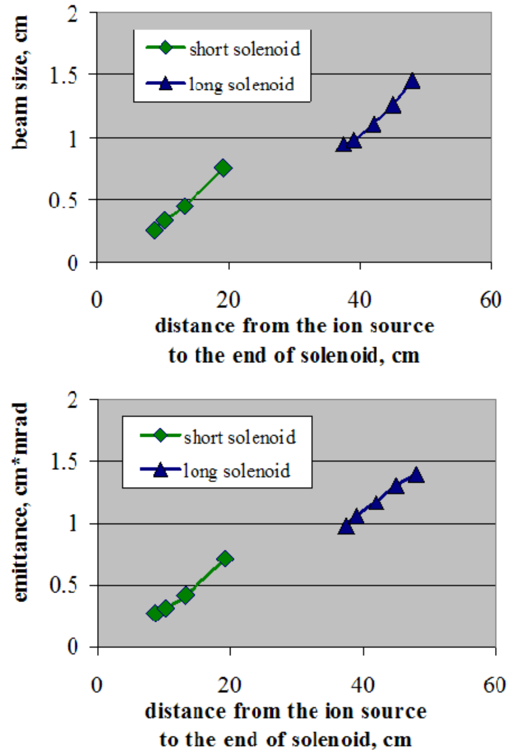

Figure 5: Beam size at the end of the solenoid (top) and the total emittance at the end of the transport line (bottom) for the long and the short solenoid (I = 0 mA, ΔW/W = 4%).

BUNCHER SIMULATIONS

A buncher is placed at the end of the S-line at a distance of 2412 mm from ion source. It provides for longitudinal beam focusing and decreases the energy width of ± 4% core to less than ± 0.5%. Synchronous phase is -90°. It is planned to make use of the already existing in GSI 108 MHz 3-gap buncher. The design voltage is 1 MV. 3D electric field of the buncher is calculated by the DYNAMION code solving the Laplace equation on the base of the real topology of gaps and tubes: length, inner/outer diameters and rounding (Fig. 6).The particle motion was calculated for an input divergence of ± 172 mrad and for different combinations of input beam current and energy spread (Table 1).

Table 1: Combinations of the input beam current and energy spread for the buncher simulations.

I (mA)	ΔW/W (%)
0	± 4
0	± 64
35	± 4
560	± 64

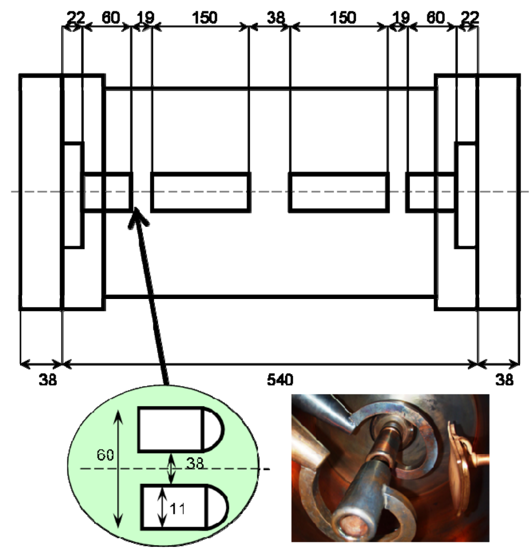

Figure 6: 3-gap buncher geometry.

For each case the magnetic field in the solenoid was adjusted in order to get a maximum particle transmission through the buncher. Figure 7 shows the beam transformation in the buncher for I = 0 mA and ΔW/W = ± 4%. The buncher voltage of 500 kV was adjusted in order to minimize the energy spread.

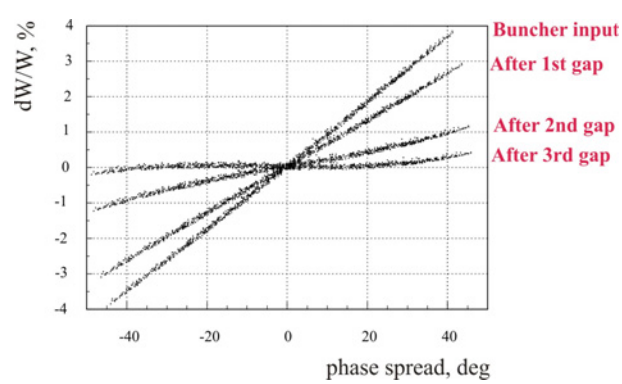

Figure 7: Beam transformation in the buncher, I = 0 mA, ΔW/W = ± 4% and x′ = ±172 mrad.

Calculations with a beam current of 35 mA show a remarkable influence of the space charge effects on the dynamics. A beam transmission for the whole transport line is close to 100%. For an increased energy spread of up to 64% the current was varied proportionally up to 560 mA. For the planned experiment it is important to note that the emittance growth due to the energy spread will inevitably lead to transmission loss. The beam transmission along the S-line (1) including the buncher is shown on Fig. 8 for three cases.

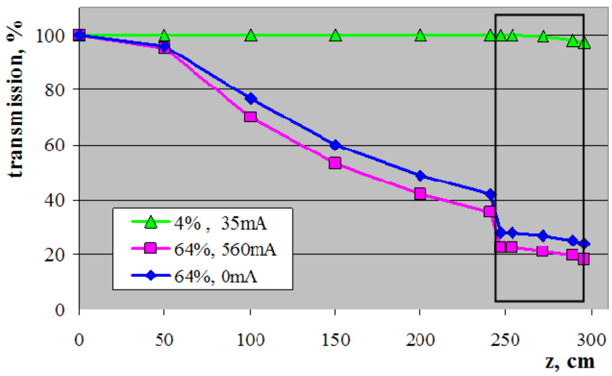

Figure 8: Transmission along the S-line with buncher.

The black box represents the buncher position. For an input current of 35mA and an energy spread of 4% the particle losses (about 2%) occur only in the buncher. For an energy spread of 64% the transmission decreases starting from the solenoid (radius of 30 mm) due to the large spread of focusing angles generated by the energy spread. Additionally the beam extends due to the space charge, but this influence for the overall transmission is minor even for the high current case of 560 mA. The most serious reason for the low particle transmission is an intrinsic energy spread of the laser ion source.

Only about 20% of the initial particles can be potentially captured in the RF bucket. Behind the buncher the total transmission is about 18 %. In Fig. 9 the pulse spread Δp/p at the buncher exit is plotted versus the phase deviation ($-600° \leq \varphi \leq 600°$), including more than three rf periods. It is seen, that the required bunch rotation is successfully implemented only for central part of the energy distribution.

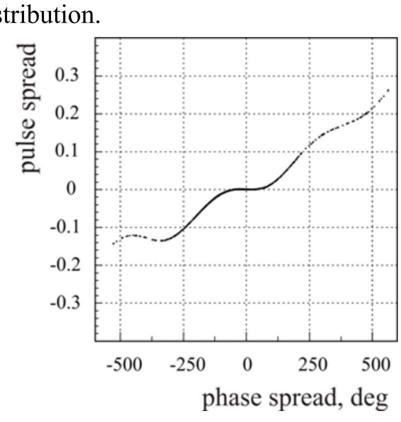

Figure 9: Longitudinal phase space portrait behind the rf cavity (I = 560 mA, ΔW/W = ± 64%).

A detailed analysis of the longitudinal phase space distribution indicates about 10% of initial particles inside a phase spread of ± 90° (within energy spread of about ± 2% after rotation). In spite of it, only about 5% of the particles (≈ 30 mA) are inside an energy spread of ±0.1% (typical requirement for the conventional proton linac [10]).

CONCLUSION AND OUTLOOK

The versatile multiparticle code DYNAMION is an adequate tool for beam dynamics simulations for LIS transport lines. The motion of particles was calculated taking into account nonlinearity of the external electromagnetic field, chromaticity effects, high order aberrations and space charge influence. Recent investigations were performed for a wide range of input beam parameters and for different layouts of the transport line, including the buncher.

The laser ion source provides for an extremely high beam brilliance, while recent investigations of the particle collimation show serious limitations, mainly due to the huge energy spectra of laser generated protons. Even neglecting space charge effects, only a small amount, about 5% of the initial beam current of 560 mA, can be matched to conventional postaccelerator.

The very early expansion phase of the proton-electron cloud should be investigated with dedicated codes. Additionally, the influence of the strong magnetic field of the solenoid (up to 5T) on the propagation of the particle distribution has to be taken into account. The obtained results can be used as an input for advanced DYNAMION simulations. Obviously, any complication of the input beam parameters leads to a larger and faster degradation of the beam quality along the transport line.

Quadrupole and solenoid focusing was considered for different layouts of the transport line. Potentially, more intricate constructions might improve the situation.

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