SPACE CHARGE EFFECTS AND FOCUSING METHODS FOR LASER ACCELERATED ION BEAMS

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Abstract

Within the scope of the LIGHT-Project [1] high intense beams of laser accelerated ions and co-moving electrons are produced. We are interested in methods for the controlled deneutralization of the beam, e.g. using a thin metal foil to absorb the electrons. Those beams show high initial divergence angle and velocity spread [1]. Therefore methods of focusing and collimating the beam are indispensable. Hence the focusing with a pulsed power solenoid is discussed.
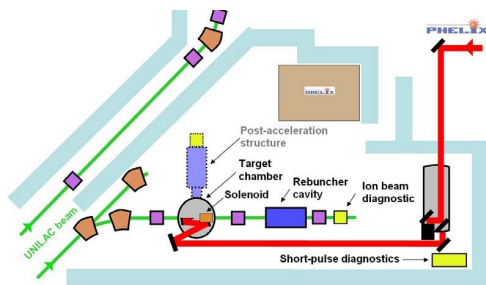
INTRODUCTION

Figure 1: Setup of the LIGHT-Project.

Currently the LIGHT-Project (**L**aser **I**on **G**eneration, **H**andling and **T**ransport)[1] is performed at the Helmholtzzentrum für Schwerionenforschung Darmstadt (former GSI) (Germany). Whithin this project, high intense ion beams are generated by laser acceleration, using GSI's PHELIX-Laser. A scetch of the used setup is given in Fig. 1. Refering to the TNSA mechanism [2], one can expect, that the generated beam is quasi-neutral, composed of protons and co-moving electrons. We are therefore interested in methods for the controlled deneutralization of the beam to get clean experimental conditions. This can be done by using a thin metal foil to absorb the electrons[1]. The properties of this thin metal foil should be such that all electrons are removed, keeping the velocity -and density distribution of the protons being unaffected. The position of the foil is determined so that space charge has no effect behind the foil. A criterion in terms of beam parameters is worked out, by which one can decide how important space charge is. Following this foil, the beam is focused and carried towards a re-buncher-cavity (see Fig. 1). The focusing with a pulsed power solenoid (see Fig. 1) is discussed.

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[1]The foil is not yet implemented in the setup.

BEAM MODEL

For the determination of space charge effects, we will use a rather simple beam model. Nevertheless it turns out, that this leads to general criterion, which only depends on the beam parameters. Let us assume we have a uniform cylindrical bunch with radius r_0 and length l_b, containing N_0 protons[2]. The charge number is $Z = 1$ and charge of each particle is $q = e$. Furthermore the beam has a longitudinal velocity $\vec{v}_\parallel$ with a velocity spread $\Delta v_\parallel$ and a transversal velocity $\vec{v}_\perp = v_\parallel r/r_0 \tan(\vartheta)$, where ϑ is the divergence angle. In the simplest case the bunch length is then given by the transversal velocity spread: $l_b(z) = l_0 + \Delta v_\parallel / v_\parallel z$, where z is the longitudinal coordinate and l_0 the initial length of the bunch. Neglecting edge effects, one finds the following envelope equation for the beam:

$$\partial_{zz}^2 \sigma = K(z)/\sigma \qquad (1)$$

Here $\sigma = r/r_0$ is the envelope radius, normalized by the initial radius. The model and geometry independent parameter

$$K(z) = \frac{Z^2 \rho}{\beta_\parallel^2 c^2 \gamma^3 m_p} \frac{e^2}{2\epsilon_0} \qquad (2)$$

is called perveance. With the particle density ρ, $\beta_\parallel = v_\parallel/c$, c the speed of light, γ the Lorentzian factor and m_p the ion mass. As one can see from Fig. 2, the result from eq. 1 is in good agreement with PIC Simulations done with VORPAL©[3].
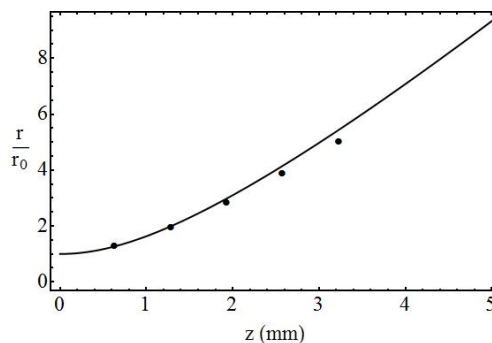

Figure 2: Beam radius from eq. 1 (black line) and simulation (dots) with VORPAL©[3].

SPACE CHARGE EFFECTS

The perveance from eq. 2 only depends on beam parameters and is a measure for the strength of space charge

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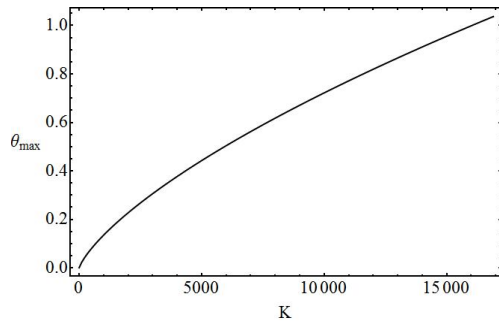[2]As one will see, the criterion can be applied for any ion.

Figure 3: Maximum divergence angle as function of K for $\vartheta_0 = 0$.

FOCUSING OF THE BEAM

The initial divergence of the laser accelerated beam is in the range of $0° \leq \vartheta_0 \leq 20°$ depending on the energy [1]. It is planned to strongly reduce this divergence by special target shapes as well as suitable laser spots. Nevertheless, the objective of the setup is to transport the proton beam into the rebuncher-cavity, which has an aperture of some mm. Therefore focusing and collimation structures are required. In the past a pulsed power solenoid was used to accomplish that aim (see Fig. 1). In the future setup it is planned to use a quadrupol-triplett instead of the solenoid.

FOCUSING WITH A SOLENOID

effects. Due to the transversal and longitudinal expansion of the beam, K decreases while propagation. Therefore the divergence angle ϑ stays constant after a propagation length z. After this saturation, space charge has vanished. The maximum divergence angle ϑ_{max} which is reached depends on the initial perveance K_0, see Fig. 3.
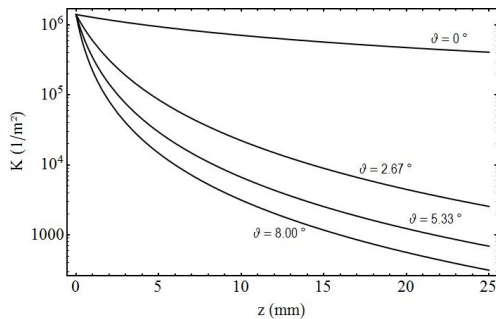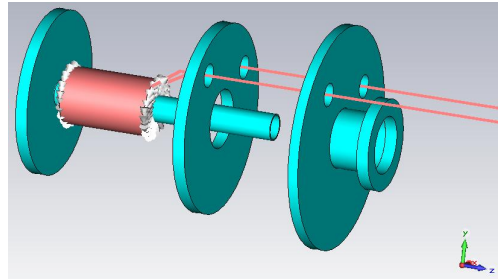

Figure 4: K as function of z for different inital angles.

Figure 4 shows the drop of K as a function of the propagation length for different initial angles in the case of space charge free drift. For example a maximum divergence angle of $\vartheta_{max} \leq 1°$ is tolerable in the setup. In the case of an initially laminar beam ($\vartheta_0 = 0$), one finds from Fig. 3 that $K \leq 15.000$ m^{-2} has to be full filled. As reference bunch we use a bunch with an average energy of 10 MeV and an energy spread of ± 1 MeV. From the measurements in [1] one gets $N_0 = 1 \cdot 10^{11}$ protons with an initial bunch length $l_0 \approx 1$ mm and radius $r_0 \approx 0,1$ mm. The primary objective of this section is to determine the position of the deneutralization foil so that space charge can be neglected after the bunch has crossed the foil. The perveance drops below the threshold value $K \leq 15.000$ m^{-2} after a space charge free drift length of at about $z \approx 1$ m (furthermore assuming $\vartheta_0 = 0$), as shown in Fig. 4. If the deneutralization foil is relocated to the position $z_{foil} = 1$ m, the divergence angle never exceeds $\vartheta_{max} \leq 1°$ and space charge can be neglected. As also shown in Fig. 4, the perveance decreases tremendously faster in the case $\vartheta_0 \neq 0$. If ϑ_0 is just $\approx 0,2°$, the foil can be placed 8 mm directly behind the proton source.

Figure 5: 3D-model of the used solenoid. Designed with CST EM Studio©[4]. Some parts of the setup are hidden for a better overview.

To verify that space charge remains negligible during the focusing with a solenoid, a CST©[4] particle tracking simulation (space charge free) is compared to a VORPAL©[3] simulation. For this purpose a 3D-model of the solenoid is designed in CST EM Studio©[4], see Fig. 5. A picture of the solenoid focal spot is given in Fig. 6 for the 10 ± 1 MeV reference bunch with $\vartheta_0 \approx 4.6°$.
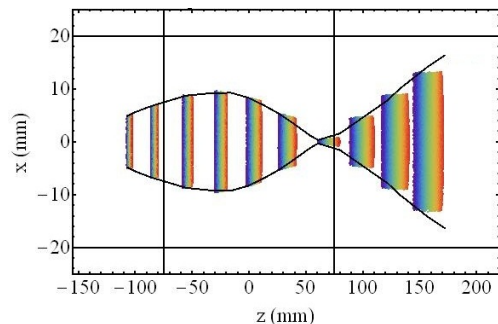

Figure 6: Stroboscopic recording of the bunch crossing the solenoid. From VORPAL©[3] simulation. The black line is the envelope trajectory from a CST©[4] particle tracking simulation (space charge free).

As can be seen in Fig. 6 both simulations show good agreement. Space charge effects can therefore be neglected during focusing. As further particle tracking simulations with CST Particle Studio©[4] showed, the power supply

wires of the solenoid (see Fig. 5) generated a magnetic dipole field, which caused a deflection of the beam, see Fig. 7. Based on this simulation, the experimental setup was improved and the wires field was removed.
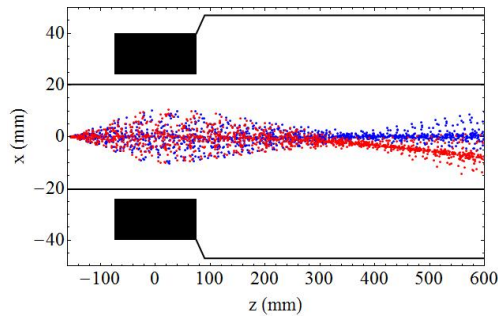

Figure 7: Particle tracking simulation with (red) and without (blue) supply wires. Done with CST Particle Studio[©][4].

INDUCTIVE COUPLING AND OHMIC LOSSES

Due to the fact that the solenoid is operated in pulsed mode, eddy currents accure in all the metal parts surrounding the solenoid, especially in the beam pipe[3]. This leads to a coupling between the solenoid and the sourrounding parts, resulting in a time shift between the maximum of the current pulse and the maximum of the magnetic flux density. Particles that should be focused by the solenoid have to be triggered such that they reach the solenoid center at the maximum of the field strength. Furthermore these eddy currents cause ohmic losses, as shown in Fig. 8.
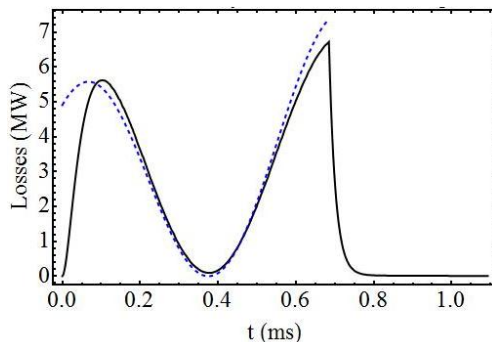

Figure 8: Ohmic losses in metal parts of the setup. Results from simulation with CST EM Studio[©][4].

CONCLUSION

A method was developed with which the influence of space charge of an arbitrary particle beam can be allocated. Within that, the beam parameter depending quantity perveance K was introduced. As shown, the evolution of the

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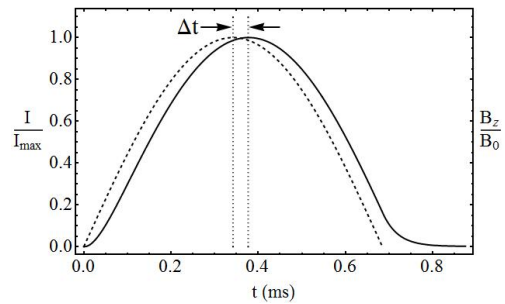[3]The beam pipe is centered in the solenoid.

Figure 9: Time shift between maximum of current and magnetic flux density. Results from simulation with CST EM Studio[©][4].

perveance $K = K(z)$ is the leading quantity to rate the importance of space charge. Using this criterion, now one can determine the position of a thin metal foil for deneutralisation such that after the foil space charge can be neglected. The results from eq. 1 where compared to simulation results to verify its validity. The validity of the criterion could also be demonstrated for focusing. Moreover an improvement of the experimental setup could be achieved based on the results of particle tracking simulations.

OUTLOOK

In the further work it is planned to work out a quality criterion, by which it can be decided what focusing method suits best for a given objective. Therefore further focusing structures will be taken into account (e.g. quadrupol-tripletts).

REFERENCES

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[3] Tech-X Corporation: *VORPAL[©]*, URL: www.txcorp.com, Boulder, USA (2012)

[4] CST Computer Simulation Technology AG: *CST Studio[©]*, URL: "'http://www.cst.com'", Deutschland Darmstadt (2012)