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THE INTERACTION BETWEEN ELECTRONS AND IONS IN COMOVING AND STATIC ELECTRON COLUMNS

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Abstract

The interaction between electrons and positive ion beams and its application in accelerator physics are investigated. A space charge lens called Gabor lens was developed which confines electrons in a static column by external fields. The confined electrons are used for focusing and support space charge compensation of ion beams. In this configuration the relative velocity between the ions and the electrons is maximal and corresponds to the beam velocity. In comparison an electron lens as at the Tevatron [1] is operated with a lower relative velocity in order to compensate the beam, to clean the beam abort gap or to excite the beam for beam dynamics measurements [2]. Another application is electron cooling, which needs the same velocity of the ion and the electron beam. The following study contains the superposition of electric and magnetic self-fields and their impact on the density distribution of the ion beam and of the electron beam. Recombination and ionisation processes are neglected. This is the beginning of an interface between these topics to find differences and similarities of the interaction between ions and electrons with different relative velocities. This will open up opportunities e.g. for the diagnostics of particle beams.

INTRODUCTION

The investigated Gabor lens for a static electron column is used as a focusing element in a linear accelerator [3]. Future application is planned as space charge compensation device in ring accelerators. An electron lens also fulfils this purpose with a comoving electron beam. The advantage of a static electron column is that it does not require an electron gun and the undesired effects of the fringe fields are low. Early efforts to utilise a static electron column in a ring accelerator are done at IOTA [4]. To investigate the radius influence on the interaction between a proton beam with the initial radius r_p and a static electron column with radius r_e, the cases $r_e < r_p$ and $r_e > r_p$ were simulated.

STATIC ELECTRON COLUMN

A static electron column can be confined by a superposition of electric and magnetic fields. An electrode system and e.g. a solenoid is used in a device called Gabor lens (Fig. 1).

The maximum electron density is limited in radial direction because of the Brillouin limit [5]

$$n_r = \frac{\epsilon_0 B_z^2}{2m_e}, \tag{1}$$

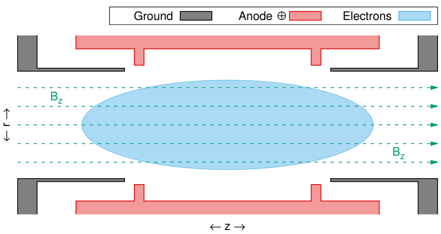

Figure 1: Schematic view of a Gabor lens to confine electrons with a superposition of magnetic and electric fields.

where ϵ_0 is the vacuum permittivity, B_z the maximum magnetic field in z-direction and m_e the electron mass.

In longitudinal direction the maximum density is limited by the anode potential Φ_A and is given by

$$n_l = \frac{4\epsilon_0 \Phi_A}{e r_e^2 \left(1 + 2\ln\frac{r_A}{r_e}\right)}, \tag{2}$$

where e is the elementary charge, r_e the maximum radius of the electron column and r_A the inner radius of the anode.

An optimal confinement is achieved if both conditions (Eq. (1) and (2)) are fulfilled at once. This results in the working function for a Gabor lens [3]

$$\Phi_A = \frac{e r_e^2 \left(1 + 2\ln\frac{r_A}{r_e}\right) B_z^2}{8m_e}. \tag{3}$$

With this system, it is possible to adjust the desired density in the static electron column by external parameters.

INTERACTION WITH AN IDEAL STATIC ELECTRON COLUMN

Fringe field effects are neglected by assuming an infinite electron column along the longitudinal axis which is called ideal static electron column. In the following, the influence of the proton beam radius r_p in comparison to the radius of this ideal static electron column r_e is discussed.

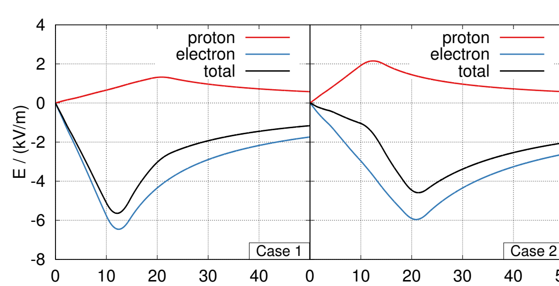

Figure 2: Radial electric fields of the initial homogeneous distributions for case 1 ($r_e < r_p$) and case 2 ($r_e > r_p$) split into the proton and electron part and the resulting field.

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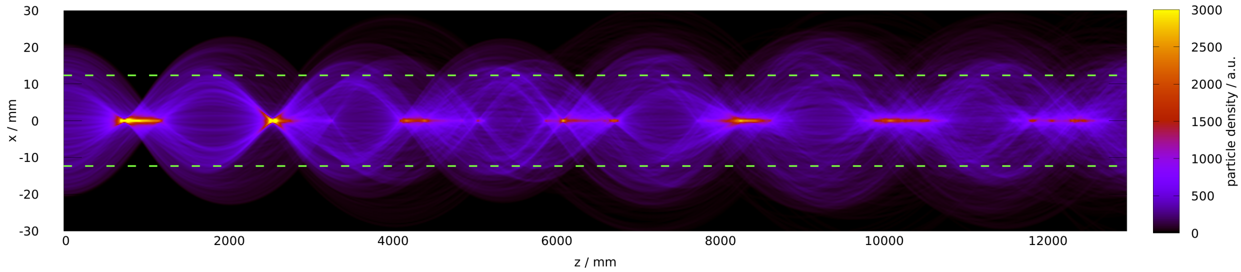

Figure 3: Particle density development for $r_e < r_p$ of an initially homogeneous proton beam ($I = 5\,\mathrm{mA}$, $E = 50\,\mathrm{keV}$) which interacts with an ideal static electron column (edge with green dashed line) with a density ratio of $n_e = 12 n_p$.

Case 1: $r_e < r_p$

In this case, the radius of the static electron column is smaller than the initial radius of the proton beam. Both have a homogeneous distribution. The resulting fields at the beginning are shown on the left side in Fig. 2.

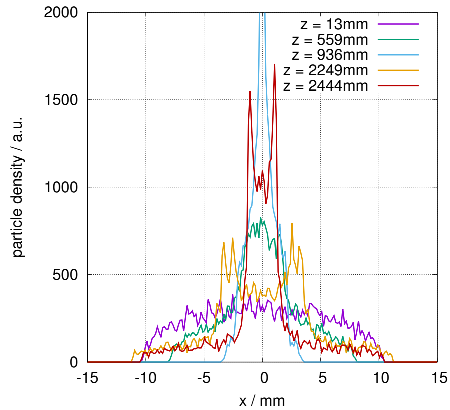

Figure 4: Beam profiles of a proton beam interacting with an ideal electron column for $r_e < r_p$.

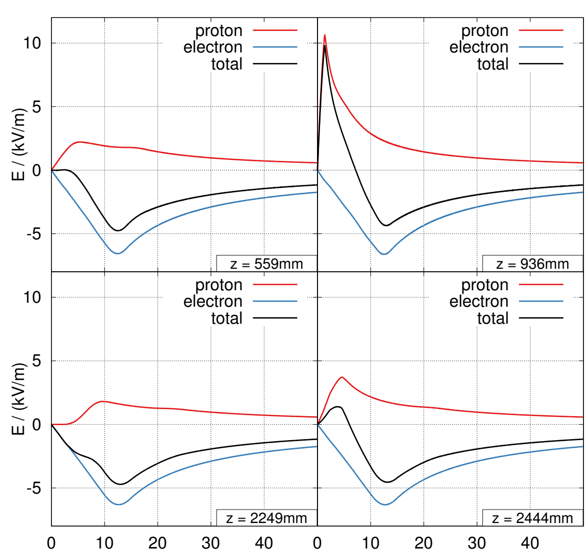

Figure 5: Electric fields for $r_e < r_p$ at different z-positions.

The total electric field shows that only the inner part ($r < r_e$) is linear. Outside the electron column, the protons are exposed to a non-linear field. This leads to shifts in focus (Fig. 3) and changes of the proton beam distribution. After a transient effect the oscillation becomes even.

Some examples of beam profiles at different positions are shown in Fig. 4. The beam profile varies from the initial homogeneous distribution to a approximately Gaussian or to a hollow beam distribution while the beam is transported through the electron column.

The corresponding electric fields are shown in Fig. 5. These indicate the extent of further deformation of the distribution.

Case 2: $r_e > r_p$

If the radius of the electron column is larger than the radius of the proton beam, the initial electric field, which has an effect on the protons, is entirely linear (Fig. 2, right).

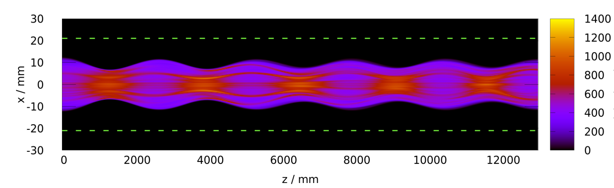

Figure 6: Particle density development for $r_e > r_p$ of a proton beam through an ideal static electron column (edge with green dashed line).

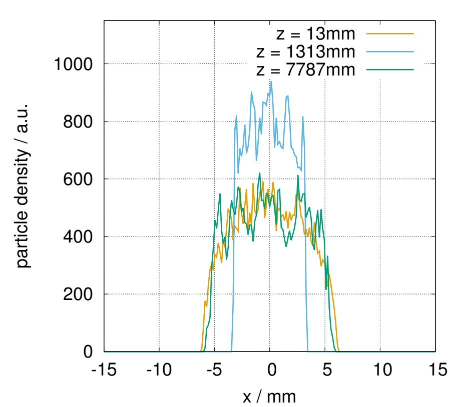

Figure 7: Beam profiles of a proton beam interacting with an ideal electron column for $r_e > r_p$.

For the simulation a proton beam with a current of $I = 5\,\mathrm{mA}$ and an energy of $E = 50\,\mathrm{keV}$ is chosen while the electron column has a density of $n_e = 1.5 n_p$. The proton

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beam is compressed up to a density where the space charge force of the proton beam outweigh the compressing force of the electron beam and the proton beam becomes larger again. After reaching the initial radius the beam is compressed again. Typical oscillation behaviour is seen in Fig. 6.

In Fig. 7 selected beam profiles are shown to illustrate that the proton distribution is compressed and decompressed without changing the distribution substantially.

Kurtosis and Emittance

If the beam radius is smaller or equal to the radius of the static electron column, the kurtosis barely changes because the beam distribution remains approximately homogeneous with a kurtosis value near two.

In the case that the static electron column is smaller than the proton beam, the kurtosis oscillates massively. In a beam focus the kurtosis takes high values, while for large beam radii the kurtosis reaches a local minimum. This local minimum rises and gets closer to a kurtosis value of 3, which means that the beam is approaching a Gaussian distribution. As a result, the non-linear field energy [6] rises.

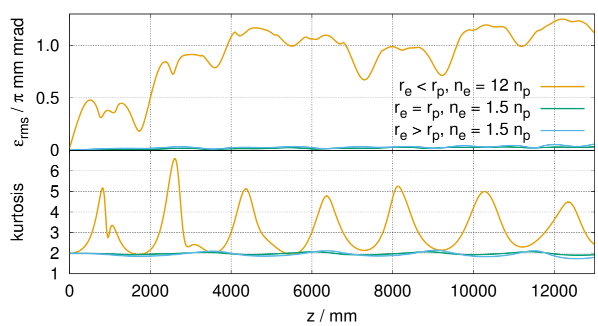

Figure 8: Development of kurtosis and emittance.

The emittance hardly changes for the case $r_e \geq r_p$. If the radius of the static electron column is smaller than the radius of the proton beam the emittance is growing (Fig. 8).

INTERACTION WITH A REALISTIC STATIC ELECTRON COLUMN

To analyse the more realistic case of periodically separated static columns, a coupled Gabor lens is used for the simulations. The density distribution within the static electron column is shown in Fig. 9.

The proton beam has a homogeneous initial distribution, a current of $I = 5$ mA and an energy of $E = 300$ keV. The beam is passed through the electron columns several times. The resulting beam profiles are plotted in Fig. 10.

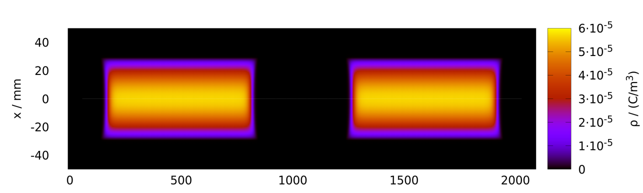

Figure 9: Electron density distribution of a double Gabor lens with $B_z = 32$ mT and $\Phi_A = 23$ kV.

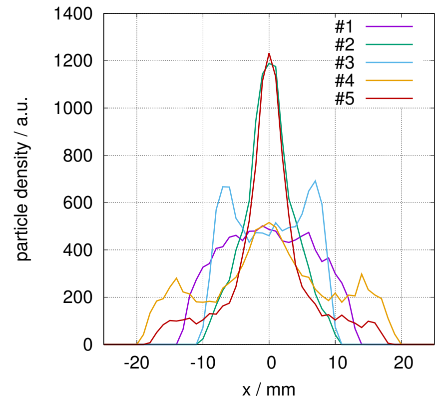

Figure 10: Beam profiles of a proton beam at different positions interacting with a realistic electron column.

In this case, the fringe fields of the electron column have an influence and it is more difficult to adjust a certain radius ratio due to the drift sections where the beam is exposed to its self-field. As a consequence, one part of the proton beam is inside of the column and the other part is outside. This correspondends to the case 1 where the static electron column is smaller than the proton beam. This explains why the resulting beam profiles are similar.

CONCLUSION AND OUTLOOK

The first results from simulations of the interaction between a static electron column and a proton beam are presented. Further investigations include numerical calculations for different initial density distributions under close examination of non-linear field energies in connection with the change in emittance. The detailed knowledge of the interaction is necessary to apply static electron columns for space charge compensation of ion beams in ring accelerators reliably.

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