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INFLUENCES OF BEAM PARAMETERS ON THE INTERACTION BETWEEN ION AND ELECTRON BEAMS

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Abstract

Electrons can be confined as a static column or as a comoving beam for applications in accelerator physics. Depending on the configuration of the electrons, they can cool [1], compensate [2] or even focus [3] the ion beam. In the case of an electron beam, the parameters must be chosen correctly to obtain the desired effects. The influences of these beam parameters on the interaction between the ion and electron beam are investigated in numerical simulations by using a particle-in-cell code [4]. The understanding of the different interaction mechanisms will allow an even better matching of the beams to each other for the intended application. With additional suitable beam diagnostics, it will be possible to draw conclusions about the interaction of the superimposed beams in order to evaluate the quality of the settings and, if necessary, to correct them.

SIMULATION SETTINGS

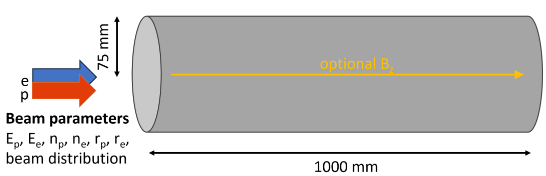

Figure 1: Schematic layout of the simulation setup.

To investigate the influence of the initial beam parameters, simulations were performed by using the particle-in-cell code Bender [4]. A proton beam is superimposed with an electron beam (Fig. 1). The simulation volume is bounded by a beam tube with a radius of 75 mm and a length of 1000 mm. In each simulation, the initial kinetic energies are set to $E_{\text{kin,protons}} = 50\,\text{keV}$ and $E_{\text{kin,electrons}} = 27.23\,\text{eV}$ so that the velocities of the beams are the same ($v_e = v_p$). The resulting transit time is $\tau = 323\,\text{ns}$. The beams start with the same radius ($r_e = r_p = 15\,\text{mm}$). In the simulations, in which the mean density is varied to study the influence of the initial density, the initial distribution is chosen the same. In addition, a longitudinal homogenous magnetic field of $B = 3\,\text{mT}$ is used in some simulations.

Table 1: Initial Beam Parameters

beam particles	E_{kin}	r	distribution
protons	50 keV	15 mm	Gaussian/KV
electrons	27.23 eV	15 mm	KV

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DENSITY INFLUENCE

In order to investigate only the influence of a density difference, all other initial beam parameters were left constant in each simulation (see Table 1), while the mean density was varied. A KV distribution was chosen as an initial distribution for the electron and proton beam to ensure linear space charge fields.

Without a Longitudinal Magnetic Field

To allow undisturbed particle interactions, simulations were first performed without a longitudinal magnetic field for different cases. First, the same density for both beams was simulated as a reference. Then, different densities were chosen: $n_e < n_p$ and $n_e > n_p$.

Case $n_e < n_p$: When the density of the protons is greater than the density of the electrons, the electrons, as they move in the z-direction, begin to oscillate radially around the beam axis, creating focal points of increased density (similar to Fig. 2). This leads to strong non-linear fields, so that a redistribution of both beams can be observed. The kurtosis of the proton beam grows from an initial value of 2 to 2.3 for the case $5n_e = n_p$ and to over 2.4 for the case $1.5n_e = n_p$ (Fig. 3b) while the kurtosis of the electrons (Fig. 3e) increases right at the beginning and oscillates around the value 2.4. This oscillation decreases in the course of the simulation. This redistribution of particles in the beam causes an emittance growth of both beams (Figs. 3a and 3d). Another important effect is the energy shift, which also occurs at different densities. The greater the density difference, the greater the energy shift, which can be seen in Figs. 4 and 5.

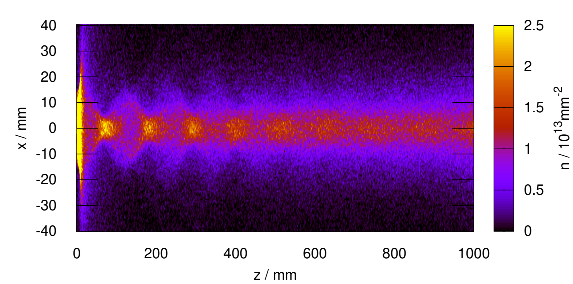
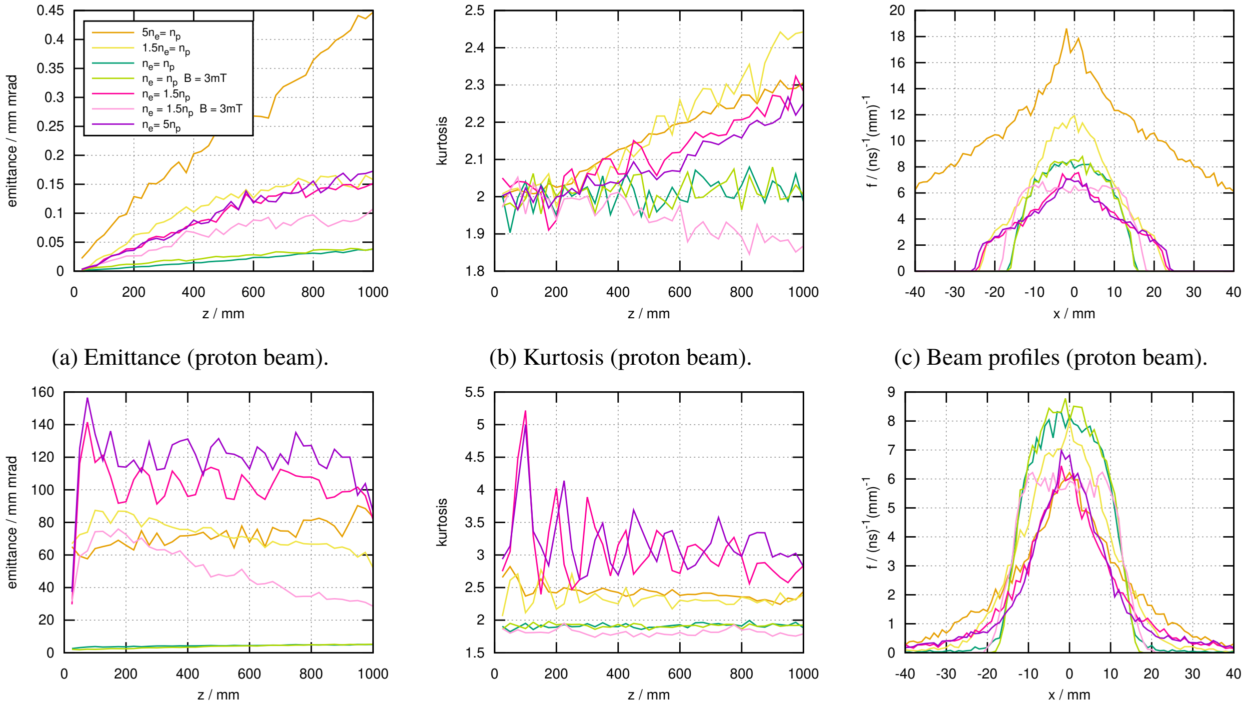


Figure 2: x-z-plane of the electron densitiy distribution for $n_e > n_p$. The electron slice is seen at the beginning, which is a result of the high space charge forces. The following oscillation of the electrons is similar to the oscillation of the electrons in the case $n_e < n_p$.



(a) Emittance (proton beam). (b) Kurtosis (proton beam). (c) Beam profiles (proton beam).

(d) Emittance (electron beam). (e) Kurtosis (electron beam). (f) Beam profiles (electron beam).

Figure 3: Comparison of emittance $\epsilon_{rms,norm} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$, kurtosis $V_x = \frac{\langle x^4\rangle}{\langle x^2\rangle^2}$ and beam profiles for the cases $n_e < n_p$, $n_e = n_p$, and $n_e > n_p$. Density differences lead to emittance growth, kurtosis change and related distribution change. A magnetic field reduces the emittance growth and leads to lower kurtosis.

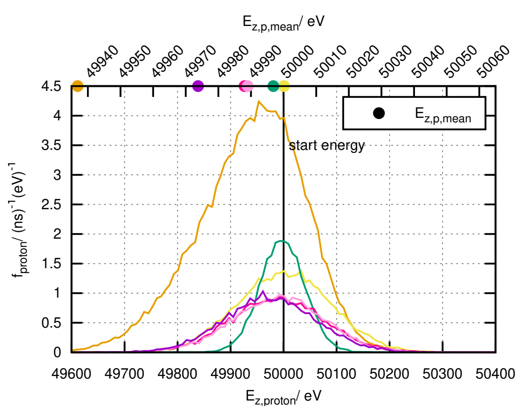


Figure 4: Kinetic energy distribution of the proton beam at $z = 1000$ mm with energy shift due to density difference.

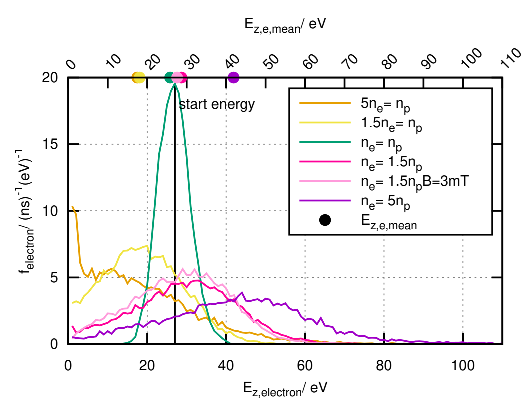


Figure 5: Kinetic energy distribution of the electron beam at $z = 1000$ mm with energy shift due to density difference.

Case $n_e > n_p$: All cases with initial $n_e > n_p$ result in $n_e < n_p$, because the space charge forces and the strong mobility of the electrons at the beginning of the simulation volume leads to a strong divergence and accumulation of the electrons in an electron slice ($E_z = 0$ eV), which reduces the following density of the electrons. In Fig. 2, the electron slice can be seen at small x values. Similar to the simulation for $n_e < n_p$ there is an oscillation of the electrons around the beam center (Fig. 2), the emittance grows, a redistribution takes place with an increasing kurtosis and an energy shift can also be observed (Fig. 3).

With a Longitudinal Magnetic Field

The simulation for $n_e = 1.5n_p$ was carried out with an additional longitudinal magnetic field. A longitudinal magnetic field is needed to avoid radial losses of electrons and to preserve the electron density. This reduces the electron slice at the beginning. This electron accumulation does not disappear completely, because the electrons, which diverged strongly without magnetic field, still have this tendency, but are held in the beam by the magnetic field and gyrate. Nevertheless, they have changed their longitudinal velocity into transversal velocity, so that they still form an electron slice

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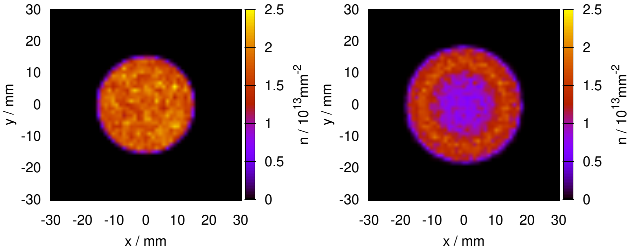


(a) start (z=50 mm). (b) end (z=1000 mm).

Figure 6: x-y-plane with the density distribution of the proton beam. The proton beam adapts to the distribution of the electron beam (hollow beam distribution).

with a well-defined radius at the beginning. The electrons in the beam directly form a slight hollow beam due to the magnetic field. This distribution remains through the whole simulation volume which can be observed by the value of the kurtosis, which is less than 2 (Fig. 3d). Because of the magnetic field, the mobility of the electrons decreases, so that the protons are radially more mobile than the electrons. The protons therefore adapt to the electrons in order to reach a state of equilibrium. At the end, the proton beam also reaches a hollow distribution (Figs. 6 and 3b). Compared to the case without a magnetic field, the additional magnetic field reduces the emittance growth (Fig. 3a). The emittance of the electrons increases globally but decreases after the initial rise (Fig. 3d). Anyhow the magnetic field does not change the already existing energy shift (Figs. 4 and 5).

DISTRIBUTION INFLUENCE

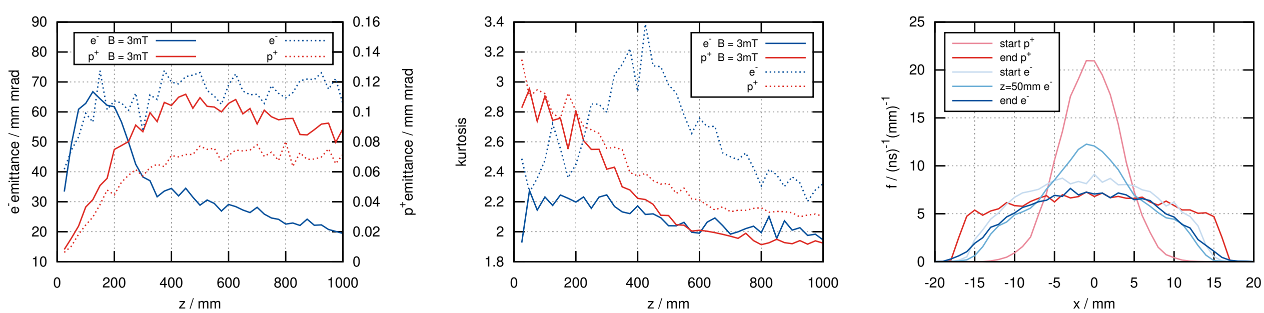
To study the distribution influence, the superposed beams have the same initial parameters as in the density influence simulations except that the distributions differ. The proton beam starts with a Gaussian distribution and the electron beam with a KV distribution. Simulations were performed without and with a longitudinal magnetic field (Fig. 7). With a magnetic field, the electron beam is kept approximately in its initial distribution, so that the proton beam reaches the KV distribution faster than without a magnetic field (Fig. 7b). The emittance growth of the electron beam reaches in both cases a maximum, but in the case with magnetic field the emittance decreases along the z-direction. In contrast, the emittance growth of the proton beam is higher in the case with magnetic field (Fig. 7a).

CONCLUSION

These investigations clearly show the influence of a density or a distribution difference. Depending on the application these influences can be disadvantageous or even advantageous. If an ion beam is to be preserved as cool as possible or even to be cooled by its interaction with the electron beam, emittance growth is by no means beneficial. An unwanted energy shift or distribution change can cause problems in the following accelerator system. Thus, it is important to choose the initial beam parameters accordingly. In a previous publication [5] the influence of the radius was already presented. In these simulations it is evident that to avoid non-linear field forces and to preserve the distribution, the electron beam radius must always be larger than the ion beam. The simulations presented in this publication show the requirement of the same density and distribution for the superposed beams if an emittance growth, an energy shift or a change of the distribution is undesired.

Nevertheless, a difference in the density distributions can also be useful. Since a magnetic field is always required for the electrons, the adapting of the ion beam to the electron beam can be used to intentionally change the distribution of the ion beam, either to obtain a different distribution or to improve the present distribution.

With more detailed investigation, in simulations as well as in experiments, it should also be possible to draw conclusions about the interaction of the beams by using the beam diagnostics of the electron beam, in order to make adjustments to the system if necessary.



(a) Emittance. (b) Kurtosis. (c) Beam profiles.

Figure 7: Emittance $\epsilon_{rms,norm} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$, kurtosis $V_x = \frac{\langle x^4\rangle}{\langle x^2\rangle^2}$ and beam profiles of the simulation results to study the distribution influence. With a magnetic field, the electron beam approximately keeps its KV distribution. The proton beam thus reaches the KV distribution faster than without a magnetic field.

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