HIGH-CURRENT BEAM TRANSPORT SIMULATIONS INCLUDING GABOR LENSES IN VARYING NON-NEUTRAL PLASMA STATES.*

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Abstract

Gabor space charge lenses have been under investigation theoretically and experimentally at IAP for many years. Especially the application in high current Low Energy Beam Transport (LEBT) sections seems efficient and attractive. The focusing properties and imaging quality of this lens type depend on the transverse and longitudinal confinement of the electron column. Different non-neutral plasma states have been observed and calculated. In general, they can be disturbed by the interaction with ion beams. This results in a shift and in a modification of the work function with a rise of aberrations and beam emittance growth. It is necessary to understand such processes for transport channels using intense ion beams to preserve the high beam brilliance. The beam transport simulations including Gabor lenses in various non-neutral plasma states will be presented and compared with experimental results.

GABOR LENS

The Gabor space charge lens is a type of cylindrical trap, which uses crossed electric and magnetic fields to confine dense (compared to the beam charge densities) electron column around the axis. The self field of such a trapped column has a large transverse component of the electric field, which can be used for focusing a beam propagating through the column.

The lens type designed at IAP in Frankfurt and investigated for many years [1,2] does not need any external source of electrons due to the natural production through the rest gas ionization inside the volume of the lens. The ignition behaviour depends on proper settings of an anode potential, magnetic field and rest gas pressure. An overview of different types of space charge lenses for focusing and manipulating of high current ion beams could be found in [3]

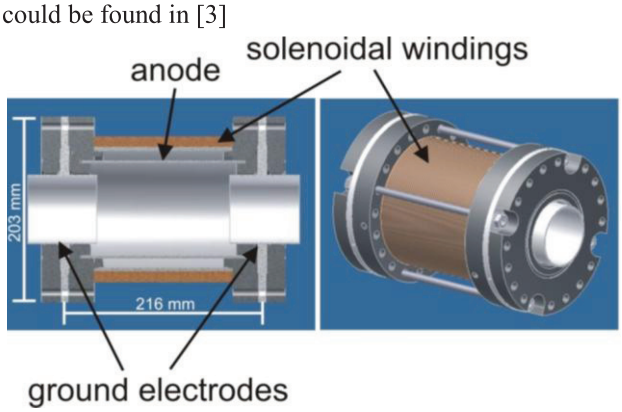

Figure 1: Layout of the Gabor lens designed and used at IAP Frankfurt.

For beam focusing purposes it is convenient to have linear focusing forces to avoid aberrations. The ideal density form of the trapped column is therefore a homogeneous distribution with quadratic potential profile. Through the settings of the external parameters this homogeneous state could be always reached and is described by so called work function [2].

HIGH SPACE CHARGE DENSITIES

In a high space charge scenario the Gabor lens provides effective focusing in cooperation with space charge compensation through the trapped electrons. Additionally, it can be used as a reservoir of compensation electrons for a whole LEBT beam line. This can improve the beam transmission and preparation for the beam injection into the RFQ acceleration structure.

However, the beam itself can disturb the operational parameters of the Gabor lens. For example, the beam impact on the electrodes or walls inside the lens will produce showers of secondary electrons, hence influencing the production process. Deviations of the parameters from the work function lead to various non-neutral plasma states, where the trapped electron column differs from a homogeneous distribution. To study the beam-column interaction experimentally a LEBT setup (Fig. 2) was built at Frankfurt University and experiments are planned this year.

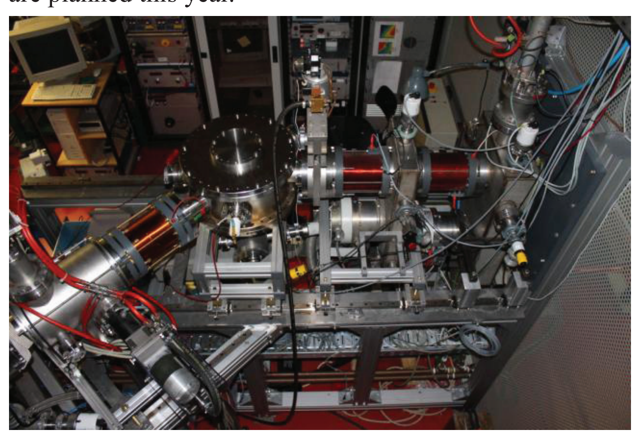

Figure 2: LEBT test setup consisting of a volume type ion source, an array of three Gabor lenses and a 45° electrostatic deflector.

SIMULATIONS

In order to study the processes connected to the high space charge transport scenario simulation tools have been developed [2].

The GAB_LENS 3D simulation code used in this work is a numerical Particle-In-Cell (PIC) code to study the dynamic evolution of the trapped electron column. First, no interaction between beam and column is assumed, so the different plasma states can be characterized.

An example for such a simulation is shown in Fig. 3. Typical parameters like magnetic field B_0=6.6mT, anode potential Φ_A=1850V, averaged electron density $n_e=10^{14}$ m^{-3} were set and the time evolution of the trapped column was calculated.

Case (A) corresponds to the longitudinal magnetic field B=0.5*B_0 with the on-axis potential Φ_0>0. The electron distribution remains constant over the entire simulation time of Δt=1µs.

Case (B) corresponds to B=B_0 with the on-axis potential $\Phi_0 \sim 0$ or slightly negative. The column exhibits a ring structure shape in integrated density but with smooth quadratic behaviour of the electric potential in radial direction.

Case (C) was simulated with higher magnetic field B=2·B_0, so the gyration radius of the electrons is smaller. The column is more locally compressed and the on-axis potential Φ_0 (z position in the middle of the lens) approaches negative values. The confinement condition (positive potential to confine electrons longitudinally) is then not fulfilled in the centre of the column. This results in a hollow profile which is, in general, unstable with rise of the diocotron surface modes. The column rotates due to the ExB fields around the axis with a typical wave motion on the circumference of the ring profile. The azimuthal density modulation characterizes the mode number l. In this case l=2.

The potential has a flat profile inside the hole, which corresponds to vanishing focusing forces. Outside of the hole, the potential behaviour is quadratic on average. Due to the lack of cylindrical symmetry and diocotron modes the radial dependence is different for different cylindrical angles φ. This is demonstrated in spread of the calculated potential data between r=0.01m and r=0.04m.

Case (D) was used with magnetic field B=3·B_0. All other parameters remained unchanged. The diocotron mode is changed to l=3 mode with a bigger hole within the confined column. The potential behaviour in radial direction is similar to the case (C).

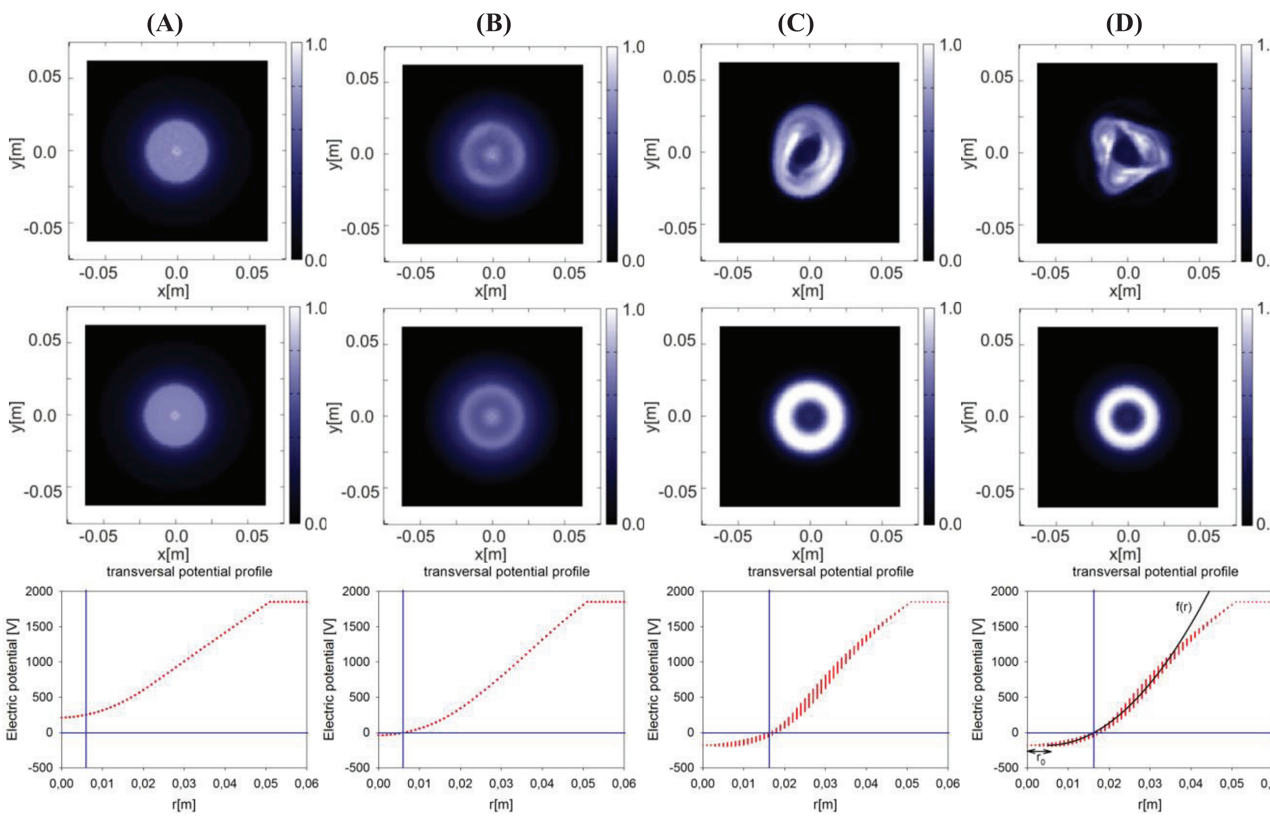

Figure 3: Example of simulated four different (A, B, C, D) non-neutral plasma states within the Gabor lens. In the first row, the z-integrated electron density is depicted, at t=1µs. In the second row the effective density averaged over 1ms is shown. In a third row the according transverse potential profile in the centre plane of the Gabor lens at t=1µs is displayed.

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The typical trapped electron column rotates quickly around the axis with rotation times of approximately τ = 10ns. Transport of low energy beams through such a column along the axis (He^{1+}, 14keV, time of flight t ~ 100ns) could then be described by an effective focusing force, which is averaged potential gradient averaged over a time interval.

Various non-neutral plasma states can be processed as hollow density profile, which is demonstrated in Fig.3 in the middle row.

A simple mathematical model was therefore adopted with an approximation of the potential profile by a function f(r):

$$\begin{aligned} f(r) &= \Phi_0 + \alpha \cdot (r - r_0)^2 \qquad & r \geq r_0 \\ f(r) &= \Phi_0 & r < r_0 \end{aligned} \quad (1)$$

Parameters Φ_0, α, r_0 define the plasma state and the focusing properties of the lens. These parameters were used in the following beam tracking simulations.

Particle tracking was done using transfer maps. The single step transfer map consists of the 1/2drift-kick-1/2drift system, where focusing forces are expressed by $\nabla f(r)$. In case of the parameter set with r_0>0, is the transfer map nonlinear.

The simulated beam line consists of the drift length L_1=0.2m, focusing Gabor lens with the length L_2=0.1m and end drift of the length L_3=0.5m. A He^{1+} beam with energy W=14keV was transported through the system with assuming of 100% space charge compensation. 50000 macroparticles on a 4D Kapchinski-Vladimirski (K-V) initial distribution were tracked in 100 steps through the Gabor lens. The influence of the hollow profile on phase space distribution was studied (Fig. 4).

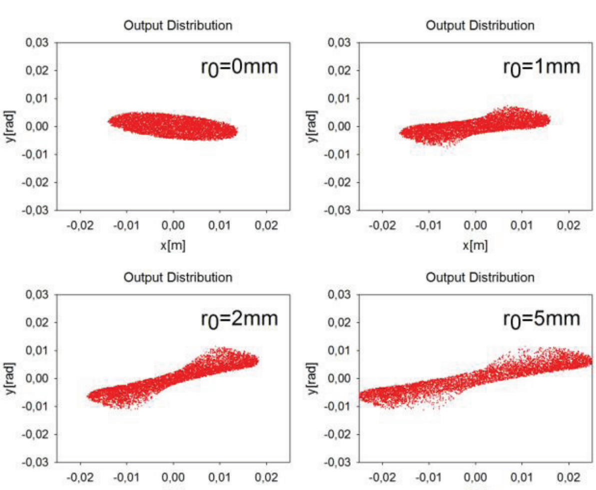

Figure 4: Output phase space distributions of the He^{1+} at 14keV. The electron free zone is limited by the variable radius r_0.

The beam transport through the homogeneous electron column (r_0=0mm) reproduced aberration free in the simulations.

The output phase space distribution is already changed by adopting only small hole in the trapped electron column with a radius r_0=1mm. Some of on axis particles experience reduced focusing forces so the phase space distribution will change in slope, dimension and form due to the non linearity.

CONCLUSION AND OUTLOOK

Gabor lenses have been under investigations for many years at Frankfurt University. It seems promising to use this type of space charge lens especially in low energy beam transport sections due to the natural production of compensation electrons and straightforward construction.

To understand the interaction between beam and electron column a new test stand with three Gabor lenses is under construction. Experiments for studying space charge compensation and decompensation of the ion beam are planned. Also, beam optics, especially aberrations under different conditions should be studied in a detail and compared with numerical simulations.

3D simulations showed different non-neutral plasma states, which are dependent on external parameter settings. Until now, simulations have only considered electrons without a permanent flow of residual gas ions exiting the lens longitudinally. It is planned to extend the simulations and study the perturbation due to the residual gas ions and its influence on beam optics.

Numerical models were developed to investigate beam focusing in quickly rotating plasma states with a hollow profile. Such states can be produced in experiments when the beam hits the inner walls or electrodes of the lens causing enhanced production of electrons. Additional electrons lower the on axis potential below 0V, so they are no more confined in this area and can leave.

It is planned to extend the potential model for radii greater then confined electron column, where quadratic potential approximation is no more valid and implement it into the particle tracking simulation code.

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