SPACE-CHARGE COMPENSATION OF INTENSE ION BEAMS BY NONNEUTRAL PLASMA COLUMNS*

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Abstract

Gabor lenses were conceived to focus a passing ion beam using the electrical field of a confined nonneutral plasma column. Beside its application as focusing device, in Gabor lenses space-charge effects can be studied in detail.

The influence of the electron distribution on emittance and space-charge dominated ion beams was investigated in beam transport experiments [1]. In this contribution we want to emphasize one result of these experiments. The measurements indicated a strong contribution of secondary electrons on beam dynamics. Secondary electrons are produced within the transport channel, particularly by interaction of the beam with the surface of the slit-grid emittance scanner. This effect might lead to an increase of the filling degree and to an improved focusing performance of the lens.

Assuming that the loss and production rates within the lens volume and the transport channel determine the equilibrium state of the nonneutral plasma column, the electron cloud was characterized as a function of the external fields and the residual gas pressure in small-scale table top experiments.

In this contribution experimental results will be presented in comparison with numerical simulations.

BEAM TRANSPORT EXPERIMENTS

A number of diagnostic as well as beam transport experiments were performed in order to investigate how the nonneutral plasma properties are mapped onto the ion beam. At first, the electron density distribution and the plasma parameters were determined in diagnostic experiments without beam. Afterwards the lens was used as focusing device for the transport of an emittance dominated helium and a space charge dominated argon beam to study its performance with respect to image quality and space charge compensation.

Electron Density Distribution

Figure 1 represents the results of the emittance dominated beam transport experiments.

One important result is that the electron density distribution determines the phase space distribution of the beam. In case of a hollow electron distribution, passing beam ions experience a strong force at the edge of the column and none in the center. For a homogeneous electron density distribution the focusing is linear and therefore the beam is transported without aberrations if the radius of the column is larger than the beam radius. Still, it was found that for given lens parameters the measured electron densities and the electron

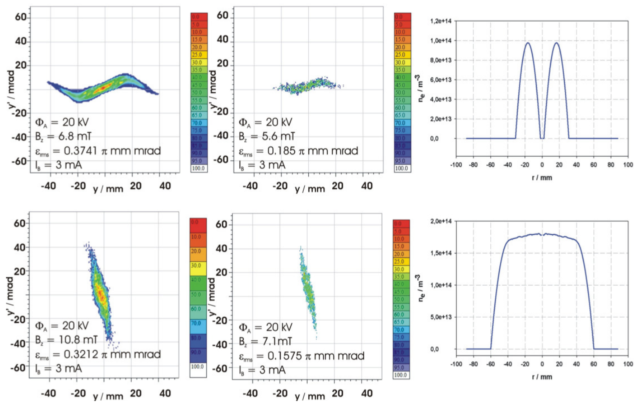

Figure 1: Comparison of measurement (left) and simulation of the transported He+ beam (center) as well as simulated electron density distribution (right) [2].

density distribution in the diagnostic experiments differed from the results of the beam transport experiments.

An example of the space-charge dominated beam experiments is depicted in Fig. 2.

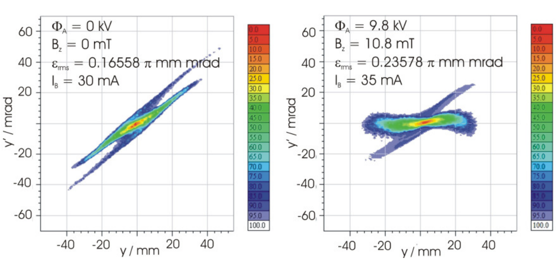

Figure 2: Phase space distribution of the drifted beam when the lens was switched off (left) and of the transported Ar^+ beam when the lens was switched on (right) [2].

Indeed, the focusing performance of the Gabor lens looks very promising, but neither the diagnostic measurements nor the performed numerical simulations show comparable results.

Influence of Beam Intensity on the Focusing Performance

Furthermore, for the same parameter set-up of the Gabor lens it was observed that the focusing strength increases with the beam current which indicates an increased density of the confined electron column. Figure 3 illustartes the phase space distribution of a 2.2 keV/u Ar^+ beam measured behind the lens for different beam currents.

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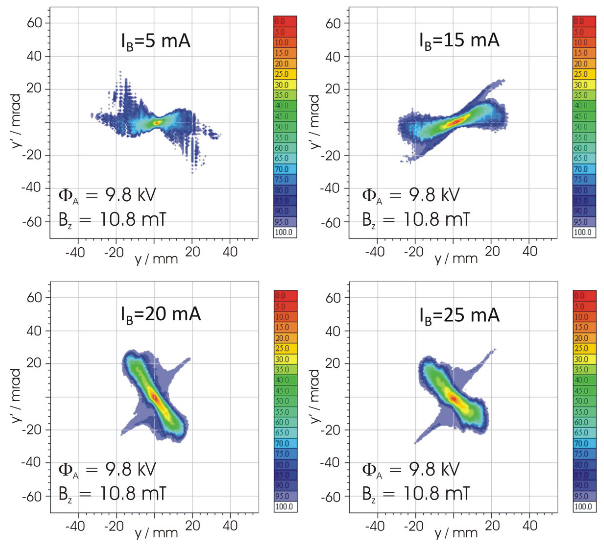

Figure 3: Influence of the ion current on the focusing performance of the lens.

One possible explanation for this observation is the enhanced ionization rate of the residual gas due to the higher beam intensity. Another source of electrons could be transmission losses of the beam on the chamber wall or secondary electrons produced during the measurement by the slit-grid emittance scanner. However, as a result of the external fields no additional electrons should be confined inside the lens volume.

In order to further investigate the confinement with respect to the external parameters, the production and loss processes within the Gabor lens have been investigated.

ELECTRON PRODUCTION AND LOSSES

Several diagnostic experiments were performed in order to investigate the electron loss and production processes in more detail. These processes are assumed to have a major impact on the equilibrium state of the nonneutral plasma.

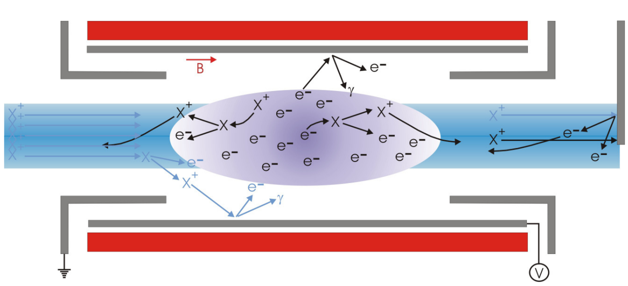

Figure 4: Scheme of the assumed production processes.

Interactions of electrons, atoms, ions from residual gas and the beam as depicted in Fig. 4 lead to an electron built-up within small time scales below 1 ms [3]. The build-up as a function of the external fields and the residual gas pressure was measured by a CCD camera with high quantum efficiency. The first signal of plasma emission that results from residual gas excited by electrons was defined as "ignition point" for a given parameter set-up.

The results of these measurements for different confinement lengths are presented in Fig. 5. Note that the anode potential Φ_A is normalized to the square of the lens' radius in order to compare different lens types.

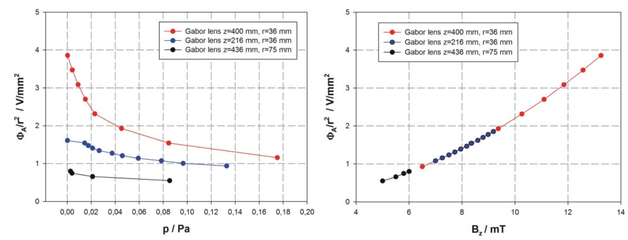

Figure 5: Measured ignition curves of the nonneutral plasma for helium as a function of the potential (left). The anode potential was configured according to the lens work function and normalized to the radius in order to compare all lens types (right).

The confinement of electrons within the Gabor lens is not perfect. Owing to particle collisions, field inhomogeneities and the finite electron temperature, electrons are lost in transverse and longitudinal direction. In longitudinal direction the electron is confined by the potential well created by the electrode system, while it has a degree of freedom along the magnetic field lines. Electrons are lost if the kinetic energy is high enough to leave the potential. Since residual gas ions are also extracted from the lens the experimental evidence of these losses is very difficult.

The transverse electron losses are a result of collisional transport across the magnetic field lines. Depending on their kinetic energy lost electrons can produce X-ray radiation and are detected by a γ-spectrometer. Figure 6 shows the measured gamma count rate as a function of the anode potential Φ_A (for B_z=11.9 mT, p=$1.7{\cdot}10^{-5}$ Pa) and the magnetic field on axis B_z (for Φ_A=22 kV, p=$5.1{\cdot}10^{-5}$ Pa). The detected intensity I_x was divided by the ion current I and the residual gas pressure p to minimize the influence of a variation in the plasma state during the measurement.

The loss rate represented by the X-ray intensity increases exponentially as a function of the anode potential while it decreases for stronger magnetic confining fields.

Influence on Secondary Electron Production on Plasma State

Another indirect evidence for the influence of produced secondary electrons on the plasma state is shown in Fig. 7. The residual gas ion current is measured by a Faraday cup (FDC) including a repeller electrode which is used to keep produced secondary electrons inside the detector.

It is assumed that these electrons are confined in the potential of the extracted residual gas ions and retroact on the electron column. By increasing the negative potential of the repeller electrodes the emission intensity decreases as a result of less electrons interacting with the residual gas.

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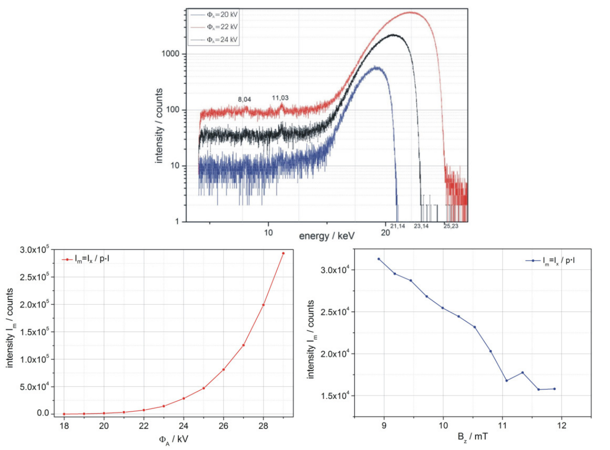

Figure 6: Example of measured X-ray emission spectrum (top), x-ray emission as a function of the anode potential Φ_A (bottom, left) and the magnetic field B_z (bottom, right) [4].

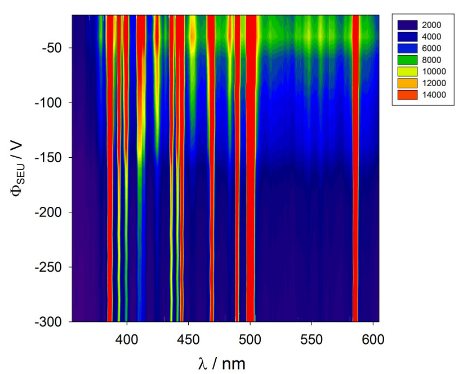

Figure 7: Measured intensity profile in the wavelength region from 360 to 600 nm as a function of the repeller potential for lens parameters of Φ_A=5.4 kV and B_z=8.72 mT [5].

DISCUSSION AND OUTLOOK

In this contribution assumed production and loss mechanisms are discussed and first measurements of electron production and losses within the volume of a Gabor lens are presented.

The results of beam transport as well as diagnostic experiments indicate a strong influence of the secondary electron production on the nonneutral plasma state. Yet, a measurement of the different contributions is difficult to realize and an experimental evidence is still needed.

Another possible explanation for the observed change in the focusing strength discussed in the first paragraph is the reduction of the electron loss channels due to the positive beam potential. As presented in Fig. 8 the superposition of the beam, the space charge and the anode potential creates a barrier for electrons that are able to escape in longitudinal direction.

Beside reliable non-invasive diagnostic techniques an extensive numerical model is needed to understand the influence of the previously discussed effects on the electron confinement and on the transport of high intensity ion beams using Gabor lenses.

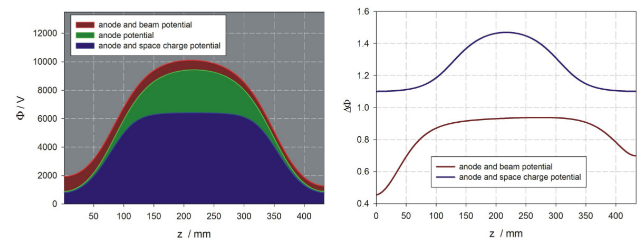

Figure 8: Superposition of the anode potential, the space charge potential of the electron cloud and the uncompensated beam potential for an 3.1 keV/u, 35 mA Ar^+-beam in longitudinal direction.

The 3D Particle-in-Cell Code bender has been developed to improve the understanding of the dynamics of the compensation and the resultant steady state by implementing ionization of residual gas as well as secondary electron production on surfaces [6]. First simulations using bender were performed to study the electron cloud build-up inside the Gabor lens and are shown in Fig. 9.

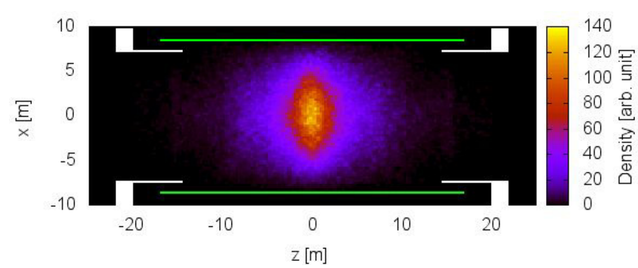

Figure 9: State of the nonneutral plasma after 140 μs for Φ_A=9.8 kV, B_z=10.8 mT and p=$1\cdot10^{-3}$ Pa (Ar) [3].

In future work the interaction of the ion beam with the confined electron cloud with respect to the production and loss processes will be studied numerically and experimentally in more detail.

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