# ELECTRON CLOUD DYNAMICS IN A GABOR SPACE CHARGE LENS*

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*Abstract*

Inside Gabor space charge lenses, external fields confine electrons forming a homogeneously distributed electron cloud. Its linear electric space charge field enables the focusing of high intensity heavy ion beams without aberrations. The focusing performance depends on the properties of the nonneutral plasma.

In a small-scale table top experiment, different types of space charge lenses are used to characterize the collective behaviour of the confined electron cloud using new non-interceptive diagnostic methods. The plasma parameters, e.g. electron temperature and density, are important to an improved understanding of loss and production mechanisms as well as the electron cloud dynamics. In this context, the evolution of instabilities caused by the enclosing fields has been investigated in detail.

Experimental results will be presented and compared to numerical simulations.

## SPACE CHARGE LENSES

Over the last 10 years different types of space charge lenses have been built and investigated at the Institute for Applied Physics (IAP) of the Frankfurt University (see Fig. 1).

The original concept of the lens consists of a cylindric anode and ground electrodes surrounded by a solenoid. The overall length of the system is $l_{tot}$=216 mm with maximum magnetic field of $B_{z,max}$=28 mT and potential of $\Phi_z$=6.5 kV. Its focusing capabilities have been investigated in detail by [1].

In addition, a space charge lens segmented and scaled in z-direction ($l_{tot}$=400 mm) was constructed to determine the plasma parameters of the confined electron cloud as well as to develop related diagnostic techniques. By using the segmented anode, field gradients can be created. Moreover, the dependence of the confinement on the geometry of the lens can be analyzed (see *production mechanisms*).

For beam transport experiments at GSI, a scaled Gabor lens has been designed and built [2]. Beside the enlarged radius the specific feature of this system is its radially segmented anode to study possible steering effects. It can be operated with a maximum magentic field of $B_{z,max}$=0.1 T and a potential up to $\Phi_z$=50 kV.

Apart from their special applications all devices are used to study the confined electron cloud and its dynamics. Several aspects of the research are explained in the following sections.

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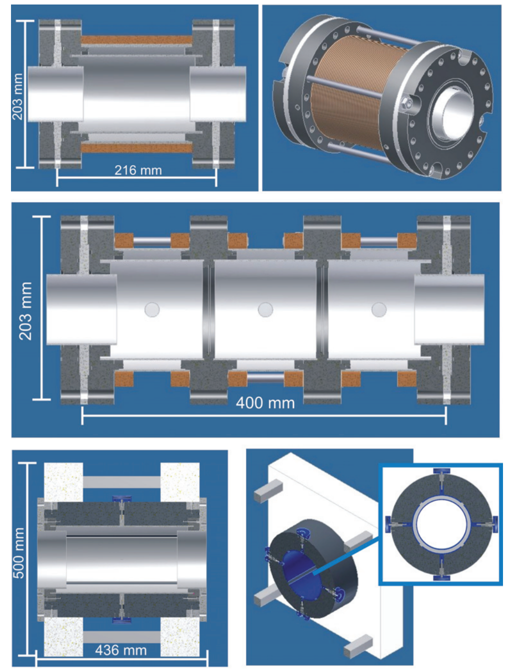


Figure 1: Different types of space charge lenses at IAP: original concept (top), scaled in z-direction (middle) and scaled in r-direction (bottom).

## TEMPERATURE MEASUREMENT

Conventional non-interceptive methods for temperature determination are not applicable to nonneutral plasmas. It is currently under investigation whether the electron temperature can be determined by the measurement of the intensity ratio of two excited states in helium and comparing it to the ratio of optical emission cross sections.

The database of optical emission cross sections in the energy region above 200 eV is insufficient. Therefore, an experiment for the determination of this kind of cross sections has been set up (see Fig. 2).

The optical method to study collision processes between electrons and atoms directly relates the emitted atomic line intensities to the electron energy. Therefore, the optical emission cross section is defined as the ratio between the number of emitted photons compared to the number of helium atoms and exciting electrons:

$$Q_{ji} = \frac{\Phi_{ji}}{\frac{I}{e} n_0} \quad (1)$$

with

$$\Phi_{ji} = \frac{I_{ji}}{t\Delta x} \quad (2)$$



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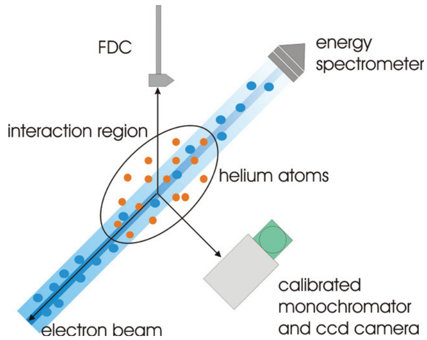


Figure 2: Measurement scheme of optical cross sections.

where $I_{ji}$ is the number of emitted photons, I the electron beam current, $n_0$ the target gas density, and $\Delta x$ is the length of the electron beam region from which radiation is collected.

In order to measure the total amount of emitted photons the optical system had to be calibrated against a known radiance source like a tungsten ribbon lamp. Because of the low residual gas pressure the integration time for one part of the measured spectrum is up to 20 minutes.

The electron current is detected by a faraday cup and the electron energy distribution function is measured by an energy spectrometer at the end of the beam line.

Presently, the measurement of optical cross sections is performed. First comparisons of the measured spectra emitted by the nonneutral plasma and the electron beam show differences in the ratio of most spectral lines, especially with a pronounced difference at a wavelength of 587 nm (see Fig. 3). A possible explanation is multiple excitation of the atomic levels in the case of a nonneutral plasma.

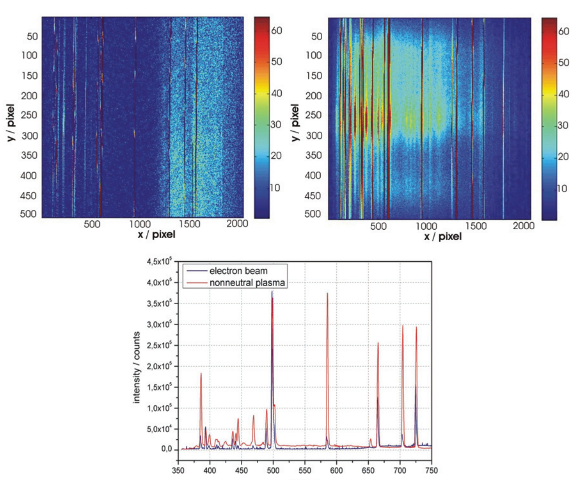


Figure 3: Measured emission spectra of helium excited by an electron beam ($W_B$=70 eV, I=4.6 $\mu$A, p=1.8e-3 hPa (He), $\Delta$t=1200 s, left), by the confined electron cloud ($\Phi_A$=5400 V, $B_z$=8.7 mT, p=4.95e-4 hPa (He), $\Delta$t=10 s, right) and the comparison of both (bottom).

## PRODUCTION MECHANISMS

Electrons confined in a Gabor space charge lens are assumed to be mainly generated by the ionisation of residual gas atoms. For the different types of space charge lenses an ignition curve was experimentally determined. Figure 4 shows the dependence of the plasma ignition on the length of the device.

Because of the higher probability of electrons produced at the edge of the potential well the assumed mean kinetic energy of the electron ensemble confined in the shorter system is much higher. This is also predicted theoretically.

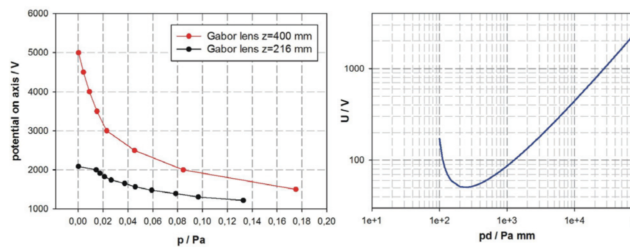


Figure 4: Measured ignition curves of the nonneutral plasma for helium as residual gas and magnetic field configured according to the lens' work function (left) compared to the theoretical prediction (right).

The observed short filling times cannot be explained by the interaction of electrons and ions with the residual gas alone. For this reason one has to consider the impact of particle losses on the production rate.

## LOSS MECHANISMS

In the case of the scaled Gabor lens electron losses can be studied by detecting the resulting bremsstrahlungs-spectrum.

Figure 5 shows the experimental setup for measuring the typical bremsstrahlungs-spectra by a $\gamma$-spectrometer placed right in front of the lens' aperture.

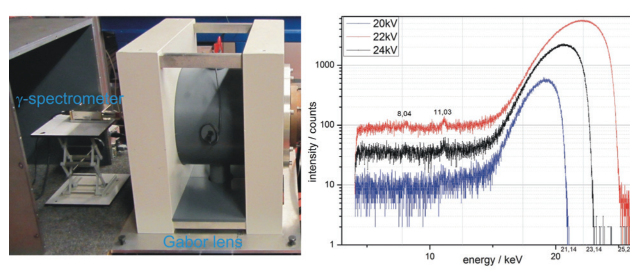


Figure 5: Experimental setup (left) and measured bremsstahlungs-spectra for different anode potentials ($B_z$=9.7 mT, p=3.4e-7 hPa, right).

The measurements show a steep increase of detected x-rays due to the anode potential. Varying the magnetic field has no significant influence on the rate of electron losses in this case (see Fig. 6).


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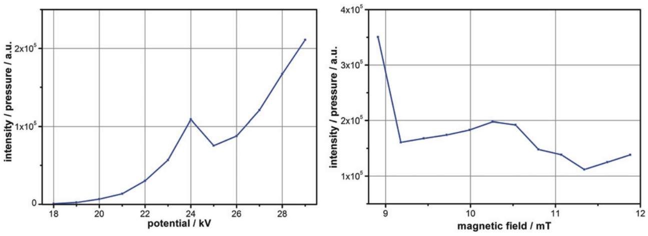


Figure 6: Dependence of produced x-rays normalized on the residual gas pressure versus the anode potential ($B_z$=11.8 mT, p=1.7e-7 hPa, $\Delta t$=120 s, left) and the magnetic field ($\Phi_A$=22 kV, p=5.1e-7 hPa, $\Delta t$=300 s, right).

The directional characteristic of emitted x-rays indicates a high production rate at the anode of the system. The determination of the dominating electron loss processes and locations is still under examination.

## ELECTRON CLOUD DYNAMICS

The state of the nonneutral plasma strongly depends on the ratio between the external magnetic and electric field strengths as well as on the residual gas pressure [3].

To establish a better understanding of the collective behavior of the electron cloud a 3D-Particle-in-Cell simulation was used. The numerical results do not only show the electron density distribution but also the approach of transversal und longitudinal electron temperature to the same level over a time scale of about 0.3 $\mu$s (see Fig. 7).

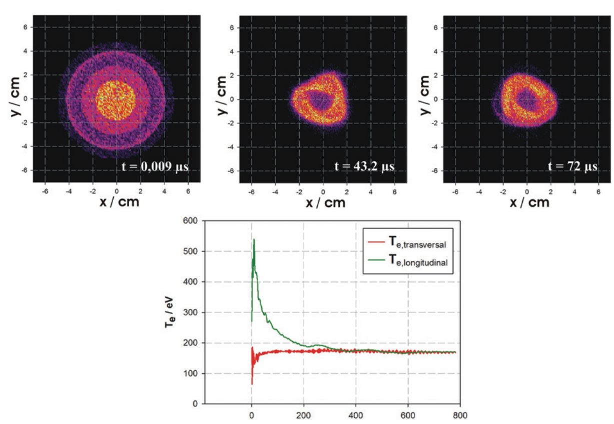


Figure 7: Example of a typical time dependent evolution of a diocotron instabilty in the space charge lens (top) and the time-dependent characteristics of the transversal and longitudinal electron energy (bottom).

The simulation and experimental results corroborate the stated model of a strong impact of the residual gas pressure on the appearance of an instability. Energy is dissipated by the interaction of electrons with the residual gas and obviously promotes the instability of the system.

Measurements also show a transient oscillation of the instability over a timescale of about 50 minutes. During this time the frequency of the related ion current signal decays exponentially (see Fig. 8).

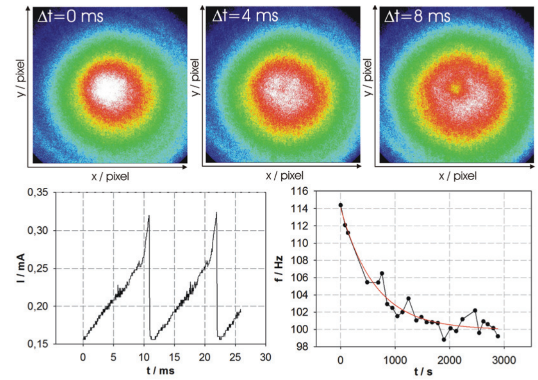


Figure 8: Measurement of an instability in the Gabor plasma lens, the correlated measurement of the extracted ion current and its frequency modulation ($\Phi_A$=3400 V, $B_z$=12 mT, p=7.9e-4 hPa (He)).

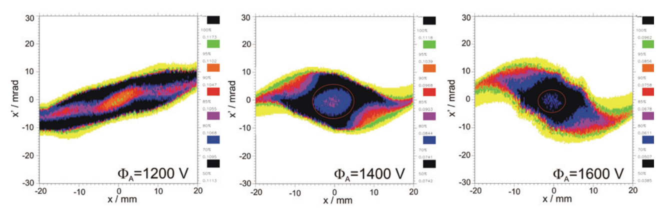


Figure 9: Influence of a plasma instability on a $He^+$ ion beam (lens parameters: $B_z$=6.5 mT, p=3e-5 hPa (He), beam parameters: $W_B$=15 keV, I=3.2 mA).

Studying these aforementioned processes is a required step to optimize the Gabor lens' performance as a focusing device.

For example figure 9 shows the influence of an unstable plasma state on the beam properties in phase space.

## CONCLUSION AND OUTLOOK

Different types of space charge lenses have been developed to study electron cloud dynamics with respect to the external parameters in detail.

As a next step, the interaction of the electron cloud with a low energy heavy ion beam will be investigated.

Beam experiments at the High Current Test Injector (HOSTI) at GSI Darmstadt are in preparation.

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