

STUDIES ON ELECTRON CLOUD DYNAMICS FOR AN OPTIMIZED SPACE CHARGE LENS DESIGN*

K. Schulte[†], M. Droba, B. Glaeser, S. Klaproth, O. Meusel, and U. Ratzinger
Institute for Applied Physics, Goethe-University Frankfurt, Germany

Abstract

Space charge lenses using a stable electron cloud for focusing low energy heavy ion beams are an alternative concept to conventional ion optics. Due to external fields electrons are confined inside the lens volume. In case of a homogeneously distributed electron cloud the linear electric space charge field enables beam focusing free of aberration.

Since the mapping quality of the lens is related to the confinement, non-destructive diagnostics has been developed to determine the plasma parameters and to characterize the collective behavior of the confined nonneutral plasma.

Moreover, a scaled up space charge lens was constructed for a detailed investigation of the nonneutral plasma properties as well as beam interactions with a stable confined electron cloud.

Experimental results will be presented in comparison with numerical simulations.

SPACE CHARGE LENS

A new space charge lens prototype was designed and constructed for the possible application at the HSI upgrade at GSI (Darmstadt). The device (Fig. 1) has an aperture of

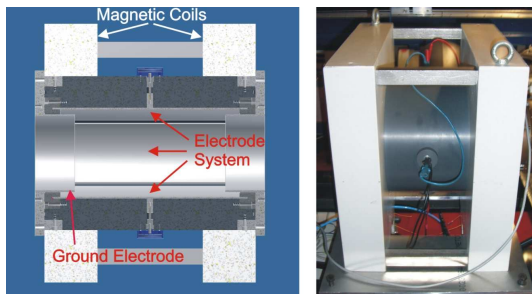


Figure 1: Mechanical drawing (left) and photograph (right) of the space charge lens prototype.

75 mm, an overall length of 436 mm with maximum magnetic field strength of 160 mT and potential of 50 kV. In order to focus a 2.2 keV/u U^{4+} -beam free of aberration a homogeneous electron distribution is required.

Numerical simulations by the use of $\Phi_A=30$ kV electrode potential and the magnetic field of $B_z=13$ mT for the confinement of the nonneutral plasma results in a nearly homogeneous electron density distribution of $n_{e,max}=2.7 \cdot 10^{14} \text{ m}^{-3}$ [1].

* Work supported by HIC for FAIR, BMBF No. 06FY90891

[†] Schulte@iap.uni-frankfurt.de

In terms of commissioning, the lens had initially to be conditioned to the nominal values to prevent sparking. First optical measurements of the plasma density distribution are presented in Fig. 2 and show the strong dependency of the plasma state on the enclosing fields. For an optimized per-

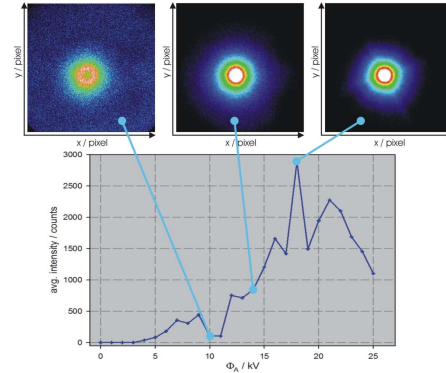


Figure 2: Measurement of the plasma light density distribution as a function of the anode potential for the space charge lens prototype, $B_z=10.5$ mT, $p=1.1 \cdot 10^{-6}$ hPa.

formance of the space charge lens the influence of the external parameters on the collective behavior of the electron cloud have to be investigated in detail. Therefore, various experiments with different types of space charge lenses have been established to determine the plasma parameters as well as to evaluate the diagnostic methods.

PLASMA INSTABILITIES

Following theoretical predictions the state of the non-neutral plasma strongly depends on the ratio of the external magnetic and electric field strengths. In this context the work function represents the configuration of external fields to form a homogeneous electron distribution inside the lens volume. Far from this configuration the appearance of instabilities can be observed (Fig. 3).

Furthermore, measurements show a dependency of the plasma state not only on the enclosing fields but also on the residual gas pressure (Fig. 4). The field and the pressure dependency of the plasma state is strongly coupled with a variation in the electron production rate.

To establish a better understanding of the collective behavior of the electron cloud in dependence on external parameters like magnetic field, potential as well as geometry a 3D-Particle-in-Cell simulation was used (Fig. 5) [3]. Furthermore, for the experimental investigation of the diocotron instability and accordingly the plasma state a time-resolved diagnostic was developed.

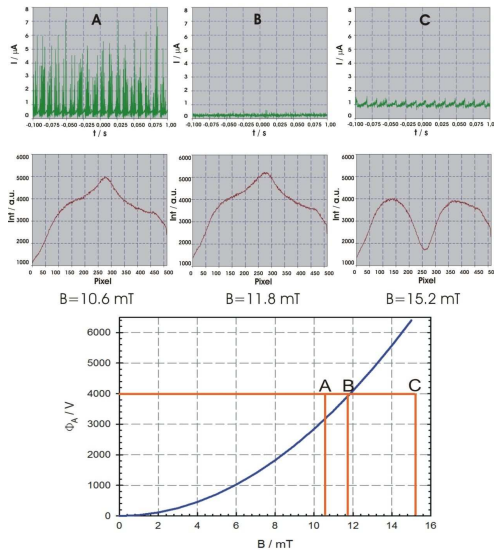


Figure 3: Measurements of the ion current and light density distribution profile in the region of instabilities (A,C) and in the region of the lens work function (B) (top), $\Phi_A=4$ kV, $p=6\cdot 10^{-4}$ hPa (He). Work function of the used space charge lens (bottom).

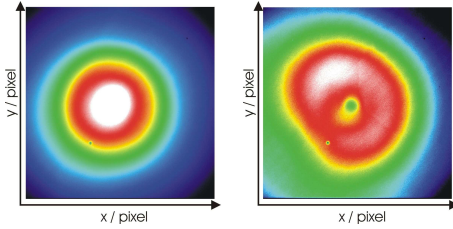


Figure 4: Picture of a diocotron instability for different pressures of helium and similar field strengths, $\Phi_A=6.5$ kV, $B_z=12.1$ mT, $p=7.8\cdot 10^{-5}$ hPa (left) and $\Phi_A=6.5$ kV, $B_z=12.9$ mT, $p=48\cdot 10^{-5}$ hPa (right).

Time-Resolved Optical Diagnostics

The evolution of the diocotron instability occurs within nanosecond to millisecond time scale and, of course, demands a high temporal resolution of the diagnostic system.

Due to the anode potential and the filling degree of the space charge lens the positive charged residual gas ions are accelerated out of the lens volume. In the case of an un-

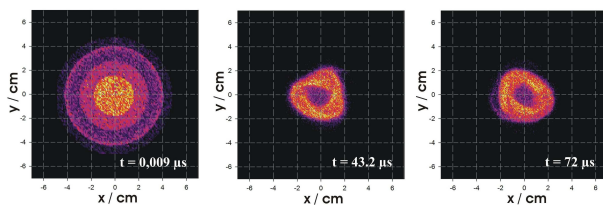


Figure 5: Numerical simulation of a typical time dependent evolution of a diocotron instability in the space charge lens.

stable electron cloud the detected ion current shows a periodic structure that is used as a trigger-signal for the time-resolved optical diagnostic. Figure 6 shows the evolution

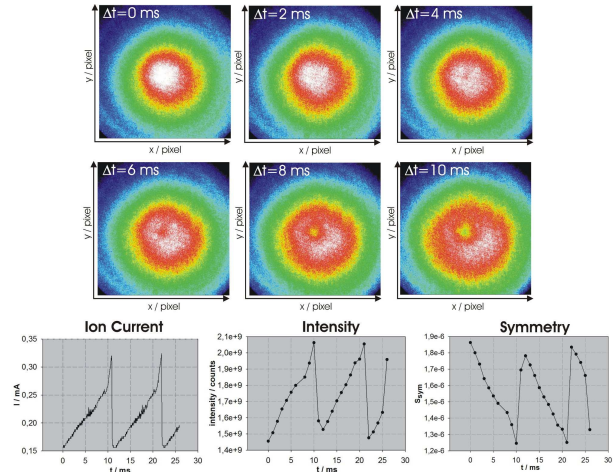


Figure 6: Time-resolved measurement of the diocotron instability within 2 ms time steps. Measurement of the ion current used as trigger-signal, intensity, and the symmetry of the plasma cloud, $\Phi_A=3.4$ kV, $B_z=12$ mT, $p=7.9\cdot 10^{-4}$ hPa (He) (right).

of the instability within 10 ms. This is equivalent to the length of one periode of the detected ion current signal.

The measured ion current, the intensity as well as the symmetry of the light density distribution are strongly correlated.

The symmetry factor is used to evaluate the plasma state from the optical measurements and is described as:

$$S_{sym} = \frac{\mu_I}{\sigma_I^2} \quad (1)$$

$$\mu_I = \frac{1}{N} \sum_{i=1}^N \int_0^R I(r, \frac{2\pi \cdot i}{N}) dr$$

$$\sigma_I^2 = \frac{1}{N} \sum_{i=1}^N \left(\int_0^R I(r, \frac{2\pi \cdot i}{N}) dr - \mu_I \right)^2$$

where I is the radial intensity from the center of mass to the edge of the plasma cloud for several angles.

Time-Resolved Emittance Measurement of Residual Gas Ions

The measurement of the time variant phase space distribution of extracted residual gas ions by a pepperpot emittance scanner enables the determination of changes in the plasma state as well as in the production region. The maximum time resolution of this diagnostic method is in the range of milliseconds [2].

As an example the measured emittance of the residual gas ions is shown in Fig. 7.

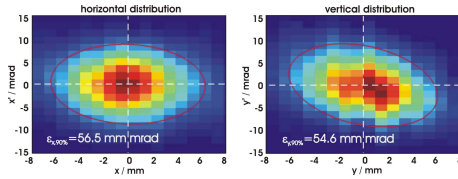


Figure 7: Measured transversal phase space distribution of emitted particles from the space charge lens.

DETERMINATION OF PLASMA PARAMETERS

Since the electric space charge field is related to the electron density as well as the electron temperature, the determination of the plasma parameters is essential for an optimized performance of the lens.

Electron Density

As a result of suppressing the applied anode voltage by enclosed electrons the extracted residual gas ions have a reduced kinetic energy. By measuring the ion energy with a momentum spectrometer one can determine the electron density by use of:

$$\bar{n}_e = \frac{4\epsilon_0\Delta\Phi}{er^2} \quad (2)$$

where $\Delta\Phi$ is the difference of the anode voltage and the suppressed voltage. r is the radius of the electrode.

Experimental results implicate that there are different regions of production within the electron plasma. This is also validated by numerical simulations (Fig. 8). The average

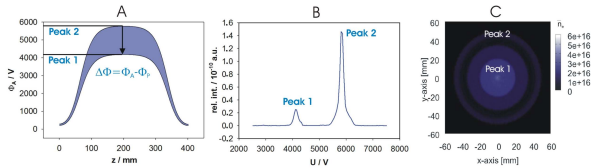


Figure 8: Scheme of electron density measurement technique. (A) represents the potential depression by the electrons and (B) shows the measured ion current for the different production regions within the plasma (C).

electron density is calculated from peak 1. Peak 2 is a result of the ion production in a sheath of the anode surface. In this region the produced electrons are rapidly attracted and do not contribute to the average density.

The measured average electron densities are in good agreement with numerical values.

Electron Temperature

For the evaluation of the plasma dynamics with respect to loss- and production mechanisms the knowledge of the electron temperature is of great importance. However, conventional diagnostic methods for determining the electron temperature are not suited for the nonneutral plasma.

To overcome the difficulties of electron temperature measurement the determination of T_e by considering the optical-emission cross sections is currently under investigation [4].

The optical method to study collision processes between electrons and atoms directly relates the emitted atomic line intensities to the electron energy. The electron temperature of the nonneutral plasma results then from the ratio of measured optical excitation functions for different emission lines.

Based on this principle the temperature using optical-emission cross section data from [5] was determined. Figure 9 shows a clear discrepancy of the results in electron temperature between experimental data and numerical prediction.

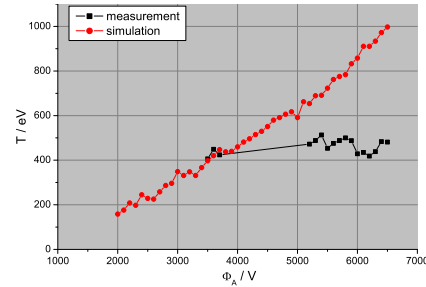


Figure 9: Measured electron temperature compared to the numerical simulation, $B_z=8.7$ mT, $p=4.8 \cdot 10^{-4}$ hPa (He).

To further investigate the interaction of electrons with neutral atoms and to expand the actual database of optical excitation functions a new experiment has been prepared.

CONCLUSION AND OUTLOOK

The space charge lens prototype was commissioned and first experimental results of the plasma state due to the enclosing fields were presented. A time-resolved optical diagnostic was developed to study plasma instabilities. Methods to determine the plasma parameters were discussed and will be further investigated.

REFERENCES

- [1] K. Schulte, "Space Charge Lens for Focusing Heavy Ion Beams", LINAC'10, Tsukuba, Japan, MOP102, (2010).
- [2] J. Pfister, "Entwicklung und Anwendung schneller Strahldiagnose für Ionenstrahlen", PhD Thesis, Goethe-University, Frankfurt a. M., 2010, p. 120-122.
- [3] M. Droba, "Development of a Numerical Model for the Investigation of Instabilities in Toroidal Enclosed Nonneutral Plasmas", private communication, 2005.
- [4] K. Schulte, "Investigation of Diagnostic Techniques on a Nonneutral Plasma", DIPAC'11, Hamburg, Germany, MOPD93, (2011).
- [5] J. H. Lees, "The Excitation Function of Helium", H. H. Wills Physical Laboratory, University of Bristol, 1932, p. 173-186.