DEVELOPMENT OF A DE-FOCUSING SPACE CHARGE LENS FOR POSITIVE ION BEAMS

T. Dönges*, V. Britten, M. Droba, A.P. Ho, O. Meusel, J. Rausch,
Goethe Universität Frankfurt, Frankfurt am Main, Germany

Abstract

Space charge lenses are ion-optical devices that focus an ion beam by the intrinsic electric field of confined non-neutral plasmas, for example electron clouds. This was first proposed by Dennis Gabor in the year 1947 [1] and is therefore also known as Gabor-lenses.

Previous studies have shown the strong linear focusing forces of a confined electron plasma [2]. In this paper, the first confinement of a pure proton plasma in a Gabor-lens will be discussed. The confinement of a positive space charge column provides either a linear de-focusing force for positively charged ion beams or a linear focusing force for negatively charged heavy ion beams. Very first results of proton confinements and their diagnostics will be presented. A special focus lies on the diagnosis of the proton density distribution, as well as the comparison between the behavior of the proton and electron clouds.

INTRODUCTION

Various Gabor-lenses have been studied at the Institute of Applied Physics in Frankfurt for over 20 years. Until now, the experimental focus has been on the confinement of electron clouds. In this paper the first experiments related to proton confinement are presented and discussed.

Gabor-lenses are magnetron like traps for charged particles. The radial confinement is ensured by a longitudinal magnetic field, while the longitudinal confinement is realized by a longitudinal potential, shaped by an electrode system consisting of three cylindrical tubes.

For the experiments a reliable Gabor-lens GL9000, which is integrated into an automated test setup with various diagnostic options, was used.

There are well known and tested methods for determining the trapping efficiencies of the lens κ_l, κ_r [3] and the density distributions off electron clouds. These methods were examined for their possible applicability to proton clouds and their limits were evaluated.

Initial attempts to determine the longitudinal trapping efficiency κ_l by measuring the longitudinal accelerated and extracted electrons using a momentum spectrometer were unsuccessful. The strong magnetic fields of the solenoid cause the electrons to follow the field lines, making momentum spectroscopy of them impossible with the existing setup.

Measuring the currents on the cathode (Leakage-Current LC) on the other hand, enables an estimation to be drawn about production and loss rates. They do not allow an exact determination of the proton density, but are helpful as additional parameters for characterizing the plasma and are therefore presented here and compared with those of electron clouds.

The residual gas within the volume interacts with the existing plasma, which makes optical analysis possible. In this context, several measurements were taken with a CCD camera in different wavelength ranges and were evaluated.

THEORY

The maximum density n_{max} for the trapped charged particles is determined for radial confinement by:

$$n_{r,\mathrm{max}} = \frac{\epsilon_0 B^2}{2m} \tag{1}$$

and for the longitudinal confinement:

$$n_{l,\mathrm{max}} = \frac{4\epsilon_0 \phi}{er^2} , \tag{2}$$

with magnetic field B, applied potential ϕ and r is the radius of the confined plasma. Equalizing the two densities gives the operation function for the Gabor lens:

$$\phi = \frac{B^2 er^2}{8m} . \tag{3}$$

Except for the mass of the particles, the operation function of the lens for electrons and protons should therefore not differ. With a correspondingly higher scaled magnetic field by a factor of $\sqrt{m_{\mathrm{proton}}/m_{\mathrm{electron}}} = \sqrt{1836.15} \approx 42.85$ with respect to the larger mass, a comparable behavior is been expected.

As a focusing element for positivly charged ion beams with confined electrons the magnetic field of the lens can be neglected. With the significantly higher magnetic field required for the confinement of protons, the focusing effect of the magnetic field is no longer negligible. If the magnetic field of the Gabor lens is approached by means of a solenoid Eq. (5), the comparison of the focusing of the magnetic field and the defocusing Eq. (4) by means of space charge shows a mutual canceling out for protons as beam particles and plasma [4],

$$\frac{1}{f_{GL}} = -\frac{q_p}{m_p} \frac{q_b L B^2}{8E_k} \tag{4}$$

$$\frac{1}{f_S} = \frac{q_b}{m_b} \frac{q_b L B^2}{8E_k} , \tag{5}$$

where the index $_p$ stands for the plasma particles of the lens and $_b$ for the beam particles. L is the length of the solenoid or plasma cloud. The de-focusing outweighs the focusing of

---

* doenges@iap.uni-frankfurt.de

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR18

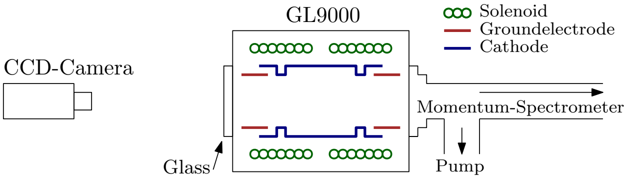

Figure 1: Simplified scheme of the setup.

the solenoid for heavier masses m_b or higher charge states q_p and is therefore suitable for use as a de-focusing element for heavy ions.

MEASUREMENTS

Setup

All measurements were taken using GL9000, illustrated in Fig. 1. The ground electrodes have an inner radius of 73 mm and are spaced 286.6 mm apart. The magnetic field on the beam axis is about 8.6 mT for a current of 10 A.

Leakage-Current

In a first step the LC was measured for electron confinement in the region of the operation function as shown in Fig. 2. The kind of fingertip stopband structures on the surface are currently being examined in a separate work [5]. For comparison, a measurement in the range from 125 A to 630 A as solenoid current I_{solenoid} would be suitable as this would take the difference in mass into account. Unfortunately, we are limited to a maximum solenoid current of 125 A, which corresponds to a current of about 3 A for electron confinement. In this range no stable confinement for electrons could be realized so far. However the confinement for proton was possible with low magnetic fields driven by a current of 40 A, witch corresponding to 0.93 A for the electron confinement with the same device. Therefore, the parameter space for the measured heat maps, shown in Figs. 2 and 3, differ for the radial confinement. The blue line is the threshold at which the LC starts to increase. It seems to correspond well with the point at which a corona discharge can be seen at the edge of the cathode. It was fitted with the following formula:

$$\phi = d^2 \frac{B^2 q}{m_e} ,$$

where d is the diameter of the gyrational movement resulting from the ExB-drift and was determined here using the data to be 4.3 mm, which corresponds to a first approximation of the radial distance from the ground electrode to the cathode.

It is therefore reasonable to assume that an unwanted discharge only takes place when the drift distance of the electrons emitted at the cathode becomes large, as they no longer collide directly with the ground electrode. On the other hand this effect could serve as a filling mechanism for the confinement of protons, but have to be investigated in more detail.

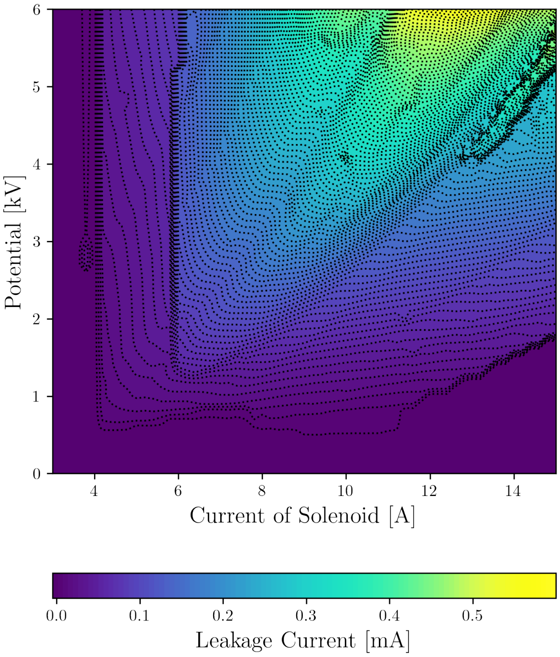

Figure 2: LC Measurement for electron confinement with a residual gas of 2.4×10^{-4} Pa H_2.

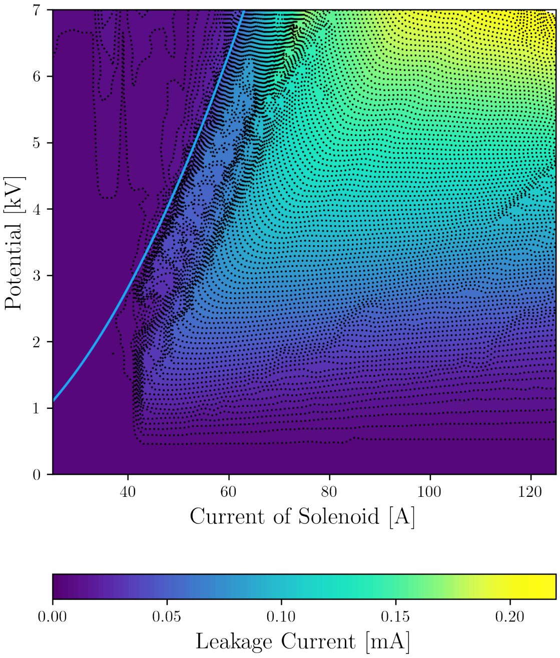

Figure 3: LC Measurement for proton confinement with a residual gas of 2.4×10^{-4} Pa H_2. The blue line represents the fitted corona-threshold.

Optical Diagnosis

For the optical diagnosis, a CCD-Camera was mounted in axial direction at a distance of 0.39 meters from the borosilicate glass window. The intensity of the residual gas fluorescence was observed in the entire visible range as well as in sections using narrow band filters. A H-alpha (656 nm), H-beta (486 nm) and an OIII (501 nm) filter were used.

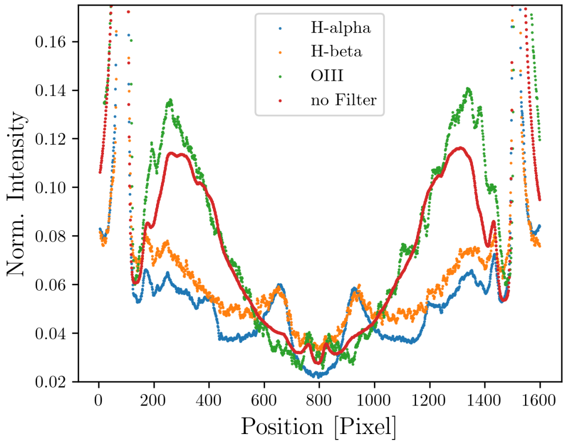

Figure 4: Residual gas fluorescence of hydrogen at ϕ = 9.9 kV, I = 120 A and a pressure of 5×10^{-4} Pa. The entire spectrum in the visible range can be seen in red. The other colors correspond to narrow band filters of the transitions: H-alpha (blue), H-beta (orange), OIII (green). All measurements were normalized.

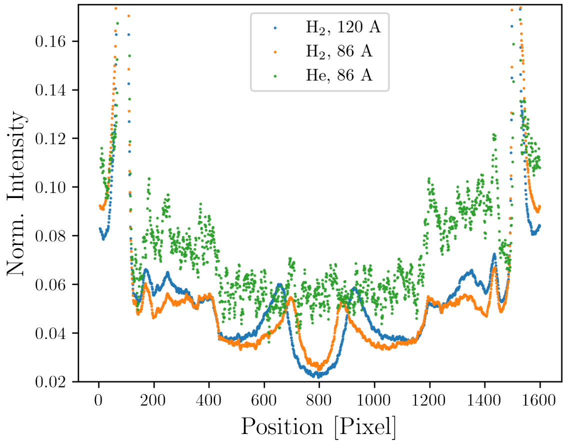

Figure 5: Residual gas fluorescence of hydrogen (blue and orange) and helium (green) at ϕ = 9.9 kV and a pressure of 5×10^{-4} Pa, through the H-alpha filter at I = 120 A (blue), I = 86 A (orange) and I = 86 A (green). All measurements were normalized.

Figure 4 shows the radial light intensity for different wavelength ranges. It can be clearly seen how that OIII image profile follows is comparable to that without a optical filter. The profiles for the H-alpha and H-beta transition deviate and show two symmetrical local maxima at positions ~650 and ~950. These can be traced back to excited hydrogen. The structures in the range of ~150 to ~400 pixels are reflections on structures of the rear vacuum tank as well as superimposed luminous phenomena in the borosilicate glass. The dominant fluorescence of the corona discharge in the gap between the rear ground electrode and the cathode can be seen at the edges.

A possible interpretation is that the peaks in the hydrogen spectrum reflect the radial density distribution of the protons as they excite the neutral hydrogen. This assumption is supported by the fact that the hydrogen peaks are not visible when helium is included as a residual gas (Fig. 5 green trace). This means that the peaks cannot be part of the continuous spectrum of luminous phenomena that form in borosilicate glass. The fluorescence in the glass could be caused by the electrons that are accelerated out of the Gabor-lens and hit the borosilicate glass. It is therefore possible to use a hydrogen filter to suppress the disturbing fluorescence in the glass in order to identify the residual gas fluorescence caused by hydrogen protons collision. Reducing the magnetic field by reducing the current should lead to a lower proton density. The decrease in light intensity and contraction of the cloud as shown in Fig. 5 (blue and orange) and is consistent with this assumption.

CONCLUSION

Even if it is not surprising that the magnetic field of GL9000 is not high enough as it is not designed for this purpose, we wanted to test the limits and gain initial experience with a robust, well-tested lens. The fact that it was still possible to carry out measurements and generate valuable data was a success. It could be shown that a proton confinement is possible, new information about filling mechanisms and diagnostics strategies could be obtained. For the later it was shown that optical spectra in the region of the H-alpha and H-beta line are suitable for investigation of the radial plasma density.

As a consequence of the presented results, a new electrode system is currently under construction which will be embedded into a solenoid that achieves magnetic field strengths over three times higher than the current setup. This will also make it possible to measure the proton confinement in the region of the operation function and enables further investigation in the field of pure proton plasma.

REFERENCES

[1] D. Gabor, “A space-charge lens for the focusing of ion beams”, *Nature* vol. 160, pp. 89–90, 1947. `doi:10.1038/160089b0`

[2] K. Schulte-Urlichs, ”Studies on the focusing performance of a Gabor lens depending on nonneutral plasma properties”, Ph.D. thesis, IAP, Goethe Univeristät Frankfurt, Frankfurt am Main, Germany, 2014. `urn:nbn:de:hebis:30:3-334310`

[3] J. Pozimski and O. Meusel, ”Space charge lenses for particle beams”, *Rev. Sci. Instrum.* 1, vol. 76, p. 063308-2, 2005. `doi:10.1063/1.1904203`

[4] V. Britten, ”Analytische und numerische Betrachtungen zu Protonenplasmen und ihre ionenoptische Wirkung in Gabor-Linsen”, Bachelor thesis, IAP, Goethe Univeristät Frankfurt, Frankfurt am Main, Germany, 2014. `urn:nbn:de:hebis:30:3-452800`

[5] M. Droba *et al.*, ”Simulation study on an electron cloud and plasma waves confined in GL2000 device”, presented at IPAC’24, Nashville, Tennessee, USA, May 2024 paper TUPS30, this conference.