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INVESTIGATION, SIMULATION AND FIRST MEASUREMENTS OF A 2M LONG ELECTRON COLUMN TRAPPED IN A GABOR LENS DEVICE

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Abstract

Various Gabor-Lenses (GL) were investigated at Goethe University. Confinements of sufficient electron densities ($n_e \sim 1 \cdot 10^{15}$ m^3) were reached without any external source of electrons. Focusing of ion beams by low energy was demonstrated, long term stability and reproducibility were approved. Main differences compared to experiments and investigations of the pure non-neutral in Penning-Malmberg traps [1] are higher residual gas pressure and therefore higher collision rates, higher bulk temperatures, self-sustaining electron production process, much higher evaporation cooling rate. GL2000 is a new 2 m long device and was mainly designed for focusing of ion beams in energy ranges up to GeV but also for investigation of non-neutral plasma parameters. The confined electron column is much longer compared to previous constructed Lenses. This makes ion and hadron beam focussing much more efficient, in addition new physical phenomena can be expected and investigated. Simulation results of steady- and thermal equilibrium states with various external parameters and first measurements will be presented. The first operational tests show that it is possible to confine a two-meter long electron column.

INTRODUCTION

The Gabor-Lens (GL) [2], is an optical device used for focusing or defocusing of charged particle beams by a trapped electron column. Recently, an overview over a wide range of space charge lenses was given by Alexey Goncharov [3]. In a Gabor-Lens the radial confinement is provided by an axial magnetic field produced by coils. The longitudinal confinement is given by a potential well generated by a system of electrodes in axial direction. The electron cloud is created due to rest gas ionization inside the lens, it does not need any external source for the electron production, like other traps for example the Penning trap. The confined electron cloud fulfills plasma criteria for collective behaviour in many cases (Debye screening, number of particles in Debye-sphere, plasma frequency) it can be described as a non-neutral plasma [4]. Over recent years various GLs were systematically investigated at Goethe University. Confinement of sufficient electron density ($n_e \sim 1 \cdot 10^{15}\,\mathrm{m}^{-3}$) was reached without any external source of electrons. Focusing of light and heavy ion beams by low energy was demonstrated, long term stability and reproducibility were approved. Thick aperture lenses were built and successfully tested [5]. Diagnostic methods based on optical detection, X-ray detection, RF-detection, rest gas monitor and spectrometer were developed and used for characterization of different non-neutral plasma states [6]. Experiments with GL as a focusing device and as an electron target for low energy ion beams were carried out to examine interactions between beam ions and electron cloud [7]. The confinement of an electron column in a toroidal configuration was also tested [8]. The radius r to length l ratio was subsequently changed from device to device. The focal length, chromatic aberrations of the lens as well as the charge exchange and charge recombination rates need to be investigated in the future.

The electron temperatures ranged typically from 10 eV to 1000 eV in these experiments, Debye lengths were calculated therefore between 1 mm and 10 cm with a typical cloud radius between 1-10 cm dependent on used external parameter settings (anode voltage, magnetic field, residual gas pressure).

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MOTIVATION

With the new device GL2000, built in 2019, an aspect ratio of r/l = 0.0375 is realized. To our knowledge, this is the lowest aspect ratio with longest overall on-axis distance of about two meters designed to date. The focal length f of a Gabor-Lens is inversely proportional to its length [4].

$$\frac{1}{f} = k^2 \cdot L = \frac{q n_e}{4\varepsilon_0} \frac{L}{W_b}, \tag{1}$$

where k is the focusing strength, L the length of the device and W_b in eV is the energy of the beam.

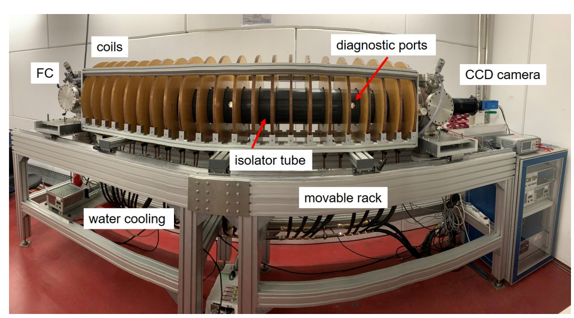

Figure 1: Setup of the experiment GL2000 in a concrete shielding.

For a given electron density $n_e \sim 1 \cdot 10^{15}\mathrm{m}^{-3}$ GL2000 can be used for the focusing of ion beams with higher kinetic energy W_b compared to previous experiments. Further the focusing of relativistic (W_b in GeV range) highly charged ion beams can be studied and arrays of GL2000 applied as a final focus for fixed target experiments as discussed in NA61/Shine Collaboration at CERN [9]. It also enables

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new possibilities in research with very long confined static electron clouds.

Static charged particle columns are comparable with ion or electron beams passing through long accelerator or transport chains (e.g. LINAC, Synchrotrons) for long times. Inspired by Paul-Trap-Simulator of the Princton Plasma Physics Laboratory [10] it is planned to investigate the non-neutral plasma confined in GL2000 on the premise that it is a charged particle beam propagating in a periodic transport channel of several kilometers length in an experiment of only two meters. Basic physical properties of the charged particle ensembles can be studied while changing external conditions continuously.

In the GL2000 experiment, it will be possible to excite plasma oscillations, for example through a pulsed magnetic field or by using RF-waves. Due to the length of two meters, it is possible to excite and measure low frequency waves while minimizing the boundary effects.

EXPERIMENTAL DESIGN

GL2000 consists of a two-meter-long anode tube, which leads to a very small r/l ratio with an inner diameter of 164.3 mm. The anode tube is made of stainless steel and equipped with six diagnostic ports for in situ diagnostics. The magnetic field is generated by 22 water-cooled copper coils in a pancake configuration (Fig. 1). These are arranged equidistantly over a length of two meters. Small position deviations of about 1 cm only exist in the area of the diagnostic ports. The coil excitation current can be set to a maximum of 500 A, resulting in a maximum on-axis field of $B_z = 0.5$ T.

The individual pancake connections allow the generation of various magnetic field configurations, such as homogeneous or alternating with existing gradients. Furthermore it is possible to pulse one or more pancakes or to use them as a detector for current fluctuations induced by the confined non-neutral plasma. In a standard electric field configuration, the closing copper electrodes are connected to ground and a positive high voltage is applied to the anode tube. The anode in this setup has been designed for a potential Φ_A up to 30 kV. The ground electrodes are electrically insulated against all flanges, so that investigations in the so-called Penning-mode are possible. In the Penning-mode, in contrast to previous configurations, the anode is at ground potential while the electrodes are charged negatively.

The GL2000 experiment will be equipped with various diagnostic instruments that can be installed in the setup or are developed for this experiment.

SIMULATION OF ELECTRONS INSIDE THE GL

First numerical simulations have been performed with the self-consistent code GABORM to evaluate physical phenomena and to compare the numerical model with the experimental results [11]. By the use of an additional numerical code more information about the interaction of the electrons with RGA and RGI or the production rate with respect to the rise time can be studied. Another interesting aspect is the cooling by inelastic electron-atom collisions as a function of the RGA-density or RGA-density gradient. Therefore a numerical algorithm was developed for a simulation of a single electron collision with RGA using Bethe-Bloch formula. It delivers the number of impacts N, the electron velocity v, the collision frequency t, and the mean free path λ for different GL settings. Impact ionization and total cross sections σ are approximated by given parameters [12]. This simple model shows that at the beginning of the confinement only electrons created at the edge of the potential well contribute to the ionization process. The electron collides with atoms with the velocity v at the distance of the mean free path length λ. In doing so it releases energy at the level of the binding energy, in this example, of helium $E_B = 24.59$ eV. The electron continues to collide with residual gas atoms until it has lost all its kinetic energy. Using the electron energy and residual gas density as input parameters, the algorithm calculates the electron movement from the first to the last impact. The code helps to estimate the electron production rate and to identify the energy transfer from anode to electron to RGA as a function of confinement time. Later it will be implemented in a Monte-Carlo-Code for detailed simulation of the production, interaction and loss processes in Gabor-Lenses. Fig. 2 shows the dependence of the total ionization cross-section for helium as a function of the confinement time of a single electron. The comparison of production and

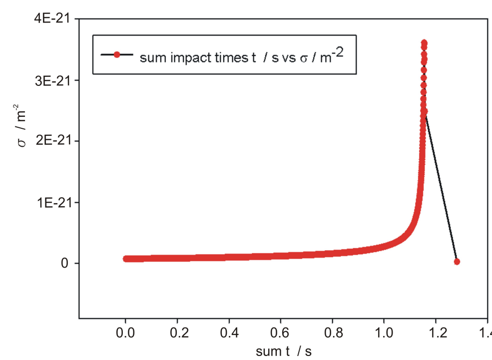

Figure 2: Neutral helium total ionization cross-section as a function of the summation of impact time. In this example the electron energy is set on 30 keV at t=0 s and the density of the residual gas atoms is $1 \cdot 10^{17}$ m^{-3}. The electron production rate is 953.125 s^{-1}.

loss rates will also deliver information about the minimum field configuration in combination with the residual gas pressure which is needed to provide the confinement inside a GL. For a given residual gas pressure of $1 \cdot 10^{-5}$ hPa a minimum anode voltage of $\Phi_{A,min} = 6$ kV and a minimum magnetic field strength of $B_{z,min} = 11$ mT is needed to provide a stable confinement in GL2000, for example.

FIRST MEASUREMENTS

After construction and assembly, GL2000 was installed in a dedicated concrete shielding because X-ray radiation

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occurs due to the application of high anode voltage. The wave length of the radiation depends on the longitudinal confinement, with respect to the energy of the confined electrons. The intensity of the radiation is inversely proportional to the magnetic field [13]. This means the higher magnetic field prevents electron losses at the inner surfaces of the lens. On the other hand the electron losses can be used for a scrubbing procedure to remove impurities from the surface. Therefore the so called ”conditioning procedure” of GL2000 was started in DC-mode with $\Phi_{A,min} = 6\,kV$ to prevent sparks and unwanted discharges. The magnetic field was then reduced from 18 mT to 9.1 mT, as shown in Fig. 3 to increase the radial electron losses. The modified operation

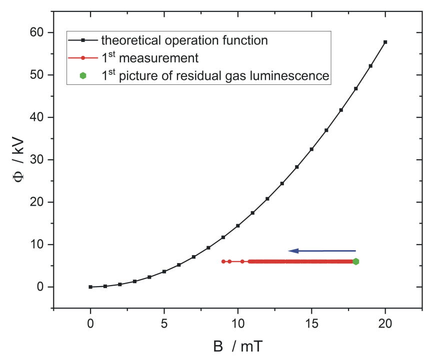

Figure 3: Operation function and first conditioning procedure of GL2000. The arrow shows the direction of the measurements.

function [7] is a superposition of the maximum densities $n_{e,max,rad} = n_{e,max,long}$ and results in:

$$\Phi_A = \frac{eR_P^2(1 + 2ln(\frac{R_A}{R_P}))B_z^2}{8m_e}, \quad (2)$$

where R_P is the radius of the electron cloud and R_A is the radius of the anode tube.

Thus Eq. 2 gives the specific operation function (OF) for a Gabor-Lens depending on its geometry. For GL2000 the OF is shown in Fig. 3. In the first run of GL2000 argon gas was used as residual gas at a pressure of $1 \cdot 10^{-5}$ hPa. The magnetic field was adjusted at 18 mT. After applying an anode voltage the CCD camera observed immediately a residual gas fluorescence induced by the confined electrons, see Fig. 4. Assuming that the excited state of the atoms has a short lifetime and the argon gas is distributed homogeneously, the luminescence represents the electron density distribution within the GL. In addition to the excitation, electron impact ionization occurs.

While the electrons are trapped in the GL, the argon ions are expelled out of the volume in longitudinal direction. The properties of ion stream current and momentum distribution provide a global information about the electron cloud [14]. It also effects to a load on the HV power supply for the anode. During commissioning, the ion current was measured by the Faraday cup. The residual gas pressure rises immediately

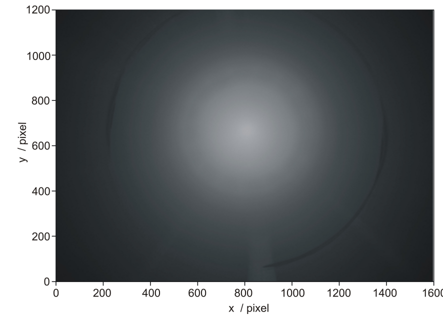

Figure 4: Residual-gas luminescence of argon during electron cloud confinement with GL settings: Φ_A= 6 kV, B_z = 18 mT.

after applying a new magnetic field strength. The data were measured after the desorption had subsided and the pressure was again constantly close to the originally adjusted value. This means that the data is not determined by the increased residual gas pressure during electron scrubbing.

The loss current at the anode tube as well as the Faraday cup current decreases for a decreasing B_z.The residual gas luminescence also becomes less intense when the magnetic field is reduced.

The probability of ionization and induced fluorescence is a function of the confined electron density, when the average kinetic energy of the ensemble is assumed to be constant. Then load power, ion current and luminescence should correlate with respect to the electron density. The result indicates that the electron density is decreasing. The experimental data show fluctuations in the Faraday cup as well as in the loss current signals in the interval of B_z from 11 mT to 14 mT. These fluctuations also coincided with the visual observations of the residual gas luminescence, which at times became very faint and then increased in intensity. Below 11 mT no confinement was observed.

CONCLUSION

A low aspect ratio Gabor-Lens was designed and constructed for focusing of high energy ion beams. Phase one of the project was the functional test and conditioning of GL2000 and the equipped diagnostic tools. In comparison with other GLs an increased minimum potential and magnetic field for a stable electron confinement at a given pressure was observed. This was assumed due to the low aspect ratio of GL2000 and therefore higher radial electron loss rate. The first measurement results give an indication of an imbalance between loss and production rates of the electrons confined in GL2000.

In a next step it is planned to measure the electron density as a function of the confinement strength. Experiments for the estimation of radial electron losses are in preparation.

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