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DENSITY MEASUREMENTS AND SIMULATIONS ON CONFINED ELECTRON COLUMN IN GL2000 GABOR-LENS DEVICE

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Abstract

GL2000 Gabor-lens (GL) is a 2 m long device built mainly for focusing and space charge compensation of hadron beams in energy ranges up to GeV. The electron cloud is initially produced by cold-cathode method with gradually ionisation of residual gas and is confined in a cylindrical trap much longer compared to previous constructed lenses. Density measurements were carried out at the test-stand in Goethe University in 2024. Outgoing stream of residual gas ions was detected within cylindrical spectrometer mounted on axis outside of the lens. Due to the dependency of the kinetic energy on starting potential, the on-axis potential and therefore confined average charge density can be derived. Measured densities were evaluated in a range of 10^{14}-10^{15} m^{-3}. A large scale multi-particles Monte-Carlo-PIC (particle-in-cell) simulations with electrons and ions were carried out to understand collective phenomena in non-neutral plasma and to use the latter for linear and non-linear beam manipulation. Measurements and simulation results will be presented.

INTRODUCTION

GL2000 Gabor-lens [1-3] device is a cylindrical trap for confinement of about 2 m long rotating electron column in static magnetic and electric fields. Stable and homogenous cloud of sufficient density are created and could be applied for focusing of hadron beams in GeV range. Dynamic processes and waves in an electron column can be applied for hadron beam handling and collimations.

High precision measurements of the operation map diagram (anode current I_A as a function of magnetic field B and anode potential ϕ) were fulfilled and presented in 2023. A cylindrical spectrometer was installed downstream on axis, right after GL2000 at the end of the Van-de-Graaff beamline V2 in 2024. Detection of the residual gas ion particles outgoing from the GL2000 volume and measurement of their kinetic energy give an information about the electric potential drop on axis in comparison to the anode voltage Φ_A. This drop is proportional to the average electron density confined in GL2000. Results are presented below.

Another measurement campaign has started in 2025. Spectrometer was replaced by a filter channel with an aperture and beam experiments with protons, He^{1+}, Xe^{1+} in an energy range 500 keV – 1 MeV were fulfilled.

DENSITY MEASUREMENT

The electrostatic cylindrical spectrometer of Hughes-Rojansky type [4] was used to detect stream of ions outgoing from GL2000 volume. Main parameters and overall design could be find in [5, 6] and they are summarised in Table 1.

Table 1: Cylinder Spectrometer

Inner radius	37 mm
Outer radius	19 mm
Slit width	0.5 mm
Acceptance angle	6.34°
Central radius	30.6 mm
Bending angle	124.2°
Max. Voltage	2 kV

Some modifications were carried out for the system also. Channeltron (Channel Electron Multiplier) was demounted and Faraday cup was placed direct after the output slit. Electrodes voltage was set between zero on inner electrode and so called spectrometer voltage U_S on the outer part. Therefore, the spectrometer constant κ, which defines the ratio between measured kinetic ion energy and spectrometer voltage U_S, has to be modified and will be in this case κ=1.733. Due to the limitation of the maximum spectrometer voltage, a terminal pre-Voltage was used to cover whole energy spectrum between 0 and 20 kV.

The mounted spectrometer with GL2000 and isolation flange are showed in Fig. 1.

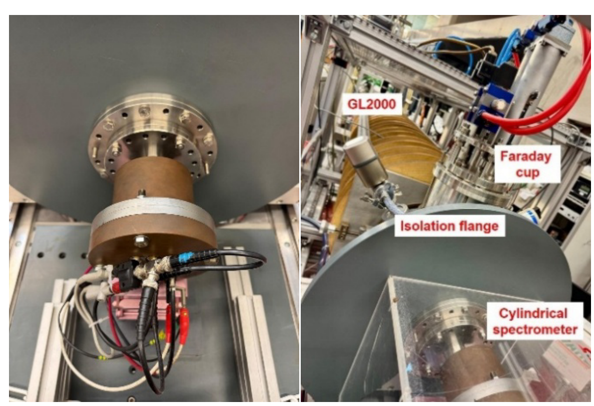

Figure 1: Cylindrical spectrometer mounted at the end of the Van-de-Graaff beam-line V2.

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Initial tests with spectrometer showed a negative current signals for the low voltage settings U_S < 500 V. Our interpretation is that the secondary electrons produced in the entrance region of the spectrometer distort positive ion signal.

An example of a measurement is showed in Fig. 2. The gray-scaled area corresponds to the voltage interval influenced by secondary electrons. At the voltage higher than 500 V such influence is no more visible and the onset of an ion signal can be demonstrated. The second x-axis with the recalculated corresponding ion energy is depicted on the top of the graph.

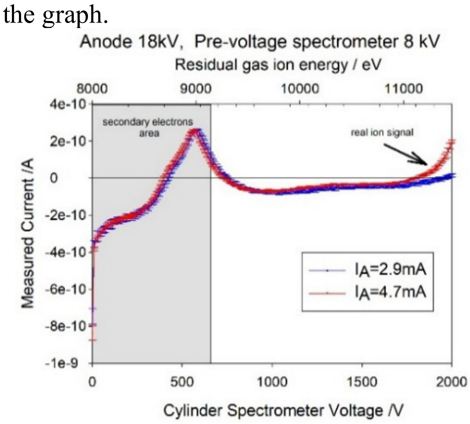

Figure 2: Detection of rest gas ions outgoing from GL2000 device. Negative signal is detected for spectrometer voltage U_S < 500 V and onset of the ion signal for U_S > 1800 V. Corresponding residual gas ions energy is depicted on the top x-axis.

Under an assumption of a filling GL2000 homogenous with electrons, there will be a potential drop on the axis. Most of residual gas ions are produced in the volume of the GL2000 and possess potential energy defined between the on-axis potential and anode potential. They are extracted and accelerated towards spectrometer. Therefore, there exists a lower cut-off edge of an ion signal and terminal voltage has to be set optimal for the detection (U_S>500 V).

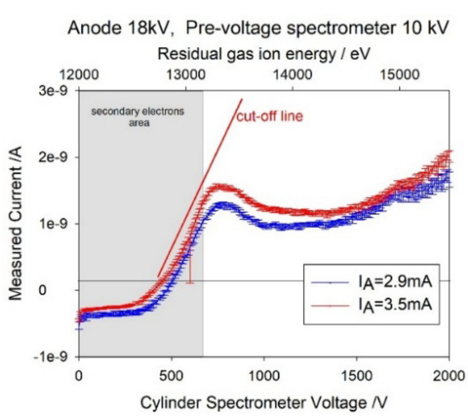

Figure 3: Cut-off edge of the residual gas ion energy found for the terminal voltage set to 10 kV. This corresponds to the on-axis potential of approximately 13 kV and potential drop of about $\Delta\Phi$ = 5 kV.

An example of a measurement with convenient parameters is depicted in Fig. 3. Two measurements of a different non neutral plasma states are presented. Same anode voltage of 18 kV, same residual gas pressure, but different magnetic field settings of the GL2000 was used. Average electron density is proportional to the anode current and shift of cut-off edge with higher confined density to the lower energies can be observed.

Enhanced vacuum level feedback control enhances reproducibility and minimises fluctuations, which is demonstrated with small error bars. Single data point in graph corresponds to 10 measurements at the same spectrometer voltage U_S. Deviation of the measurements is represented by error bars.

Measurements were repeated at different anode voltage and magnetic field level. Calculated average electron densities are showed in dependence on delivered power by the anode power supply in Fig. 4.

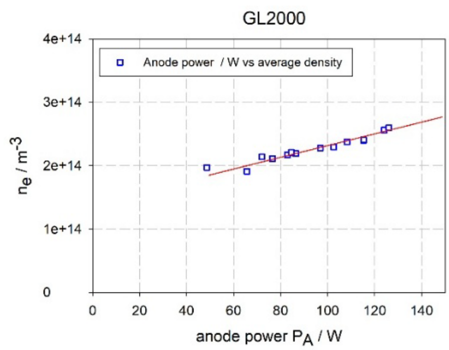

Figure 4: Measured average electron density in dependence on work done by anode power supply in Watt.

SIMULATION

In order to evaluate residual gas ion spectrum and distribution of the electron column in GL2000 device, a large scale parallel multi-particles simulation PIC(particle-in-cell)-code *gab_lens_m3* [3] was used. A new Monte-Carlo Collision(MCC) routine for elastic scattering on neutral residual gas was written and implemented.

Electron distribution, initial homogenous, is evolving till it reaches balance between losses, production and distribution function. Static anode potential ϕ_A =10 kV, magnetic field B = 9-18 mT and average electron density $n=7\cdot10^{13}$ m^{-3} were used as starting condition for first tests. Generation of the new particles are redistributed by ratio 10:1 radially, where production rate is 10 times higher in volume within R_G (ground electrode radius) < r < R_A (anode electrode radius). This kind of simulation should test a hypothesis of an initial cold cathode production. An example of transversal profiles of the electron and ion distributions for time 3.08 µs are shown in Fig. 5.

During evolution in time, electron distribution function is changing and adapting to the external fields and ion distribution. The ions are slowly accelerated towards axis and due to the scattering and electric fields in a fringing area they are leaving volume of GL2000 device longitudinally. The initial synchronous motion of ions will disappear at a later simulation time and density distribution will poses a

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maximum on the axis. The local electron density will follow the ion distribution with some relaxation time. Due to the scattering and turbulent ExB radial transport, electrons will be redistributed and heated in such a way, that overall radial electric field will reach linearity.

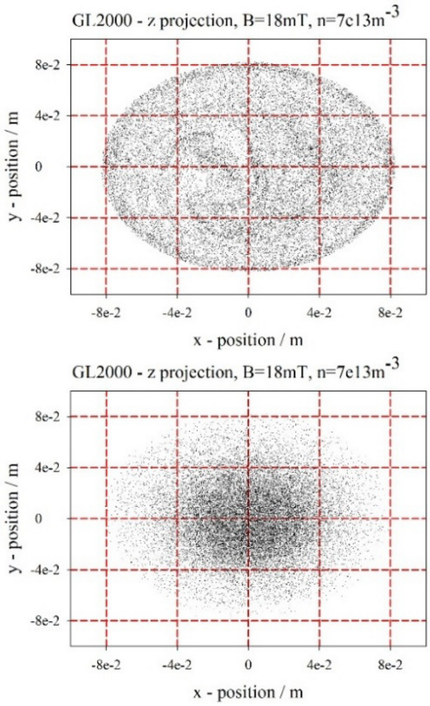

Figure 5: Transversal profile of simulated electron column (top) and residual gas ions (bottom) in time step τ=3.08 µs.

The kinetic energy of ions is detected outside of GL2000 and an example is shown in Fig. 6. Energy spectrum of outgoing ions (He^{1+} in this case) shows cutting edge at about 7.8 keV with some minor fluctuation bellow. This are residuals of the initial process where the on-axis potential is fluctuating as well

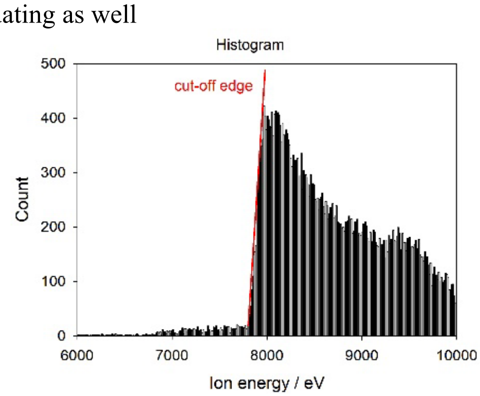

Figure 6: The ion energy distribution for extracted ions from GL2000 volume at the same time step τ=3.08 µs as in Fig. 5. Cut-off edge in kinetic energy corresponds to approximately 7.8 kV on-axis potential.

High energy spectrum with particles starting at the anode (10 keV) is still underestimated due to the short simulation time.

The 3D-MCC-PIC study will continue on the FUCHS Cluster [7] of the Goethe University and various runs are planned to be simulated in 2025.

BEAM TRANSPORT EXPERIMENTS

Beam transport experiments through the GL2000 device were conducted with protons, He^{1+}, Xe^{1+} ions in energy range 500 keV – 1 MeV. Beam was injected from the van-de-Graaff accelerator, passing the GL2000 on axis and detected by the filter channel [8] with two detection electrodes (cylindrical wall electrode with an aperture and faraday cup behind aperture, both with secondary electrons attenuation) at the end of the V2 beamline. The onset of the focusing effect of the confined electron column could be demonstrated clearly in Fig. 7.

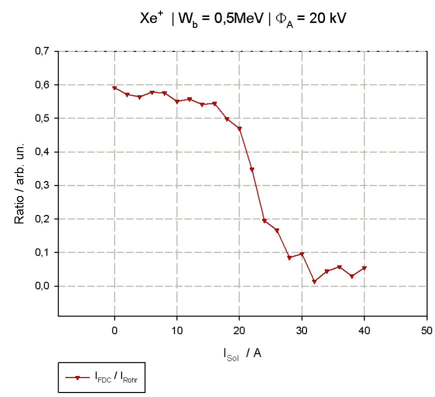

Figure 7: Transmission coefficient of the filter channel. Ratio of a beam current coming through the aperture and current stopped before is depicted in dependence on the magnetic field (electrical current of the GL2000 coils) set at a constant anode voltage of 20kV.

Interesting effect was observed if the beam was stopped by silica glass at the end of beamline. With the GL2000 off, there was the charging up effect accompanied by x-rays emission. This effects completely disappeared with the GL2000 on. It seems, that electron cloud confinement neutralised generation of the x-rays.

CONCLUSION

A two-meter-long electron column was investigated to characterised confined electron density and focusing properties of the electron cloud for a beams in sub MeV range. Experimental and numerical results show stable and reproducible confinement properties. Further experiments are in preparation with the aim of the residual gas scaling, plasma wave detection and enhancement of electron production.

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