THE 3D-PIC SIMULATION OF THE BEAM-PLASMA INTERACTION INSIDE OF GABOR LENSES*

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Abstract

Experimental results of the beam transport through a Gabor lens system were not fully understood in the past. The measurement campaign presented at IPAC2013 will be considered as an example with an alternative explanation. Simulation results done by the TraceWin code will be presented and beam impact on the electron column discussed. Especially production of secondary electrons by an ion impact can have massive influence on plasma state and creating waves and instabilities. Additionally, a large scale multi-particles 3D Monte-Carlo-PIC (particle-in-cell) simulations with electrons and ions were carried out. Goal was to understand collective phenomena in non-neutral plasma generated by passing beam in various scenarios. Up to 10^7 macroparticles were implemented in parallel processing on 50 processors of the FUCHS Cluster. Possible influence on the focusing properties and imaging quality will be evaluated and the dependence on time scale and ion beam energy discussed. Simulation results will be presented with an impact on future designs.

INTRODUCTION

Gabor-lens(GL) [1-3] is a cylindrical trap for creation and confinement of rotating electron column in static magnetic and electric fields. Stable and homogenous electron clouds of sufficient densities ($n \sim 10^{14}$ m^{-3}) can be created at specific conditions inside of the lens. Many different types of GL devices were built and studied in Frankfurt University in recent years. Their main application in accelerator physics are space charge compensation and hadron beam focusing from keV up to GeV range. Dynamic processes and waves in an electron column can be generated and applied for hadron beam handling and collimations. The progress in vacuum level control and diagnostics improve reproducibility and stability of the working points. Understanding of diffusion processes across the electric and magnetic fields was important for evaluation of the electron losses and overall efficiency of a production process. The last point also raises questions about possible acting of the GL as a reservoir for the space charge compensation both beam upstream and downstream in a connection with low energy beam lines. That lead also for some reconsideration of the experiments done in the past. Palkovic[4-6] studied focusing properties of the GL placed direct after a duo-plasmatron source in late 80´s. The about 50 mA proton beam was focused at 44 keV kinetic energy and angle acceptance of the ±40 mrad. The measured large emittance growth of the factor 4 was explained as explosive growth due to the space charge explosion direct after the source in a few cm distance in front of a GL.Schulte [7,8] tested 3 mA, 50 keV He^+ and 35 mA, 124 keV Ar^+ beam focusing with a GL at the GSI High Current Test Injector (HOSTI) in mid-2012. The beam phase space distributions were measured with and without GL potential at the end of the beam-line. Because of lost (GL off) and captured (GL on) beam particles overall efficiency was hard to evaluate exactly. Simulations started with back-tracing of the measured distribution at GL off, thus this calculated distribution was used as a starting distribution in all further simulations at various conditions. However, this approach ignored losses along the beam path and underestimated starting emittance. Reversely, emittance growth was overestimated. Assumption of the hollow electron column at low magnetic field levels was another fact needed for the explanations and comparison between simulations and measurements. However, this contradicts experiences from the electron density measurements. In the following, we present different approach, based on the knowledge of the S-shaped initial distribution, similar to that measured at the HOSTI direct behind ion source downstream in 2009 [9].

LEBT SIMULATION

The numerical simulations were carried out with TraceWin code and all geometry data can be found in [8,9]. Initial beam parameters were set I_b=3 mA, W=50 keV He^+ in a distance of 210 mm (Fig. 6.8 in [8]) in front of the GL. GL itself was implemented as modelled cylindrical field map with linear radial electric field. Initial particle distribution was chosen to be of a Gaussian-type with a modified S-shape contour, as seen in Fig. 1 (left).

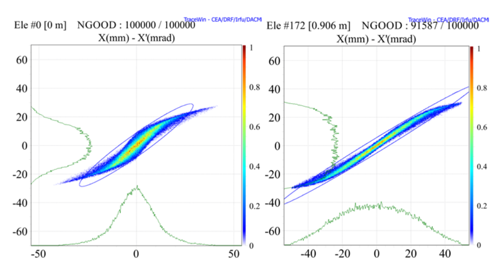

Figure 1: Input(left) and output(right) particle distribution. GL was off and overall transmission achieves 91,6% level.

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The results are summarised in Table 1 and showed good agreement between measured and simulated normalised transversal rms-emittance (in 25% interval, case 6. not included).

Table 1: Simulated RMS-Emittance

Nr.	Magnetic field[mT]	Measured $\varepsilon_{rms,n}$ [mm mrad]	Simulated $\varepsilon_{rms,n}$ [mm mrad]
1.	0	0.166	0.209
2.	6.8	0.374	0.366
3.	8.1	0.453	0.339
4.	9.5	0.318	0.331
5.	10.8	0.321	0.326
6.	12.2	0.940	1.38

The shape of the initial distribution was optimised to get the best agreement for the case 5. The GL in the case 6 was in unstable operation mode and measurements showed some specific ion beam distribution. However, under assumption of the hollow electron density distribution confined in the GL, the transported beam distribution almost agrees with the measured one. (Fig. 2).

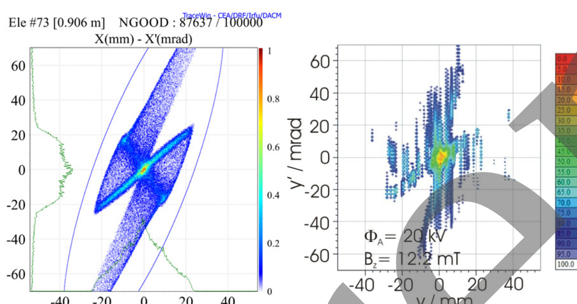

Figure 2: Simulated (left) and measured (right) phase space distribution for the case 6.

Beam envelope along the beam line is depicted on Fig. 3. There is a focal point inside the GL, which is positioned between z=210 mm (entrance) and z=646 mm (exit)

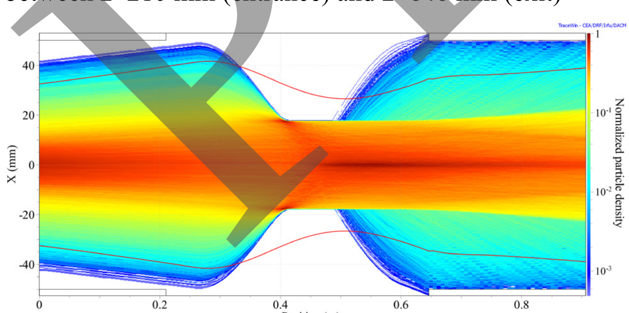

Figure 3: Simulated beam envelope along the beam path for the case 6. Overall transmission reached 87,6%.

The beam particles with a larger radial position are highly over-focused in that case, although core-particles sees no focusing effect and diverge. In reality, high amount of over-focused ions is lost on ground electrode in the GL and this significantly increased the secondary electrons production at r = R_G (ground electrode radius). Conversely, it means that electron density rises at larger radius and there will be self-reinforcing focusing effect on beam particles. How many beam particles reaches ground electrodes depend on many parameters that can vary rapidly and the GL-operation will be highly unstable as observed in reality too.

Additionally, the previous initial distribution (distribution 1.) had not a perfect agreement with measurement for the case 1 (GL switched off) as originally expected. It was generally not possible to find a distribution with a good agreement for both GL-on and GL-off states at once. The better agreement was achieved with higher initial angles and higher emittance (distribution 2.) for the case 1 (Fig. 4).

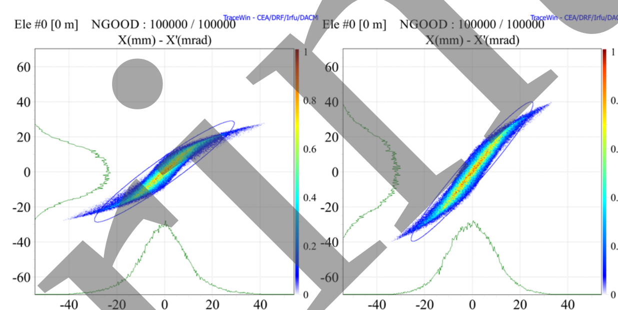

Figure 4: Comparison of the distribution 1 (left) and distribution 2 (right). Simulation showed more particle losses (85,7%) for the distribution 2 along the beamline.

Possible explanations of such behaviour would be a variation of ion source parameters in measurements or a variation in space-charge compensations degree in the beamline. The last one would mean, that the GL-on state would enhance the space charge compensation degree upstream of the beam. The results are summarised in Table 2.

Table 2: RMS-Emittance Deviations

Nr.	Magnetic field[mT]	Distribution 1	Distribution 2
1.	0	+25%	+3.6%
2.	6.8	-10%	-25.6%
3.	8.1	-25%	-36%
4.	9.5	+6.6%	-8%
5.	10.8	+1.6%	-9.9%

3D-PIC/MCC SIMULATION

Simulation of the electron column as a static electric field was done in the previous section. No recoil of the electron distribution was considered in that case.

Dedicated large scale multi-particles 3D Monte-Carlo-PIC-simulation campaign was started on FUCHS-Cluster[10] with the goal to explain relevant collective phenomena in non-neutral plasma generated by passing of an ion beam.

Simulation code *gab_lens_m3*[3] was implemented with some modifications and including of an ion beam transport.

An electron column confined in GL2000-device have been chosen and parameters Φ_A=10 kV, B=18 mT were set. The Uranium beam U^{28+} with starting relativistic velocity β=0.155 and beam current of I_b=16 emA was injected and transported through the electron column. Cylindrical mesh with overall number of (N_r, N_θ, Nz)=84x61x2250 mesh points were used with 1 mm step space resolution. Initial radial symmetric KV-beam distribution with normalised transversal rms-emittance $\varepsilon_{rms,n}$=5 mm·mrad was generated with number of macro-particles 10^7 for ions and $3.4\cdot10^7$ for electrons. Initial beam momentum spread $\Delta p/p=10^{-3}$ was set as well. Beam was distributed along whole z-axis under assumption of drift motion only (without any forces) at the initial state. Simulation time step $\Delta t=2.48\cdot10^{-11}$ s was chosen and electron production probability was set in ratio 10:1 between the shell surface near anode and bulk of the electron column (with higher production in gaps between ground and anode electrode). Simulations in the past [3] showed that for a pure electron column there will be a density equalizing process due to the natural trap geometry and balance between production and losses. Average electron density $n_e=7\cdot10^{13}$ m^{-3} and respectively charge density $\rho_e=1.12\cdot10^{-5}$ C m^{-3} was generated in GL. In comparison, beam charge density inside of GL came to approximately $\rho_b=1.5\cdot10^{-7}$ C m^{-3}.

Simulations results show typically behaviour of filling-in process in the first Δt=129 ns (Fig. 5).

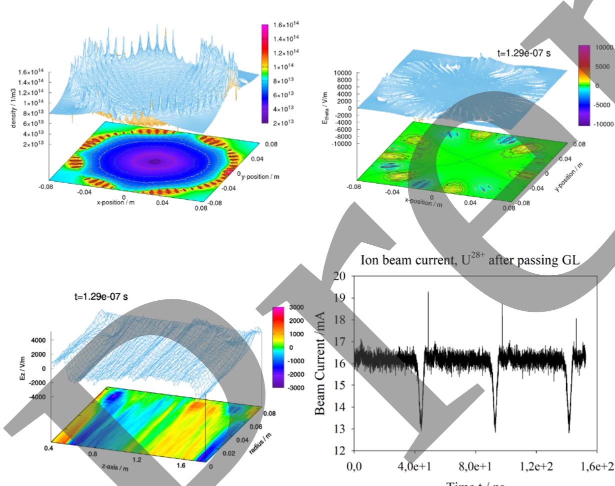

Figure 5: Early stage of the simulation - transversal profile in the middle of the GL (left-up), electric field E_θ (right-up), electric field E_z (left-down), beam current after passing GL(right-down). Characteristic peak-down signal was created in particle distribution at (t=0, z=0) for diagnostics purposes.

Results show higher density profile at large radii, thus hollow electron distribution is established. After some initial time, diocotron wave rises (Fig. 5, right-up) and helps to redistribute the electron charge. Electrostatic waves are observed longitudinally also (Fig. 5, left down). Bulk electron density of about $4\cdot10^{13}$ m^{-3} results in plasma frequency of f_p=56.77 MHz, which is inverse proportional to the reaction time t_p=17.6 ns. This is shorter than the ion beam passing time t_b=40 ns, which means that an electron column can already react on ion beam disturbance.

Beam focusing effect in a trapped electron column is demonstrated on Fig. 6.

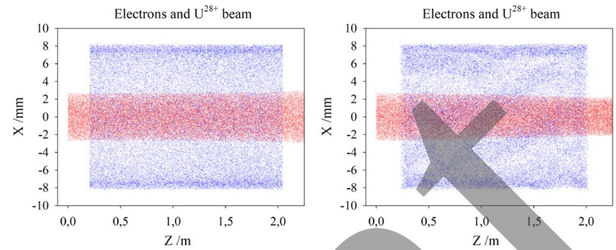

Figure 6: Uranium beam (red) and electron distribution (blue) at the initial state (left) and at the simulation time t=150 ns (right).

The simulation campaign is being continued, redistribution of the electrons will be saturated approximately at t=1 µs, as was demonstrated in previous work [3]. Because of this transient regime, the on-axis potential vary rapidly and will influence beam transport in the first 150 ns. However, no changing in momentum spread was detected so far.

CONCLUSION

The numerical simulations show an impact of the ion beam on the dynamic of confined pure electron clouds. On the other hand, space charge compensation and the self-field of the non-neural plasma acts on beam dynamic.

A low energy beam transport channel consisting of four GLs was constructed at Goethe University (Fig. 7) to study the impact the increased space-charge compensation due to the electron reservoirs or even an over-compensation due to longitudinal electron losses from the GLs. This will help to provide ultra-intensity beam transport for future high power applications.

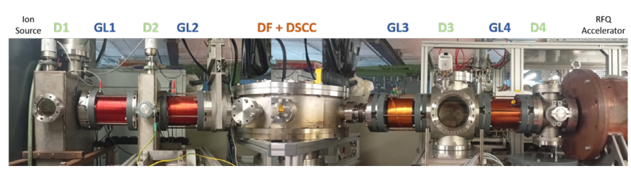

Figure 7: Low energy beam transport channel at Goethe University (GL – Gabor Lens, D – Diagnostic chamber, DF+DSCC – Deflector and De-compensator).

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