GABOR LENS PERFORMANCE STUDIES AT THE GSI HIGH CURRENT TEST INJECTOR *

K. Schulte†, M. Droba, O. Meusel, U. Ratzinger, Institute for Applied Physics, Frankfurt, Germany
A. Adonin, R. Berezov, R. Hollinger, J. Pfister, GSI, Darmstadt, Germany

Abstract

At the Institute for Applied Physics (IAP) the application of Gabor space charge lenses as a focusing device for low energy ion beams has already been studied for several years.
Inside Gabor lenses electrons are confined by external fields. In case of a homogeneously distributed electron cloud the resulting linear electric space charge field enables the focusing of high intensity heavy ion beams without emittance growth. Therefore, the Gabor lens is a promising approach for mass-independent focusing with possible space charge compensation of ion beams.
In mid-2012 the performance of a prototype lens has successfully been tested at the GSI High Current Test Injector (HOSTI). GSI and IAP are currently investigating the possible application of such a device for the operation at the new frontend of the High Current Injector (HSI) for FAIR. This contribution will present the results of beam transport experiments at HOSTI as well as the determination of related plasma properties.

PROTOTYPE GABOR LENS

As a part of the planned FAIR project at GSI the requirements of the existing High Current Injector (HSI) concerning brightness and intensity of the delivered beam are going to increase [1]. Especially the transport of intense i.e. space charge dominated beams is a major challenge for the low energy beam transport section.
The application of a Gabor lens in this case is a promising approach concerning a controlled confinement of electrons within the beam potential. To investigate the transport of an ion beam regarding to beam radius, ion current and energy, pulsed beam operation and to acquire experience in an real accelerator environment, a prototype Gabor lens had been designed for focusing a $^{238}U^{4+}$ beam with an energy of 2.2 keV/u at a maximum radius of r_B=50 mm [2].

BEAM TRANSPORT MEAUSREMENTS

The experiments were divided into measurements of an emittance dominated and a space charge dominated beam transport.
In a first step the transport of a 3 mA, 50 keV He^+ beam as a function of the Gabor lens parameters was investigated. In the discussed case the perveance and, therefore, the influence of the space charge on the transport is negligible, so one can basically study the performance of the Gabor lens as a focusing device.
In a second step experiments using a 35 mA, 124 keV Ar^+ beam were performed. By increasing the beam current not only the perveance increases by a factor of 8.2 but also the ion number density gradually reaches the order of magnitude of the electron density confined by the Gabor lens. Furthermore, an increased production of secondary electrons from residual gas ionization and beam losses on the beam pipe can be expected.
For this reason the space charge dominated beam transport measurements at HOSTI were a necessary step towards investigating the influence of the previously mentioned processes on the focusing performance and the general evaluation of the quality of the ion beam transport by the prototype Gabor lens.

Experimental Setup

A picture and the scheme of the HOSTI beamline after the installation of the prototype lens is shown in Fig. 1. The ion beam was provided by a MUCIS ion source that

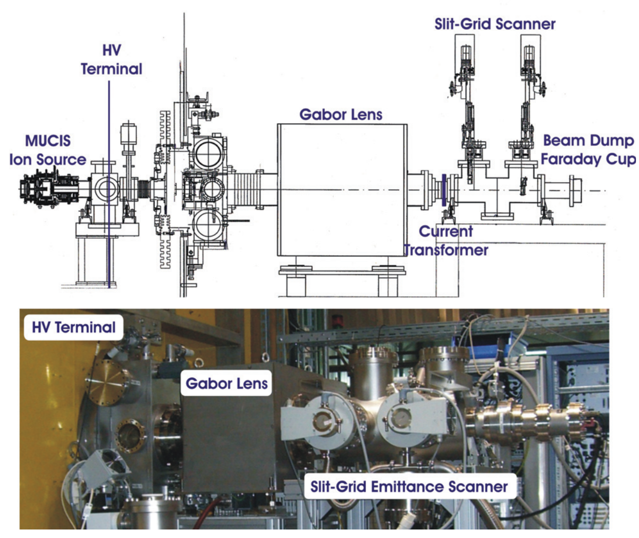

Figure 1: Scheme and photograph of the experimental setup for the beam transport measurements at GSI.

was operated in 1 Hz mode with 1.25 ms pulse length for all presented measurements. The extracted beam is then accelerated up to its maximum energy by a dc-post-acceleration system. The emittance of the ion beam was measured by a slit-grid-scanner and the claimed current in the following was detected by a current transformer installed right behind the lens.

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† Schulte@iap.uni-frankfurt.de

Emittance Dominated Beam Transport

The focusing strength of the Gabor lens is mainly dependent on the electron density n_e and the acceleration voltage U_{acc} of the ion beam:

$$\frac{1}{f} = \frac{\Delta y'}{y} = k_G^2 l = \frac{e n_e l}{4\epsilon_0 U_{acc}} \qquad (1)$$

In the first approximation the electron density is a function of the confining fields and scales linearly with the anode potential and quadratically with the magnetic field.

In order to achieve a rapid rise in the electron density and, as a consequence, an increase in the focusing strength the magnetic confining field was varied during the beam transport and the emittance was measured.

Figure 2 shows some results for different lens settings in comparison to the drifted beam. While the plasma state was simulated using the code GABOR-M [3] for the given lens parameters, the illustrated beam transport simulations were calculated by the transport code LINTRA. In the presented case a space charge compensation of 95% was assumed. The measurements clearly show the influence of electron

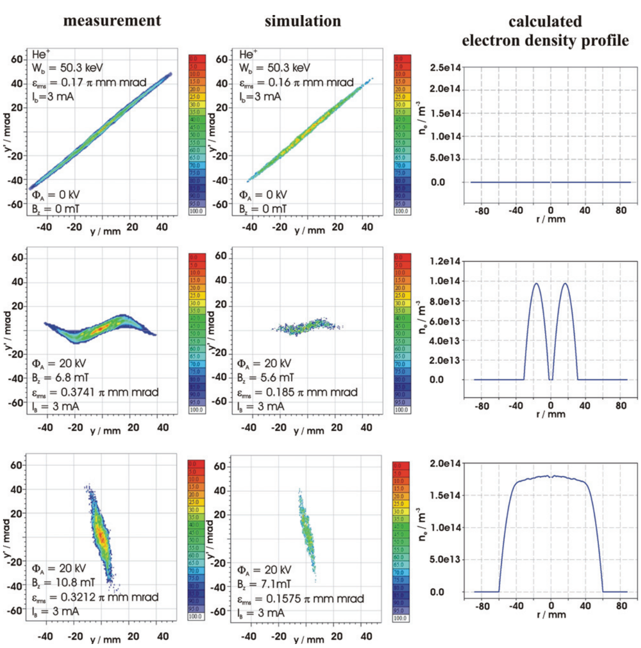

Figure 2: Comparison between measurement (left) and simulation of the transported He^+ beam (center) as well as the simulated electron density distribution (right).

density distribution on the emittance shape. Especially a hollow electron distribution leads to major aberrations in the phase space distribution. Close to the operation point of the lens (B_z=11.26 mT, Φ_A=20 kV) the density becomes homogeneous and for this reason the emittance decreases.

Figure 3 shows the rms-emittance $\epsilon_{rms,97\%}$ as well as the kurtosis V_y as a function of the lens parameters. Right behind the working point of the lens the plasma becomes unstable that leads to a rapid rise in the emittance. The kurtosis describes the peakedness of the particle distribution

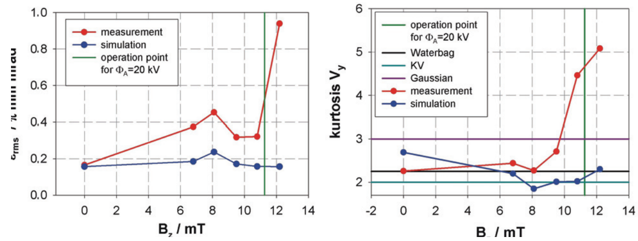

Figure 3: Comparison between measurement and simulation of the rms-emittance $\epsilon_{rms,97\%}$ (left) and the kurtosis V_y (right) as a function of the magnetic field B_z.

in the y-dimension and indicates that the beam distribution evolves from a former Waterbag to a Gaussian distribution. By the analysis of the emittance dominated beam transport measurements the strong influence of the shape of the electron density distribution on the focusing performance of the Gabor lens could be demonstrated. In this context the setup of lens parameters regarding to the operation function is of great importance to optimize the beam transport and to ensure the stability of the confined electron cloud.

Space Charge Dominated Beam Transport

The discussion of the beam transport experiments becomes more complicated with increasing ion current. The space charge of the beam increases and at the same time the production of secondary electrons and, consequently, the filling degree of the Gabor lens as well. The possible evidence of this competing effects is presented in Fig. 4. For the same lens parameters the ion current was increased

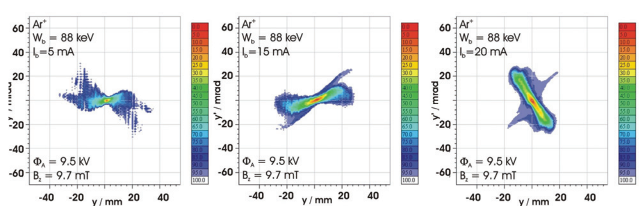

Figure 4: Possible influence of the secondary electron production by the beam on the focusing strength of the prototype lens.

and by this the focusing strength of the lens increases, too. At this point it shall be mentioned that this relevant effects need to be further investigated and the measurement represents a first reference only.

Unfortunately, the secondary electron production on the vacuum pipe by beam losses or by interaction of the beam with residual gas is not included in the transport program at the moment and, therefore, the simulation provides no reasonable results to compare with the measurement.

Figure 5 presents an excerpt from the results of the beam transport experiments in case of a space charge dominated 3.1 keV/u Ar^+ beam with a maximum intensity of I_B=35 mA. The hight current measurements were performed with an iris of 50 mm at the entrance of the lens to

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protect the insulator from the beam and to prevent sparking in the Gabor lens. In analogy to the measurements of the emittance dominated beam the focusing strength of the lens was increased by the variation of the confining magnetic field.

A parallel beam is attained for lens parameters of

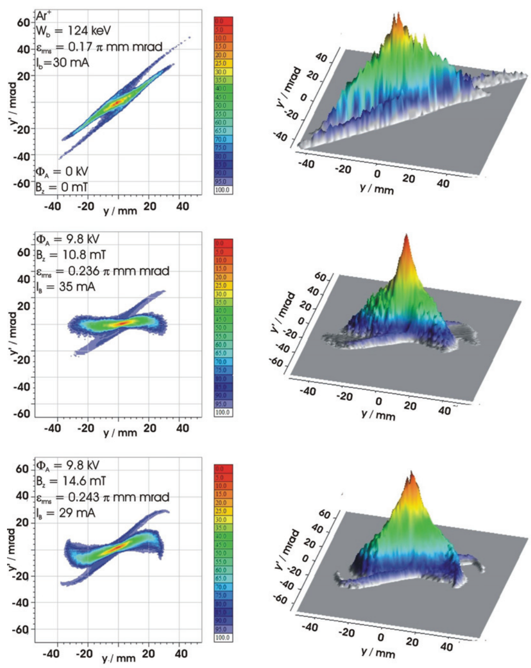

Figure 5: Measured emittance (left) and emittance profile (right) for an 3.1 keV/u Ar^+ beam as a function of the lens parameters.

Φ_A=9.8 kV and B_z=10.8 mT. With increasing magnetic field (B_z=14.6 mT) the appearance of plasma instabilities is observed that lead to an emittance growth of the beam. Figure 6 shows the kurtosis and the rms-emittance of the beam as a function of the lens parameters.

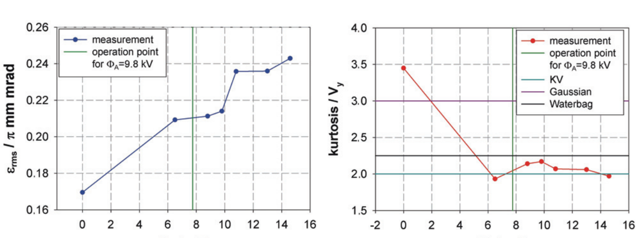

Figure 6: Measured rms-emittance $\epsilon_{\mathrm{rms},97\%}$ (left) and kurtosis V_{y}(right) as a function of the confining magnetic field.

Based on the trend of the kurtosis the beam profile shape transitions from a former Gaussian into a Waterbag or KV distribution, so the beam becomes more homogeneous.

The space charge dominated beam transport measurements could demonstrate that a Gabor lens is suitable for the transport of high current ion beams without reasonable emittance growth. For a parallel beam the rms-emittance $\epsilon_{\mathrm{rms},97\%}$ only increases by 40%.

NONNEUTRAL PLASMA DIAGNOSTICS

Nonneutral plasma diagnostic measurements were performed performed separately from the beam transport experiments for the same lens parameters with Helium and Argon as residual gas. As a part of the outcomes the results of the density measurements shall be presented.

The electron density $\mathrm{n_{e,w\,beam}}$ is measured by the change in the divergence angle of the passing beam according to equation 1. In comparison to this method the density $\mathrm{n_{e,w/o\,beam}}$ may also be determined by measuring the energy of extracted residual gas ions from the lens volume. From the detected ion energy compared to the energy it should have gained within the potential well, one may conclude on the potential depression due to confined electrons [4].

Figure 6 shows the results for both of the diagnostic techniques in comparison to the numerical simulations $\mathrm{n_{e,sim}}$.

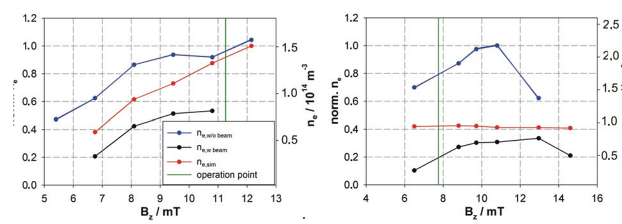

Figure 7: Comparison between measured and simulated densities for Helium (left) and Argon (right) as residual gas. The legend is valid for both plots.

OUTLOOK

It can be summarized that the transport of a space charge dominated beam by a Gabor lens appears to be very promising and the evaluation of the Gabor lens as focusing device for the HSI Upgrade at GSI is progressed.

Improvements in the lens design concerning the magnetic field and the insulator of the electrode system are currently under discussion.

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