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FOCUSING OF HIGHLY CHARGED ION BEAMS USING GABOR-LENSES*

J. Rausch†, O. Meusel, T. Dönges, K. I. Thoma[1], M. Droba, H. Podlech[2]
Goethe University Frankfurt, Frankfurt a.M., Germany
[1]also at GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany
[2]also at Helmholtz Research Academy Hesse for FAIR (HFHF), Frankfurt a.M., Germany

Abstract

A Gabor-lens is an ion optical device using the electric self-field of a stable confined electron column providing the focusing strength. This lens type was investigated in detail and it was shown that it is possible to use it in a LEBT for intense heavy ion beams. The homogeneous electron density results in linear focusing forces and provides space charge compensation of the beam. On the other hand it is not clear, how the charge state changes when a highly charged ion beam passes the pure electron plasma confined in a Gabor-lens. Therefore, an experiment was designed, which enables the possibility to transport an 15 keV Ar8+-beam through a Gabor-lens and estimate the collisional three-body (e – e – ion) recombination to lower charge states. A variation of the relative velocity of the beam with respect to the electron plasma was performed and it was possible to measure the electron density at the same time. Experimental results are presented and future strategies for the transport of highly charged intense ion beams are discussed.

INTRODUCTION

While also investigations are made for the use of Gabor-lenses in high energy beam transport lines [1,2], its property of providing space charge compensation during linear focusing makes the Gabor-lens (GL) suitable especially for LEBT sections of highly charged ion beams where space charge forces are the limiting factor in the design of transport lines. While these properties of GLs are well understood, the direct interaction of highly charged ions with the electron column has to be investigated in detail. Changes of charge state would lead to losses in the further structure and therefore mitigate the advantages of providing space charge compensated beam transport. Both charge changes due to recombination and impact-ionization must be considered. Identification of changed charge states is achieved by the use of a momentum spectrometer which at the same time provides information about the state of the confined electron column. Previous work [3] to set up this momentum spectrometer has shown the necessity of detailed investigations on the interaction of beam ions with electrons in a GL.

* Work supported by Federal Ministry of Education and Research (BMBF) #05P18RFRB1
† rausch@iap.uni-frankfurt.de

SETUP

Gabor-Lens

The Gabor-lens uses a superposition of axial magnetic and electric fields to confine electrons which are generated in an avalanche ionization of the residual gas and from secondary electrons by particle impact on the GL structure. The inside of the GL is set to a positive electric potential for electron confinement, which is partially compensated by the spacecharge of accumulated electrons leading to longtiudinal losses. The longitudinal electric potential is shown in Fig. 1.

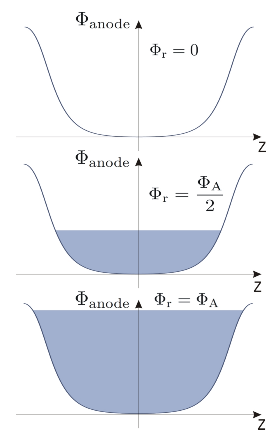

Figure 1: Longitudinal potential distribution in the GL at an anode potential Φ_A and compensation by the spacecharge potential Φ_r of the electrons. [4]

While confining electrons, positive ions are emitted along the axis. The maximum density of electrons confined is limited by the production and loss rates. However the actual density of the electron column can be acquired from the spectrum of produced ions. Their maxmimum energy directly relates to the potential inside the lens from which the charge density can be obtained. The filling ratio is the ratio between the actual and theoretically possible electron density.

Momentum Spectrometer

The momentum spectrometer uses two Faraday cups for a highly sensitive measurement of ion current in two beam directions. The straight and a deflected direction are strictly determined by apertures in the beam path. Since deflection is achieved by the use of a magnetic dipole field, the spectrometer is sensitive both to the momentum p and charge

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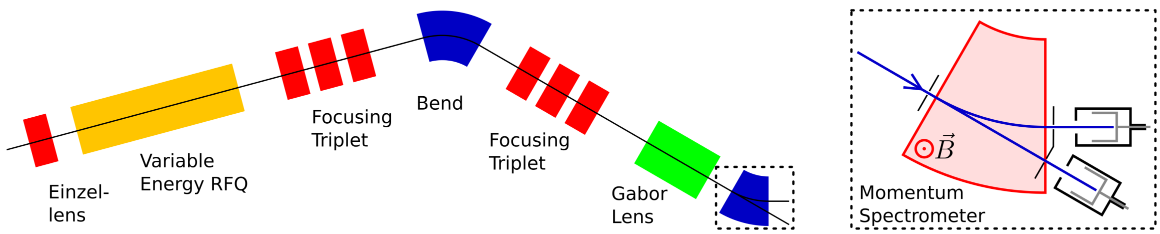

Figure 2: The setup of the beamline used. Quadrupole triplets allow for focussing, the GL is placed after a 45°-bend. The spectrometer consists of two Faraday-Cups arranged behind a 45°-bend and two apertures.

state q of particles:

$$B\rho = \frac{p}{q} \quad (1)$$

Its broad range of deflection strength enables the observation of both the ions emitted from the GL as well as the beam ions in one measurement of the same spectrum.

Beamline

For the experiments a highly charged Argon-beam was used. Ar^{8+} at the energy of 120keV was provided by an ECR-ion source [5]. The beam transport line, besides initial focusing and bends into the used beamline, consists of a variable energy RFQ and focussing quadrupole triplets. It is shown in Fig. 2. The beam then enters the GL which can be configured in different states to

1. resemble a drift section, for observations of the effects of residual gas inside the transport line,
2. study the effects of the magnetic and electric fields of the GL setup on the beam separately and without confined electrons and
3. investigate the spectra of beam ions after interactions with a confined electron column and therefore to determine the changes in charge state of beam ions induced by this electron plasma.

EXPERIMENTS

Beam Spectrum

The momentum spectrum of the provided Argon beam is shown in Figs. 3 and 4. A large peak of the main charge fraction is measured at the expected particle momentum corresponding to the beam energy. Ions with lower charge states are also present indicating charge changes due to recombination processes in the beamline at a residual gas pressure of 5×10^{-7} mbar. In contrast, no higher charge states could be observed. To increase the rate of changes in charge states a higher residual gas pressure was introduced. Beam fractions with smaller charge could be observed down to Ar 4+. Due to the bending magnets' filtering properties these ions can be generated only in residual gas interaction in the last straight section of the beamline, where a differential pumping stage divides it from the rest of the beam transport lines at pressures of better than 1×10^{-8} mbar.

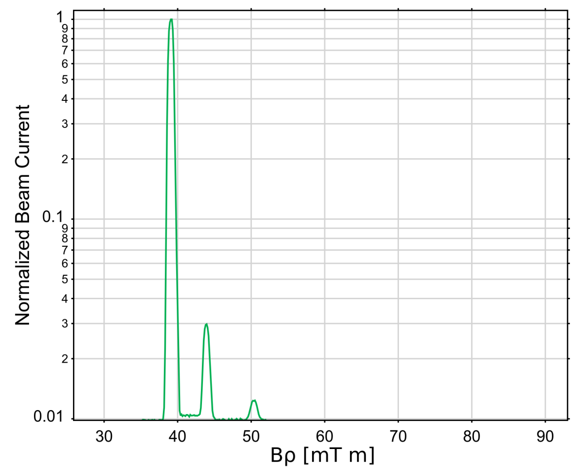

Figure 3: Spectrum of the Argon beam showing the main peak of Ar^{8+} ions and smaller peaks for lower charge states. at a pressure of 5×10^{-7} mbar. No higher charge state is observed.

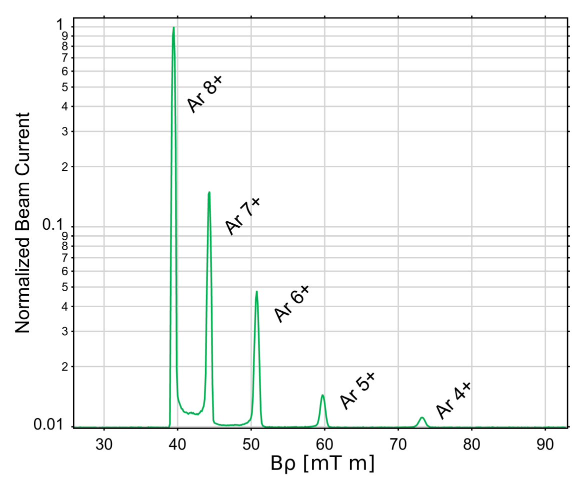

Figure 4: Spectrum of the Argon beam showing the main peak of Ar^{8+} ions and smaller peaks for lower charge states at a pressure of 4×10^{-6} mbar. No higher charge state is observed.

Influence of Magnetic and Electric Field

The absolute intensity after the apertures depends on the focussing of the beam. The solenoidal magnetic field as well as the electric Einzellens configuration of the Gabor-lens

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lead to focussing (and potential over-focussing) of the beam and therefore varying absolute intensities at the detector even with no electron column confined. Therefore measurements of changed charge states are always shown as normalized intensities. A further effect in this setup is, that, due to their very low energy, beam ions can be significantly slowed down in the positive confinement potential of the GL leading to a much higher interaction rate with residual gas.

Spectrum with Electron Confinement

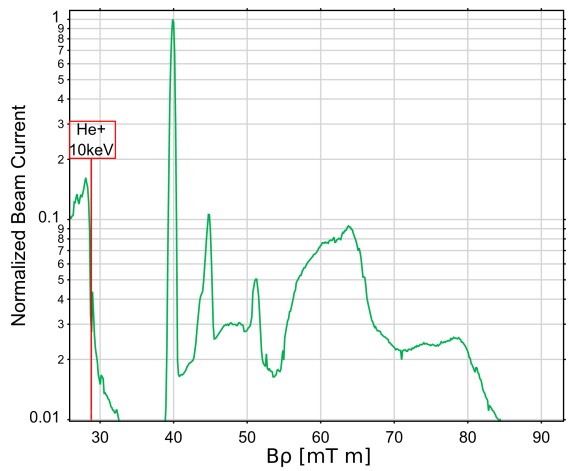

Figure 5: Spectrum of the Argon beam after propagating through the GL electron column at a pressure of 4×10^{-6} mbar. Beam fractions with different charge states are overlayed with the ion emission spectrum of the GL itself.

The spectrum of the Argon beam after propagating through a confined electron column of an estimated charge density of $n_e \approx 1.5 \times 10^{14}\,\mathrm{m}^{-3}$ was measured and is shown in Fig. 5. The measurements show that charge changes of beam ions can be investigated with the spectrometer even with a confined electron column present in the lens. However the spectrum of GL-emitted ions is overlayed on the beam spectrum and has to be subtracted to retrieve exact information about the quantities of charge species. Also the potential inside the GL and therefore the filling ratio can be obtained from the maximum energy of known emitted particle species in the GL spectrum as shown here for an anode potential of 15 kV and with particle energy from Fig. 5:

$$\kappa = \frac{\Phi_e}{\Phi_{GL}} = \frac{(15-10)\,\mathrm{kV}}{15\,\mathrm{kV}} = \frac{1}{3}. \quad (2)$$

Charge Changes in Potential

To investigate the increased rate of charge changes when slowing the beam, the GL was set to potential without confinement for a comparison measurement. The spectrum (Fig. 6) shows an increased amount of charge changes especially of higher order.

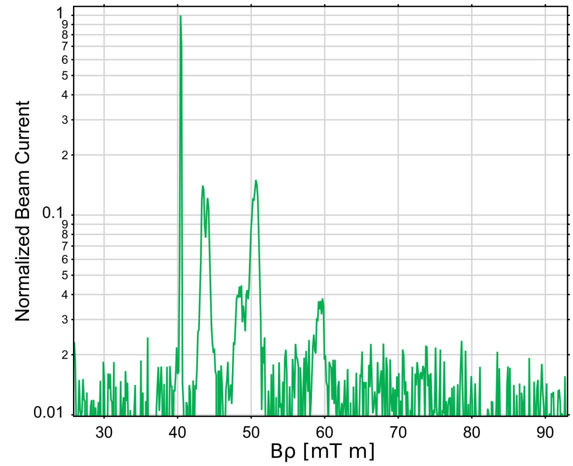

Figure 6: Spectrum of the Argon beam affected by the electric field with the GL at a potential of 15 kV but no electrons confined.

RESULTS

The charge changes of the beam were shown to be observable up to Ar 4+ in increased residual gas density. In combination with the GL setup the pattern of charge changes stays the same and the main beam is conserved although absolute quantities of each charge species vary. The observation of the effect of the GL setup on these can be determined using the momentum spectrometer. While charge changes due to recombination processes occur, no ionization to a higher charge state could be detected. From the peak intensities the amount of less charged ions is comparable to that in an equivalent stopping potential, as would be used in an electrostatic Einzellens. While the spectrum of GL-emitted ions is an overlay of the beam spectrum, it can be shifted to an non-interfering region by choice of the residual gas composition. Further investigations can be done to determine the absolute rate of charge changes.

CONCLUSION

It is shown that the rate of charge changes inside an Argon^{8+} beam at the very low energy of 120 keV can be obtained with the used setup. Furthermore the possible influence of a GL on the charge changes of an ion beam could be investigated. This lead to the observation that no increase of charge changes is induced by the use of a GL in comparison to an unaffected beam, while an introduced stopping potential like that of an Einzellens does lead to increased charge changes. This implies that the use of GLs for space carge compensation and as a linear focusing optical device inside an LEBT section is not hindered by charge change effects.

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