LOW ENERGY BEAM TRANSPORT USING SPACE CHARGE LENSES

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Abstract

At the frontend of an accelerator the transversal focusing suffers from high space charge forces. Space charge lenses (SCL) provide strong cylinder symmetric electrostatic focusing by a confined nonneutral plasma. The density distribution of the enclosed space charge is defined by the enclosure conditions in transverse and longitudinal direction. For a homogeneous charge density distribution the resulting electrostatic field and therefrom the focusing forces inside the space charge cloud are linear. Additionally, in case of a positive ion beam, the space charge of the confined electrons causes compensation of the ion beam space charge forces.
To study the capabilities of a Gabor double lens system to match an ion beam into an RFQ a testinjector was installed at the IAP and put into operation successfully. Beam profiles and emittance measurements as well as measurements of the beam energy and energy spread have already been performed and show satisfactory results and no significant deviation from the theoretical predictions. To investigate the beam focusing of bunched beams using this lens type at beam energies up to 500 keV a new high field Gabor lens was built and installed behind of the RFQ.

THEORY

The focal strength of a SCL is determined by the spatial space charge density distribution. The space charge density distribution is a function of the transversal and longitudinal enclosure conditions [1,2]. Gabor showed [3] for a radial confinement by a magnetic field, that in absence of external electric fields, the transversal enclosure condition is given by the Brillouin flow [4] and therefrom the maximum electron density can be calculated by:

$$n_{e,rad} = \frac{\varepsilon_0}{2m_e} B_z^2 \qquad (1)$$

The upper limit for the longitudinal enclosure can be calculated by the space charge potential of a homogeneous cloud of radius r_A, which has to be smaller then the anode potential V_A, resulting in:

$$n_{e,l} = \frac{4\varepsilon_0 V_A}{e r_A} \qquad (2)$$

Both of these relations solely overestimate the space charge density significantly. Additionally the longitudinal enclosure condition is drastically influenced by thermalization of the enclosed particles and therefrom due to losses of fast particles in the Maxwellian tail. By measurement of the focal length the average electron density can be determined. Applying the thin lens approximation for a homogeneously space charge filled cylinder the average electron density is given by:

$$\frac{1}{f} = \frac{r'}{r_0} = k^2 \cdot l = \frac{\overline{n}_e \cdot e}{4\varepsilon_0 \cdot W_B} \cdot l \qquad (3)$$

(refraction power k, divergence angel r´, beam radius r_0 and energy W_B, the length of the space charge cloud l, focal length f). The length of the cloud can be estimated by the distance between the two grounded electrodes (see fig. 5). Introducing the radial and longitudinal filling factors [5] $\kappa_{r,l}$ [$0 \leq \kappa_{r,l} \leq 1$] and using Eq. (1),(2) and (3) the trapping efficiency can be expressed by:

$$\kappa_r = \frac{\overline{n}_e}{n_{e,r}} \quad ; \quad \kappa_l = \frac{\overline{n}_e}{n_{e,l}} \qquad (4)$$

THE HE$^+$ - TEST INJECTOR

A test injector to study the matching of a space charge dominated ion beam into an RFQ has been constructed and installed at IAP. The schematic layout of the experiment is shown in figure 1.

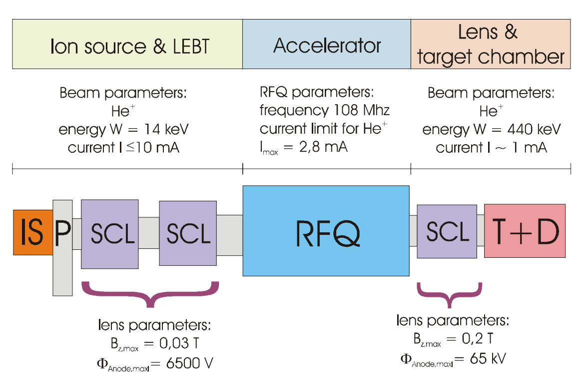

Figure 1: Schematic drawing of the experimental set up.

In a first step the low energy beam transport (LEBT) and the injection of a space charge dominated ion beam into an RFQ using Gabor lenses was studied. After beam acceleration by the four rod RFQ, the beam passes a high field Gabor lens. This allows to investigate beam focusing after an increase of the beam energy by a factor of 30 and including a more or less pronounced micro bunch structure, depending on the drift length RFQ – Gabor lens.

LOW ENERGY BEAM TRANSPORT

The front end of the injector consists of a volume type ion source, a differential pumping stage, the Gabor lens LEBT system and several beam diagnostic devices.

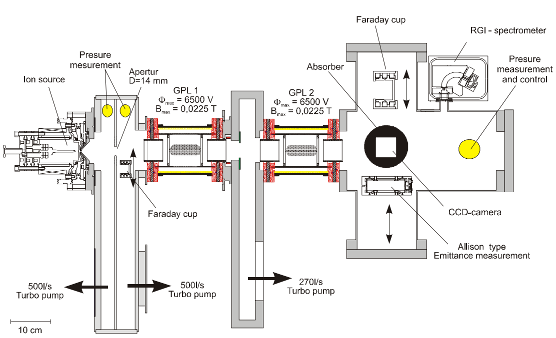

Figure 2: Schematic drawing of the front end of the injector.

The ion source delivers a maximum beam current of 10 mA He^+ at 14 keV. After commissioning of the ion source the emittance of the beam behind of the differential pumping stage was measured (see fig. 3 left, He^+, 14 keV, 4.5mA, $\varepsilon_{n,rms,100\%}$ = 0.0225 πmmmrad).

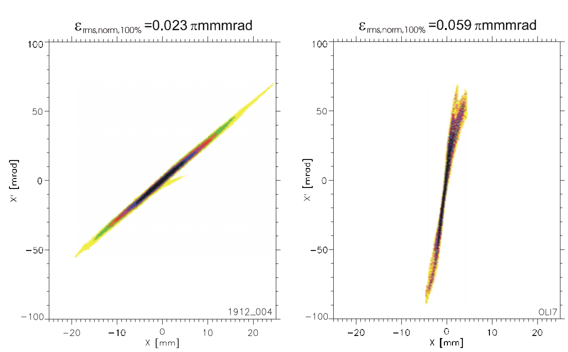

Figure 3: Measured beam emittance behind the differential pumping stage (left) and behind the LEBT – system (right) at I=8.4mA.

After installation of the two Gabor lenses the emittance at the RFQ injection point was measured using improved ion current (see fig. 3 right, He^+, 14 keV, 8.4 mA, $\varepsilon_{n,rms,100\%}$ = 0.0598 πmmmrad). In figure 3 (right) the phase space distribution just behind the focus of the beam is shown. The following lens parameters were used: first lens V_A = 1.8 kV and $B_{z,max} = 5.76 \cdot 10^{-3}$ T, second lens V_A = 2.1 kV and $B_{z,max} = 6.24 \cdot 10^{-3}$ T for the presented results. For these measurements the calculated focal lengths were f = 0.366 m for the first and f = 0.22 m for the second lens. Therefore the filling factors are κ_r = 38 % and κ_l = 49 % respectively. Our hitherto experience shows a good reproducibility of the gained results.

THE RFQ

After finalization of the LEBT measurements the RFQ was installed behind of the second Gabor lens. The design beam energies at the RFQ entrance and exit are 3.5 AkeV and 110 AkeV respectively. The maximum beam current is limited by space charge forces to 0.7 mA·A/q, the design ion being N^+. The beam energy spectrum proofs that the necessary design power for the acceleration of He^+ is 8 kW as predicted by simulations [6]. For a power level of 8 kW the measured energy spread is below 5 % and the accelerated beam current already reached 50 % of the RFQ space charge limit. Beam profile and emittance measurements have already be performed. In figure 4 the measured phase space distribution behind the RFQ is shown (left, x-plane, $\varepsilon_{n,rms,100\%}$ = 0.175 πmmmrad, right, y-plane, $\varepsilon_{n,rms,100\%}$ = 0.192 πmmmrad).

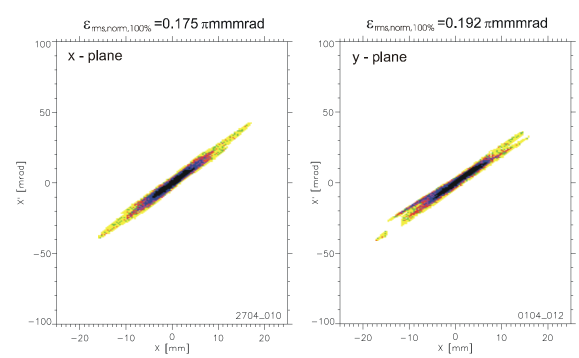

Figure 4: Measured beam emittance behind the RFQ in x-plane (left) and in y-plane (right), beam current I = 1,15 mA.

The intense centre of the beam is predicted by beam transport simulations, while the low intensity wings in the phase space distribution are due to unaccelerated halo particles (see chapter 5.).

THE HIGH FIELD GABOR LENS

Finally the test injector was extended by the high field Gabor lens. Figure 4 shows a cross sectional view and a picture of this lens.

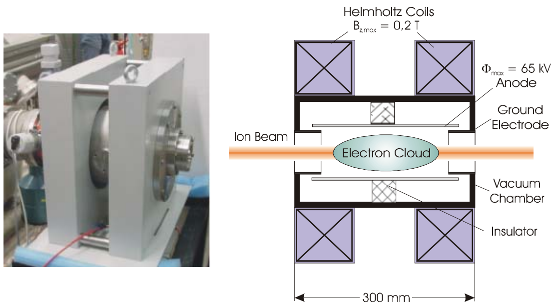

Figure 5: Picture and cross sectional view of the high field Gabor lens.

For the radial confinement the magnetic field of Helmholtz coils (up to 0.2 T on axis) is used while the longitudinal confinement is provided by an anode with radius r_A = 0.032 m and $U_{A,max}$ = 65 kV. In figure 6 the very first measured emittances behind the lens are shown. For the presented results the lens settings of V_A = 25 kV and $B_{z,max}$ = 46 mT was used. The phase space distribution in the x-plane (left, $\varepsilon_{n,rms,100\%}$ = 0.066 πmmmrad) and in y-plane (right, $\varepsilon_{n,rms,100\%}$ = 0.094 πmmmrad) are presented in figure 6.

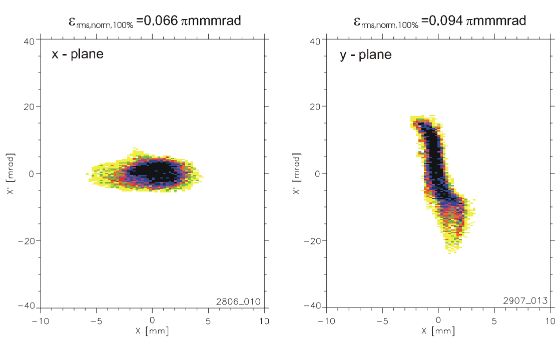

Figure 6: measured beam emittance behind the high field Gabor lens x-plane (left) and y-plane (right) using following lens settings: V_A = 25 kV and $B_{z,max}$ = 46 mT.

It is shown that the divergence angel of the core of the phase space distribution was decreased from 20mrad to 0mrad in x-plane and from 20mrad to –20mrad in y-plane. Furthermore the unaccelerated halo particles are lost due to over focusing. The beam radii at the lens centre in the x and y plane are 5mm and 10mm, respectively. For the presented emittances the focal length is approximately 0.25m and the filling factors can be calculated to be κ_r = 24 % for radial confinement and κ_l = 61 % for longitudinal confinement. The beam radius in the y-plane is a little bit larger than the radius of the space charge cloud. This causes the observed emittnace growth [7].

CONCLUSIONS

The injection of a space charge dominated ion beam into an RFQ by space charge lenses was performed successfully. The experiments show for the LEBT-system a low emittance growth, high transmission and reasonable filling factors in the Gabor lens. The injected beam was accelerated successfully by the RFQ at the design input power and the extracted beam has already reached 50% of the space charge limit for He^+. Experiments using the high field Gabor lens have started. The first beam measurements of the emittance show a good performance for beam radii smaller than the radius of the space charge cloud (see fig. 6, x-plane).

REFERENCES

[1] J.Pozimski, P.Groß, R.Dölling and T.Weis: “First experimental studies of a Gabor plasma-lens in Frankfurt”, Proc. 3rd EPAC Conf. 1992 Berlin

[2] O. Meusel, J. Pozimski, A. Jakob, A. Lakatos ”Low energy beam transport for HIDIF” HIDIF 2000 Meeting San Diego, USA, NIM A 464 (2001) p. 512-517

[3] D.Gabor: “A Space charge lens for the focusing of ion beams”, Nature 160 (1947)

[4] L. Brillouin, “A theorem of Lamor and its importance for electrons in magnetic fields”, Phys, Rev. 67, 260 (1945)

[5] Reiser, “Comparison of Gabor lens, gas focussing and electrostatic quadrupol focusing for low energy beams”, Proc. PAC Conf. 1989, Chicago, USA

[6] A.Bechtold, “Construction of an heavy ion RFQ accelerator with high duty cycle” Diploma thesis 1997

[7] J.Pozimski: “Untersuchungen zum Transport raumladungskompensierter niederenergetischer und intensiver Ionenstrahlen mit einer Gabor Plasma-Linse“, Dissertation Inst. f. Angew. Phys.,J.W.Goethe-Univ., Frankfurt am Main (1997)