Aberrations due to Solenoid Focusing of a Multiply-Charged High-Current Ion Beam

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At the output of a laser ion source, a high current of highly charged ions with a large range of charge-states is available. The focusing of such a beam by magnetic elements causes a non-linear space-charge field to develop which can induce large aberrations and emittance growth in the beam. Simulation of the beam from the CERN laser ion source will be presented for an ideal magnetic and electrostatic system using a radially symmetric model. In addition, the 3D software KOBRA3 is used for the simulation of the solenoid line. The results of these simulations will be compared with experiments performed on the CERN laser ion source with solenoids (resulting in a hollow beam) and a series of gridded electrostatic lenses.

I. INTRODUCTION

The field from a magnetic solenoid provides effective focusing of a hadron beam and is best used in the case where a beam is cylindrically symmetric. On the CERN Laser Ion Source (LIS), solenoids were used in the transport line from the source outlet to the input of the Radio Frequency Quadrupole (RFQ) accelerator. The beam from the source has a range of charge-state [1], with the most abundant being Ta^{20+} and the highest Ta^{24+}.

Despite many attempts at optimisation of this line, the transmission of the target ion (Ta^{20+} at 6.9 keV/nucleon) could not be increased above 30%.

Initially the interaction of space-charge fields from the charge-states separated by the different focusing strength of the solenoid on each charge-state, was not found by simulation. During measurements of the ion beam parameters, not only was the transmission to the RFQ found to be low, but during investigation of the ion beam profile, it was found to have a highly aberrated hollow structure with a low density of ions near the axis.

In this report it is shown that this can be attributed directly to the space-charge coupling of the different charge-states in a magnetic field, and that if a singly charged beam or electrostatic focusing is used, the ion beam remains uniform in distribution.

Two models are used to show the aberrations due to the non linear space-charge field resulting from charge-state separation in a magnetic field.

II. CYLINDRICALLY SYMMETRIC 2D MODEL

For preliminary study of the transport of an ion beam in a cylindrically symmetric 2D geometry, we make the following simple paraxial approximations for the ion trajectories. For the treatment of space-charge, the cylindrically symmetric Poisson's equation is solved, i.e.

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dV}{dr}\right)=-\frac{\rho}{\varepsilon_0}$$

Where r is the radial co-ordinate, V is the potential and ρ the charge density. In this case the approximation is that the beam extends infinitely along the beam axis at constant radius.

The radial electric field is then found by approximating the integral on a grid for each ion ray of charge q by the summation of all the rays that have a radius less than r, i.e.

$$E_r(r)=\frac{1}{2\pi\varepsilon_0 r}\sum_{i,q}\frac{I(i,q)}{v_q}$$

where I is the current in the ith ray with velocity v_q. The solenoid focusing term is given by the paraxial approximation [2]

$$\frac{dr'}{ds}=r\left(\frac{Bq}{2mv_q}\right)^2$$

where s is the distance along the beam axis, m is the ion mass and B is the axial magnetic field (which can be a function of s).

The model is run with the ion charge-state distribution on the LIS giving a total current of 60 mA. No space-charge compensation is considered, as the LIS beam is too short to allow compensation by ionisation of the residual gas. The ion energy is 60 keV per charge and the input beam is 15 mm in radius with no initial divergence, giving a zero emittance beam. The particles are evenly distributed in the radial direction. The current density is uniformly distributed.

In Figure 1 the beam is shown transported through an initial drift of 130 mm, a solenoid (for which a field table exists over a total length of 600 mm) and a final 135 mm drift. The distances were chosen for approximate comparison with experimental data.

In plot a) the trajectories of different charge-states (from 6+ to 24+) are shown for those rays starting at half the full beam radius, and the beam outer ray. The highest charge-states are bent though the highest angle and reach a beam waist first. The highest charge-states cross the r=0 axis, whereas the lower charge-states are repelled by the strong space-charge field of the beam and pass through a space-charge dominated beam waist. When all of the rays of Ta^{20+} are considered (plot b) it can be seen that the inner rays are divergent, whereas the outer rays are convergent. This is confirmed in the phase-space diagram (plot c) where very large aberrations of the beam are seen for Ta^{20+}, while Ta^{24+} has been distorted near the beam centre but otherwise has retained the initial emittance.

It can be shown that the highly aberrated beam is due only to the space-charge coupling of many charge-states, by simulating a 60 mA beam with only a single charge-state (Ta^{20+}) as shown in Figure 2. The plot of the ion rays show that no ray crossing occurs and the phase space demonstrates a low degree of aberration. A small hole still exists near the axis, but is smaller than that observed with the multiple charge-state beam. In this case decreasing the mesh size (from 0.5 mm to 0.2 mm) reduces the size of this hole. This is not the case when the resolution is increased for the simulation of the multiple charge-state beam, in which case the aberrations are still clearly present and therefore cannot be attributed to numerical errors.

In a system of electrostatic fields, a multiple charge-state ion beam has the same dynamics as a beam consisting of one charge-state. Hence an electrostatic focusing system should not show the aberration effect due to the non-linear space-charge electric field from the separation of the charge-states in a magnetic focusing system.

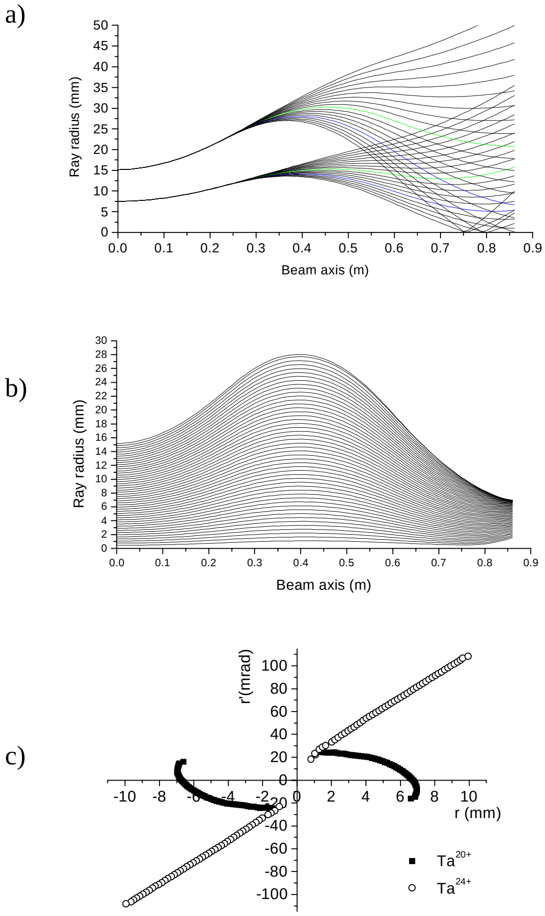

Figure 1. Model of a multiple charge-state, 60 mA ion beam (60 keV/charge), transported through a solenoid. a) Mid radius ray and outer ray trajectory for all charge-states (6+ to 24+); b) rays of 20+ beam; c) Phase diagram at output of 20+ and 24+ ions.

III. 3D RAY TRACING MODEL

For full simulation of the ion optics in 3D, the commercial code KOBRA3 [3] is used which solves the ray trajectories, in a self consistent manner with the Poisson and Lorentz equation, in a 3D geometry which can include magnetic fields. The requirement of many iterations of the ray trajectories and the large number of rays, means that each simulation requires hours on a Pentium computer, instead of one minute for the 2D model case.

The common problem of the solution of equations that diverge near the axis of a cylindrically symmetric model, are avoided in the 3D case. Therefore it is very useful to use such a model to verify the beam non-linearities that are seen near the axis.

An identical set of input parameters were set for KOBRA3 for comparison with the 2D model with the exception that the solenoid was input as a full 3D B-field map from the program POISSON. In this case spherical aberrations from the solenoid can arise. The initial distribution of the rays are randomly distributed to give a uniform current density.

A phase-space output in *r-r'* for the multiple charge-state simulation is shown in Figure 3a. The form of the Ta^{20+} phase-space is consistent with that shown at the output of the 2D model, still with a characteristic hole in the centre of the distribution. The Ta^{24+} signal shows a S-shape whose origin is not clear.

The simulation of a single charge-state beam shows that no aberrations in the beam are present, however the phase-space shown in Figure 3b has acquired a large emittance compared to the zero emittance beam used at the input.

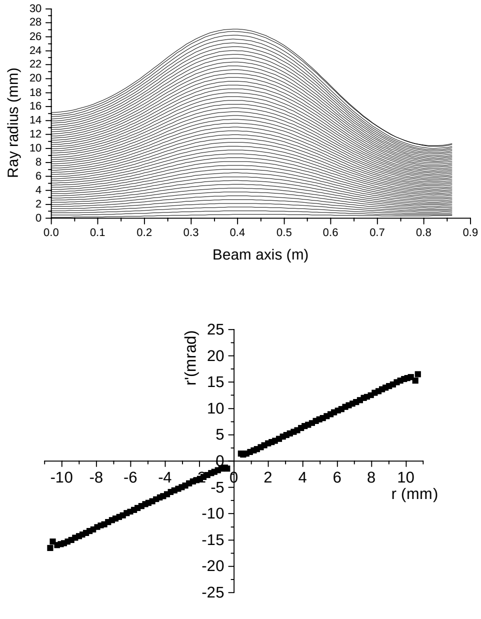

Figure 2. Model of a single charge-state (Ta^{20+}), 60 mA ion beam (60 keV/charge), transported through a solenoid. a) Rays of 20+ beam; b) phase space diagram at output.

III. EXPERIMENTAL OBSERVATIONS

The LIS at CERN has used both two solenoids and a Gridded Electrostatic Line (GEL) [4], shown in Figure 4a, to try to focus the high current, multiple charge-state beam into the RFQ. Additionally a one solenoid line was also investigated but has so far not been coupled to the accelerator.

Each line is characterised by the maximum transmitted current into a 6.5 mm aperture Faraday cup. A comparison of the three different configurations is shown in Table I, where it can be seen that the highest transmission is available for the GEL, which is confirmed qualitatively by simulations presented so far.

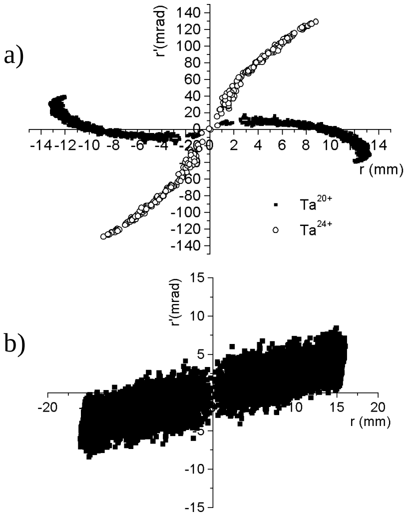

Figure 3. Phase space output in the *r*-*r*' plane from the simulation code KOBRA3. a) For a multiple charge-state beam, b) where only Ta^{20+} is transported.

The appearance of a hollow beam centre predicted by simulation has been seen experimentally after the beam waist produced by the focusing action of a solenoid The experimental scheme is shown in Figure 4b. A 3D surface intensity plot in Figure 5 shows the observed beam intensity distribution measured at the CERN Laser Ion Source.In conclusion it has been demonstrated by simulation and observed in experiment that an important aberration of the beam quality can occur due to the non-linear space charge electric field that develops in a beam due to the different focusing strengths of a magnetic lens on the different charge-states in a beam. This aberration does not occur in beam comprising only a single charge-state or when electrostatic focusing is used.

Table I. Comparison of the transmitted current from the LIS to a small aperture Faraday cup, for three different focusing line configurations. Source output was 60-70 mA with 7-8 mA of Ta^{20+}.

	2 sol [5]	1 sol [5]	GEL [4]
Total current (mA)	10	17	33
Ta^{20+} current (mA)	2	3.3	4
Transmission of Ta^{20+}	26%	42%	51%

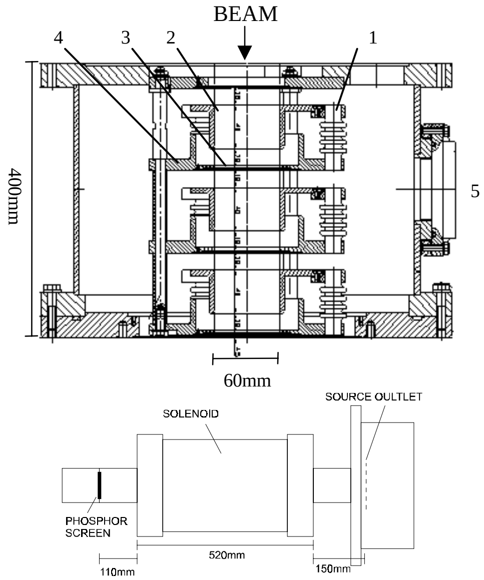

Figure 4. a) Drawing of the Gridded Electrostatic Line (GEL). 1- Ceramic isolator, 2- High Voltage electrode, 3- Grid, 4- Ground electrode, 5- HV feedthough mounting port. b) Scheme of the single solenoid line with positions of the source, solenoid and phosphor screen measurement plane. The solenoid coil diameter is 120 mm, the vacuum chamber diameter is 95 mm and the maximum on-axis field is 1.4 T.

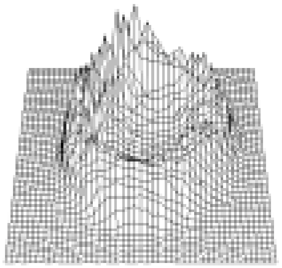

Figure 4. Surface plot of the ion beam intensity in the transverse plane, measured on the CERN Laser Ion Source after strongly focusing the beam with a solenoid. Plotted area is 65x65 mm^2.

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