NON-LINEAR BEAM TRANSPORT EFFECTS IN HIGHLY CHARGED POSITIVE ION BEAMS EXTRACTED FROM ECR ION SOURCES

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ABSTRACT

Using ECR ion sources, heavy ions with charge as high as 39+ have been injected directly into cyclotrons at intensities of a few hundred nanoampheres, as well as nearly fully-stripped light ions at intensities of a few hundred microampheres for cyclotron or synchrotron injection. These are not ion beam intensities normally considered to be space charge dominated. However, experimentally it is observed that both extremes– highly charged ions at low intensities and low charge ions at high intensities, exhibit sharp non-linear emittance growth in beam transport systems. In extreme cases, the overall beam transmission has actually been observed to decrease sharply with increasing beam intensity[1]. A correct interpretation of this emittance growth, as being a direct consequence of a non-linear growth in the beam envelope due to space charge forces, will be demonstrated using theory, simulations and experimental measurements. For proper matching of ECR ion source beams to accelerators, an aberration-free maximum beam intensity must be built into the beam transport system.

1. RTECR EMITTANCE MEASUREMENTS

Emittance measurements on the RTECR at NSCL can be made in either transverse coordinate before or after the analysis magnet. We have made 2D 'pepper pot' emittance measurements at each location, but we find a 'wire scanner' measurement at a single M/Q, after analysis in the dispersion plane of the dipole, to be most useful. Such an emittance measurement for Argon 10+ ions is shown in Fig. 1. This measurement shows an emittance with a central core and a high divergence tail. Similar measurements have been made on other ECR ion sources[2,3] . The 90% emittance is $245 mm \cdot mrad$, but there is an equal emittance in the 10% intensity tail. The 90% and 100% intensity emittances for Argon 2+ through 10+ ions are shown in Fig. 2. The emittance increases with Q, while the intensity decreases with Q. In each case, fully 1/2 of the emittance is in the 10% intensity tail. (To make such large emittance measurements, the analysis slits have been fully opened.)

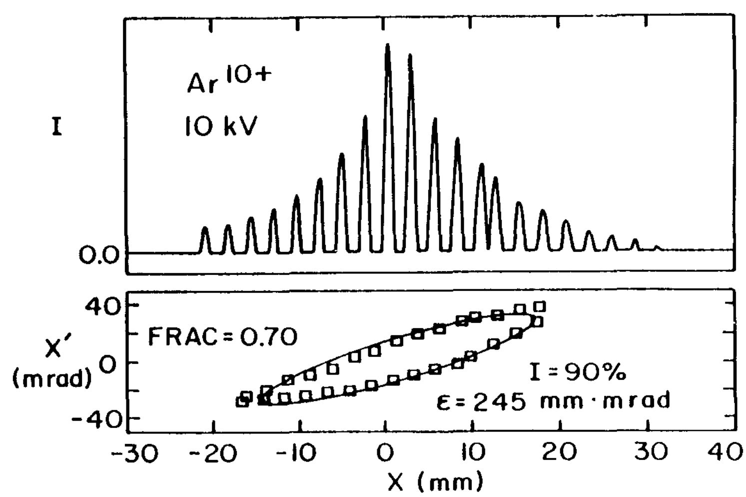

Fig. 1. The emittance of Argon 10+ ions. The 90% current level includes only about one half of the total emittance.

2. THEORETICAL ANALYSIS

Heretofore, ECR ion source beam emittance measurements like those in Fig. 2. have resisted explanation. The first question then is, how large should the emittance from an ECR ion source be?

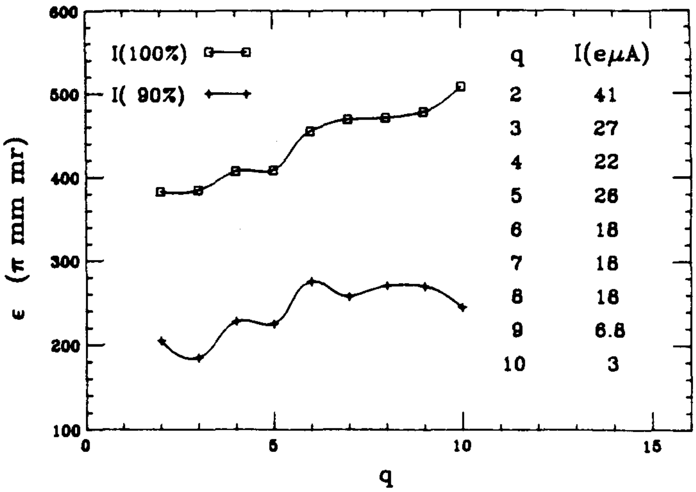

Fig. 2. Both 90% and 100% current level emittances are shown for Argon 2+ through 10+ ions extracted from the RTECR ion source.

In ECR sources, ions are extracted from the approximate maximum of the exit magnetic mirror, in a circular aperture of radius a. ECR ion sources have 3D minimum B magnetic structures[4], and in the RTECR, this is obtained through the superposition of a 30cm bore $SmCo_5$ hexapole with a warm bore tandem magnetic mirror[5]. Since a=0.8cm for the RTECR, $\vec{A} = A_\phi(r,z)\hat{\phi}$ is valid within the radius of the extraction aperture, the hexapole notwithstanding.

To estimate the emittance analytically, one assumes that the electrostatic potential has azimuthal symmetry, including both the extraction fields and the beam space charge, and that in the LEBT, the positive dc beam intensity neutralizes. One can show that the maximum emittance is determined by ions starting at the maximum starting radius r=a. Further, taking $K_Q \ll QV_{ex}$, and introducing a thermodynamic temperature T_Q, we may write the transverse emittance as

$$\epsilon = \epsilon_{xx'} = \epsilon_{yy'} = a[(\frac{T_Q}{2QV_{ex}})^{1/2} + A_\phi(a,o)\left(\frac{Q}{2MV_{ex}}\right)^{1/2}] \quad (1)$$

There are two limiting cases:

Hot Ions $$\epsilon \simeq a\left(\frac{T_\phi}{2QV_{ex}}\right)^{1/2} \quad (2)$$

Cold Ions $$\epsilon \simeq a^2QB_z(a,o)\left(\frac{Q}{2MV_{ex}}\right)^{1/2} \quad (3)$$

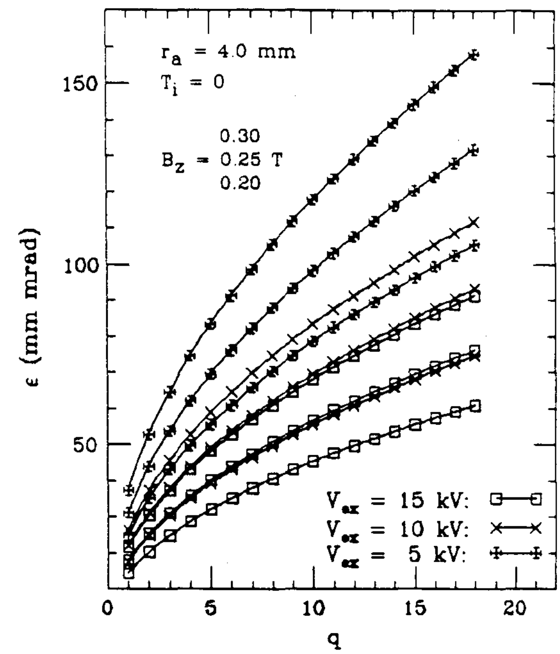

Fig. 3. Theoretical emittances of argon ions extracted from the RTECR, in the cold ion limit, for various extraction voltages and magnetic fields.

The measured thermal energy of ions extracted from the RTECR is about $6eV \times Q$ [6], and hence high ion energies are not sufficient to explain the large measured emittances, so we cannot take the hot ion limit of Eq. 2.

Figure 3 shows the magnetic field and extraction voltage dependence of argon ion beam emittance for $T_i = 0$, the limit of Eq. 3. At 10 kV, and $B_z(a,o) = 0.25T$, the predicted emittance is$70mm \cdot mrad$ for Ar^{10+}. The experimental numbers (from Fig. 2) are, in comparison $245mm \cdot mrad$ for the core, and $500mm \cdot mrad$ when including the tail, about seven times larger!

3. EXTRACTION SIMULATIONS

The acceptance of the RTECR beam transport system is $200mm \cdot mrad$ in both transverse planes [7], but the measured emittances exceed this design acceptance. Therefore, aberrations may be causing an emittance growth —but what is driving the aberrations?

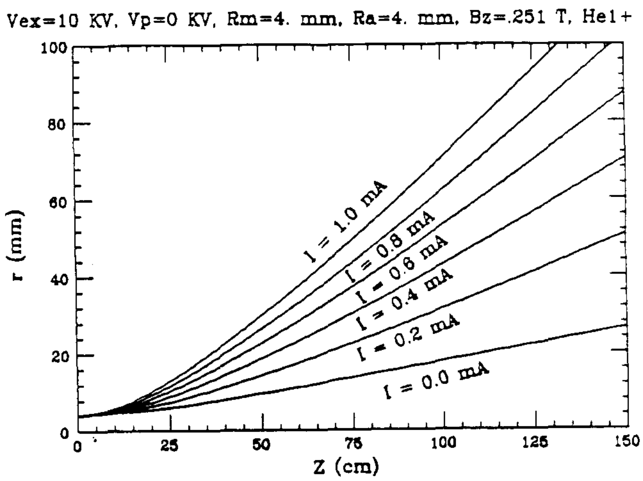

Fig. 4. As the maximum divergence increases with drift distance z, the beam envelope radius must increase with z^2. This is a significant effect, even for short drift distances, for high space charge beams.

Beam simulations with BEAM3D [8] do explain the measured emittances if we assume that there is zero neutralization of the extracted beam, as we will demonstrate. It is useful first to review how this is possible. When we view the dc beam as an ensemble of ions, then the total radial space charge force is a summation over all particles. It can be shown that the transverse divergence $\alpha_\perp$ for an ion on the edge of a drifting azimuthally symmetric beam is

$$\alpha_\perp = \left[\frac{P_\phi^2}{M^2 v_z^2 r_M^2} + \frac{Q}{\pi M \epsilon_o v_z^2} \ln\left(\frac{r}{r_m}\right) \sum \left(\frac{I_i}{v_{zi}}\right)\right]^{1/2} \quad (4)$$

Eq. 4 shows that the beam surface will have a constant maximum transverse divergence if the space charge force is zero, that is $\sum(I_i/v_{zi}) = 0$. This is of course the normal assumption in the LEBT design for ECR sources. However, with space charge, the maximum beam divergence has a strong dependence on the beam intensity. To determine the beam radius dependence on drift distance, we integrate Eq. 4 once with respect to r, and find that

$$\int_{r_m}^{r} \left[\frac{P_\phi^2}{M^2}\left(\frac{1}{r_m^2} - \frac{1}{r^2}\right) + \frac{Q}{\pi M \epsilon_o} \ln\left(\frac{I_i}{v_{zi}}\right)\right]^{-1/2} dr = t \quad (5)$$

There exists no analytical solution for the left side of Eq. 5, but numerical integration techniques can be used to estimate the integral. Let $r = r_m + x$ and assume that x is small (i.e., a short drift distance). We have, after performing the integration

$$r - r_m = \frac{1}{4}\left[\frac{2P_\phi^2}{M^2 r_m^3} + \frac{Q}{\pi M \epsilon_o r_m} \sum\left(\frac{I_i}{v_{zi}}\right)\right] \frac{z^2}{v_z^2} \quad (6)$$

Figure 4 shows the growth of a He^+ ion beam envelope for various intensities. In a 1 meter drift, there is a 4-fold increase in beam radius for a 1 emA He^+ beam over a beam with zero net space charge. The consequence of this non-linear radial space charge induced growth is that the beam expands faster than would be the case assuming a constant maximum divergence.

4. SPACE CHARGE AND HELIUM 1+ TRANSIT OF THE FIRST FOCUSSING SOLENOID

To study the radial space charge question, we simulated the beam formation process in the RTECR with BEAM3D, through the transit of the first focussing solenoid, up to the entrance of the analysis dipole. To study the extraction from the RTECR, we use He^+ beams of various intensities.

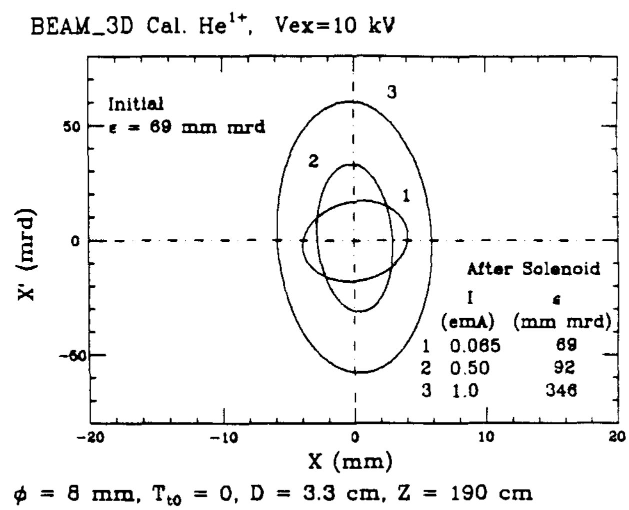

Fig. 5. The effective emittance of He^{1+} after crossing the focussing solenoid for various beam intensities. In each case, the extraction is space charge limited, the beam energy is of 10keV, and the emittance after extraction is $69mm \cdot mrad$.

We have found that it is possible to tune this ion source to produce He^+ beams over a wide range of intensities (0.01–1.5 emA), without producing significant He^{2+} intensities, which would complicate the analysis. Helium is the only species for which it is possible to produce an approximately mono-charged total extracted current in the RTECR.

Figure 5 shows the BEAM3D estimate of emittance growth due to space charge for He^{+} beams when crossing the focussing solenoid. This emittance growth is the result of spherical aberration due to the space charge growth of the beam envelope before entering the solenoid. As is seen, no emittance growth is observed at $65e\mu A$ intensity, while at 1emA, the emittance growth is nearly 6-fold. Hence, theoretically, the radial space charge force could cause a large emittance growth due to aberrations in the transit of the focussing solenoid, but does that happen?

A

B

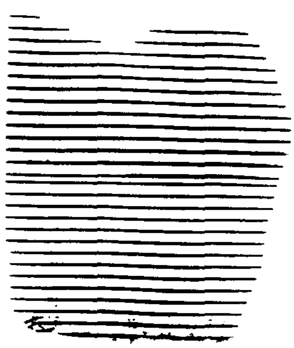

Fig. 6. A and B are Kapton foil burns after the RTECR focussing solenoid with He^{+} beams of 65 and 550 $e\mu A$ respectively.

Figure 6 shows actual kapton foil burns for $65e\mu A$ and $550e\mu A$ He^{+} beams after transit of the solenoid. The $65e\mu A$ He^{+} shows a round image of the RTECR extraction aperture, while the $550e\mu A$ beam completely fills the $10cm \times 10cm$ kapton foil, in good agreement with the prediction of Fig. 7. Further, the emittance of the $65e\mu A$ He^{+} beam of Fig. 6 can be extracted, and is measured to be is $69mm \cdot mrad$, in exact agreement with the calculated starting emittance of Fig. 5. Such an emittance corresponds to the cold ion limit given in Eq. 3. The emittance of the $550e\mu A$ beam cannot be obtained from Fig. 6, since the left boundary of the beam cannot be determined, but is greater than $250mm \cdot mrad$.

5. SUMMARY AND CONCLUSIONS

The main point here is that dc beams extracted from ECR ion sources, like the RTECR, do not neutralize. Then the beam envelope growth will depend quadratically on the product of the drift distance z and the total intensity in the LEBT: $\Delta r \propto I\Delta z^2$. All LEBT designs for ECR ion sources assumed $\Delta r \propto \alpha\Delta z$, where α is the starting transverse divergence. Hence all focussing magnets are too far 'downstream'. The beam envelopes are then larger than anticipated, filling magnet apertures, exciting aberrations, and diluting the phase space and LEBT transmission. To correct this effect, proper LEBT requires 'designing in' the desired maximum beam current to be transported, which essentially means increasing the focussing.

This paper began with a measurement of Ar^{10+} emittance that had a central core and a high divergence tail. We can now say that the starting emittance is dominated by the fact that the ions are extracted from a magnetic field. However, the measured emittance (after analysis) is dominated by second order aberrations during the transverse of the analysis dipole—again due to space charge blow up of the beam, as we will demonstrate in a future paper.

6. REFERENCES

1) Baron, E., Cyclotron '86, Tokyo, Ionics., (1986) p. 234.
2) Clark, D., Int. Conf. ECR ion sources, (MSU, East Lansing, Michigan, 1987), p. 433.
3) Hagedoorn, H., Int. Conf. ECR Ion Sources, (MSU East Lansing, Michigan, 1987), p. 389.
4) Geller, R., 8th Int. Conf. on Cyclotrons, (Bloomington Indiana, 1978), p. 2120.
5) Antaya, T., 7th Workshop on ECR Ion Sources, (Julich Germany, 1986), p. 72.
6) Antaya, T., Proc. Int. Conf. ECRs, (Grenoble, France, 1988), p. 707.
7) Harwood, L.H., Cyclotron '86, Tokyo, Ionics., (1986) p. 488.
8) Xie, Z.Q., MSUCP-60, (1989).