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TRANSPORT EXPERIMENTS WITH NEUTRALIZED AND SPACE CHARGE DOMINATED DENEUTRALIZED 2 mA 80 keV Xe^{+1} BEAMS*

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Abstract

The Argonne National Laboratory Ion Beam Fusion group is presently studying the transport and charge neutralization of beams of heavy ions using a small PDPE (Penning Discharge Pierce Extraction) ion source. This source is a scaled down version of the high current high brightness source of the 1.5 MeV Heavy Ion Preaccelerator.[1] Both sources were developed by Hughes Research Laboratories.

This report gives results obtained with a low vacuum system (up to 5×10^{-7} torr static vacuum) and an 80 keV dc Xe^{+1} beam. The emphasis of these measurements was on neutralization times and space charge blow up of the beam.

Experimental Setup

The system used for the reported measurements consisted mainly of aluminum parts and was put together from existing vacuum components. Fig. 1 outlines the experimental setup, giving critical dimensions. The source injects into the beam line consisting of two diagnostic boxes separated by a 3 m long 7.5 cm diam vacuum pipe. A symmetric magnetic quadrupole triplet focusses the beam 4.3 m downstream of the source. A 1 cm titanium aperture is positioned inside the first box 43 cm from the beam waist. The intensity of the beam is measured at the end of the first box using a Faraday cup. This cup can be removed from the beam path, without breaking the vacuum, so that the ion beam can continue through the beam pipe and downstream to the second box. The Faraday cup of the second box is also removable and is located 4.3 m from the ion source aperture. The transmitted beam cross section can be observed and measured on the Pyrex glass plate at the end of the second diagnostic box. Fig. 2 is an end-on shot of the beam taken from this glass end plate. Both diagnostic boxes have large glass covered side ports parallel to the beam path enabling visual observation of the beam size all along its passage through the boxes.

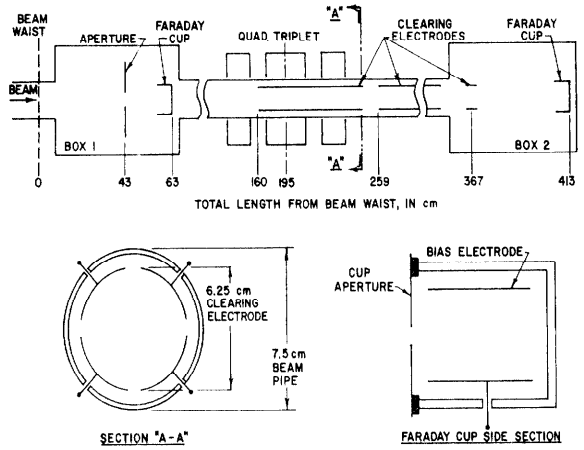

Fig. 1: Experimental setup, clearing electrode and cup details

Two sets of electron clearing electrodes are placed along the beam path inside the vacuum pipe. One set is 91.5 cm long and it is located inside the quadrupole triplet while the downstream one is 85 cm long and ends near the entrance of the second box. A third very short clearing electrode is positioned inside the second box. Each one of the long clearing electrode sets consists of four cylindrical segments insulated from each other and from the vacuum walls. These structures are coaxially located inside the beam pipe and have a 6.3 cm inner diam. A clearing potential can be applied to each one of the clearing electrode plates through separate vacuum feed-throughs. The short clearing electrode is a 2.5 cm long pipe of 5 cm inner diam.

The Faraday cup of the second vacuum box has a stainless steel aperture at its entrance (Fig. 1) electrically insulated from the cup body and from the biasing inner cylinder, and has a 1.3 cm diam circular opening. The inner cylindrical electrode is at -210 V and serves to suppress the secondary electron emission from the collecting surface of the cup.

Experimental Results

A. Transmission

At first a systematic study of the source parameters and their influence on current, beam emittance and transmission was undertaken. Under normal operating conditions a normalized emittance of 0.0015 mrad cm was measured. A 2 mA transmitted beam to the second box Faraday cup was obtained while the current in the first box was 2.2 mA.[2]

B. Neutralization Studies

These experiments were performed with beam currents of the order of 1 mA in order to reduce the excessive beam spattering of the Faraday cup and metal deposition on the insulated feedthroughs. Still after a few weeks of operation at that level, a 3 mm hole was drilled through the 0.7 cm thick steel bottom of the water cooled cup (Fig. 3).

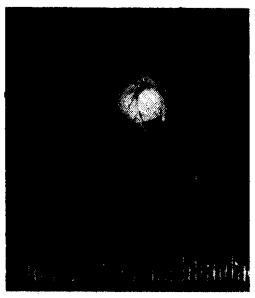

Fig. 2: Beam impacting on the end glass port of second box

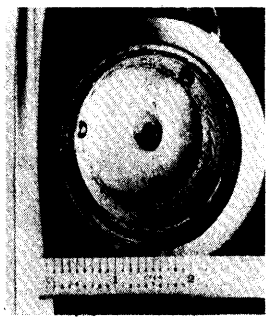

Fig. 3: Faraday cup, aperture removed to show beam caused erosion

The quadrupole triplet was set to the calculated current values to give best focussing on the second cup. This setting was optimized visually to obtain the smallest possible spot size (smaller than 3 mm in diam) on the cup aperture. At the same time the beam emerging from the beam pipe and entering the second box became parallel and remained less than 3 mm in diam all along its trajectory throughout the box.

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a. Deneutralization with dc clearing potential

DC positive potentials were applied on each of the clearing electrode sets and the beam was observed to blow up and illuminate part of the aperture of the second box Faraday cup, while the current on the cup decreased. This current is due to the part of the beam which passes through the 1.3 cm opening of the aperture. For small values of clearing bias (up to +70 V), the shape of the deneutralized beam cross section was almost circular (the circumference was slightly modified to a circular star shape reminiscent of a third order geometric aberration) and independent of the clearing field configuration. For higher clearing voltages the shape of the beam was affected by the clearing field pattern; that is, how the four segments of the clearing electrodes are biased and connected together.

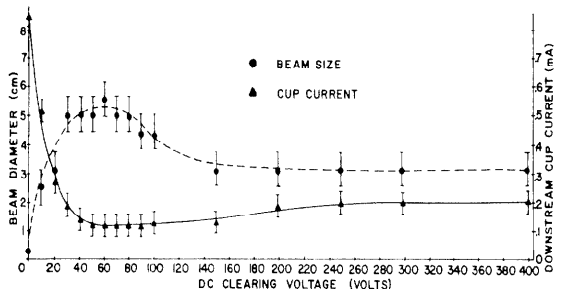

Fig. 4: Measured beam size and current for different values of clearing potential.

A +6 V bias was enough to blow up the beam to a size barely grazing the 1.3 cm opening of the cup aperture. Fig. 4 gives the results of a study of the beam size on the aperture as a function of the clearing voltage on the short electrode. The aperture used for these measurements had 2 scales etched on its surface and along 2 diam to facilitate beam size estimation. Simultaneously the current on the Faraday cup was registered and it is also shown in Fig. 4. A potential of +60 V was enough to blow up the beam to its maximum size or equivalently to minimize the current of the part of the beam filling the 1.3 cm opening of the aperture. Further increase of the clearing bias up to +200 V gradually reduced the beam size. For potentials higher than 200 V and as high as 400 V the size remained unchanged. Negative biases on the short electrode had no apparent effect on the beam, that is the beam continued to be well focussed and 3 mm in diam.

b. Pulsed clearing potential

A pulsed positive voltage was applied on the short clearing electrode. Fig. 5 shows a typical beam response for a 200 V pulse. The apparent "deneutralization" time or beam decrease time is of the order of 5 μs while the observed neutralization time is relatively much longer. There is about a 3 μs delay between the pulse start and the moment at which the current on the cup starts to decrease. This delay is not a strong function of the pulse height and is fairly independent of the pulse width (Figs. 6 and 7).

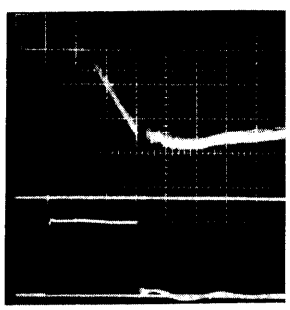

Fig. 5: Typical beam response to a +200 V, 6 μs pulse. From top to bottom: 1st trace-beam current 0.2 mA/Div., 2nd trace-base line for the beam current, 3rd trace-clearing pulse 100 V/Div., 4th trace-base line for the clearing pulse.

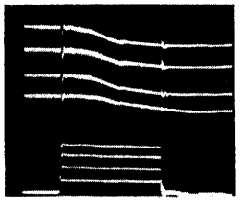

Fig. 6: Multiple exposure. Four beam traces for four clearing pulses of different amplitudes. Top beam trace (1 mA/div.) corresponds to top pulse trace (100 V/div.), etc. Current base line shifted from trace to trace for clarity. Time base 2 μs/div.

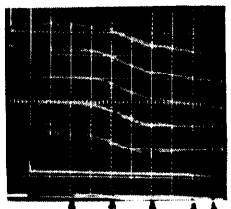

Fig. 7: Multiple exposure. Five beam traces for 5 clearing pulses of different width. Top beam trace (0.5 mA/div.) corresponds to the largest pulse width (9 μs, 1 μs/div.). Pulse height 100 V (100 V/div.). End of pulse indicated by arrows.

Figs. 8 and 9 are photographs taken with a longer time base on the scope (100 μs/div.) and for two different vacuum conditions (nominal pressure on the gauge of the second box 7.6×10^{-6} torr and 5.5×10^{-5} torr respectively). The neutralization time is of the order of 200 μs for the 7.6×10^{-6} torr nominal vacuum while it falls to 40 μs for the higher pressure (5.5×10^{-5} torr). These measurements were repeated with various field patterns of the other clearing electrodes. The neutralization time was found to be independent of the clearing electrode used, the clearing field configuration, the clearing pulse amplitude (above ∿ + 70 V) and pulse duration (above 0.25 μs). The neutralization time was also found to be independent of the beam current as shown in Fig. 10. Figs. 8 through 10 strongly suggest that the beam is slowly self neutralizing with electron producing beam-residual gas interactions. The vacuum walls do not participate in the beam neutralizing electron production since the beam is very well focussed and far away from it.

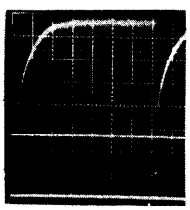

Fig. 8: Beam current ∿ 1 mA (0.2 mA/div.). Pulse width 6 μs height 100 V. Higher vacuum.

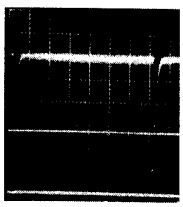

Fig. 9: Lower vacuum same scales and pulse as Fig. 8.

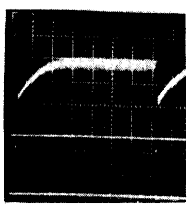

Fig. 10: Same vacuum as Fig. 8 but with smaller beam current scales the same.

Discussion of the Results

A. Beam potential well

The dc clearing deneutralization results indicate that the blown up beam reaches its maximum size for 60 V clearing potential. This suggests that the beam potential well should be of the same order of magnitude. The static calculation of the beam potential well gives 135 V at the beam envelope and 160 V at the axis.

B. Current distribution of the deneutralized beam

Assuming a uniform charge distribution of the blown up beam, one should expect a decrease of the cup current by a factor equal to the surface ratio of the

1.3 cm hole to the blown up beam size. The measured current ratio on the Faraday cup with the clearing bias of +60 V on and off was 0.14 while the surface ratio was 0.06. This suggests that the observed blown up beam does not have a uniform current distribution in its maximum size. For biases higher than + 200 the beam becomes uniform since the two ratios agree very well. (Fig. 4.)

C. Background gas ionization as the main source of beam neutralizing electrons

One of the most interesting results reported here is the direct dependence of neutralization on the residual gas pressure. Assuming that the background gas is practically all xenon (detailed test of vacuum variation with different pumping speeds and xenon flow rates have confirmed this assumption. Also, the observed dark blue light of the beam path is the characteristic color of xenon excitation) and assuming that all the electrons produced are trapped by the beam and that the "shrinking" beam is almost fully neutralized when it reaches the same size as the cup aperture hole (1.3 cm diam.), one can calculate the electron production cross section σ from the observed neutralization time t using the expression $\sigma = (t.v.\bar{\eta}_o)^{-1}$, where v is the velocity of beam ions and $\bar{\eta}_o$ is the average number density of the residual gas. The apparatus limited us to perform the neutralization time measurements only for 2 nominal pressures in the second box, 7.6×10^{-6} torr and 5×10^{-5} torr, while the first box pressure was respectively 6.8×10^{-6} torr and 8.4×10^{-6} torr (Figs. 8 and 9). The nominal vacuum values indicated by the vacuum gauges were corrected to account for the fact that the background gas was xenon and not nitrogen (correction factor 1/2.8). The estimated cross sections from the measured neutralization times for the 2 vacuum conditions are $\sigma = 16 \times 10^{-16}$ cm^2, higher vacuum and $\sigma = 18 \times 10^{-16}$ cm^2, lower vacuum. Given the simplicity of the setup this agreement is quite remarkable. For a given spot size and magnet strength, if beam neutralization is needed and if one relies solely on background gas ionization, this experiment indicates that it cannot be attained in < 200 μs for higher than ∿ 1×10^{-6} torr vacuum.

The measured neutralization cross section should be equal to the total ionization cross section which is the sum of the cross section of the following processes:

$$\bar{X}e^{1+} + Xe^{o} \rightarrow \bar{X}e^{n+} + Xe^{m+} + (m + n - 1)e$$

To our knowledge there are not as yet any reported measurements of this cross section, nor any theoretical calculations. Most recently H. G. Berry[3] and his group measured the following cross section:

$$\left.\begin{aligned} \bar{X}e^{+} + Xe^{o} &\rightarrow \bar{X}e^{+} + Xe^{+} + e, \ \sigma_{11}^{a} \\ &\rightarrow \bar{X}e^{+} + Xe^{o}, \ \sigma_{11}^{b} \end{aligned}\right\} \sigma_{11}(> 1^{o})$$

$$\rightarrow \bar{X}e^{o} + Xe^{+}, \ \sigma_{10}$$

$$\rightarrow \bar{X}e^{2+} + Xe^{o} + e, \ \sigma_{12}$$

The σ_{12} was found to be 1.3×10^{-16} cm^2; the σ_{11} was measured only for angles larger than 1^o and found to be 0.36×10^{-16} cm^2, while the charge exchange cross section (σ_{10}) was 20×10^{-16} cm^2. All these values are for incident 80 keV single ionized xenon ($\bar{X}e^{+}$) on stationary neutrals (Xe^{o}). From theoretical considerations the σ_{11}^{a} cross section is expected to peak strongly forward and the contribution from scattering into a smaller than 1^o could be 50-100 times greater; that is, of the order of magnitude of σ_{10}. This is indeed the case with the σ_{10} cross section. One then could say with reasonable certainty that the cross section obtained by our measurements (σ ∿ 17×10^{-16} cm^2) is a good candidate for the total ionization cross section.

D. Estimation of charge exchange cross section

If we assume that all the beam losses between box-one and box-two are due to beam-gas interactions then the transmission ratio is given by the expression

$$\frac{I_1 - I_2}{I_1} = \bar{\eta}_o \, \ell \, \sigma_{10},$$

where I_2 and I_1 are the currents read on the second and first cup respectively, $\bar{\eta}_o$ is the average residual gas number density along the beam path ℓ between the two cups, and σ_{10} is the specific interaction cross section.

The transmission between the first box and the second box measured for vacuum conditions similar to those of Fig. 8 was 90%. This transmission ratio gives a $\sigma_{10} = 32 \times 10^{-16}$ cm^2 while the transmission ratio estimated from Fig. 9 gives $\sigma_{10} = 29 \times 10^{-16}$ cm^2.

These values are in a very good agreement with the charge exchange cross section measured in reference 3. Hence the observed Xe^{+} beam losses from the first Faraday cup to the second are consistent with the Xe^{+} - Xe^{o} charge exchange cross section. This agreement further strengthens the conclusion that the beam neutralizes itself with a similar atomic process, that is "beam residual gas ionization".

E. Spatial extent of beam deneutralization

The delay time between the start of the clearing pulse and the current decrease is ∿ 3 μs. The distance between the short clearing electrode and the second Faraday cup aperture is 40 cm or equivalently 1.2 μs beam transit time. If we assume that the electron removal time (real deneutralization time) is very small (much smaller than 1 μs), then the observed delay time of 3 μs should be equal to the time it takes the deneutralized beam to increase its envelope to 1.3 cm in diam (size of aperture hole). One then could conclude that the beam is being deneutralized for a total length of ∿ 100 cm upstream of the second Faraday cup, or 60 cm upstream of the clearing electrode. The observed "deneutralization" times or beam decrease time of ∿ 5 μs indicates that the beam is being deneutralized even further upstream and for up to ∿ 3 m from the Faraday cup.

References

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