SPACE CHARGE NEUTRALIZATION STUDIES OF AN H^- BEAM

R. Baartman and D. Yuan
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Abstract

We have used a 1 mA cw H^- beam from the TRIUMF cusp source to study space charge neutralization at 12 keV as a function of the pressure of the background H_2 gas. At 10^{-6} Torr the neutralization level was found to be 96% with a time constant of 80 μs. At 10^{-4} Torr there is possibly slight overcompensation (100.7%±0.4%) and the time constant was found to be 4 μs. We discuss these results and explain them qualitatively.

Introduction

Space charge neutralization occurs when particles of charge opposite to the beam charge are captured by the beam's potential well. The positive neutralizing ions (for a negative beam) are created by collision of the beam particles with the background gas particles. Neutralization builds up to an equilibrium level f (= ratio of neutralizing charge density to beam charge density) in a characteristic time τ which depends upon ionization cross section. We have measured τ and f as a function of H_2 gas pressure for a 12 keV H^- beam.

τ–Measurement

The arrangement shown in Fig. 1 was used to measure the space charge neutralization time constant. Pulses (300 V at 1 kHz) were applied to deflection plates. At the instant the deflecting voltage falls to zero (fall time < 1 μs), the beam comes back on axis but is unneutralized. Because the space charge forces blow up the beam, a large fraction of the beam is intercepted by the aperture. As neutralization builds up, beam divergence decreases and the aperture current falls.

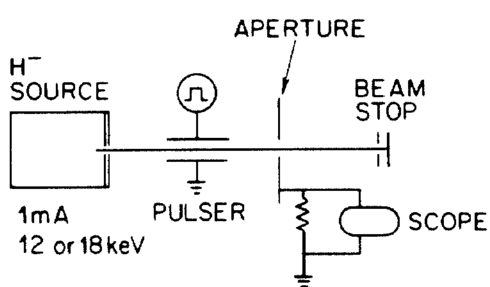

Fig. 1. Apparatus used to measure space charge neutralization time constant.

Figure 2 shows a typical scope trace. Experimental results for the fall time of the aperture current are shown in Fig. 3. Data were taken for beam energies of 12 keV and 18 keV.

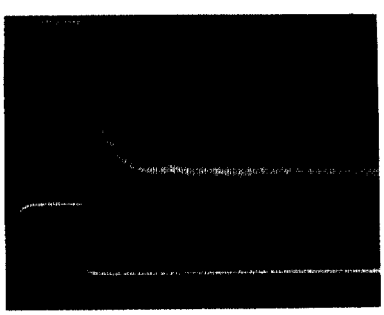

Fig. 2. Scope trace obtained from the apparatus in Fig. 1. The upper trace is the aperture current, the lower trace is the pulser voltage. The horizontal scale is 50 μs/div. This particular photograph is for a pressure of 1.2×10^{-5} Torr.

One can show that the neutralization time constant should be given roughly by

$$\tau = (\sigma_i n v)^{-1} , \qquad (1)$$

where v is the beam velocity, n is the background gas density and σ_i is the cross section for a beam particle to ionize a background gas particle. (1) can be understood as being simply the mean free time between ionizing collisions. Since we expect $\tau \propto 1/v$, the 18 keV data of Fig. 3 have been scaled to the 12 keV data by multiplying τ by $\sqrt{18/12}$.

Equation (1) is also plotted in Fig. 3 with σ_i fitted to give agreement in the 10^{-4} to 10^{-5} Torr range. The cross section obtained in this way is $(5\pm2) \times 10^{-16}$ cm^2. This is higher than the value of 1×10^{16} cm^2 quoted in the literature.[1] However, a considerable systematic error is probably incurred by assuming the background gas pressure on axis to be the same as that at the vacuum chamber walls where the ion gauge was located. Also, τ appears to be significantly smaller than predicted by (1) for pressures below $\sim 4 \times 10^{-6}$ Torr. This is probably due to the presence of other species of molecules in the background gas. N_2, for example, has a 5 times larger ionization cross section than H_2. Nevertheless, the data of Fig. 3 are consistent with the data point – $\tau \approx 70$ μs at $P = 5 \times 10^{-6}$ Torr, $E = 18$ keV – which we extracted from results given in Ref. 2.

f–Measurement

Two emittance-measuring devices (see Fig. 4) were used to determine the emittance figures before and after a 0.53 m drift. These devices are of a design developed by P. Allison[3]: they consist of electrostatic deflection plates located between two 60 μm slits. As the assembly is stepped through the beam, an x' profile is taken at each step by recording the beam transmitted through the two slits as a function of deflecting voltage. Typical results are shown in Fig. 5.

The numerical emittance data, which consist of current values at each of the points on a (x, x') grid, are analysed to give

$$\sigma_x = \sqrt{\overline{x^2}},\ \sigma_{x'} = \sqrt{\overline{x'^2}},\ \epsilon_{4\text{rms}} = 4\sqrt{\overline{x^2}\,\overline{x'^2} - \overline{xx'}^2}\ .$$

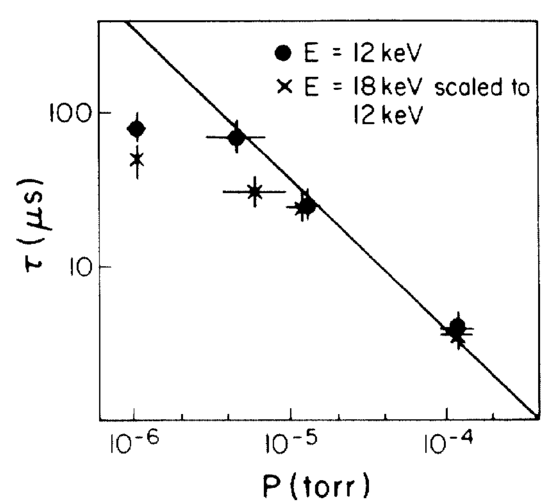

Fig. 3. Measured space charge neutralization time constant as a function of (H_2) background gas pressure. The 18 keV data were scaled upwards (see text).

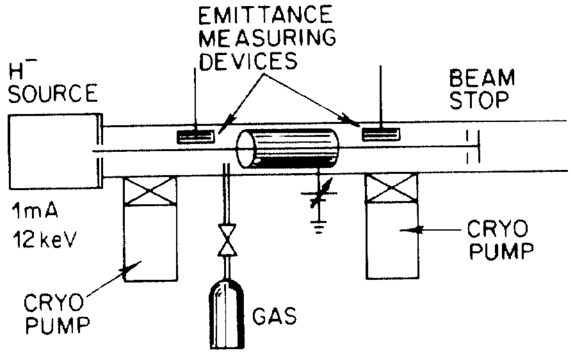

Fig. 4. Apparatus used to measure space charge neutralization strength. The emittance devices are 0.53 m apart. For this experiment only H_2 gas was used.

Sacherer[4] showed that the Kapchinski–Vladiminski beam envelope equations are exact for rms values of beam size and emittance. Therefore, to determine the space charge effect, these equations were integrated through the 0.53 m drift using the measured rms values at the first emittance station as initial conditions; the beam current was varied in the calculation to match the calculated and observed rms values at the second emittance station. The neutralization parameter f is equal to one minus the ratio of fitted and actual currents. Results are shown in Table I.

It is well known that negative ion beams are easily neutralized. The reason is that positive ions are thermalized at approximately room temperature and therefore do not have enough kinetic energy to escape the potential well of the beam. Unneutralized, the depth of the well between the edge and the centre of the beam is

$$V_c = (30\Omega/\beta)I \qquad (2)$$

or about 6 V in our experiment ($\beta = 0.005, I = 1$ mA). Roughly, one would expect the neutralization to reach a level such that

$$1 - f \sim \frac{kT}{eV_c} ,$$

which is only 0.4% for room temperature. This naïve picture disagrees with the results in Table I, especially for fairly good vacuum.

Table I. Experimental results of space charge neutralization vs. pressure. For any given entry, the upper rms parameters were measured at the first emittance station and the lower at the second. Space charge forces are evident through a change in $\sigma_{x'}$. Except in the case of the last entry, the uncertainty in neutralization is ±0.4%. This arises mainly from a ±1% uncertainty in $\sigma_{x'}$.

H_2 pressure (Torr)	ϵ_{4rms} (mm-mrad)	σ_x (mm)	$\sigma_{x'}$ (mrad)	I_{eff} (mA)	Neutralization (%)
1.1×10^{-6}	23.6 26.5	3.10 6.55	6.31 6.93	0.044	95.6
5×10^{-6}	23.7 26.1	3.01 6.31	6.09 6.68	0.040	96.0
1.4×10^{-5}	23.3 25.4	2.97 6.15	5.78 6.21	0.030	97.0
1.2×10^{-4} (Stripping loss = 50%/metre)	22.7 23.5	2.86 5.64	5.43 5.34	−0.006	100.7
1.1×10^{-6} (Cylinder at 20 V)	24.2 42.0	2.93 7.5	6.23 12.9	0.5	~50

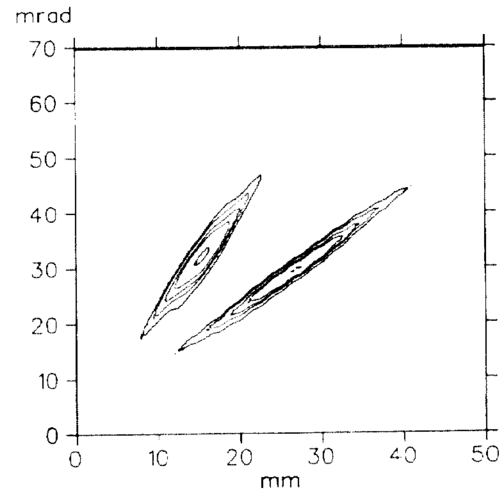

Fig. 5. Emittance figures measured at the two stations superposed on the same graph. In both cases, the outer contour contained 88% of the beam. This particular example is for the base pressure (1×10^{-6} Torr).

The reason is probably that neutralizing particles can escape longitudinally: a room temperature H_2 molecule will travel ~10 cm during the measured neutralization time constant of 80 μs.

On the other hand, overcompensation ($f > 1$) can occur for fairly high pressures. This occurs when surplus positive ions cannot escape the region of the beam in a time interval which is small compared with the neutralization time constant τ. (Electrons of course continue to be expelled almost instantaneously on this time scale because they travel 60 times faster for a given energy and also tend to gain more energy in an ionizing collision.) Experimentally, we found $\tau = 4$ μs at $P = 1 \times 10^{-4}$ Torr. During this time a room temperature H_2 molecule can travel only about 5 mm. The beam diameter was between 5 and 10 mm so this explanation is consistent with our data, i.e., with overcompensation occurring for pressures greater than ~1 $\times 10^{-4}$ Torr. Overcompensation has also been observed by others.[5] It must be pointed out, however, that this self-focusing of the beam is of little practical use because at $P_{H_2} = 1 \times 10^{-4}$ Torr, H^- ions are being stripped at the rate of 50% per metre.

It should be noted that although there was some doubt about the accuracy of the pressure measurement, the qualitative explanation of the measured values of f is still valid since it depends only upon τ and not directly upon the pressure calibration.

For the last entry in Table I the cylinder (see Fig. 4) was biased at −20 V. Since this is larger than the unneutralized space charge potential, we expect neutralizing particles to tend to be expelled from the drift region. Indeed, the divergence was found to double. The neutralization parameter was difficult to estimate in this case because of the large emittance growth.

References

[1] L. Vályi, Atom and Ion Sources (Wiley, London, 1977), p. 38.

[2] H.S. Chang, G.-G. Winter, H. Krause, N. Schirm and I. Teßmann, "First results from the LEBT with H^- source", DESY HERA report 87-04.

[3] P.W. Allison, J.D. Sherman and D.B. Holtkamp, "An emittance scanner for intense low-energy ion beams", IEEE NS-30, 2204 (1983).

[4] F.J. Sacherer, "Rms envelope equations with space charge", IEEE NS-18, 1105 (1971).

[5] P. Allison (Moderator), "Panel session: Transport of negative ion beams", Proceedings 4th Int. Symp. on Production and Neutralization of Negative Ions and Beams, AIP Conf. Proc. 158 (AIP, New York, 1986), p. 520.