BEAM POTENTIAL MEASUREMENT OF AN INTENSE H^- BEAM BY USE OF THE EMISSIVE PROBE TECHNIQUE*

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Summary

An emissive probe has been developed to study the beam-plasma potential generated by a 20-keV, 30-mA/cm^2 quiescent H^- beam propagating in Xe background gas. An axial ion trap has been built, and its influence on the measured potentials is reported. The peak plasma potential at 10^{12} cm^{-3} Xe density increased from +5V to +10V when the ion-trap voltage was increased from zero to +80V. The quiescent H^- beam rms emittance, measured 34 cm from the ion source, increased from 0.012 to 0.023 π•cm•mrad when the Xe density was decreased from 2.2 x 10^{12} cm^{-3} to zero.

Introduction

Propagation of 15- to 20-keV H^- beams with 50-mA/cm^2 current densities is known to be subject to instabilities.[1] Our experience with 20-keV H^- transport for a 100-keV H^- injector[2] led to the conclusion that 20-keV H^- beam-emittance growth could be controlled by propagating the beam in Xe background gas with 10^{12} cm^{-3} density. This method is an impractical solution for long beam transports because of the H^- stripping losses. We have used the emissive probe technique[3] to measure beam potentials associated with 20-keV H^- beams at various Xe gas densities and have found positive potentials in agreement with earlier work.[4] Applying a positive 80-V potential to an axial ion trap increased the measured potential from 5 to 10 V.

Experimental

H^- beam measurements were made using an ion trap, Faraday cup, emissive probe, and an emittance-measuring station located at 5.0, 5.6, 12.8, and 33.9 cm from the ion source emission aperture. The emissive probe can be driven radially through the beam with 1% position accuracy. The 4X source has a circular ion-extraction system that yields an axisymmetric H^- beam.[5] Measurements discussed below were made with the 4X source operating in the quiescent mode (Mode III) 5 with typical H^- current (i_{H^-}) and current density (j_{H^-}) of 50 mA and 30 mA/cm^2.

The emissive-probe filament was coupled to a non-inverting amplifier with R = 1 MΩ, the resistive load to ground. The circuit allowed probe measurements over the full range of Xe densities without amplifier adjustments. A battery supply for heating the filament was chosen to reduce stray capacitance (~100 pF) and 60-cycle noise. For typical dc heating currents, which were used in all measurements, 1-2 V was dropped on the 1-cm-long tungsten filaments. A 4.4-mA thermionically emitted current was measured from the 0.0025-cm-diam tungsten filament (miniaturized probe) by biasing the circuit to -120 V, which corresponded to a 0.5-A/cm^2 current density.

Two emissive probe designs were used. The first had a 0.30-cm-diam, two-hole ceramic tube that was shielded with a 0.48-cm-diam stainless sheath. The 0.005-cm-diam tungsten filament was spot-welded to 0.05-cm-diam Ni wires that carried the heating current through the ceramic. Measurements with moderate Xe density revealed a positive potential as the probe first passed into the beam, but then a negative potential as it traveled farther into the beam. We attribute this behavior to perturbations of the beam plasma by secondary-electron production of the H^- beam striking the metallic sheath. To test this hypothesis, a miniaturized probe was constructed by plating a 0.178-cm-diam, two-holed ceramic tube with 0.002-cm tungsten coating, thus reducing our probe diameter by a factor of 2.6. This miniaturized probe used a 0.0025-cm-diam tungsten filament. The potential trace taken with the new probe under similar conditions showed that the perturbation was much reduced. At lower Xe density, the perturbed trace was again observed with the miniaturized probe, leading us to conclude that accurate measurements can be made only for $n_{Xe} \gtrsim 5 \times 10^{11}$cm^{-3} with the miniaturized probe geometry and H^- beam parameters.

An axial ion trap was installed on the magnetic field clamp (the exit position) of the 4x source. The trap was modeled with the SNOW code,[6] and it was found that +80 V on the trap was sufficient voltage to drain electrons from a 1-2-mA positive ion beam. This analysis did not include plasma effects.

Emissive-Probe Analysis

Analysis of the emissive-probe potential is complicated by effects associated with the 20-keV H^- beam--secondary-electron emission (from the tungsten filament) and the intercepted H^- current. These effects can be included in the equations relating the probe current (i_{pr}), probe potential (v_{pr}), and plasma potential (v_{pl}):

$v_{pr} \le v_{pl}$,

$$i_{pr}(v_{pr}) = -i_e \exp^{e(v_{pr}-v_{pl})/kTe} + i_i + i_T + i_s - i_b \quad , \qquad (1)$$

and

$v_{pr} > v_{pl}$

$$i_{pr}(v_{pr}) = -i_e + i_s \exp^{-e(v_{pr}-v_{pl})/kT_s} + i_T \exp^{-e(v_{pr}-v_{pl})/kT_w} - i_b + i_i = \begin{bmatrix} i_i \text{ when } v_{pr} \le v_{pl} + kT_e/2 \\ 0 \text{ when } v_{pr} > v_{pl} + kT_e/2 \end{bmatrix} , \qquad (2)$$

$$v_{pr} = i_{pr} R \qquad (3)$$

where

kT_e	=	plasma electron energy (eV)	≃ 5 eV
kT_s	=	secondary-electron energy (eV)	= 2→5 eV
kT_w	=	thermionic electron energy (eV)	= 0.216 eV
i_e	=	saturated probe current from plasma electrons	= 4.8 x 10^{-6} A (low electron density) = 2.4 x 10^{-4} A (high electron density)

*Work supported by the US Air Force Office of Scientific Research.

i_i = saturated probe current from plasma ions = 5.0×10^{-6} A

i_T = thermionic electron current = 4.4×10^{-3} A

i_s = secondary-electron current = $\left(j_{H^-}\right)\left(\gamma_e\right)\left(A_w/2\right)$ = 2.0×10^{-4} A

i_b = intercepted H^- beam current = $\left(j_{H^-}\right)\left(A_w/2\right)$ = 1.2×10^{-4} A

γ_e = secondary-electron emission coefficient = 1.7

A_w = filament area = 8×10^{-3} cm^2

Equations (1) and (2) were analyzed to investigate differences between the plasma potential and the probe voltage measurement [Eq. (3)]. This analysis predicts that at high electron density, the measured probe potential is accurate to $\sim 2kT_w/e$ whereas at low electron densities, this accuracy is $\sim 0.5kT_s/e$. Space-charge effects were not included in this analysis.

Results

All beam-potential measurements discussed here were acquired with the second (miniaturized) probe. A potential measurement is shown in the oscillogram of Fig. 1, where the probe potential is recorded versus probe position. The traces were taken with $n_{Xe} = 1.2 \times 10^{12}$ cm^{-3}, the lower amplitude trace with ion trap voltage (v_t) equal to zero, and the larger amplitude trace with v_t = +80 V. A summary of the peak probe voltage versus Xe density for a 20-keV, 50-mA H^- beam is shown in Fig. 2(A). The error bars represent the repeatability of the measurements. The potential for v_t = 0 increases from +4.5 to 6.0 V as Xe density increases from 5×10^{11} to 2.2×10^{12} cm^{-3}. At the lower Xe densities, v_t = +80 V does not alter the measured potential, but at Xe densities greater than 7×10^{11} cm^{-3}, a marked change occurs between the trap voltage on/off measurements; the probe voltage almost doubles with +80 V trap voltage when n_{Xe} increases from 7×10^{11} to 10×10^{11} cm^{-3}.

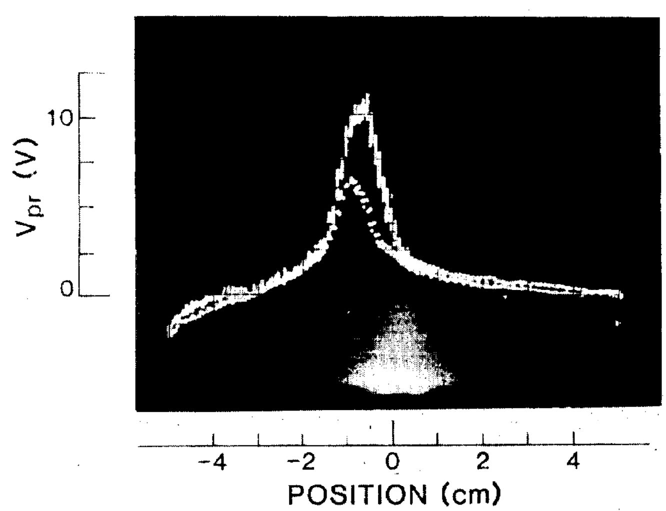

Fig. 1. Oscillogram of the measured probe voltage versus radial position. The lower trace has v_t = 0, the upper curve has v_t = 80 V.

A phenomenon associated with the increased probe voltages at $n_{Xe} = 7 \times 10^{11}$ cm^{-3} is the increase noted in the trap current. The total electron current produced in ionization of background gas by the H^- beam is

$$i_{TOTAL} = \left(i_{H^-}\right)\left(L\right)\left(n_{H_2}\Sigma_{H_2}\sigma_e + n_{Xe}\Sigma_{Xe}\sigma_e\right) , \qquad (4)$$

where

L = total beam length in the diagnostics box = 52 cm

n_{H_2}, n_{Xe} = hydrogen, Xe gas densities

$\Sigma_{H_2}\sigma_e = \sigma_i + \sigma_{-10} + 2\sigma_{-11}$ (sum of electron producing cross sections in hydrogen)

$\Sigma_{Xe}\sigma_e$ = (sum of electron producing cross sections in Xe)

In Fig. 2(B), the measured ion-trap current (i_{TRAP}) divided by the calculated current (Eq. 4) is plotted versus n_{Xe}. At $n_{Xe} = 7 \times 10^{11}$ cm^{-3}, the trap current increases dramatically, and (at the larger Xe densities) the trap current can account for almost all of the electrons produced by the H^- beam passing through the neutralizing gas. This result suggests the physical picture that, at a critical Xe density for our H^- beam-parameters, electrons are efficiently drained out of the beam plasma by the trap, leaving a more positive beam potential.

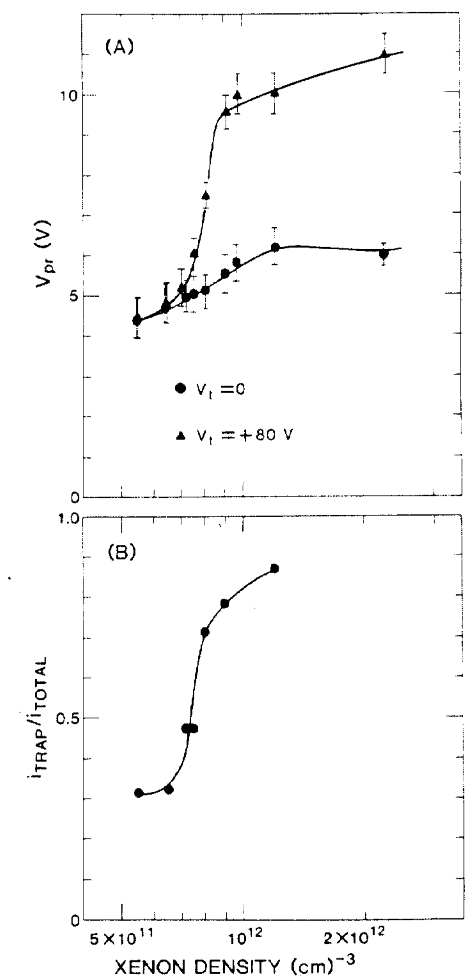

Fig. 2(A). Plot of the measured peak probe voltage versus Xe density for v_t = 0 and +80 V.
Fig. 2(B). Plot of the ratio of the measured trap current to the total calculated electron current versus the Xe density for v_t = 80 V.

The probe voltage and trap current were measured as a function of v_t, for $n_{Xe} = 9.5 \times 10^{11}\ cm^{-3}$; the results are shown in Fig. 3. At the fixed Xe density, the probe voltage doubled as v_t increased from 0 to +160 V [see Fig. 3(A)]. The trap current actually exceeds the predicted electron current [see Fig. 3(B)]; the enhanced electron current probably originates in other processes--such as secondary-electron emission from beam striking the end wall--that are not included in Eq. (4).

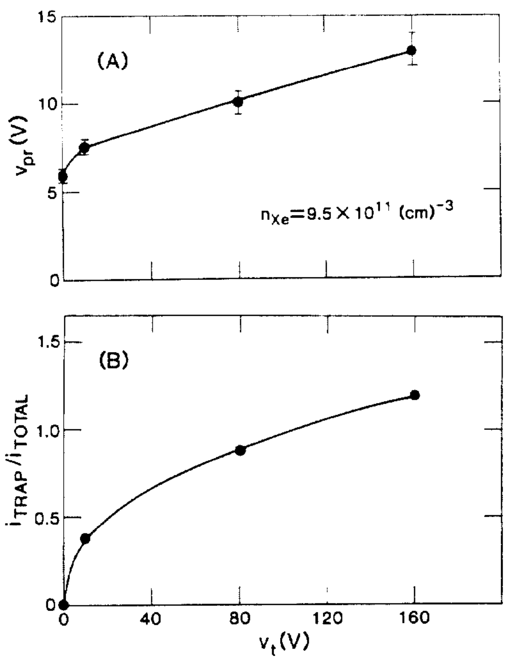

Fig. 3(A). Plot of the measured peak probe voltage versus v_t at a fixed Xe density, $n_{Xe} = 9.5 \times 10^{11}\ (cm)^{-3}$.

Fig. 3(B). Plot of the ratio of the measured trap current to the total calculated electron current versus v_t.

The quiescent H^- beam emittance, as determined by electric-sweep-type analyzers,[7] was measured over a 34-cm drift length with and without Xe gas in the chamber. A background hydrogen-gas density of $1.5 \times 10^{12}\ cm^{-3}$ always exists from source operation. The measured rms emittance increased from 0.012 to 0.023 π•cm•mrad when the Xe density was decreased from $2.2 \times 10^{12}\ cm^{-3}$ to zero.

Conclusions

Emissive probe measurements show that the beam-plasma potential is positive for Xe densities greater than $5 \times 10^{11}\ cm^{-3}$. The potentials are in approximate agreement with the Holmes[8] neutralization theory adapted to H^- beams. Application of +80 V on an axial ion trap doubles the measured probe voltages for Xe densities $\geq 9 \times 10^{11} cm^{-3}$. In this case, the trap current is consistent with collecting all the electrons produced by ionization and charge-changing cross sections of the H^- beam in the neutralizing gas, which suggests that longitudinal effects are important. The gas focusing concept[4] has been corroborated because after a 34-cm drift, the beam size is progressively reduced as the measured beam potential becomes more positive. H^- beam-transport instabilities[1,2] over this drift distance are severe enough to cause x2 H^- beam emittance growth. The emittance at extraction (~0.012 π•cm•mrad) is recovered by beam transport in a Xe gas density of $10^{12}\ cm^{-3}$.

Acknowledgments

We acknowledge the technical assistance of Stuart Orbesen and Mark Hollander for help in preparing these experiments.

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