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Measurement of Proton Autoneutralization Potential

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A proton space charge having multi-MeV kinetic energy was injected through a thin ground plane to extract electrons and produce a time-dependent autoneutralization space potential. An electron-emitting floating-potential resistive divider was used to measure the space potential during 20 ns of the proton current pulse. During this time, proton kinetic energy fell from 10.6 MeV to 8.5 MeV and thus the space potential (taken as $1.09\times$ the floating potential) fell from 5.8 kV to 4.6 kV.

INTRODUCTION

The measurement of multi-megavolt-potential time histories with nanosecond resolution is a formidable task facing researchers in pulsed power. This paper describes an experiment that exploits the autoneutralization phenomenon¹ and utilizes simple electric-probe technology² to accomplish this task.³ First, however, we review the autoneutralization model and develop an appropriate probe theory for designing probes and interpreting data.

AUTONEUTRALIZATION MODEL

Figure 1 shows the one-dimensional autoneutralization model formulated by Humphries *et al.*¹ on which this experiment is based. When a proton space charge ($n_+ \text{ cm}^{-3}$) having multi-MeV kinetic energy (E_k) erupts through a thin ground plane, it can extract a compensating electron charge ($n_e = n_+$) and current density ($j_e = -j_+$) and produce a neutral moving ($\langle v_e \rangle = v_+$) proton-electron plasma; this plasma has a positive space potential $V_S = (m_e/m_+)E_k$ above ground. Such one-dimensional acceleration of cold electrons requires one-half of an ion kinetic Debye length ($h_{DL} = \sqrt{E_k \text{ volts}/n_+ \text{ cm}^{-3}}$ cm), which is based on the proton kinetic energy and density. Within the distance $h_{DL}/2$ of the ground plane, the space potential and average electron velocity exhibit a damped spatial oscillation. Electrons exiting the acceleration zone have average kinetic energy $V_S = (m_e/m_+)E_k$, average velocity $\langle v_e \rangle = v_+$, and a temperature $T_e = 0.043 V_S$ (volts), which represents a three-dimensional randomization of the

one-dimensional velocity spread accumulated during acceleration. Beyond $h_{DI}/2$, the ratio of proton plasma space potential to average proton kinetic energy is

$$\frac{V_S}{E_K} = \frac{m_e}{m_p} = \frac{1}{1836.1} = \frac{0.545 \text{ kV of space potential}}{\text{MeV of kinetic energy}}$$

An electric probe sampling downstream of the acceleration zone should see a plasma with the following properties:

- E_K kinetic energy, V,
- $j_+ = en_+v_+$, proton current density, A/cm²,
- $v_+ = \sqrt{2eE_K/m_+}$, proton velocity unchanged by autoneutralization as $m_e/m_+ \ll 1$, cm/s,
- $n_e = n_+$, cm⁻³,
- $v_{ex} = v_+$, cm/s,
- $V_S = (m_e/m_+)E_K$, V,
- $T_e = 0.043V_S$, V.

EXPERIMENT

Proton current density pulse

Figure 2 shows the current-density j_+ and kinetic-energy E_K time histories (curves 2 and 3, respectively) of the driving proton pulse at the floating WP (wire probe) location. The values of E_K are labeled on curve 3, and the peak j_+ value of 4.2 A/cm² occurs at 10.6 MeV, which corresponds to 507 V on Fig. 2. The $E_K(t)$ and $j_+(t)$ scalings used for Fig. 2 are discussed in detail in *Data and Interpretation* below. The proton kinetic energy drops from 15 MeV to below 6 MeV in 0.1 μ s. The proton current density pulse has a FWHM (full width at half-maximum) of 18 ns and a total proton current of 166 A after the ground mesh. Table I lists its spatial properties.

Drift tube

The stainless steel drift tube is 70.7 cm long and has an i.d. of 29.2 cm and o.d. of 30.5 cm. The entrance collimator is 4.8 cm in diameter and is covered by a mesh (92.2% open area) made of 10-mil-diameter steel wire on a 6.35-mm (0.25 in.) grid (Fig. 3). The "nose" of the current pulse arrives at the endwall (70.7 cm) as the "tail" leaves the mesh. The drift tube sidewall is always outside the diameter of the current pulse. A vacuum of 10^{-6} Torr was maintained inside the drift tube.

Wire probe

The WP (Fig. 4) consists of a 6.35-mm-diameter (0.25 in.) brass rod extending into the plasma from a ceramic high-voltage insulator that is well outside the plasma diameter. The broadside area of this brass rod exposed to the plasma is 2.41 cm^2 . The rod connects through the insulator to $2050 \text{ }\Omega$ of probe impedance and $50 \text{ }\Omega$ of signal cable impedance, which gives a total impedance of $2100 \text{ }\Omega$. The probe impedance is distributed over ten 2-W carbon resistors connected in series by short brass rods of equal diameter (0.7 cm) and potted inside a 3.8-cm-diameter (1.5 in.) tube. The entire coaxial impedance structure is 30.5 cm (12 in.) long and has an estimated inductance of 64.4 nH and a measured capacitance of 30 pF . Inductance effects are negligible in this experiment. The response time of this probe is estimated to be 1.5 ns . An elementary circuit model (having a step function space potential connected to ground through the $2050\text{-}\Omega$ probe in series with both the 30-pF and $50\text{-}\Omega$ signal line in parallel) produces a probe impulse response (e -folding) risetime of 1.46 ns . Measured WP response to pulsed electron (Febetron) irradiation of the probe tip is consistent with this model. This probe can easily track space potential variations on a 5-ns time scale.

PROBE THEORY

The WP is an electron-emitting floating-potential probe with a sheath drop ($V_s - V_E$), which is about 10% of either the space or floating potential.² The floating potential V_E is that *expected* for a perfectly absorbing probe having infinite impedance. The measured probe potential V_i is the sum of the "floating" and "emission" terms discussed below.

Because the kinetic particle fluxes $n_e v_e$ and $n_i(v_e)$ are equal, this probe senses space potential V_s by draining a current less than the net imbalance in thermal currents swept into the probe sheath. The electron saturation current is up to four times greater than in stationary situations because the plasma is swept into the probe at much higher speed than by thermal diffusion. Lower-impedance higher-current probes can float near V_e . Although neutralized, the kinetic particle fluxes do register an effect on the probe. Proton impacts on the brass tip eject electrons and contribute a positive enhancement to the space potential signal. This effect can easily be modeled and removed from the data or eliminated by a more elaborate tip construction. A hollow Faraday-cage probe electrode that traps ejected electrons can be constructed using a "proton-thick" cone whose "proton-thin" base foil faces the incoming plasma.

Floating potential

Because $m_e/m_p \gg T_+/T_e \gg 1$ for this autoneutralized plasma, the proton number density and thermal velocity are negligibly affected by the electron-retarding sheath drop $\Delta V = V_S - V_F$. Equating the thermal current densities at the probe surface and canceling common factors produces a relationship between floating potential and space potential²⁻⁵:

$$\sqrt{\frac{T_e}{m_e}} \exp\left(\frac{-\Delta V}{T_e}\right) = \sqrt{\frac{T_+}{m_+}}, \quad (1)$$

$$V_F = V_S + 0.5 T_e \ln\left(\frac{T_+ m_e}{T_e m_+}\right), \quad (2)$$

$$\frac{V_F}{V_S} = 1 + 0.0215 \ln\left(\frac{T_+ m_e}{T_e m_+}\right). \quad (3)$$

The value of V_F/V_S is 1 when proton and electron thermal speeds are equal and is 0.84 for an isothermal plasma. The midpoint of this range is 0.92, occurring at $T_+/T_e = 40$, and implies a ratio of proton kinetic energy to floating potential of

$$\frac{E_K}{V_F} = 1.09 \frac{m_+}{m_e} = 1996. \quad (4)$$

Probe current

The maximum current that a plasma voltage probe can draw is the electron thermal current swept into the probe sheath. If the probe draws more current, the sheath expands into the plasma, and the probe potential deviates below the floating potential. In the case of the autoneutralization floating probe,

$$I_P = \frac{V_F}{R} \leq 0.234 j_+ A_P, \quad (5)$$

where R is the total impedance to ground. The electron thermal current density swept into the probe sheath is four times that of a thermally equivalent stationary plasma. As the plasma velocity is normal to the probe area and much higher than any thermal speed, electrons diffusing in any of the four

directions parallel or perpendicular to this area are swept into the sheath. The electron thermal current density swept into the sheath is $en_e\langle c \rangle$, where $\langle c \rangle = \sqrt{(8eT_e)/(\pi m_e)}$ is the magnitude of average electron thermal velocity with T_e in volts. Substituting $T_e = 0.043 V_S$ in $\langle c \rangle$ produces

$$en_e\langle c \rangle = 0.234j_+ \quad (6)$$

as the limiting current density that a floating autoneutralization probe can draw.

The condition $I_p \leq 0.234j_+A_p$ is equivalent to $V_E \leq 0.234V_i$ for a perfectly absorbing probe. This condition is most closely met in the experiment between 30 and 50 ns, when j_+ is near its peak of 4.2 A/cm^2 . Figure 2 shows $V_E/42$ (curve 3) and $V_i/42$ (curve 2).

Electron emission model

To extract the time history of the autoneutralization potential from the probe signal in this experiment, a time-dependent model of proton impact-induced electron emission had to be invoked. This model relies on published electron kinetic ejection data.

Let γ_i represent the number of electrons ejected into 4π per proton impact. McDaniel⁶ showed that proton γ_i vs $E_K \leq 2 \text{ MeV}$ into metals where γ_i is ~ 2 at $E_K = 0.5 \text{ MeV}$ and γ_i is ~ 0.5 at $E_K = 2 \text{ MeV}$; γ_i scales as $1/E_K$ and extrapolates naturally to ~ 0.1 at 10 MeV . For this experiment, γ_i is modeled as $\gamma_i = 1.1/E_K\text{-MeV}$, and the time-dependent electron-emission current density from the probe is $\gamma_i j_+$. The peak emission-current density of 0.44 A/cm^2 is reached when $E_K = 10.6 \text{ MeV}$ and $j_+ = 4.2 \text{ A/cm}^2$.

An electron-emitting floating-potential probe should see a total probe potential of

$$V_f = V_{\text{collective}} = (V_E = 0.92V_S) + (V_i = j_+ A_p R) \gamma_i \quad (7)$$

as long as plasma exists in the vicinity of the probe tip. V_E is the floating potential expected for a perfectly absorbing probe, and V_i is the high-impedance Faraday-cup equivalent of the proton current density. Curves 2, 3, and 4 in Fig. 2 show $V_i(t)$, $V_E(t)$, and $V_{\text{collective}}(t)$, respectively.

DATA AND INTERPRETATION

Data

Figure 2 displays the voltage probe data, the time histories of the proton pulse kinetic energy and current density, and the probe voltage enhancement resulting from electron kinetic ejection. The x-axis gives time in nanoseconds, and the y-axis gives volts into the 50- Ω signal cable (which equals the probe voltage divided by 42).

Curve 1 ($V_p/42$) is the measured probe voltage, which peaked at 181 V.

Curve 2 ($V_i = j_i A_p R$)/42 is the probe voltage equivalent of the proton current density. The peak of 507 V occurred when $E_K = 10.6$ MeV.

Curve 3 ($V_E/42$) is the autoneutralization floating potential for a perfectly absorbing infinite-impedance probe. This curve is a scaling of proton kinetic energy vs time, and several $E_K(t)$ values are noted.

Curve 4 ($V_E + \gamma_i V_i$)/42 is the sum of curve 3 and the actual electron-emission voltage enhancement.

Interpretation

When the ion kinetic Debye length $h_{Di} > 70.7$ cm (curve 1 = curve 2), the proton current density $j_i < 0.84$ A/cm², no plasma exists on the scale of the drift tube, and the voltage probe acts as a high-impedance Faraday cup that collects unneutralized j_i through area A_p :

$$V_i = V_p(1 + \gamma_i). \quad (8)$$

The probe data $V_i(t)$ tracks $j_i(t)$, and electron-emission effects are small.

When the ion kinetic Debye length $h_{Di} < 70.7$ cm (curve 1 = curve 4), the proton current density $j_i > 0.84$ A/cm², and plasma phenomena are encountered, then between 30 and 50 ns, the proton current density is near its peak of 4.2 A/cm², $h_{Di}/2$ is ~ 15 cm, $v_{\perp}$ is $\sim 4.4 \times 10^9$ cm/s, $n_i \leq 5.9 \times 10^9$ /cm³, $T_e \leq 248$ V, and the Debye length h_D (based on T_e) is ~ 0.15 cm. During this interval, the probe voltage V_p drops from 7.6 kV to 5.0 kV while the floating potential V_E drops from 5.3 kV to 4.2 kV. The maximum electron-emission voltage enhancement $\gamma_i V_i$ is 2.3 kV or 44% of the floating potential. The electron emission part of the signal is easily removed, and the remaining

floating potential signal is interpreted as a measured time history of diminishing autoneutralization space potential to within 10%. This precision is an insensitive function of the uncertainty in T_+/T_e . For $1 \leq T_+/T_e \leq m_+/m_e = 1836.1$,

$$(V_f - \gamma V_i) = V_E = (0.92 \pm 0.08)V_S. \quad (9)$$

The floating-probe data between 30 and 50 ns can be interpreted as a 10%, <5-ns-resolution measurement of proton space charge kinetic energy in the 10-MeV range dropping at a rate of 0.1 MeV/ns.

CONCLUSION

A 4.2-A/cm², 18-ns FWHM proton current pulse with 10.6 MeV kinetic energy at the current peak and with 8.5 MeV kinetic energy 20 ns later was injected through a ground plane into a 70.7-cm-long drift tube to produce a time-dependent autoneutralization space potential. A 2.1-k Ω , 42:1 voltage-dividing floating-potential probe was used to track this space potential within 10%, once the effect of proton-impact-induced electron kinetic ejection was removed. During 20 ns of plasma history, the space potential, taken as 1.09 times the floating potential, fell from 5.8 kV to 4.6 kV, as expected from

$$\frac{V_S}{E_k} \approx \frac{m_e}{m_+} = \frac{1}{1836.1} \cdot \frac{0.545 \text{ kV of space potential}}{\text{MeV of kinetic energy}}.$$

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TABLE I. Spatial properties of the proton current density pulse, j_+ .

Location	Distance (cm)	Peak j_+ (A/cm ²)	Average diameter (cm)
Mesh	0	9.16	4.8
WP	13.7	4.20	7.1

Figur. 1. One-dimensional autoneutralization model formulated by Humphries *et al.*¹ on which this experiment is based. When a proton space charge having multi-MeV kinetic energy erupts through a thin ground plane, it can extract a compensating electron charge and current density and produce a neutral moving proton-electron plasma with a positive space potential above ground.

Figure 2. Curve 1: WP data. Curve 2: current-density j_+ time history of the driving proton pulse at the floating WP location. Curve 3: kinetic-energy E_K time history at the same location. Curve 4: Electron-emission signal enhancement added to curve 3.

Figure 3. (a) End view of the stainless steel drift tube toward the entrance collimator. This perspective shows the alignment of the mesh and the WP. (b) Side view showing the relative locations of the WP, mesh, and collimator.

Figure 4. Wire probe, consisting of a brass rod extending into the plasma from a ceramic high-voltage insulator and low-inductance resistor chain.

FIG. 1

FIG. 2

(a)

(b)

FIG. 3