Gas Ionization by Beam Electron Collisions and by Electron Avalanching in the Self E_z Field of a 2 kA Relativistic Electron Beam Focused on a Conducting Target

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Gas Ionization by Beam Electron Collisions and by Electron
Avalanching in the Self Ez Field of a 2 kA Relativistic Electron Beam
Focused on a Conducting Target

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Abstract

About 1.5×10^{12} positive ions are predicted to be required to disrupt the focusing (for 0.25 cm radius and 0.2 electric neutralization fraction). Beam electron collisions are predicted to produce this number in 20 ns with 6×10^{15} water molecules/cm². Electron avalanching is predicted to be intense at time zero in a gas layer about 10^{-3} cm thick with 1.4×10^{16} cm⁻². With increasing time, space charge reduces the E-field and so the avalanching decreases. With 0.25 cm radius, 1.9×10^{11} are predicted in 0.6 ns and with 1 cm radius, 7.4×10^{11} are predicted in 1.5 ns.

I Introduction

Flash x-ray radiography for hydrodynamics testing requires that the electron beam have non-time dependent focusing on the target. Positive ions produced by gas ionization can cause disruption of the spot size on the converter target. We review two gas ionization processes.

II Minimum number of positive ions required to defocus the beam

We calculate the number of ions to defocus the beam as

$$C = f \lambda L_d \tag{1}$$

where λ is the number of beam electrons per cm,

$$\lambda = \frac{I_b}{e \beta c} \tag{2}$$

where I_b is the beam current (A), $e = 1.6 \times 10^{-19}$ coulomb, β is the beam velocity divided by c and c is 3×10^{10} cm/sec. f is the number of ions/cm divided by λ and L_d is George Caporaso's "disruption length"

$$L_d = a \sqrt{\frac{\pi \beta^2 \gamma I_0}{f I_b}} \tag{3}$$

where a is the beam radius, γ is the beam electron total energy in rest mass units and $I_0 = 17050$ A. Combining Eqs 1,2 and 3

$$C = \frac{a}{ec} \sqrt{\pi \gamma f I_0 I_b} . \quad 4$$

Using Darht parameters, $\gamma = 41$ and $I_b = 2000$ A and using $a = 0.25$ cm and $f = 0.2$ as an example, $C = 1.54 \times 10^{12}$.

III Gas ionization by beam electron collisions

The number of ions produced by beam electron collisions in time τ (sec) with gas density $n_g (cm^{-3})$ with cross section $\sigma_b (cm^2)$ and length l (cm) is

$$C_b = \frac{I_b \tau \sigma_b n_g l}{e} \quad 5$$

H_2O seems to be the most common molecule desorbed from metal targets with $\sigma_b = 10^{-18} (cm^2)$ (1). As an example of the amount of gas required to result in defocusing, we solve for $n_g l$ in Eq 5 and set $C_b = 1.54 \times 10^{12}$ from I above, and use $\tau = 20 \times 10^{-9}$ sec, giving $n_g l = 6 \times 10^{15} cm^{-2}$. If protons are required because of transit time considerations, then assuming that only .09 protons are produced per H_2O ionization, $n_g l$ would have to be about 11 times larger.

IV Electron Avalanche Gas Ionization in the Self Ez Field of a Relativistic Electron Beam Focused on a Conducting Target

Electrons in a collision- dominated regime in a gas in an E-field lose most of their directed momentum in collisions with gas molecules and accelerate between collisions. The rate of increase with distance of the number of electrons N , in an avalanche is

$$\frac{dN}{dz} = N n_g < \sigma > \quad 6$$

where $< \sigma >$ is the average over the velocity distribution function of the cross sections contributing to ionization. $< \sigma >$ is difficult to predict theoretically but it can be shown to be a function of E / n_g where E is the electric field strength and n_g is the gas molecule density (2). The ionization coefficient α is defined by

$$\alpha = n_g < \sigma > \quad 7$$

and Eq1 becomes

$$\frac{dN}{dz} = \alpha [z] N \quad 8$$

where α may be a function of z because the cumulated ion space charge makes E a function of z . Separating variables and integrating Eq 8

$$\frac{dN}{N} = \alpha[z]dz$$

$$\ln \frac{N[z]}{N[z_{\min}]} = \int_{z_0=z_{\min}}^z \alpha[z_0]dz_0$$

$$N[z] = N[z_{\min}]e^{\int_{z_0=z_{\min}}^z \alpha[z_0]dz_0}$$

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where $N[z_{\min}]$ is the number of “seed” electrons starting at $z_{\min}$ and $N[z]$ is the number of electrons in the avalanche at z , see Fig 1.

Fig 1 Geometry of the calculation

Beam electrons produce seed electrons uniformly in z . The number per cm produced in a time τ is

$$\frac{I_b \tau \sigma_b n_g}{1.6 \times 10^{-19} \text{ coul}}$$

where I_b is the beam current in amperes,

τ is the time in seconds,

σ_b is the cross section in cm^2 ,

n_g is the gas molecule density in cm^{-3}

Integrating over the source positions

$$N[z, \tau] = \frac{I_b \tau \sigma_b n_g}{1.6 \times 10^{-19}} \int_{z_{\min}=0}^z e^{\int_{z_0=0}^z \alpha[z_0] dz_0} dz_{\min} \quad 10$$

If α is a constant, independent of z , (i.e. if the space charge modification of E is negligible), then the double integral in Eq 5 can be done analytically with the result

$$N[z, \tau] = \frac{I_b \tau \sigma_b n_g z}{1.6 \times 10^{-19}} \frac{(e^{\alpha z} - 1)}{\alpha z} \quad 11$$

$N[z, \tau]$ is the number of ionizations between 0 and z after the time, τ . The first factor on the right is the number of seed ionizations produced in the length z in the time τ , and the second factor is the multiplication due to avalanching.

Several authors (Hughes, Welch and Davis) have pointed out that if the area gas density is 10^{15} per cm^{-2} , and the cross section is 10^{-16} cm^2 , then avalanching is unimportant. We postulate that beam heating of the target causes a gas layer to form with an area density of about 1.4×10^{16} molecules/ cm^2 and with a thickness l , of about 10^{-3} cm. The electrons have a large drift velocity of about 2×10^8 cm/sec and we model the time for the electrons to be collected at the target as $\leq \tau$. The positive ions resulting from ionization are modeled as immobilized. Ions quickly cumulate to where they modify the E-field and Eq 11 is not valid. We do a computer calculation with many small time steps. We solve Eq 10 for the number of ions produced in a time step. The number of ions cumulated after a particular time step is used in Poisson's equation to calculate a new E-field. α is calculated using E from the previous time step. Depletion of the gas density is neglected.

If an electron beam of current I_b (Amp) is focused to radius a (cm) on a conducting target, then E_z at the target is, (in the absence of ions), (3)

$$E_0 = 120 I_b / a \quad 12$$

in volts/cm.

We use a one-dimensional Poisson's equation

$$\frac{dE_z}{dz} = 4\pi en = (4e/a^2) \frac{dC}{dz}, \text{ (esu)} \quad 13$$

where n is the ion density, (cm^{-3}), e is the electronic charge and C is the cumulated N from the different time steps.

$$dE_z = (4e/a^2) dC$$

$$\Delta E_z = (4e/a^2) C[z]$$

where ΔE_z is the change in E_z at z .

If the ion sheath thickness is small compared to the length where the vacuum E is $\sim E_0$, then the boundary condition is

$$E_z = E_0 \text{ at } z=0$$

so

$$E_z = E_0 - \frac{4 \times 4.8 \times 10^{-10} \times 300}{a^2} C[z] \quad 14$$

Good measurements of α/n_g vs E/n_g for H_2O are not available, but the curve is similar to that of N_2 (4). We use modern measurements for N_2 (5), see Fig 2.

Fig2 α/n_g vs E/n_g for N_2 gas

Here

$$alphan = 10^{16} \alpha / n_g$$

$$td = 10^{17} E / n_g .$$

The gas density increases with time, and when it reaches about $1.4 \times 10^{19} \text{ cm}^{-3}$ (for $I_b = 2000 \text{ A}$, $a = 0.5 \text{ cm}$), alphan is a maximum of about 2.9 on Fig 2. α is about $4 \times 10^3 \text{ cm}^{-1}$ and avalanching is intense. As ions cumulate, E decreases and α decreases.

Figs 3a through 5b present results for three values of beam radius with $I_b = 2000 \text{ A}$, $\sigma_b = 10^{-18} \text{ cm}^2$, $n_g l = 1.41 \times 10^{16} \text{ H}_2\text{O} / \text{cm}^2$ and $td = 3394$ at time zero.

Fig 3a Cumulated ions vs z for various time steps, $a=0.25$ cm, $l=0.5 \times 10^{-3}$ cm,,
 $n_g=2.83 \times 10^{19}$ cm $^{-3}$, time steps= 2.5×10^{-12} sec.

Fig3b E vs z correspondding to Fig 3a

Fig4a Cumulated ions vs z for various time steps, $a=0.5$ cm, $l=10^{-3}$ cm, $n_g=1.41 \times 10^{19}$ cm $^{-3}$, time steps= 5×10^{-12} sec

Fig 4b E corresponding to Fig 4a

Fig5a Cumulated ions vs z for various time steps, $a=1$ cm, $l=2 \times 10^{-3}$ cm
 $n_g=0.707 \times 10^{19} \text{ cm}^{-3}$, time steps= 10^{-11} sec

Fig 5b E vs z corresponding to Fig 5a

For small times, the cumulated number, C increases with z according to Eq 11. With increasing time, Ez is decreased at large z and so the growth decreases at large z . For large times and large z , e.g. $t=250$ on Figs 3,4 and 5, most of the increase vs z is due to beam electron collisions.

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