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INTENSE ION BEAM TRANSPORT IN NEUTRAL GAS*

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Abstract

An analysis is made of the gas breakdown that occurs when an intense ion beam is injected into neutral gas and a high electrical conductivity is produced, providing charge and current neutralization for beam transport.

Introduction

Intense ion beam transport in neutral gas is used in several light ion fusion (LIF) transport schemes,[1-3] in some heavy ion fusion (HIF) transport schemes,[1,4] and between accelerating gaps in some multi-gap linear accelerator schemes. Here, the macroscopic properties of charge neutralization and current neutralization are examined. Then, as shown in Fig. 1, the microscopic properties of gas breakdown are examined, including ion impact ionization, secondary electron impact ionization, electron avalanching, and ohmic heating. These results are combined to give a physical picture of gas breakdown, including growth of the plasma electrical conductivity.

For LIF parameters for the light ion laboratory microfusion facility (LMF),[5] it is desirable to have the plasma conductivity reach a modest value ($\sim 10^{10}$ s^{-1}) very quickly (< 1 ns), and then rise much higher ($\sim 10^{14}$ s^{-1}) by the time of peak ion current to avoid the filamentation instability. Estimates for LMF parameters are given showing the desired growth in $\sigma(t)$.

Charge Neutralization

Charge neutralization is required for intense ion beam transport when the ion current I_i exceeds the space charge limiting current I_l.

$$I_l = \beta_i(\gamma_i - 1)[M_p c^3/e](A/Z)[1 + 2\ln(R/r_b)]^{-1} \approx (\tfrac{1}{2})\beta_i^3(A/Z)(31\text{MA})[1 + 2\ln(R/r_b)]^{-1} \quad (1)$$

where the ion axial velocity is $\beta_i c$, $\gamma_i = (1 - \beta_i^2)^{-1/2}$, c is the speed of light, M_p is the proton mass, A is the ion mass number, e is the electron charge, r_b is the beam radius (solid beam), and R is the metallic guide tube radius. The current I_l is the current that would create an electrostatic potential depression equal to $\varepsilon_i/(Ze)$, so that for $I_i \gtrsim I_l$ the beam would stop. Here ε_i is the ion energy and Z is the ion charge state in the gas. To permit beam propagation, a neutralizing electron background of density n_e must be present with an adequate value of the charge neutralization fraction $f_i = n_e/(Zn_i)$ where n_i is the ion beam density. For LMF type parameters (30 MeV Li^{+3}, $R \approx r_b$, particle current $I_b = 1$ MA, $I_i = ZI_b = 3$ MA), $I_i \approx 97\, I_l$ so $f_i > 0.99$ is required.

If no charge neutralization is provided, large space charge fields will be produced quickly that will draw electrons from nearby surfaces by field emission. For injection through a foil (that bounds the gas transport region), the electric field at the foil would be

$$E = 2\pi J_i t^2/t_r \qquad 0 \le t \le t_r \quad (2)$$

where J_i is the peak current density and t_r is the ion current risetime. For LMF parameters ($J_i = 3 \times 2$ kA/cm^2, $t_r \approx 10$ ns), this is

$$E = 3.4 \times 10^6\, [t(\text{ns})]^2 \text{ V/cm} . \quad (3)$$

This shows that on a nanosecond time scale, electric fields large enough to cause field emission would be created.

Given that electrons will be provided by gas ionization, field emission, or drawn from plasma surfaces, it is of interest to estimate how well charge-neutralized the beam front can become. Based on electron trapping arguments,[6] the potential well depth at the beam front will always be $\gtrsim \Delta\phi$ where

$$e\Delta\phi = 1/2\, m_e \beta_i^2 c^2 \quad (4)$$

and m_e is the electron mass. For LMF parameters (30 MeV Li), this is $\Delta\phi \approx 2.3$ kV.

Current Neutralization

Current neutralization is required for intense ion beam transport when the ion current exceeds the Alfven magnetic limiting current

$$I_A = \beta_i\gamma_i(M_p c^3/e)\,(A/Z) \approx \beta_i\,(A/Z)\,(31\text{ MA}) . \quad (5)$$

Generally it is desirable to have current neutralization so that the net current $I_{net} = I_i\,(1 - f_m) < I_A$, where $f_m = I_p/I_i$ is the fractional current neutralization and I_p is the plasma return current. For LMF parameters, $I_i \approx (0.4)I_A$ so the beam could propagate with betatron particle trajectories for $f_m = 0$. However, for certain LMF transport scenarios,[3] it is desirable to have essentially complete current neutralization ($f_m \approx 1$) so that the trajectories will be ballistic.

The evolution of the net current can be described as follows. For beam injection into neutral gas, the electrical conductivity σ starts at zero, but quickly rises as the gas is ionized and heated. The plasma current density evolves according to[7]

$$J_p/t_d + \partial J_p/\partial t = -\partial J_b/\partial t \quad (6)$$

where the magnetic diffusion time is $t_d = 4\pi\sigma r_b^2/c^2$ and J_b is the beam current density. The simplest picture of the evolution of J_p and J_{net} is shown in Fig. 2. Initially $\sigma = 0$, $t_d = 0$, $J_p = 0$, and $J_{net} \approx J_b$. If, at some later time τ the conductivity has suddenly increased so t_d is large ($t_d \gg t_b$ where t_b is the ion beam pulse length), then from then on, the magnetic field will be frozen at its value at $t = \tau$. Specifically, analysis of (6) shows

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$$J_{net} \approx J_b(t) \qquad 0 \le t \le \tau$$
$$J_{net} \approx J_b(\tau) \qquad \tau \le t \le t_r \; . \tag{7}$$

To have good current neutralization therefore requires that σ rise quickly so $t_d \gg t_b$.

Gas Breakdown

Ion beam induced gas breakdown occurs by several processes as follows.

(1) Ion impact ionization occurs throughout the whole ion beam pulse. Growth of the plasma electron density is given by

$$dn_e/dt = n_b(t)/t_i \tag{8}$$

where the ion impact ionization time is $t_i = (n_g \beta_i c \sigma_c)^{-1}$, n_g is the neutral gas density, and σ_c is the cross section. It can be shown that σ_c scales roughly as

$$\sigma_c \sim Z^2/(\varepsilon_b \beta_i^2) \tag{9}$$

where ε_b is the electron binding energy. For 1 MeV protons on hydrogen, $t_i \approx 0.55$ ns/p(Torr).[8] Using (9), it follows that for LMF parameters (30 MeV Li^{+3} on helium), $t_i \approx 0.23$ ns/p(Torr).

(2) Secondary electron ionization is caused as the newly created plasma electrons are accelerated toward the ion beam by the beam's space charge. The electrons may be trapped and continue to oscillate in the potential well near the beam head. These electrons ionize the gas by electron impact ionization,

$$dn_e/dt = n_e^f(t)/t_e \tag{10}$$

where n_e^f is the "fast" electron density and t_e is the electron impact ionization time. Typically $t_e < t_i$ for these energetic electrons.

(3) Electron avalanching occurs when an electric field E is present[7] and the parameter E/p is in an optimal range ($10^2 \lesssim$ E/p (Volts/cm/Torr) $\lesssim 10^5$) where p is the neutral gas pressure. For higher E/p values, the electron may leave the system before it does substantial ionization. For lower E/p values, the electron may never gain enough energy to make ionizing collisions. The E fields that can drive avalanches are space charge fields (before $f_i = 1$), induced electric fields at the head of the beam (for $f_i = 1$ and $f_m < 1$), and the later time induced electric field that drives the plasma return current. When ion impact ionization and avalanching are the dominant processes,

$$dn_e/dt = n_b(t)/t_i + n_e(t)/\tau_a \tag{11}$$

where the electron avalanche time $\tau_a = \tau_{FP}/(8 \ln 10)$ and τ_{FP} is the formative time investigated by Felsenthal and Proud for many gases.[9] For example, for helium with E/p = 600 V/cm/Torr, $\tau_a \approx 1$ ns. Note that exponential growth in n_e will occur on the τ_a timescale.

For $f_i = 1$ and $f_m = 0$, the induced electric field at the beam head, on axis, will be

$$E_{in} = -[I_i/(c^2 t_r)]\,[1 + 2 \ln (R/r_b)] \; . \tag{12}$$

As the beam becomes current neutralized, E_{in} will be determined by dI_{net}/dt.

(4) Ohmic heating is the return current heating that occurs after breakdown and field freezing when the return current is described by

$$J_p = \sigma E \; . \tag{13}$$

Since for good current neutralization, $|J_p| = |J_i|$,

$$E = n_i e Z \beta_i c/\sigma \; . \tag{14}$$

The power dissipation (W/cm³) for ohmic heating is

$$P = J_i^2/\sigma \tag{15}$$

and this goes into ionization and heating of the gas. It can be shown that the maximum energy gain of an electron in the E field given by (14) in one collision time is

$$\Delta\varepsilon = 1/2\, m_e \beta_i^2 c^2 (Z n_b/n_e)^2 \; . \tag{16}$$

For LMF parameters (30 MeV Li) this shows $\Delta\varepsilon$ is large enough to cause ionizing collision until $n_e/(Zn_b)$ exceeds about 10.

A physical picture of how the above four ionizing and heating mechanisms combine to cause gas breakdown is as follows. (i) The charge neutralization phase begins with ion impact ionization and secondary electron impact ionization. The E fields are electrostatic and are large. (ii) The current neutralization phase includes ion impact ionization and electron avalanching. The E fields are inductive and are decreasing. (iii) The ohmic heating phase continues with ion impact ionization and ohmic heating. The E fields are small. Throughout the entire process, note the continual presence and importance of ion impact ionization.

Conductivity Growth

At each stage of the gas breakdown, the electrical conductivity σ is given by (for no magnetic field)

$$\sigma_0 = n_e e^2/(m_e \nu) \tag{17}$$

where the collision frequency $\nu = \nu_{en} + \nu_{ei}$, the electron neutral collision frequency is given by

$$\nu_{en} = (5.9 \times 10^7)\,[T_e(eV)]^{1/2}\, P_c p(Torr) \tag{18}$$

and the electron-ion collision frequency is given by

$$\nu_{ei} = (1.5 \times 10^{-6})\, n_e Z_g\, (\ln\Lambda) [T_e(eV)]^{-3/2} \; . \tag{19}$$

Here P_c is the "probability of collision,"[10] and Z_g is the gas atomic number. Combining (17)-(19) and using $\ln\Lambda \approx 10$,

$$\sigma_0 = (2.5\times10^8) n_e \Big[(5.9\times10^7) p(Torr) P_c [T_e(eV)]^{1/2} + (1.5\times10^{-5}) n_e Z_g [T_e(eV)]^{-3/2}\Big]^{-1} \tag{20}$$

Early in the ion beam pulse σ_0 is dominated by ν_{en}, whereas later in the pulse σ_0 is typically dominated by ν_{ei}.

If a transverse magnetic field is present (either a self magnetic field or an external magnetic field) then the relevant conductivities are $\sigma_{\parallel}$ along B and $\sigma_{\perp}$ perpendicular to B (Pedersen conductivity),

$$\sigma_{\parallel} = \sigma_0$$
$$\sigma_{\perp} = \sigma_0 \, [1 + (\omega_{ce}/\nu)^2]^{-1} \tag{21}$$

where $\omega_{ce} = eB/(m_e c)$. For $\nu/\omega_{ce} \ll 1$, $\sigma_{\perp} \ll \sigma_0$, and current neutralization is impeded. For $\nu/\omega_{ce} \gg 1$, $\sigma_{\perp} \approx \sigma_0$ and current neutralization proceeds.

LMF Example

Transport scenarios for LMF include a ballistic lens scheme which uses ballistic transport in gas; and wall-confined channel transport and wire-guided transport, both of which use ballistic focused transport at their input. Therefore neutral gas transport is relevant to all approaches.

The parameters associated with one ion beam in LMF are: 30 MeV Li^{+1} at the diode, 30 MeV Li^{+3} after the gas cell foil, 1 MA peak particle current, t_r = 10 ns, t_b = 30 ns, r_b = 18 cm, $R \approx r_b$, and 1 Torr helium gas.

The first consideration for LMF ballistic/lens transport is that the frozen net current be as small as possible. Ion impact ionization alone will make a plasma density equal to the ion beam density at the time $t = 2\,t_i \approx 0.46$ ns. At this time, (20) gives $\sigma_0 \approx 5 \times 10^{10}$ s^{-1} and t_d = 225 ns, so already $t_d \gg t_b$. In addition, the net current at this time should be less than the beam current because the charge neutralizing electrons will flow in a direction that aids current neutralization. Thus field freezing should occur easily in < 1 ns and the current neutralization should be very high.

The second consideration for LMF transport is that the plasma-conductivity be high (~10^{14} s^{-1}) when the full current is reached, to avoid the filamentation instability. Ion impact ionization alone will create a plasma density $n_e \approx 10^{14}$ cm^{-3} and $\sigma > 10^{13}$ s^{-1}. Including electron avalanching and ohmic heating shows $n_e > 10^{15}$ cm^{-3} and $\sigma \approx 10^{14}$ s^{-1}.

Conclusions

The basic mechanisms of gas breakdown have been examined, and examples for LMF have been given. The processes should now be examined with computer simulations and explicit experiments with extracted ion beams.

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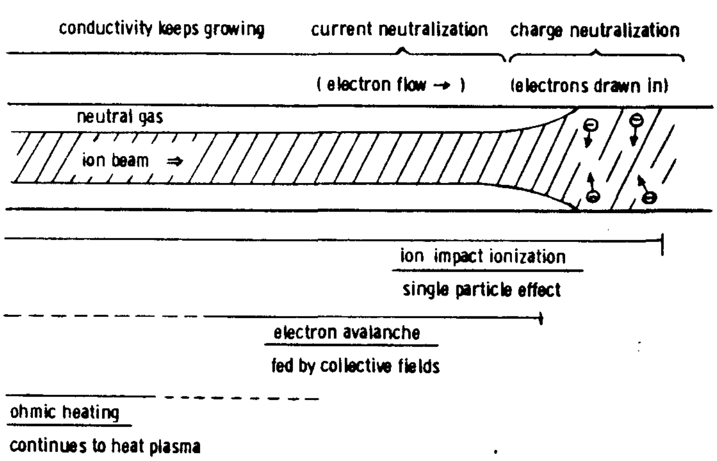

Fig. 1. Gas breakdown processes.

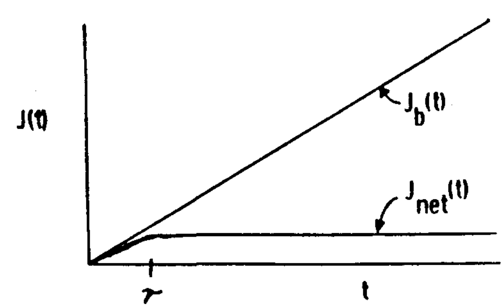

Fig. 2. Current neutralization.