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PHYSICS OF GAS BREAKDOWN FOR ION BEAM TRANSPORT IN GASES T1

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Summary

Detailed analysis, experiments, and computer simulations are producing a new understanding of gas breakdown during intense ion beam transport in neutral gas. Charge neutralization of beam micro clumps is shown to limit the net clump potentials to a non-zero value $\phi_{\min}$, which can lead to divergence growth and axial energy spreading. At pressures ≥ 1 Torr, plasma shielding should substantially reduce this effect. Current neutralization has been studied in experiments on the GAMBLE II accelerator. The importance of fast electrons (knock-ons and runaways) has been established in IPROP simulations, which are in agreement with the experiments. For light ion fusion parameters with pressures ≥ 1 Torr, very small net current fractions ($\ll 1\%$) appear feasible, permitting ballistic transport in gas. Self-pinched transport requires higher net current fractions ($\geq 2\%$) and preliminary IPROP code results indicate that this appears achievable for small-radius intense beams in lower pressure gases (≤ 1 Torr). Several self-pinched transport concepts look promising. The importance of these results for both light ion fusion and heavy ion fusion is discussed.

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1. Introduction

The propagation of an intense ion beam from an accelerator to a fusion target plays an important role in the feasibility of both light ion fusion (LIF) and heavy ion fusion (HIF). Several possible ion beam propagation modes involve transport in neutral gas [1,2]. For ballistic propagation in gas, it is generally assumed that perfect charge and current neutralization occur. For self-pinch propagation it is generally desired that a sizeable net current be achieved. This paper discusses research designed to understand gas breakdown, and to examine fundamental limits on charge neutralization and current neutralization. Based on GAMBLE II gas breakdown experiments and IPROP simulations, a new understanding of gas breakdown is evolving [3]. Results summarized here suggest that both ballistic transport and self-pinch transport may be feasible in appropriate parameter regimes for LIF. Implications of these results for HIF are also discussed.

2. Charge Neutralization

For transport of intense ion beams in neutral gas, it is generally assumed that charge neutralization is perfect. Complete charge neutralization means that there is a neutralizing background of electrons with density n_e exactly equal to the total ion density (beam density n_b plus background ion density n_i) everywhere in space and time. In reality, there may be deviations from perfect charge neutrality. These can be referred to as macro or micro charge non-neutrality. Macro charge non-neutrality refers to global charge non-neutrality which, if uniform, leads to linear spreading of the beam; this effect can, within limits, be accommodated for by initial over-focussing of the beam. If macro charge non-neutrality is non-uniform, it may lead to serious distortions of the beam. Micro charge non-neutrality refers to local non-neutral clumps in the beam that can produce local transverse and axial spreading; these effects can produce emittance increases that may result in larger spot sizes. In this section, we examine the effects of micro charge non-neutrality.

The fundamental concept is that small charge clumps can only be charge neutralized down to some minimum potential $\phi_{\min}$ [4]. Such charge clumps may be produced by noise, instabilities, or other non-uniform beam effects. Consider first the effects of electron trapping to reduce the net potential (later, we will consider plasma shielding effects). Trappable electrons may be available

from walls, hot electron plasmas (created by the beam), or by gas ionization near the bottom of the potential well. A physical picture of how $\phi_{\min}$ occurs is most easily seen by transforming to the moving ion clump frame. In that frame, a stationary potential well of depth ϕ occurs. Electrons born in the potential well (e.g., by gas ionization) will have a velocity $-v_i$ and kinetic energy $1/2 m_e v_i^2$, where v_i is the original ion velocity and m_e is the electron mass. Electrons will be trapped only if $e\phi > 1/2 m_e v_i^2$. Therefore, the self consistent net potential will not be reduced below $e\phi_{\min} = 1/2 m_e v_i^2$. (Detailed calculations and simulation results show $e\phi_{\min}$ may actually be larger by a factor of 1-4 [5].)

If there are no other neutralizing mechanisms, a spherical ion charge clump of radius ξ and potential $e\phi_{\min}$ will simply expand to a radius $\gg \xi$. The resultant transverse microdivergence will be $\theta_\mu = [(m_e/M_p)(Z_i/A)]^{1/2}$ where Z_i is the ion charge state during transport, M_p is the proton mass, and A is the atomic number. Simultaneously, the resultant axial energy spread is $\Delta\epsilon_{||}/\epsilon_{||} = \pm 2\theta_\mu$. The characteristic clump expansion time is $\tau = (2\xi/v_i)/\theta_\mu$ and the characteristic transit length is $L = 2\xi/\theta_\mu$. These results are based solely on electron trapping arguments. The effects of plasmas, collisions, and an external magnetic field may enhance or reduce these results. Typically at the higher gas pressures (1-10 Torr), plasma shielding should reduce these results, whereas at lower pressures ($\lesssim 0.1$ Torr) these results may have significant consequences.

Computer simulations in 2-D with plasma to bunch density ratios of 0-100 have been performed. In general, wakes form and rapid oscillations occur, but the peak potential is still $\sim \phi_{\min}$ and the peak electric fields are still $\sim \phi_{\min}/\xi$. Emittance growth and axial energy spreading are observed [4].

For LIF parameters (electrical current density $J_i = 5 \text{ kA/cm}^2$ and $\beta = v_i/c = 0.1$ corresponding to 5 MeV p or 30 MeV Li) we only need $\xi \gtrsim 0.02 \text{ cm}$ and a clump electrical current $\sim 9 \text{ A}$ to produce $e\phi_{\min} = 1/2 m_e v_i^2 = 2.6 \text{ keV}$. The basic results predict (i) no dependence of θ_μ on diode voltage, (ii) proton $\theta_\mu = (m_e/M_p)^{1/2} \approx 23 \text{ mrad}$, (iii) non-protonic $\theta_\mu \geq$ proton θ_μ for proton-contaminated beams, and (iv) $\Delta\epsilon_{||}/\epsilon_{||} \approx \pm 2\theta_\mu = \pm 4.6\%$. The characteristic clump expansion time is $\tau \approx 0.6 \text{ ns}$ and the transit length is $L = 1.7 \text{ cm}$. The mechanism could easily occur in the "charge-neutral" region inside the diode, or in the gas transport region. Predictions (i) - (iv) are consistent with LIF data. It should be noted that this contribution to θ_μ would add in

quadrature with other contributions to θ_μ . To fully assess this mechanism for LIF, further research is needed (e.g., measurements of ion source micro-nonuniformities) to evaluate potential micro clump levels.

For HIF parameters (particle current 4 kA, particle current density $J_i^P = 12.7 \text{ A/cm}^2$, electrical current density (assuming $Z_i = 40$) $J_i = 508 \text{ A/cm}^2$, $Z = 55$, $A = 133$, and $\beta = 0.3$ corresponding to $\sim 6 \text{ GeV Cs}$), we would need $\xi \geq 0.4 \text{ cm}$ and a clump electrical current $\sim 230 \text{ A}$ to produce $e\phi_{\min} = 1/2 m_e v_i^2 = 23 \text{ keV}$. Results predict $\theta_\mu = 12.7 \text{ mrad}$, a characteristic clump expansion time of $\tau \approx 7 \text{ ns}$, and a transit length of $L = 63 \text{ cm}$. Note that the mechanism for LIF occurs on a microscale ($\xi \sim \text{sub mm}$, $\tau \sim \text{sub ns}$, $L \sim \text{cm}$), whereas for HIF it occurs on a macroscale ($\xi \sim \text{cm}$, $\tau \sim 10 \text{ ns}$, $L \sim \text{meter}$). For HIF it would be unlikely to have a high level of macro ion clumps, because the beam should be well phase-mixed by the time it reaches the final transport region. Also, the most likely instability to generate bunches is the ion-electron two-stream instability, and this has been shown to be benign [6]. Thus, for HIF, this mechanism does not appear to be troublesome; however this conclusion should be verified, especially for the lower pressures ($\lesssim 10^{-1} \text{ Torr}$).

3. Current Neutralization

For ballistic transport of ion beams in gas, it is generally desired that current neutralization be perfect. Complete current neutralization means that there is a neutralizing background electron current density J_p that exactly matches the ion beam current density J_b . Overall, the net current is $I_{\text{net}} = I_b + I_p$, where I_b is the beam current and I_p is the plasma current. To achieve a small I_{net} means that the background electrical conductivity σ must rise quickly so that $t_d \gg t_b$ is achieved very early in the beam risetime ($< 1 \text{ ns}$ typically). Here the magnetic diffusion time is $t_d = 4\pi\sigma r_b^2/c^2$, t_b is the beam pulse length, r_b is the beam radius, and c is the speed of light. In addition, σ must be high enough throughout the pulse to avoid the filamentation instability.

The physical processes involved in gas breakdown and the growth of σ include ion impact ionization, secondary electron impact ionization, electron avalanching, and late time Ohmic heating [7]. Energetic electrons can be created in ionizing collisions between beam ions and neutral gas atoms (ion impact ionization), in momentum-changing collisions between beam ions and free electrons (knock-on collisions), and from free electron acceleration in electric fields

(avalanching). in the 1 Torr pressure regime, the mean free path between collisions can be of the order of the beam radius; then the gas breakdown processes are “non-local” and they must be followed accurately in space and time.

The first experiments designed to study beam-induced gas breakdown and conductivity growth have been performed on the GAMBLE II accelerator at NRL [3]. In these experiments, a 1 MeV proton beam produced in a pinch reflex diode is injected through a 2 μm polycarbonate foil into a 40 cm long collimator section, and then through another 2 μm polycarbonate foil into an experimental transport section. The collimator section has entrance and exit apertures of 1.5 cm radius, and is filled with 1 Torr air. A 1 kA/cm² beam enters the experimental section which is filled with helium, air, or neon at pressures in the range of 0.25 - 4.0 Torr. Diagnostics include carbon activation, K α X-ray imaging of aluminum targets, a visible light photodiode, a framing camera, net current B-dot monitors, HeNe interferometry to measure electron density, and diode voltage and current monitors. Net current fractions ranged from 2.3% to 8% and peak electron densities were of order 10^{15} cm^{-3} corresponding to ionization fractions of 0.6% to 4.6%.

IPROP and DYNAPROP simulations were performed to evaluate net currents and electron densities. IPROP is a 3-D EM hybrid code with a full tensor conductivity [8]. Beam ions are treated as particles, and fast electrons ($>100 \text{ eV}$) are also treated as particles. Slow electrons ($< 100 \text{ eV}$) are treated as a fluid, while plasma ions are treated as a stationary background. Maxwell’s equations are used to solve for the fields. The important unique feature is that the fast electrons (e.g., knock-ons and runaways) are followed explicitly, and that these are the particles responsible for non-local breakdown effects. Because azimuthal symmetry was assumed, IPROP was used in a 2 1/2-D mode. DYNAPROP is a 1-D code based on a resistive plasma model in which the beam dynamics are described by an envelope equation [9]. The plasma properties (density, temperature) are determined by rate equations, and the net current is calculated from a circuit equation.

Figure 1 shows a comparison of the net current in the GAMBLE II experiments with IPROP and DYNAPROP results. Many such comparisons have been made; this example illustrates the main effects. If fast electrons are not included, note that both IPROP and DYNAPROP predict a net current much higher than that observed in the experiment by the B-dot

monitored at $r = 4$ cm. By including fast electrons in IPROP good agreement is obtained with the experiments. Note that fast electrons outside the beam radius contribute significantly to the return current, so that the net current at $r = 4$ cm is considerably smaller than the net current at the beam radius of 1.5 cm. These comparisons show that fast electrons and non-local effects play an important role in gas breakdown and that the magnetic field within the beam channel can be larger than that measured outside the beam channel.

IPROP has also been used to compare with net current measurements for the barrel diode geometry of PBFA II, including applied magnetic field effects. IPROP predicts $\geq 99.8\%$ neutralization for 1 MeV Li ions in 4 Torr argon on PBFA II. It is important to note that the net current fraction here is even smaller than in the GAMBLE II experiments because the total current is higher (~ 1 MA instead of ~ 7 kA), the ions are Li^{+3} which ionize faster than protons, and the gas is argon which is easier to ionize than helium.

These results are extremely encouraging and suggest that, from a net current viewpoint, ballistic transport in gas appears to be a viable option for both LIF and HIF.

4. Self-Pinched Propagation

For self-pinched transport, the ion beam is focused down to a small radius and then transported at small radius to the target. The ion beam is contained by the net self magnetic field. Different versions of this mode use, e.g., a low pressure gas, a laser preformed channel with radius larger than the beam radius, an annular preformed plasma, etc. For all cases, the required net current in the "channel" is $I_c = 1/2(R/r_s)^2\theta_\mu^2 I_m$ where R is the initial beam radius, r_s is the channel spot radius, θ_μ is the beam microdivergence, and $I_m = \beta\gamma(A/Z)M_{pc}^3/e$ is the Alfven current. Typically net currents of about 50 kA are needed for LIF beams, and somewhat smaller net currents are needed for pre-stripped HIF beams.

The strategy for LIF is to note that for typical LMF parameters only $\sim 2\%$ net currents are needed for self-pinched transport. Since many parameters control the net current (beam radius, total current, ion species, gas type, gas pressure, etc.), it is conceivable that self-pinched transport may work. Past work at LLNL, LBL, SNL, and NRL has always indicated that gas breakdown is too good in the 1 Torr regime and that net currents are too small for self-pinched transport for LIF or HIF. However, by going to lower pressures, and/or by using a laser preformed plasma,

sufficiently large net currents may be achievable.

Recent IPROP simulations with protons indicate that sizeable net currents should be achievable [10]. As the beam intensity increases ($50 \rightarrow 500$ kA, $3 \rightarrow 0.75$ cm radius) and the pressure decreases below 1 Torr, IPROP simulations show a trend toward higher net current fractions in the range of 1-12%. A different self-pinched transport scheme uses a preformed annular plasma (with inner radius about equal to the beam radius) in < 0.1 Torr gas. For a 50 kA, 45 MeV proton beam in 0.001-0.1 Torr nitrogen, IPROP simulations predict net current fractions of 10-40% for this annular plasma transport scheme. These preliminary results are encouraging.

5. Conclusions

Gas breakdown research has produced the following results of importance to both LIF and HIF:

(1) Charge neutralization of beam micro clumps will be limited to finite values of $\phi_{\min}$, which can lead to divergence growth and axial energy spreading. At pressures $\gtrsim 1$ Torr, plasma shielding should substantially reduce this effect.

(2) Current neutralization for beam injection into neutral gas has been studied in the GAMBLE II experiments. The importance of fast electrons (knock-ons and runaways) has been established in IPROP simulations, which are in agreement with the experiments. For LIF parameters with pressures $\gtrsim 1$ Torr, very small net current fractions ($\ll 1\%$) appear feasible, permitting ballistic transport in gas.

(3) Self-pinched transport requires higher net current fractions ($\gtrsim 2\%$) and preliminary IPROP code results indicate that these appear achievable for small-radius intense beams in lower pressure gases ($\lesssim 1$ Torr). Several self-pinched transport concepts looks promising.

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Figure 1 Net current fraction contained within a given radius for the GAMBLE II experiments, IPROP 2 1/2-D simulations, and DYNAPROP 1-D simulations (1 MeV p, ~ 6 kA, ~ 1 kA/cm², $r_b = 1.5$ cm, B-dot at $r = 4$ cm, 1 Torr He).

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