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# IPROP Simulations of the GAMBLE II Proton Transport Experiment*

D. R. Welch
Mission Research Corporation
1720 Randolph Road SE, Albuquerque, NM 87106 USA

*Abstract*

We have simulated the proton transport of the 6-kA, 1-MV GAMBLE II experiment using a modified version of the IPROP particle-in-cell code. IPROP now uses a hybrid model in which plasma electrons are divided into high-energy macro particle and thermal-fluid components. This model includes "knock-on" bound-electron collision and runaway sources for high-energy electrons. Using IPROP, we have calculated net currents in reasonable agreement with the experiment ranging from 5–11% of the total current in pressures from 0.25–4 torr helium. In the simulations, the pinch current sample by the 1.5-cm beam was 2–3 times larger than the net current at 4-cm radius. The attenuation of net current at larger radii was the result of a highly-conductive energetic component of plasma electrons surrounding the beam.

Having benchmarked IPROP against experiment, we have examined higher-current ion beams with respect to possible transport for inertial confinement fusion. We present some preliminary findings.

## I. INTRODUCTION

The efficient transport and focusing of intense ion beams is essential for ion-driven inertial confinement fusion (ICF).[1,2] Research in the area of ion-beam transport is just beginning. Two of the basic concepts considered for ion beams are ballistic[1] and self-pinched[3] transport. In the ballistic mode, a low-pressure gas provides near ballistic transport by effectively neutralizing all self fields. The most exciting concept is self-pinched transport where the gas and gas pressure (~1 torr) are chosen to provide only partial current neutralization so that the residual magnetic field confines the beam. If sufficiently-high magnetic fields can be attained, even a hot beam can be pinched and the demands on accelerator emittance becomes somewhat less stringent.

The physics of the ballistic and self-pinched transport is complex, characterized by nanosecond breakdown of the gas.[2] Extremely rapid gas breakdown is necessary for the >99% current neutralization desired for good ballistic transport. For self-pinched transport, sufficient magnetic field must penetrate the plasma generated in the gas to provide the confinement before the gas becomes highly conductive. The breakdown process is dominated by an electric-field driven avalanche of secondary electrons which may involve sufficient fields to produce electron runaway.[4] The transport of these plasma electrons into the ion beam to provide neutralization may be hindered by applied or beam-generated magnetic fields. In addition, at the pressures near a torr, electron **E**×**B** drift may be as important as Ohmic current ($\sigma$E), where the conductivity $\sigma = en_e/m_e\nu_m$, $n_e$ is the plasma electron density and $\nu_m$ is the momentum transfer frequency. We have modified the IPROP charged-particle beam propagation code,[5] which had used a simple scalar conductivity model for plasma electrons, into a hybrid code which assumes plasma electrons have both fluid and high-energy particle components. This model includes a formalism for electron runaway.

In this paper, we first discuss the modifications to the IPROP code necessary to model breakdown in a low-pressure gas. Using the new modeling, we present simulations of the GAMBLE II proton transport experiment at Naval Research Laboratory (NRL). Energetic plasma electrons are shown to greatly attenuate net currents (beam plus plasma current) outside the ion beam. We then proceed to discuss preliminary findings for high-current ion beams with respect to ballistic and self-pinched transport for ICF.

## II. HYBRID PLASMA-ELECTRON MODEL

The behavior of the secondary plasma electrons is the key to quantifying the gas breakdown driven by an intense ion beam. If the plasma-electron population remains highly collisional with a thermal distribution, plasma electrons drift and diffuse slowly. However, energetic electrons (>100 eV) have much longer mean-free paths. The non-local energy deposition of these fast secondaries carries conductivity away from or even ahead of the beam. In addition, these electrons have a much smaller collision frequency and, thus, contribute more to conductivity. The energetic electrons attempt to decrease the net current as they co-move with the ion beam. Thus, a non-thermal component to the plasma-electron distribution has a significant impact on gas breakdown.

The two sources of energetic electrons are "knock-on" collisions and runaway. The velocity distribution of knock-on bound electrons is forward-directed in an impact ionization event. The energy distribution is roughly as $1/E^2$ with the maximum secondary velocity that of the impacting electron or twice the impacting ion velocity. If an electron in an electric field increasingly gains momentum between

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collisions, it is said to be in runaway. Runaway in a given gas typically occurs above some E/$p$ threshold. As the gas breaks down, the rising current drives an inductive electric field which attempts to resist further net-current rise. This field pushes electrons ahead of the ion beam. For a weakly relativistic ion beam, the beam space charge precedes the beam front which draws in electrons. These trapped electrons have a strong effect on both net current, and possibly, instability growth.

We have characterized the runaway phenomenon with the PIC code IPROP. By turning off the electromagnetic field solver and substituting uniform electric (and/or magnetic) fields, we allow swarms of electrons to drift in the field and scatter elastically and inelastically (including ionization, which creates new particles) with various gases (Ar, $N_2$, and He). The elastic scattering is assumed to be isotropic with momentum-transfer cross sections taken from experimental data. Using an initial 10,000 particles, we approximate the full velocity distribution and characterized drift velocities, electron average energies, and collision frequencies.

To determine the source of runaway electrons as a function of E/$p$, we define a cutoff energy, $E_c$, above which an accelerating electron is assumed to be in runaway. We typically choose $E_c$ = 100 eV for two reasons. First, electrons below 100 eV cannot move far on the nanosecond time scale of gas breakdown. Second, for $E$ > 100 eV, electron binding energies become less important and $\nu_m$ declines rapidly. The steady-state depletion rate ($\alpha_r$) of low-energy plasma electrons accelerating past $E_c$ scales as $(E/p)^2$ for nitrogen and helium. The runaway depletion exceeds the avalanche production rate for electrons below 100 eV when E/$p$ > 2 MV/cm-atm in $N_2$ and >0.5 MV/cm-atm for He. The velocity distribution of the runaways as they exceed $E_c$ is peaked in the direction of **E**. The root-mean squared (RMS) velocity perpendicular to **E** is roughly that of the velocity parallel to **E** with only a slight dependence on E/$p$. At very high E/$p$, the velocity becomes more strongly peaked in the **E** direction. The runaway electrons can be incorporated into a simulation code as a volumetric source of new macro particles emitted from a colder fluid of electrons.

Having characterized the runaway source, in IPROP we now divide plasma electrons into two components: a low-energy electron fluid and a mobile high-energy macro particle group. We model the bulk of the electrons as a fluid, particularly late in time when the plasma is collisional and densities are high, to avoid temporal resolution of the plasma oscillations which should physically damp. Plasma electrons with energies $E < E_c$ eV are treated as a fluid with $T_e$, $\nu_m$, and $\alpha$ — all functions of E/$p$ and $p$. Electrons can either be removed from the fluid through the runaway sink or be added to the fluid due to electrons slowing down below $E_c$. Macro-particle electrons are created due to runaway and energetic forward scattering of a bound electron from a neutral gas molecule, which produces an electron with energy above $E_c$.

In IPROP, Maxwell's equations are solved with two current-density sources $\mathbf{J}_b$ and $\mathbf{J}_p$ (macro particles and fluid plasma). $\mathbf{J}_b$ is simply the sum of all macro-particle current including that of plasma-electron ($E > E_c$), beam and wall emission particles. The fluid plasma motion is the sum of Ohmic currents and electron **E**×**B** drift (ions can not move on breakdown time scales).

## III. GAMBLE II SIMULATIONS

When plasma-electron motion is not inhibited by strong external magnetic fields, the net current produced by an ion beam in an ~1-torr gas may be quite small as described in Section II. The GAMBLE II proton beam experiment at NRL produced net currents that were only a few percent of the 4–8 kA (30 ns rise time) proton current.[6] The experimental and simulation geometry consisted of a 20-cm long, 7.6-cm radius metal pipe and a 1.5-cm proton beam with a 50 milliradian divergence. We assume constant energy (0.7–1 MV) and a shot-dependent current rise to a constant current. The total beam pulse length was 68 ns. For direct comparison with experiment, we positioned a $B_\theta$ probe at $z$ = 11 cm and a 4-cm radius. The net current measured at $r$ = 4 cm is not necessarily the pinch current sampled by the ion beam. The simulations suggest that significant plasma current exists between the beam and the monitor, reducing the observed net current up to a factor of 3. For three helium shots, IPROP and experimental net current fractions (net current to beam current ratio, $f_{net}$) at $r$ = 4 cm were compared. We find agreement of the IPROP code calculations at $r$ = 4 cm to within 30% of the measurements with 0.047–0.106 net current fractions.

The effect of energetic secondaries, of which electron runaway is the primary source early in time and knock-ons late in time, is to further attenuate magnetic fields outside the beam radius. In Fig. 1, we compare the radial dependence of the net current for IPROP simulations with and without the energetic electron component for shot 5479 at 1 torr. Although the net current at 4 cm in the full IPROP simulation is only half that of the simulation without runaways (and knock-ons), the net current at the beam radius is actually enhanced 20%. In the full simulation, hot electrons diffuse outwardly in radius and produce additional secondary electrons in the runaway simulation. These electrons attenuate the net current greatly at larger radii. In the beam region where self-magnetic fields are significant, the hot electrons are less collisional than the thermal fluid electrons with $\omega_c/\nu_m \approx$ 2–4 at 1 torr. Any further decrease in collisionality degrades the conductivity across the magnetic field lines. Thus, the IPROP simulations, which include energetic electrons, yield a greater net current at smaller radii (10–20% of beam current) than the simulations without energetic electrons.

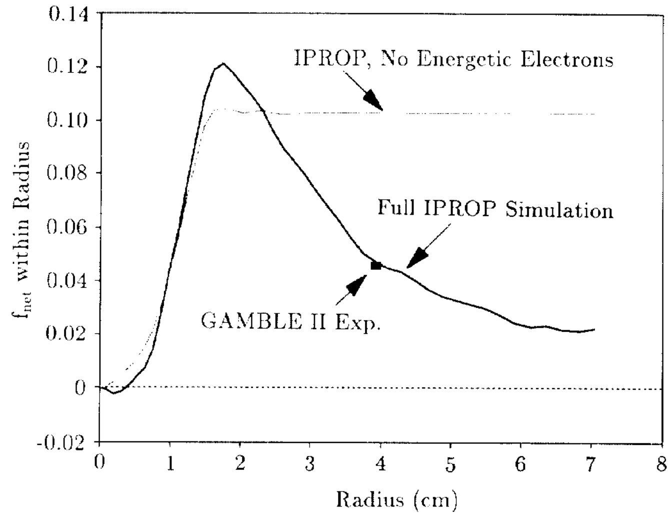


Fig. 1. The net current fraction calculated at all radii is plotted for IPROP simulations of GAMBLE II shot 5479 in 1 torr helium with and without energetic electrons. The values were calculated 68 ns into the simulations 10 cm from injection. The maximum experimental value at 4-cm is also plotted.

# IV. INITIAL HIGH-CURRENT RESULTS

We have begun examining transport of more intense proton beams (50–500 kA, 0.75-3 cm radii) with IPROP and now present some preliminary results. Simulations show a trend to higher net current fractions for more intense beams in lower-pressure helium gas with fraction ranging from 1–12% near the injection plane. Prospects for good ballistic look promising for large radius beams (>1 cm) in helium near 1 torr. The net current may actually drop with propagation distance as energetic co-moving electrons build up near the beam front. Pre-ionization and a higher atomic number gas such as argon reduced net current fractions to <1%.

We simulated a 100 kA, 5-MeV proton beam which exhibited adequate self-pinched propagation. The beam was propagated 40 cm showing a pinching radius for beam slices more than 4 ns into the beam pulse. This time corresponds to the point at which the effective pinch current exceeded 2 kA. This current roughly matches the 20-milliradian divergence of the beam. Although the maximum pinch current declined away from the injection point, a pinch current of 5 kA (7 ns into the beam pulse) was calculated 20 beam radii from injection.

Another promising configuration for self-pinched transport involves pre-ionization of an annular plasma channel with inner radius roughly that of the beam radius (annular plasma transport, APT) in a <100 mtorr gas. IPROP and IVORY (a pure PIC electromagnetic cousin of IPROP) simulations predict a 6–20 kA pinch current for a 50 kA, 45-MeV proton beam in 10–100 mtorr nitrogen. The plasma provides excellent charge neutralization early in time. The gas provides enough collisionality to reduce the current neutralization and improve the charge neutralization at the higher pressures. The beam self-fields reached an equilibrium 2 ns into the pulse for 100 mtorr pressure. At pressures of <100 mtorr, the plasma channel is necessary to provide the conditions for self-pinched transport.

# V. CONCLUSIONS

The IPROP code has been modified to include a hybrid model for plasma electrons in which plasma electrons have fluid and high-energy particle components. The high current neutralization of the GAMBLE II proton beam was found to be caused by a halo of highly conductive electrons and their secondaries surrounding the beam. Preliminary examination of ion-beam transport for ICF shows good ballistic transport for >1 torr gas. Sufficient net currents for self-pinched transport looks possible for lower pressures and intense beams. The use of an annular plasma has yielded 10–40% net current fractions in 1–100 mtorr nitrogen. In future work, we will examine long-distance ion-beam equilibrium and stability.

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