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Current Neutralization in Ballistic Transport of Light Ion Beams

RICHARD F. HUBBARD, STEVEN P. SLINKER, MARTIN LAMPE,
GLENN JOYCE, AND PAUL OTTINGER

Beam Physics Branch
Plasma Physics Division

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Intense light ion beams are being considered as drivers to ignite fusion targets in the Laboratory Microfusion Facility (LMF). Ballistic transport of these beams from the diode to the target is possible only if the beam current is almost completely neutralized by plasma currents. This paper summarizes related work on relativistic electron beam and heavy ion beam propagation and describes a simple simulation model (DYNAPROP) which has been modified to treat light ion beam propagation. DYNAPROP uses an envelope equation to treat beam dynamics and uses rate equations to describe plasma and conductivity generation. The model has been applied both to the high current, 30 MeV Li^{+3} beams for LMF as well as low current, 1.2 MeV proton beams which are currently being studied on GAMBLE II at the Naval Research Laboratory. The predicted ratio of net currents to beam current is $\sim$0.1-0.2 for the GAMBLE experiment and $\sim$0.01 for LMF. The implications of these results for LMF and the GAMBLE experiments are discussed in some detail. The simple resistive model in DYNAPROP has well-known limitations in the 1 torr regime which arise primarily from the neglect of plasma electron transport. Alternative methods for treating the plasma response are discussed.

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CURRENT NEUTRALIZATION IN BALLISTIC TRANSPORT OF LIGHT ION BEAMS

I. INTRODUCTION

Transport of intense light ion beams to an inertial fusion target has been studied for some time. Interest in recent years has centered on the proposed Laboratory Microfusion Facility (LMF) which would be used to study high-gain, high-yield targets. The targets would be heated by intense laser or particle beams with peak power of several hundred TW delivered on a 10-nsec time scale. Light ion beams, which would be generated by a number of diodes employing pulsed power technology developed for the HERMES-III accelerator, are one potential candidate driver for such a system.[1]

Most recent experiments with intense ion beams employ a barrel diode geometry and involve beam transport distances of only ≈ 10 cm. However, LMF will require the beam to be extracted from the diode and propagated over a standoff distance L of several meters.[2-7] The beam radius R at the target located at $z = L$ must be ≈ 1 cm for the targets envisioned for LMF. The standoff requirement arises from several considerations. First, the diode and other expensive hardware must be shielded from the thermonuclear blast from the target. In addition, current plans employ time-of-flight bunching to increase the beam power as it propagates to the target. This requires a minimum distance for slower ions in the front of the beam to be overtaken by those ions in the tail of the pulse. Finally, since the number N_d of diode modules is expected to be $\approx$10-30, geometric packing constraints also limit the minimum standoff distance.

In contrast to inertial fusion energy systems which might be used for production of electricity, LMF does not require a high pulse repetition rate. Thus, beam transport in an LMF target chamber could in principle be assisted by inexpensive sacrificial structures such as current-carrying wires[5] or low-mass walls.[6] However, such structures could interfere with diagnostics and would create a radioactive disposal problem. Free-standing laser-guided discharges, which do not involve sacrificial structures, have been used to transport single ion[7] and electron[8] beams, but control of return current paths becomes exceedingly difficult for

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multi-beam systems such as LMF. For these reasons, the leading candidate for light ion transport for LMF has been ballistic focusing in a low pressure gas.[2-4] A solenoidal lens would be used to focus the beam over a distance of ≈150 cm. The beam would quickly ionize the gas, generating a plasma which could provide nearly complete space charge and current neutralization. A current-neutralized beam is one in which the beam current density J_b flowing in the z-direction is balanced by plasma current density $J_p = -J_b$ flowing in the opposite direction, so that the net current $I_n = \int dr 2\pi r(J_b + J_p)$ and azimuthal magnetic field B_θ are zero. An experiment to measure I_n in a gas cell with a moderate current (<10 kA) ion beam is in progress on GAMBLE II at NRL.

Analyses of the ballistic-focusing scheme for LMF have generally assumed complete charge and current neutralization, so individual ions travel on straight line orbits after being focused (except for scattering with the neutral gas.) With this assumption, the beam radius R at the target is primarily determined by the microdivergence θ_μ. However, at the 1 torr pressures envisioned for LMF, the plasma is weakly collisional, and finite resistivity will thus prevent complete current neutralization.[9-13] The resulting magnetic field will in general be time-dependent and will cause different portions of the beam to be focused to different locations. Even if the high conductivity "freezes" the magnetic field at a nearly constant value for most of the beam pulse, the faster particles in the beam tail will be deflected less strongly than those in the beam head. The result will be an increase in the minimum radius or "spot size" R_s which can be achieved. The effect is similar to chromatic aberrations which can occur in either optical or particle beam systems which employ focusing lens elements.

Many of the problems to be encountered in ballistic transport of light ion beams have been studied for relativistic electron beams and/or heavy ion fusion beams. Section II of this report summarizes some of the studies and techniques developed in those communities and discusses how they may be applied to the light ion beam fusion problem. In Section III, we describe a simple simulation model for treating light ion beam transport, based on the DYNAPROP[11] code originally developed to study the propagation of intense electron or heavy ion beams in air. For the present study, a new helium atomic physics and conductivity generation model has been installed. DYNAPROP simulation results for the current experiment on GAMBLE II and for LMF are presented in Section IV. These are intended only as a first cut to scope out the problem of beam charge and current neutralization, quickly and at minimal expense.

DYNAPROP assumes that the beam-generated plasma can be characterized by a local resistivity. Resistive models have been widely used to model electron and ion beam propagation at pressures of 1 torr and above. These models assume that plasma electrons remain at the same location where they are created. This assumption is reasonable in dense gases (~760 torr) because collisions with neutrals strongly inhibit electron transport. Also, these models calculate rate coefficients and collision frequencies based on the calculated electron temperature T_e or, in some cases, the ratio E/n_g of the electric field E to the neutral gas density n_g. (The E/n_g models are usually based on data obtained from discharges.) Effects of detailed changes in the electron distribution function f_e are thus neglected.

The local conductivity assumption is highly questionable at gas densities of 1 torr.[14-19] In the presence of an ion intense beam, f_e will be highly nonmaxwellian and far different from that produced in an electric discharge. In general, there will be a significant component of high energy electrons generated by close collisions between beam ions and background neutrals or ions. Fast electrons will also be produced by the strong electromagnetic fields in the beam head. The kinetic and nonlocal response of these electrons plays a significant role in determining the degree of current neutralization. In section V, we outline the options for resolving these difficult issues, and a possible sequence of numerical and analytical studies to achieve this end.

II. RELATED BEAM PROPAGATION PROGRAMS AND STUDIES

A. Intense Relativistic Electron Beam Propagation

A large effort was undertaken during the 1980's to produce intense relativistic electron beams and to study the propagation of such beams through gases and plasmas. This effort, often referred to as the Charged Particle Beam (CPB) program, was centered around two major experimental facilities: the Advanced Test Accelerator (ATA) at the Lawrence Livermore National Laboratory,[20-22] and the RADLAC accelerator at the Sandia National Laboratories.[23,24] ATA operated at 1 Hz and produced electron beams with energies of 10-40 MeV and beam currents of up to 10 kA. RADLAC was a single shot device designed to study the physics of a higher current regime. It produced beams with energies of 10-16 MeV and propagated beams with currents up to 60 kA. Beam propagation and accelerator development has been terminated at both facilities. The only active electron beam propagation facility is SuperIBEX at the Naval Research Laboratory.[8,25,26] It produces a 5 MeV beam with currents of up to 30 kA for propagation studies.

The primary focus of electron beam propagation research has been the resistive hose instability.[8,20,24-33] This instability causes complete disruption of propagation after a short distance unless specific steps are taken to reduce its growth. The instability is controlled to a large part by managing the details of plasma and conductivity generation by the beam as it passes through the air. Thus, a number of analytic and computational models were developed to study beam dynamics, electromagnetic field evolution and plasma/conductivity generation.

The propagation studies have primarily concentrated on the high density regime (0.1-1 atm) where the plasma is clearly resistive. Plasma return currents can then be treated with an Ohm's law formalism. Because the mean free path for plasma electrons in this regime is generally much smaller than the beam radius, the plasma conductivity can be said to be "local", which greatly simplifies the analysis. A second regime which was studied in some detail was the ion-focused regime (IFR),[20-22,32-37] a low density regime (10^{-6}-10^{-4} atm) in which the beam density is larger than that of the beam-generated plasma, and plasma electrons have mean free paths which are large compared with the beam radius. IFR techniques have been extensively used in the CPB program to "condition" beams prior to injection into the atmosphere in order to minimize hose instability growth.[20,24-26,32,33] ATA also employed ballistic focusing in a vacuum regime where beam particles are weakly deflected by beam-generated electromagnetic fields.[33,36] This situation is similar to that expected for LMF beams using ballistic focusing except that the latter case, the self-fields are purely magnetic.

The 1 torr regime planned for light ion fusion transport was also studied both theoretically and experimentally in the CPB program. Some early electron beam experiments suggest a stable propagation "window" where rapid conductivity production stabilizes the resistive hose instability while collisional effects suppress two-stream instabilities.[31] The ratio of the peak net current to peak beam current in these experiments,[31] as well as later experiments on ETA and ATA,[36] was typically 0.3-0.5 in the 1 torr pressure regime. Early theoretical studies used resistive models and also predicted net currents in reasonable agreement with the experiments.[31] However, more detailed studies in the mid 1980's suggested that the local conductivity assumption inherent in resistive models is not valid at low pressures. Several studies predicted that the net current is strongly influenced by a population of fast secondary electrons. The apparent agreement between theory and experiment reported in Ref. 31 may thus have been fortuitous. Beam propagation in the 1 torr regime was not considered an essential issue for the CPB program, and little theoretical work has been attempted in recent years. The complex problems associated with treating this regime are discussed in Section V.

B. Heavy Ion Beam Propagation in Fusion Target Chambers

Since the late 1970's, heavy ion beams have been considered as possible drivers for inertial fusion.[38,39] Such beams have obvious similarities with the light ion fusion beams; for example, the pulse length and beam power required for target compression and heating are similar. However, ion range scaling in the target pushes the energy to ~10 GeV with a corresponding reduction in beam particle current to 10's of kA. The heavy ion beam fusion program in the U. S. has concentrated almost exclusively on the development of induction accelerator technology necessary to reach this goal. Although accelerator parameters are strongly constrained by restrictions incident to propagation in the target chamber, relatively little effort has been spent on this problem. Because heavy ion fusion is being considered primarily as an inertial fusion energy source rather than a driver for the single-shot LMF, the typical parameters are somewhat more stringent.

Some of the past and present theoretical studies of heavy ion beam propagation in a target chamber are closely related to the problems to be encountered in LMF.[9-13,38-46] In particular, there were a number of studies of both pinched and ballistic propagation in the 1 torr regime which looked at axisymmetric transport of the beam and various beam-plasma instabilities.[9-13,40,44,45] Envelope simulation codes which assumed a resistive background plasma were developed by Yu, et al.[9,10] and Hubbard, et al.[11] Studies of ballistic propagation in this regime were largely abandoned around 1980 in part because of the complexity of the atomic and plasma physics. Recent studies of pinched propagation using a resistive model have been carried out by Fawley, Yu and Stewart.[45] These models may be applied with little modification to light ion beam transport, but it must be kept in mind that there are serious questions as to the validity of these models in the 1 torr regime.

Most studies of heavy ion beam fusion final transport have concentrated on a lower pressure regime where the plasma is nearly collisionless and the resistive models clearly do not apply. At low pressures ($<<10^{-3}$ torr), simple vacuum ballistic transport is theoretically possible but is likely to be impractical for a reactor which must be pulsed at greater than 1 Hertz.[38,39,46] Above 10^{-3} torr, ballistic transport is still possible, but beam stripping and plasma production complicate the analysis. We have recently studied the physics of these processes[42] using the FRIEZR simulation code.[33,34] We have also recently proposed a scheme for pinched propagation using a preionized plasma channel which may be possible in the pressure range of 10^{-2}-10^{-1} torr where the plasma is quasi-collisionless.[42,43]

C. Plasma and Conductivity Production in the Resistive Regime

In this section, we discuss a "generic" model for treating plasma and conductivity production by a beam propagating in a resistive plasma. The net current produced for a given set of beam and gas parameters is determined to a large extent by the details of conductivity generation. Many of the codes developed at NRL and other institutions to treat conductivity generation have the same fundamental structure and assumptions.[9-11,29,30,47-55] The plasma is assumed to be resistive with a conductivity σ defined by

$$\sigma = \frac{n_e e^2}{m_e(\nu_{en} + \nu_{ei})} \tag{1}$$

where n_e is the electron density and ν_{en} and ν_{ei} are the electron-neutral and electron-ion collision frequencies. A key assumption is that the gas is sufficiently dense that the collisions prevent plasma electrons from being transported from the position where they are created. This "local conductivity" assumption simplifies the model considerably.

The electron density is derived using a rate equation which typically has the form

$$\frac{dn_e}{dt} = \mu J_b + \alpha_e n_e - \beta_r n_e^2 - \beta_a n_e, \tag{2}$$

where the rate coefficients μ, α_e, β_r and β_a describe beam impact ionization, avalanche ionization, recombination and attachment, respectively. The rate coefficients are usually specified as functions of either the electron temperature T_e or the ratio E/n_g of the electric field E to the gas density n_g. The rates depend on the detailed atomic and molecular cross sections for the background gas. The collision frequencies are also usually specified as functions of T_e or E/n_g.

The model is closed by calculating the electric field and the electron temperature. In the simplest models, the electric field is purely inductive and axial with $E = E_z$ determined from a circuit equation based on a transmission line model of the beam-plasma system. More elaborate models solve Maxwell's equations in the resistive regime where the plasma current density is given by $J_p = \sigma E$. In some models, the electron temperature T_e is determined from a rate equation of the general form

$$\frac{d}{dt}\left(\frac{3}{2}n_e T_e\right) = \mu J_b \Delta\epsilon + \sigma E^2 - n_e W_i(\alpha_e - \beta_r n_e - \beta_a) - Q_e, \tag{3}$$

where $\Delta\epsilon$ is the energy deposited in the plasma per electron-ion pair, W_i is the ionization potential and Q_e represents cooling due to nonionizing collisions between electrons and neutrals or ions. In many cases, an approximate equilibrium exists in which the last term is balanced by the σE^2 ohmic heating term, and the plasma is weakly ionized ($n_e << n_g$). In this regime, one can show that T_e may be specified as a function of E/n_g, which eliminates the need for a rate equation to determine T_e.

The model described above is typical of the type used in beam propagation codes. Beam-induced ionization of air is in reality much more complicated owing in part to the large number of species and possible reactions. Detailed air chemistry codes, such as NRL's CHMAIR,[47] ETWAC[48] and HITECH[49] codes, use rate equations of the form

$$\frac{dn_i}{dt} = S_i + \sum_{j,k} R_{jk}(T_m) n_j n_k . \tag{4}$$

The indices i, j, and k represent different species, S_i is a source term for species i, and the *rate coefficient* R_{jk} *is in general a function of one of the temperatures* T_m. For example, in CHMAIR, dozens of species and reactions are followed, and the model calculates electron, gas and N_2 vibrational temperatures. Because of this complexity, it is fortunate for the purposes of analysis that a single monatomic gas such as He will probably be used as the propagation medium in LMF.

D. Beam Dynamics and Maxwell's Equations in Beam Simulation Codes

Self-consistent simulation codes which treat beam propagation in the resistive regime require that a conductivity generation model such as those described above be coupled to a beam dynamics model and a model describing the electromagnetic fields. Beam dynamics in simulation codes for intense beam propagation may be approached in several ways. The simplest models employ an axisymmetric envelope equation model such as the Lee-Cooper model.[52] Envelope models assume that the transverse beam velocity $v_\perp$ is much smaller than the axial velocity v_z (paraxial approximation) and that the beam current density profile $J_b(r)$ does not change its shape as the beam expands or contracts. The DYNAPROP code described in Section III is one such model. Codes such as NRL's VIPER model[28] and LLNL's EMPULSE model[31,53] use the envelope model to treat axisymmetric (m = 0) beam dynamics and a linearized phenomenological model such as the spread mass or multi-component model to treat deviations from axisymmetry. These codes have been extensively used to study resistive hose instability in relativistic electron beams.

Particle simulation codes offer more complete description of beam dynamics but are computationally more expensive. NRL's axisymmetric SIMM0 code[54] treats electron beam propagation in the resistive regime and assumes that the axial velocity $v_z \simeq c$ is constant. In this case, the quantity $\tau = t - z/c$ is a constant of the motion for beam particles, and these particles remain a constant distance from the beam head. SARLAC[29] and SIMM1[55] are three-dimensional extensions of SIMM0. The NRL simulation codes FRIEZR[33,34,42] and ELBA[56,57] do not assume constant v_z and do not assume that the plasma can be characterized by a resistivity, but rather follow the motion of beam and plasma particles using a fully-relativistic particle pushing algorithm.

The simplest treatments of electromagnetic fields in the resistive regime employ a circuit model which has a system inductance that varies logarithmically with the ratio of the beam radius to the wall radius. For ultrarelativistic beams, the wall radius in the inductive logarithm is replaced by the radius at which electrostatic neutralization occurs, if the latter is smaller. The model used in the DYNAPROP code is discussed in more detail in Section III.B. VIPER, EMPULSE, SIMM0 and SARLAC use Lee's ultrarelativistic approximation to the full 3-D Maxwell's equations.[27,28] In this approximation, the field equations involve only derivatives in τ and r with no explicit t or z dependence. The z dependence occurs implicitly through the dynamics of the beam as it propagates. FRIEZR,[34] ELBA[56,57] and IPROP[30] solve the full Maxwell's equations and do not employ the ultrarelativistic approximation in the field solver or the beam dynamics.

E. Quasi-Collisionless Beam Simulation Codes

At densities below about 0.1 torr, the plasma electrons are nearly free of momentum-transfer collisions, and the resistive models generally do not apply. However, collisions between beam or plasma particles and neutral gas atoms are effective sources of additional ionization. This is the regime for ion-focused regime (IFR) propagation of electron beams and is also of interest for heavy ion beam fusion. In contrast to the resistive case where electrostatic effects are negligible, the beam-generated electrostatic fields can dominate plasma dynamics. FRIEZR, ELBA, BUCKSHOT,[58] BEAMFIRE[53] and some versions of IPROP are examples of these quasi-collisionless simulation codes.

In their present form, codes of this type are not directly applicable to the 1 torr regime of interest for LMF where plasma collisions are important, and where it becomes prohibitively expensive to resolve the electron plasma frequency within the code. Possible methods for adapting such codes to the 1 torr regime are discussed in Section V.

III. DESCRIPTION OF THE DYNAPROP MODEL

A. Beam Dynamics

The DYNAPROP code was developed to treat axisymmetric propagation of ion or electron beams in the resistive regime. The code employs z and $\zeta = \beta ct - z$ in place of z and t. This "Doppler-shifted" coordinate system has been used extensively in beam propagation models developed at NRL and elsewhere. Derivatives are transformed according to[27,28]

$$\left(\frac{\partial}{\partial t}\right)_z = \beta c\left(\frac{\partial}{\partial \zeta}\right)_z \tag{5a}$$

$$\left(\frac{\partial}{\partial z}\right)_t = \left(\frac{\partial}{\partial z}\right)_\zeta - \left(\frac{\partial}{\partial \zeta}\right)_z \tag{5b}$$

$$\frac{d}{dt} = \left(\frac{\partial}{\partial t}\right)_z + \beta c\left(\frac{\partial}{\partial z}\right)_t = \beta c\left(\frac{\partial}{\partial z}\right)_\zeta \tag{5c}$$

Beam dynamics are treated using the Lee-Cooper envelope equation.[52] The model describes the evolution of the beam radius R(ζ, z) under the influence of the beam-generated magnetic field B_θ and beam emittance ϵ_n. The coordinate ζ is a constant of the motion for beam partic`s in this model, and the radius of an individual slice of the beam at constant ζ satisfies

$$\beta^2 c^2 \frac{\partial^2 R}{\partial z^2} = \frac{\epsilon_n^2 - \gamma^2 R^2 U - \gamma R^3 \beta c \frac{\partial R}{\partial z} \beta c \frac{\partial \gamma}{\partial z}}{\gamma^2 R^3}. \tag{6}$$

The quantity U represents the strength of the pinching magnetic field. If the beam is assumed to be charge neutralized, and the net current has the same radial profile as the beam, then[52]

$$U = \frac{Q_b \beta I_n}{(M_b/m_e)\gamma I_o}. \tag{7}$$

Here Q_b is the average charge state of the beam, M_b/m_e is the ratio of the beam ion mass to the electron mass, and $I_o = m_e c^3/e = 17$ kA is the Alfven current for electrons (omitting the $\beta\gamma$ factor).

The initial conditions require specification of γ_o, R_o, $dR/dz = R_o'$ and ϵ_{no} values at $z = 0$. These are usually assumed to be independent of ζ. The initial normalized emittance ϵ_{no} is related to the microdivergence θ_μ by $\epsilon_{no} = \beta\gamma R_o \theta_\mu$. Also required is the beam current $I_b(\zeta)$ which feeds back into the envelope equation through net current and conductivity generation equations.

The emittance increases as the beam propagates in z due to scattering of the beam by the background gas. Included as an option in the code is a phenomenological model of emittance growth due to anharmonic effects. This model, developed by Yu and Lee,[9] has an adjustable parameter α_ϵ which has been set to zero in most cases. The emittance growth equation is

$$\beta c \frac{\partial \epsilon_n^2}{\partial z} = \frac{2\gamma R^2 Q_b^2 Z_g (Z_g + 1) n_g}{(M_b/m_e)^2 (\beta\gamma)} \left(\frac{4\pi e^4}{M_b^2 c}\right) \log\left(\frac{192\beta\gamma M_b}{Z_g^{1/3} m_e}\right)$$

$$+ \alpha_\epsilon \gamma^2 R^2 \left| \beta^2 c^2 \frac{\partial^2 R}{\partial z^2} \right| |U|^{1/2} . \qquad (8)$$

In the first term (the scattering term), Z_g and n_g are the atomic number and density of the neutral gas.

The LMF beam will use a voltage ramp to produce a $\beta(\zeta)$ variation which will lead to pulse compression. In its present form, the DYNAPROP model does not allow for beam segments to overtake one another and thus cannot treat this important effect. A straightforward method exists for eliminating this limitation. (For relativistic electron beams, the DYNAPROP model readily accommodates variations in $\gamma(\zeta)$ within the pulse since $\beta \approx 1$ for all beam slices.) However, beam energy variations may also be induced through its interaction with the gas and plasma. Collisional and Ohmic energy losses are the dominant processes; these are monitored by solving

$$\beta c \frac{\partial \gamma}{\partial z} = - \frac{dW}{dx} \frac{\beta c P(atm)}{M_b c^2} + \frac{Q_b e E_z \beta c}{M_b c^2}. \tag{9}$$

where dW/dx is the collisional energy loss rate at 1 atm.

B. Circuit Model

DYNAPROP uses a circuit equation model for the net current I_n to treat the coupling between the beam and plasma. The particular form of the net current equation is taken from Sharp, et al.[59] The system has an effective inductance per unit length given by $L = \ln(R_w^2/R^2) + 1/4$ where R_w is the wall radius of the propagation chamber. The net current is given by[11,59]

$$\frac{\partial I_n}{\partial \zeta} = \frac{\kappa I_b - \left[\kappa - \left(1 + \frac{1}{8} R^2 \kappa^2\right) \frac{\beta c}{R} \frac{\partial R}{\partial \zeta}\right] I_n}{\beta \left(1 + \frac{1}{8} \kappa^2 R^2 L\right)}. \tag{10}$$

where $\kappa \equiv 4\pi \sigma_o / c$ and σ_o is the on-axis conductivity. Eq. (10) reduces to more familiar forms in the limit $\kappa^2 R^2 L/8 >> 1$ and $\partial L/\partial \zeta = 0$.

The axial electric field E_z for the circuit model, expressed in V/cm for I_n in amps, is[11]

$$E_z = - 29.97 \beta \left(L \frac{\partial I_n}{\partial \zeta} + \frac{\partial L}{\partial \zeta}\right) I_n. \tag{11}$$

C. Plasma and Conductivity Generation

The plasma generation model used in the original DYNAPROP code[11] used rate coefficients for air. The planned propagation experiments on GAMBLE will probably use helium, and this gas is a likely candidate for LMF as well. For these reasons, we have replaced the original air chemistry with a helium model, based in part on calculations by Ali and Slinker for electron beam propagation in helium at high pressures (~1 atm).[60] This is similar to the "VIPER" chemistry model[50,61] which has been used in the VIPER, SIMMO, SIMM1 and SARLAC simulation codes. The rate equation for the electron density is similar in structure to Eq. (2) except that the derivative substitution in Eq. (5a) has been employed, and a radial integration performed, so that the line density $N_e = \pi R^2 n_e$ is used instead of n_e. The density rate equation is

$$\frac{\partial N_e}{\partial \zeta} = \frac{1}{\beta c}\,\frac{P(\mathrm{atm})}{\Delta W}\,\frac{dW}{dx}\,\frac{I_b}{e}\left(1 - \frac{n_e}{Z_g n_g}\right) + \frac{\alpha_e N_e}{\beta c}$$

$$- \frac{\pi R^2}{\beta c}\left[\frac{4.26 \times 10^{-13}}{T_e^{0.63}}\, n_e^2 + \frac{1.48 \times 10^{-17}}{T_e^{2.12}}\, n_e^{2.37}\right.$$

$$\left. + \frac{1.94 \times 10^{-27}}{T_e^{4.5}}\, n_e^3\right]. \qquad (12)$$

For helium, $\Delta W = 46$ eV per electron-ion pair,[62] and the collisional energy loss rate dW/dx for protons on helium is taken from Green and Peterson[63] based on analytical fits to data from Whaling.[64] For the GAMBLE experiment, which uses 1.2 MeV protons and ~1 torr of helium, dW/dx = 0.58 kV/cm-torr. For the Li^{+3} ions used for LMF simulations, dW/dx may be estimated by multiplying the dW/dx for protons at an equivalent velocity[63] by $Q_b^2 = 9$. The last 3 terms in Eq. (12) are for recombination processes which are important at high densities but generally negligible at 1 torr.

The avalanche rate α_e in Eq. (12) and the electron-neutral collision frequency ν_{en} in the conductivity equation (1) are both assumed to be functions of E/n_g and v_{dr} where v_{dr} is the drift velocity. The model uses fits to $v_{dr}(E/n_g)$ compiled by Dutton[65] based on swarm data in helium. The collision frequency is[65]

$$\nu_{en} = \frac{1.76\times10^{-2}}{v_{dr}}\left(\frac{E}{n_g}\right)_{Tn}, \qquad (13)$$

where the Tn subscript indicates that E/n_g is in Townsends (10^{-17}v-cm^2). The avalanche rate has the general form

$$\alpha_e = \left(\frac{\alpha_d}{n_g}\right) v_{dr} n_g, \tag{14}$$

where data for the ratio α_d/n_g is taken from Dutton.[65]

The original DYNAPROP air chemistry model[11] used a temperature equation similar to Eq. (3). The new helium model utilizes some rate coefficients which are functions of E/n_g or E/P instead of T_e, and uses a $T_e(E/n_g)$ function for helium originally developed by Ali[60] based on fits to experimental data. The assumed relationship is

$$T_e(E/P) = 1.23(E/P)^{0.51} + T_o, \tag{15}$$

with E/P in v/cm-torr. T_o is an effective minimum temperature which is primarily determined by direct beam heating. For light ion fusion beams, the recombination terms in Eq. (12) are negligible, so T_e appears primarily in the electron-ion collision frequency in Eq. (1). This frequency is given by[66]

$$\nu_{ei} = 2.9\text{x}10^{-6} \frac{n_e \ln\Lambda}{T_e^{3/2}}, \tag{16}$$

where $\ln\Lambda$ is the Coulomb logarithm.[66]

The helium model was based on considerations of electron beam propagation at much higher pressures than are planned for LMF. E/n_g calculated in the code often exceeds 10^3 Townsends, especially in the beam head. Swarm data on drift velocities and avalanche rates in this regime are scarce, and a large fraction of the electron population may be in a runaway regime. The implications of this are discussed in Section V.

IV. DYNAPROP RESULTS

A. Predictions for GAMBLE Experiment

A series of ~1 torr propagation experiments is in progress on the GAMBLE II ion beam generator at NRL.[67] GAMBLE typically produces 500 kA of 1.2 MeV protons. For the initial experiments, the beam will be apertured to 10 kA or less in order to reduce the microdivergence. It will then be propagated in a short helium-filled gas cell. A variety of diagnostics will be used to characterize the beam at the entrance to the transport channel. A B-dot probe and a resistive shunt will be used to measure the net current in the transport cell, and a charge collector will measure the transported beam current. The net current measurements are the most important since they can be compared directly with theoretical models and give some indication as to whether beam-induced magnetic fields will cause unacceptable orbit deflections in LMF.

DYNAPROP simulations have assumed the following nominal beam parameters: Peak current I_{bo} = 10 kA, beam energy = 1.2 MeV (protons), pulse length ζ_{max} = 120 cm (~90 nsec), rise length ζ_r = 60 cm, injection radius R_o = 1 cm and initial microdivergence θ_μ = 50 mrad. The background gas is 1 torr He contained in a 50 cm long cell with wall radius R_w = 10 cm. The beam current has the form $I_b(\zeta) = I_{bo}\tanh(\zeta/\zeta_r)$ and thus rises from zero at the head of the beam ($\zeta = 0$) to its peak value I_{bo} in the beam tail. The beam is injected unfocused with $R_o' = dR/dz(z = 0) = 0$. The simulations assume a minimum temperature T_o = 0.5 eV in Eq. (15). Results are summarized in Table I.

Figure 1 plots $I_n(\zeta)$ (top frame) and $R(\zeta)$ (bottom frame) at z = 0, 10,..., 50 cm for the nominal beam and gas cell parameters used in the DYNAPROP simulations. Each curve represents a fixed z-location and thus corresponds to a time-resolved laboratory measurement (such as a net current trace from a B-dot probe) taken at a fixed position. The net current rises steadily to ~1.2-1.5 kA and varies weakly with z due to the logarithmic change in inductance. $R(\zeta)$ is slightly smaller in the beam tail than in the head; this is due to a weak pinching effect which scales with $I_n(\zeta)$. Figure 2 plots the on-axis electron density $n_{eo}(\zeta)$ and on-axis conductivity $\sigma_o(\zeta)$ at the same locations. Peak electron density at z = 0 is 3×10^{15} cm^{-3} which corresponds to an ionization fraction ~0.07 at 1 torr. The density curves steadily decrease as the beam expands during propagation. The on-axis conductivity $\sigma_0(\zeta)$ tracks the electron density, as expected. Peak conductivity is $\sim 10^{14}$ sec^{-1}.

Figure 3 plots $I_n(\zeta)$ and $R(\zeta)$ at the same locations and for the same parameters with the avalanche coefficient α set to zero. This slows the rise in conductivity and leads to a substantially higher peak net current. The stronger net current results in reduction in beam expansion.

In the regime where the conductivity is determined primarily by beam impact ionization, one can show that the net current is determined by the total current, rather than the current density.[28] Beam deflections scale primarily with *total* net current rather than current density, so it is desirable to allow more of the GAMBLE ion beam current into the gas cell even at the expense of higher microdivergence and reduced current density. It is known from electron beam propagation theory and experiments that in the regime $I_n << I_b$, the net current increases slowly with I_{bo}. This is because the rapid rise in conductivity "freezes" the magnetic field in at a modest value. Figure 4 plots results from a simulation with I_{bo} set to 100 kA. The peak net current (top frame) is less than a factor of 2 higher as compared with the corresponding 10 kA case (Fig. 1).

The results from a number of additional simulations are also summarized in Table I and discussed below. I_n increases slowly with increases in gas pressure P or beam current I_{bo}. The net current decreases weakly with increasing wall radius a_w due to the logarithmic change in inductance. Changes in minimum temperature T_o or current rise length ζ_r also have a modest effect. Neglecting recombination or scattering has a negligible effect. The presence of a preionized plasma with a moderate electron density $n_o = 10^{12}$-10^{13} cm^{-3} causes a modest drop in the peak net current. Neglecting the depletion of neutral gas density, which is included in the $(1 - n_e/Z_g n_g)$ term in Eq. (12), causes a moderate increase in conductivity and decrease in I_n for the high current (100 kA) simulation. These effects are qualitatively as expected given their effect on the conductivity; increases in conductivity or plasma density produce smaller net current values. Changes in the beam radius R due to changes in parameters or model assumptions are consistent with the observed changes in I_n.

B. Converging Beam Simulations and Predictions for LMF

The DYNAPROP model was also run with parameters and atomic physics modified for the Li^{+3} beam to be used in LMF. Nominal parameters are: beam energy $W_o = 30$ MeV, $R_o = 10$ cm, $\theta_\mu = 6.7$ mrad, $\zeta_p = 120$ cm, $\zeta_r = 60$ cm, P = 1 torr (He), $a_w = 50$ cm and nominal focus distance L = 150 cm. The ballistic-focused or converging beam was injected with $R_o' = -R_o/L$, so in the absence of self-fields and scattering, it would reach a minimum spot size radius $R_{so} = \theta_\mu L = 1$ cm at z = L. Converging beam simulations were also carried out for the 1.2 MeV GAMBLE proton beam. Results are compiled in Table II.

Figure 5 shows results for the nominal GAMBLE parameters assuming $I_{bo} = 100$ kA, L = 150 cm and a 6.7 mrad microdivergence, so that $R_{so} = 1$ cm (which is experimentally unattainable with the present device.) Results are output at z = 0, 50, 100, 130, 140 and 150 cm. The net current is similar to previous cases. $R(\zeta)$ is nearly constant except near the focus where the net current variation within the pulse is sufficient to cause different portions of the beam to focus at different positions.

Figure 6 plots $I_n(\zeta)$ and $R(\zeta)$ for a 30 MeV, 300 kA Li^{+3} beam. The net current is higher than in the previous case, but rapid ionization and conductivity generation causes the net current to "freeze" at a nearly constant value for $\zeta \gtrsim 10$ cm. (Avalanche ionization in the first few nsec is playing a major role in determining the conductivity and net current variations.) Thus, there is relative little variation in $R(\zeta)$ within the pulse. However, as seen in Table II, the location z_f of the focus is still shifted to 140 cm. When the beam current is raised to 1500 kA (Fig. 7), the net current freezes in at 10-13 kA. This induces a substantial shift in the focus (to $z_f \approx 120$ cm) and actually pinches the beam to a significantly smaller radius. Curves are at z = 0, 46, 93, 111, 120 and 130 cm. In these cases, the helium becomes almost completely ionized, so further increases in beam current do not produce substantial changes in conductivity. Thus, the factor of 5 increase in beam current produces a factor of 4 increase in net current. (The atomic physics model is of questionable validity in this high current regime, however.)

In the absence of variations in the beam velocity $\beta(\zeta)$ within the pulse, a substantial shift in z_f would be tolerable provided I_n freezes in at a nearly constant value. All but a small portion of the beam would focus near the same point, and the target position or focusing strength can be shifted to accommodate the change.[11] However, LMF will have substantial $\beta(\zeta)$ variations in order to produce the desired time-of-flight pulse compression.[1-3] Thus, the higher velocity beam tail will focus further downstream than the beam head, resulting in a substantial number of ions missing the target. More careful analysis is required to determine if this will be acceptable.

V. IMPROVED TREATMENTS OF PLASMA AND BEAM DYNAMICS

The DYNAPROP model is simple and very fast computationally, but it has a number of shortcomings which have been studied in considerable detail in the CPB program. In this section, we discuss the validity of the model and describe several approaches which could be employed to overcome the deficiencies.

A. Fast Secondary Electrons

Intense ion beams produce copious quantities of fast secondary electrons, often called delta-rays. These electrons are generated by beam-impact ionization and produce additional impact ionization in the same manner as beam ions. Even if electron transport effects are ignored, the the details of the distribution function f_e for these electrons may affect both the rate of plasma production and the effective collision frequency. In the 1 torr pressure regime, the presence of a large number of nearly collisionless electrons with energies >100 eV can provide a population for carrying large plasma currents, thus reducing the net current from what one would estimate based on a single bulk plasma temperature.

These electrons are created with axial velocities primarily in the forward direction. A significant number have axial velocities which exceed βc and may actually outrun the beam.[12] Analytical estimates of the current carried by these "knock-on" electrons have been made by Hubbard et al.[12] for heavy ion fusion beams. For such beams at 1 torr, the current carried by knock-ons may easily exceed the beam current. This led to concerns that the fields generated by this precursor knock-on "beam" would cause unacceptable deflections of the beam ion orbits.

For relativistic electron beams, the inclusion of delta ray effects generally increases the predicted net current.[14-19,68] However, for ion beams, we believe that such effects will decrease the predicted I_n. For light ion beams, the relative number of fast electrons is similar to that for heavy ion beams. However, even those electrons which do not outrun the beam have a forward axial velocity component and will thus *reduce* the net current. As noted previously, the presence of a large population of nearly-collisionless electrons in the distribution function effectively increases the conductivity and makes it easier to carry a plasma return current. Another effect which will influence the net current is $J \times B$ motion of the delta rays in the azimuthal field.[14,15] These delta ray electrons carry a strong radial current $J_{r\delta}$ because the electrons are generated by discrete beam-neutral collisions which produce electrons with substantial velocity components perpendicular to the beam axis. For relativistic electron beams, the axial flow of delta ray electrons is further enhanced by the $J \times B$ force which pushes the electrons in the forward direction; they are pushed in the opposite direction if B_θ is generated by a positive ion beam. Thus, $J \times B$ effects enhance the net current for ion beams. Further study is required to determine which of these effects dominates in the ion beam fusion case, so it is not obvious whether including these nonlocal effects in a resistive model will increase or decrease the predicted net current. However, since $I_n << I_b$, it is likely that the $J \times B$ effect will be less important, so the most likely effect is a *reduction* in the predicted net current.

Relativistic electrons may also be produced by the intense electric fields produced at the head of the ion beam. Although it is expected that nearly-complete space charge neutralization will occur rapidly near the beam head, there is a brief period in which enormous electrostatic fields are present. The hot plasma electron population created by these fields will persist and may affect neutralization and beam dynamics throughout the pulse. The actual neutralization process is also poorly understood. Although relativistic electron beams can eject plasma electrons to achieve local space charge neutralization, ion beams must either draw in electrons from outside (where there is relatively little ionization) or expel plasma ions. For a converging (ballistic-focused) beam, ion expulsion may take place quickly when the beam radius is small but is relatively slow in the early stages of propagation when R is large and the radial electric field E_r is small.[40,42] For LMF, the inductive field E_z is likely to produce substantial electron acceleration in the beam head as well.

We have conducted a preliminary investigation of the charge neutralization process for ballistically-focused heavy ion beams using the FRIEZR code.[42] These studies were carried out in the 10^{-3} torr regime where the plasma electrons are nearly collisionless, and space charge neutralization is only partially achieved. The situation is more complicated in the

1 torr LMF regime where electron collisions affect plasma transport and charge neutralization is achieved very close to the beam head.

B. Methods for Modeling Plasma Dynamics in the 1 Torr Regime

Several options exist for modeling the effect of fast electrons. The simplest approaches treat these electrons as a current and ionization source which is added to the beam. An analytical model of this sort has been used in as an option in the DYNAPROP code for heavy ion beam propagation.[12] Since radial motion of these electrons is at least as important as their axial motion, a radially-resolved field and conductivity package would significantly enhance DYNAPROP's capabilities. NRL's VIPER electron beam propagation code has radially-resolved fields and conductivity, but does not at this point include electron inertial effects or delta ray currents.

One may also treat fast secondaries directly in a particle simulation code. Monte Carlo methods are used to create fast simulation electrons at the positions of a randomly-chosen subset of simulation beam particles. We have used this method to create stripped or "drop-off" electrons in FRIEZR simulations of heavy ion beam propagation.[42] A similar method has been used by Welch[68] to treat delta ray effects in propagating electron beams. If the bulk plasma is still treated as resistive, then the simulation time step is probably determined by the need to resolve the delta ray electron gyrofrequency. For a 1 cm radius beam with net currents of a few kiloamps, $\omega_{ce} = 10^{10}\ \mathrm{sec}^{-1}$. Such a model would not treat the charge neutralization process correctly but might be reasonable in the body of the beam.

The treatment of collisions in the low temperature bulk plasma in the 1 torr regime offers formidable obstacles, particularly in the beam head where space charge effects are important. Perhaps the most rigorous approach would be to use particle simulation in conjunction with Monte Carlo methods with no resistive assumptions about the bulk plasma. The primary purpose of such a code would be to study the nature of the charge neutralization process. One would scatter some fraction of the plasma particles at each time step. This is clearly a major undertaking. A fundamental problem with this brute force method arises from the need to resolve the electron plasma frequency ω_{pe}. (Plasma simulation codes are usually numerically unstable if this criterion is not met;[69] resistive codes avoid this problem.)

For LMF, the plasma will be nearly fully ionized near the target, so ω_{pe} can exceed 10^{13} sec^{-1}, making the code prohibitively expensive. However, it is likely that the fundamental physics of the neutralization process does not require ω_{pe} to be resolved since ω_{pe} is much faster than other physical time scales. Implicit particle simulation algorithms offer a potential fix for this problem since they allow the time step to be much longer that the inverse plasma frequency in situations where the constraint arises purely from numerical (nonphysical) considerations.[70,71]

There have also been attempts to model the plasma with a multi-fluid approach. An example is the LOCHEM code developed by SAIC for relativistic electron beams.[18,19] Plasma electrons are arbitrarily divided into high and low energy groups, and their motion followed by solving fluid equations. This model reproduces some of the qualitative features seen in the NUTS Boltzmann code,[14,15] including net current enhancement. A fluid treatment cannot be rigorously justified, particularly at low pressures where a substantial portion of the electron distribution may be in the runaway regime.

A more rigorous approach is to solve the Boltzmann equation for the electron distribution function f_e and calculate rates and collision frequencies based on energy-dependent cross sections for the various atomic and molecular processes. The simplest approach is to ignore plasma transport and treat the time evolution of f_e at a single point in space, where f_e is a function of the electron energy ϵ. The SED code at NRL is an example of such a code.[16] SED includes Ohmic heating and beam deposition as source terms and detailed energy-dependent cross sections for a variety of elastic and inelastic collisional processes in air. This code could be modified to treat the light ion fusion problem. This would require replacing air cross sections with those for helium and changing the beam source term. As presently configured, the code does not include contributions from delta ray currents.

Yu[14,15] developed a Boltzmann code (NUTS) which treats nonlocal plasma transport by using a two-term expansion in spherical harmonics. This code was applied to a variety of electron beam problems but has not been used much in recent years. The primary goal was to explain the substantial net current enhancements seen in ETA propagation experiments in dense gases. NUTS did predict significantly higher net currents than could be explained by purely resistive models; much of the forward current came from JxB motion of delta rays as described in the previous section. (This current enhancement effect is now believed to be due primarily to large amplitude hose motion rather than delta ray effects.) NUTS was also intended to model the low pressure regime which is of interest to LMF. However, numerical problems were frequently encountered in that regime.

Two-term or higher multi-pole expansions of the Boltzmann equation have been widely used. However, the validity of this approximation is questionable in highly anisotropic situations such as those encountered with beams, and the approach gives incorrect results for most highly-anisotropic test problems.[17] Colombant and Lampe[17] have investigated moment approaches to solving the nonlocal Boltzmann equation in highly anisotropic situations such as those encountered with plasmas produced by intense beams. However, a reliable general algorithm has not yet been found.[17]

Perhaps the most rigorous approach would be to solve the full Boltzmann equation by extending algorithms developed for solving the collisionless Boltzmann (Vlasov) equation. This is probably prohibitively expensive on a CRAY but might be feasible on a massively-parallel machine such as a Connection Machine. We have been developing a new algorithm for solving the Vlasov equation on such machines[72] and might at some point in the future be able to extend it to the Boltzmann equation.

C. Beam Dynamics

The LMF beam[1-3] has two key features which are not currently being treated by the envelope model in DYNAPROP. First, the LMF diode produces a hollow beam. Hollow beams may in principle be treated by envelope codes such as DYNAPROP and VIPER provided that the beam remains self-similar. However, this is usually not a good assumption since the beam fills in as it propagates. Also, the net current and plasma generation equations explicitly assumed a Bennett current density profile; a hollow profile would cause minor changes in some of the coefficients. A second important feature is the voltage ramp which will be applied to the LMF in order to generate pulse compression by a factor of 2-4. The voltage ramp presents some obvious problems for the envelope beam dynamics model since β varies within the pulse. However, the voltage schedule can be chosen so that individual beam segments are compressed in ζ as they propagate without overtaking one another. Thus, the inclusion of a voltage ramp in the model appears to be straightforward.

A more direct solution to treating these effects would be to replace the envelope equation by an axisymmetric particle simulation algorithm such as that contained in the FRIEZR[34,42,43] and SIMM0[54] codes. Codes of this nature are relatively fast, especially if particles are not permitted to move between beam slices. SIMM0 has a code structure similar to DYNAPROP. The DYNAPROP conductivity model can be readily transferred to a particle code. An axisymmetric field solver would be required to replace the circuit equation. Such a model would give radially-resolved current density and conductivity profiles and could treat hollow beams of the sort expected for LMF. Proper treatment of the voltage ramp and pulse compression could be accomplished by relaxing the requirement that particles remain at constant ζ. One beam simulation code which allows such motion is SARLAC-SOS. This code combines the 3-D SARLAC treatment[29] of beam propagation in the resistive regime with the FRIEZR[34] particle pushing algorithm. A similar structure could be applied to treating the voltage ramp problem.

D. Summary and Recommendation for Future Work

The DYNAPROP studies described herein are only a first cut to scope out the problem of beam charge and current neutralization, within a very brief period and at minimal expense. The DYNAPROP studies indicate that it may be difficult to achieve adequate current neutralization. More detailed studies are needed to provide a realistic and accurate delineation of the regime (if any) in which ballistic propagation is feasible. The work will require resolution of a number of different physics issues, and should probably be addressed by sequential development of the required numerical codes and theoretical models. Some of the required code elements are available, while others would involve varying degrees of development. Close collaboration between theory and experiment is essential given the major uncertainties in the validity of various theoretical approaches. The experiments will not be in the regime of ultimate interest (e.g., I_b will be lower, θ_μ will be higher) and will need to be scaled. In addition, it may be difficult to measure the really determinative quantities, such as the net current within the beam, and so it will very likely be necessary to use theory to extend and interpret the meaning of the experimental results.

A first step would be use an axisymmetric particle simulation code such as SIMM0[54,55] in place of the DYNAPROP beam envelope model. The plasma would still be modeled as a local resistive medium, but the use of SIMM0 would yield a radially resolved calculation of the fields, plasma evolution and beam response. This would provide a much more detailed and accurate picture of the current neutralization process, and a firm foundation for further development of plasma kinetic models.

One could in principle follow the axisymmetric studies with a three-dimensional simulation code based on SARLAC.[29] Fortunately, there does not appear to be any need for three-dimensional modeling of a single beam, since at this time no non-axisymmetric process has been identified as a key issue. However, there are a number of issues associated with multiple beam propagation, including interactions between adjacent beams, and the overlapping beams onto the target. The BIC code[73] developed by Langdon for HIF target chamber propagation is capable of treating ballistically-focused multiple beamlets, but the code is not designed to treat the 1 torr "resistive" regime. It may be possible at some point to adapt the multiple beam techniques in BIC to a resistive simulation code such as SIMM0, but this would be a major undertaking.

For high current light ion beams propagating in a gas at ~1 torr density, we expect that the plasma response will not be adequately represented by a local resistive model. The bulk of the electrons <u>will</u> be a thermal population that can be represented by a resistivity, but there will also be a substantial population of high energy electrons whose response must be calculated kinetically. It is inappropriate to represent the entire plasma electron population by straightforward (explicit) particle simulation techniques, because the very large plasma frequency would limit the time steps to extremely small values (~ 10^{-13} s) that are of no practical interest.

A first step to calculate the (highly non-Maxwellian) electron energy distribution, could be to implement the SED code,[16] an existing code which solves the Boltzmann equation over the complete course of secondary electron cascade, in the presence of the calculated electric fields. Again, it would be straightforward to substitute the light ion beam/He medium models for the existing REB/air models in the SED code. SED is an isotropic model that will calculate energy distributions, but not directed flows of delta rays and other high energy electrons.

The next step along the straightforward development path might be to solve the Boltzmann equation anisotropically (i.e. in 3-D velocity space) and nonlocally (in 2-D axisymmetric configuration space), but this is a goal that is really beyond anybody's present capabilities. Techniques have been developed for solving the Boltzmann equation in near-isotropic conditions, e.g. by using spherical harmonic expansions. As discussed in Section V.B, attempts were made[14,15,17] in the 1980's to apply these to REB propagation in gas densities of the order of 1 torr, but these were not very successful because the models can give misleading and erroneous results when conditions are strongly axisotropic. A multi-fluid approach[18,19] also was tried, but was flawed because of the nonlocality of the electron trajectories. It may be possible at some point to combine Monte Carlo collision modeling algorithms with those Vlasov equation algorithms being developed on the Connection Machine in 2-D configuration/3-D velocity space.[72] and extend these techniques to treat the Boltzmann equation. However, for the present, we believe that it will be most useful to proceed by developing less comprehensive models that are tailored specifically for the problem at hand.

There are two primary sources for the high energy electrons that respond kinetically: (1) acceleration of plasma electrons in the large electric fields that are present in the beam head, prior to the achievement of charge neutrality, and (2) high energy secondaries (delta rays or knock-ons) due to close collisions (throughout the duration of the beam) between beam ions and gas atoms. Since the latter are relatively few in number, it makes sense to model them via particle simulation, as an appendage to a model like SIMM0 that represents the bulk of the plasma electrons via a resistivity. It may be possible to do this in a straightforward explicit fashion. At worst, it may be necessary to use an iterative approach in which the delta rays are, in the first iteration, moved in the fields calculated from the resistive model. A subsequent iteration would then include the delta ray charge and current distributions in a recalculation of the fields. Models of this type typically converge in one or two iterations, and avoid numerical instabilities due to inadequate resolution of plasma oscillations.

The population of high energy electrons excited by fields at the head of the beam also may play an important role. Since these electrons are relatively collision-free, they provide a highly conductive element that can facilitate current neutralization. A first step to model these electrons should surely be a non-self-consistent (possibly analytic) calculation of this energy distribution function, based on an estimate of the fields from a resistive model such as SIMM0. This would lead to the calculation of an effective conductivity to represent this component. This approach could be iterated, similarly to the discussion of the previous paragraph, to provide effectively an implicit particle simulation treatment of the charge neutralization process. Alternatively, one might wish to begin with an existing axisymmetric code such as FRIEZR, which represents the plasma electrons as well as the beam via particle simulation, and insert an implicit particle push algorithm[70,71] to permit time steps much larger than ω_{pe}^{-1}. In either case, it would also be necessary to restructure the code for efficient modeling of nonrelativistic beams, and to install an appropriate scattering and slowing-down model.

VI. DISCUSSION AND CONCLUSIONS

The feasibility of using ballistic propagation of light ion beams in the Laboratory Microfusion Facility (LMF) will be determined by two primary factors. First, the microdivergence of the ion beam must be improved by a factor of 2-3 over that produced by the best existing diodes. In addition, those deviations from ballistic orbits which are introduced by the beam-generated electromagnetic fields must be kept at an acceptable level. In the absence of beam-plasma instabilities, these deflections are produced by the residual net current arising from the finite conductivity of the beam-produced plasma. This involves physics issues which have not been studied extensively for light ion fusion beams but will be addressed in part by proton beam experiments on GAMBLE II at NRL. However, beam propagation has been extensively studied during the past decade for relativistic electron beams and to a lesser extent for heavy ion fusion beams. In particular, codes such as DYNAPROP, which treat the plasma as resistive, may be readily adapted to study ion beam propagation for the GAMBLE experiments and LMF.

DYNAPROP results for the ~10 kA GAMBLE experiment predict that the ratio I_n/I_b will be 0.1-0.2. This is consistent with previous experimental and theoretical results for propagating electron beams. The I_n/I_b ratio in ~10 kA electron beams is typically 0.3-0.5 at 1 torr. However, the rate of plasma generation by the ion beam is equivalent to that of an electron beam of >100 kA, for which the I_n/I_b ratio is typically in the 0.1-0.2 range. For the much higher ion currents to be used in LMF, DYNAPROP predicts $I_n/I_b \sim 0.01$. The resulting net current for the full LMF parameters could thus exceed 10 kA. This is sufficient to shift the focus by more than 10 cm and could cause a substantial fraction of the beam to miss the target. The fraction which miss the target depends on the details of the voltage ramp and how early in the pulse the net current "freezes" in; further study is required to determine a practical limit on the allowable net current. For net currents of ~50 kA, it is almost certain that ballistic focusing will not be practical, but self-pinched propagation might be possible. DYNAPROP thus predicts net currents in an uncomfortable transition regime; strong enough to make ballistic propagation uncertain but probably too weak for pinched propagation.

It should be noted that it is only the net current which flows within the beam that influences the ion trajectories. This quantity, which is often refered to as the effective current,[28] is difficult to measure experimentally. Since a significant plasma return current frequently flows outside the beam, an experiment which measures a small *total* net cuurent is not sufficient to validate the feasibility of ballistic transport. Radially resolved theoretical and numerical calculations are needed to infer the effective current from experimental data.

As discussed in Section V, the validity of the atomic physics and resistive plasma models in DYNAPROP is very questionable in the 1 torr regime. There are a number of competing processes which could cause DYNAPROP to either overestimate or underestimate the net current. The experiments on GAMBLE could have some obvious implications on the feasibility for various transport schemes and may provide considerable guidance for future theoretical modelling. If the experimental I_n/I_b is significantly higher than predicted by DYNAPROP, ballistic propagation for LMF would be very risky, but self-pinched propagation (which has been generally assumed to be impossible for ion beam fusion parameters) might be worth serious consideration. Such a result might indicate that $J_{r\delta} \times B_\theta$ effects play a prominent role in plasma transport, or that the conventional atomic and conductivity physics models are deficient at high current densities. However, if I_n/I_b is much smaller than predicted by DYNAPROP, the prospects for ballistic focusing for LMF would be substantially enhanced. Not only would ion trajectory deflections be smaller, but potentially-dangerous resistive instabilities such as the filamentation mode, would have substantially lower growth rates. An anomalously low experimental net current would suggest that enhanced conductivity due to the presence of energetic secondary electrons dominate plasma transport. Either a Boltzmann model or a resistive particle simulation code using Monte Carlo methods to generate the energetic electron population offer possible approaches to treating the problem.

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TABLE I. Summary of DYNAPROP simulations of the GAMBLE II ion beam transport experiment. Nominal simulation parameters: Peak current I_{bo} = 10 kA, beam energy = 1.2 Mev (protons), pulse length ζ_{max} = 120 cm (~90 nsec), rise length ζ_r = 60 cm, injection radius R_o = 1 cm, initial microdivergence θ_μ = 50 mrad. The background gas was 1 torr He contained in a 50 cm long cell with wall radius R_w = 10 cm. Tabulated results are for $\zeta = \zeta_{max}$ = 120 cm (~90 nsec into the pulse).

Parameter	I_n(z=0)	I_n(z=40cm)	R(z=40cm)
Nominal	1230 A	1550 A	1.82 cm
No avalanche	2120	2400	1.53
I_{bo} = 100 kA	1920	2430	1.55
I_{bo} = 100 kA (Constant n_g)	2270	2480	1.49
I_{bo} = 20 kA	1440	1760	1.75
P = 2 torr	1530	1870	1.72
P = 0.5 torr	1100	1370	1.86
a_w = 100 cm	700	760	2.01
a_w = 5 cm	1630	2280	1.66
Recombination neglected	1230	1540	1.82
Scattering neglected	1230	1550	1.81
T_o = 8 eV	1170	1420	1.83
ζ_r = 30 cm	1370	1670	1.78
Preionized ($n_o = 10^{12}$ cm^{-3})	1170	1490	1.85
Preionized ($n_o = 10^{13}$ cm^{-3})	1010	1130	1.92

TABLE II. Summary of DYNAPROP converging beam simulations of the GAMBLE II and LMF parameters. Nominal LMF simulation parameters: Peak current I_{bo} = 30-1500 kA, beam energy = 30 Mev (Li^{+3}), pulse length ζ_{max} = 120 cm (~40 nsec), rise length ζ_r = 60 cm, injection radius R_o = 10 cm, initial microdivergence θ_μ = 6.7 mrad. The nominal focal length L = 150 cm, but self-fields shift the focus to $z = z_f$. The uncertainty in the exact location of z_f is typically ~5 cm. $I_n(0, \zeta_p)$ is at z = 0 and ζ = 120 cm. $R_s(\zeta_p/2)$ and $R_s(\zeta_p)$ are at $z = z_f$ and ζ = 60 or 120 cm. The background gas is was 1 torr He contained in a cell with wall radius R_w = 50 cm.

Parameters	I_{bo}	$I_n(z{=}0)$	z_f	$R_s(\zeta_p/2)$	$R_s(\zeta_p)$
1.2 MeV protons	10 kA	1.48 kA	130 cm	1.03 cm	0.88 cm
1.2 MeV protons	100	2.12	130	0.81	0.77
30 MeV Li^{+3}	30	1.64	148	0.96	0.96
30 MeV Li^{+3}	300	3.82	139	0.81	0.81
20 MeV Li^{+3}	300	2.69	139	0.87	0.83
30 MeV Li^{+3}	1500	13.7	120	0.58	0.59

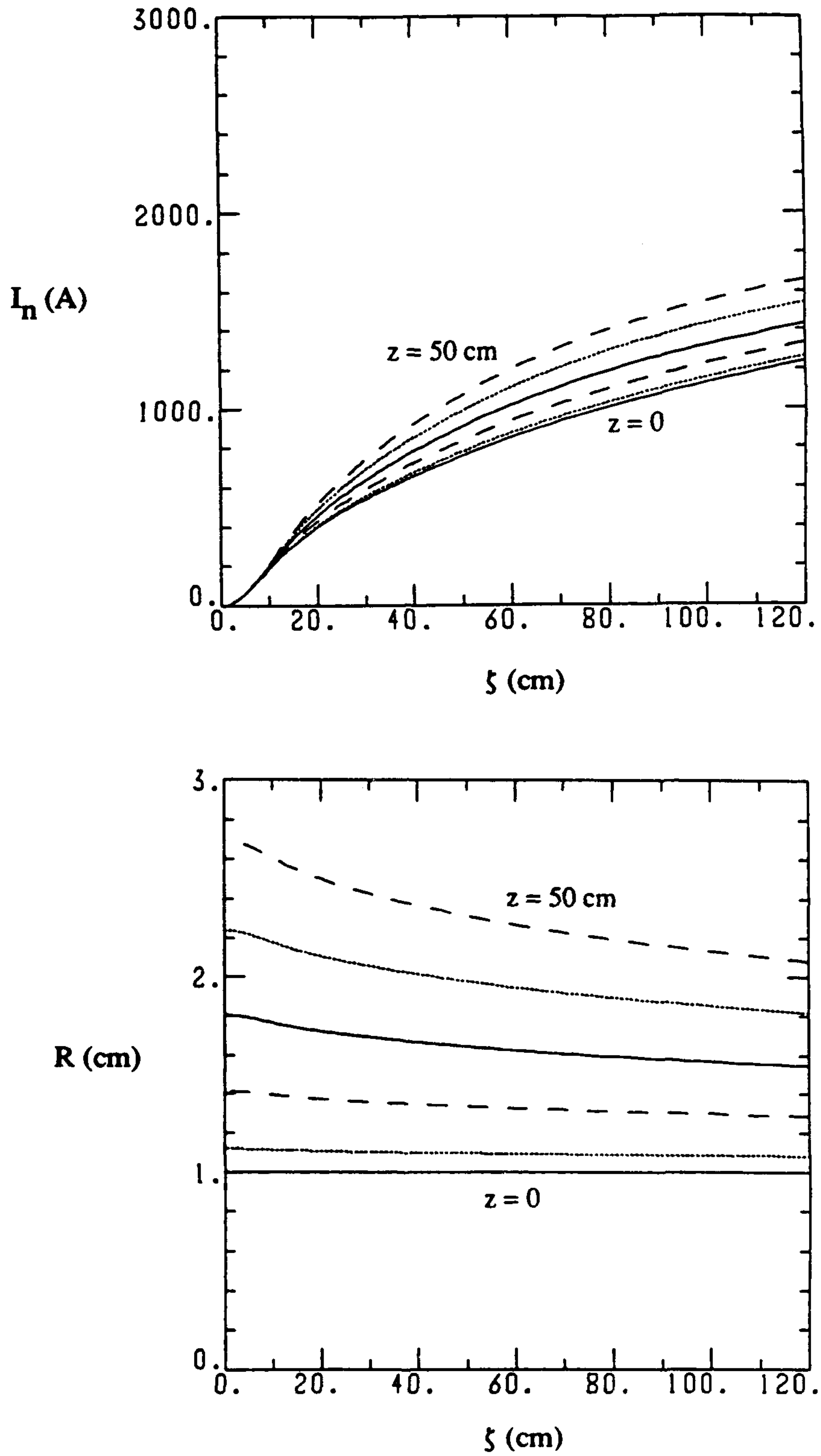

FIG. 1. Net current $I_n(\zeta)$ (top frame) and beam radius $R(\zeta)$ (bottom frame) for DYNAPROP simulation with nominal GAMBLE beam and gas cell parameters and standard atomic physics model. Net current peaks at 1.2-1.6 kA. The rising net current causes a weak pinching of the beam, so that the beam radius decreases as ζ increases. Individual curves are for z = 0, 10, 20, 30, 40 and 50 cm.

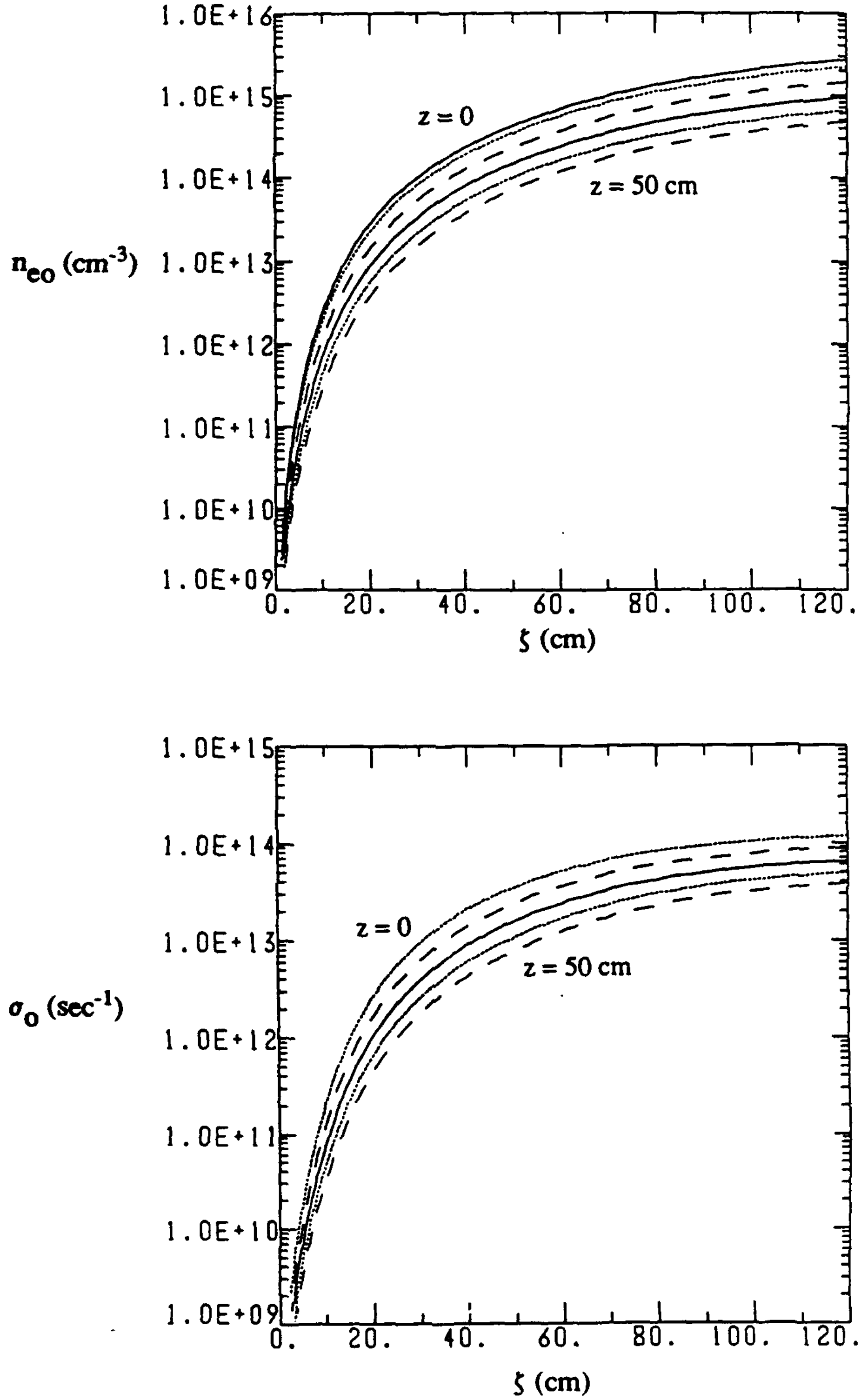

FIG. 2. On-axis electron density $n_{eo}(\zeta)$ (top frame) and conductivity $\sigma_o(\zeta)$ (bottom frame) for the DYNAPROP nominal case shown in Fig. 1. Both quantities increase with ζ and decrease as the beam propagates in z.

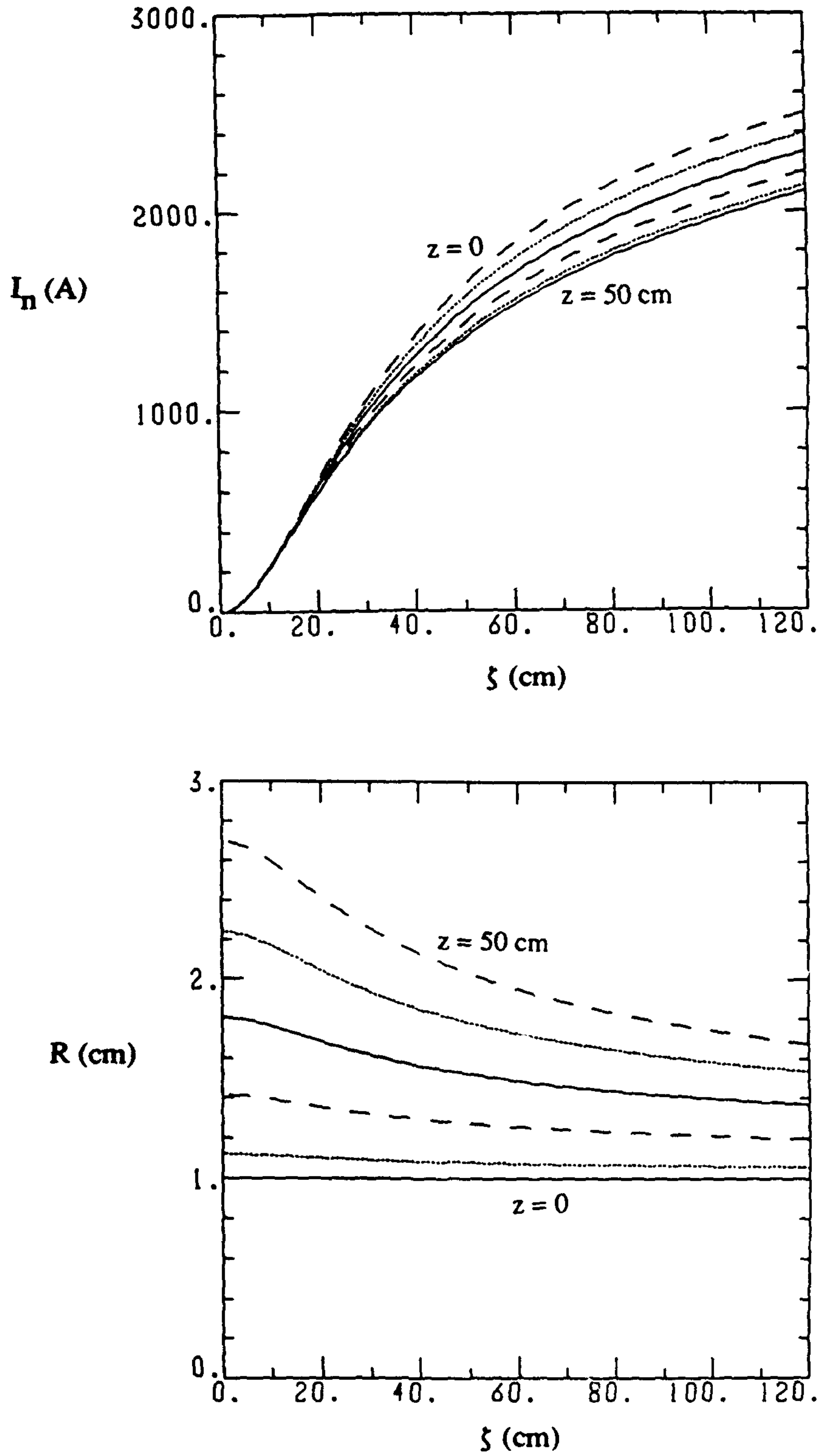

FIG. 3. Net current $I_n(\zeta)$ (top frame) and beam radius $R(\zeta)$ (bottom frame) for DYNAPROP simulation with nominal GAMBLE beam and gas cell parameters. Avalanche ionization is neglected in the atomic physics model which results in a slower rise in conductivity and a larger peak net current (2.1-2.5 kA) than in Fig. 1. Individual curves are for z = 0, 10, 20, 30, 40 and 50 cm.

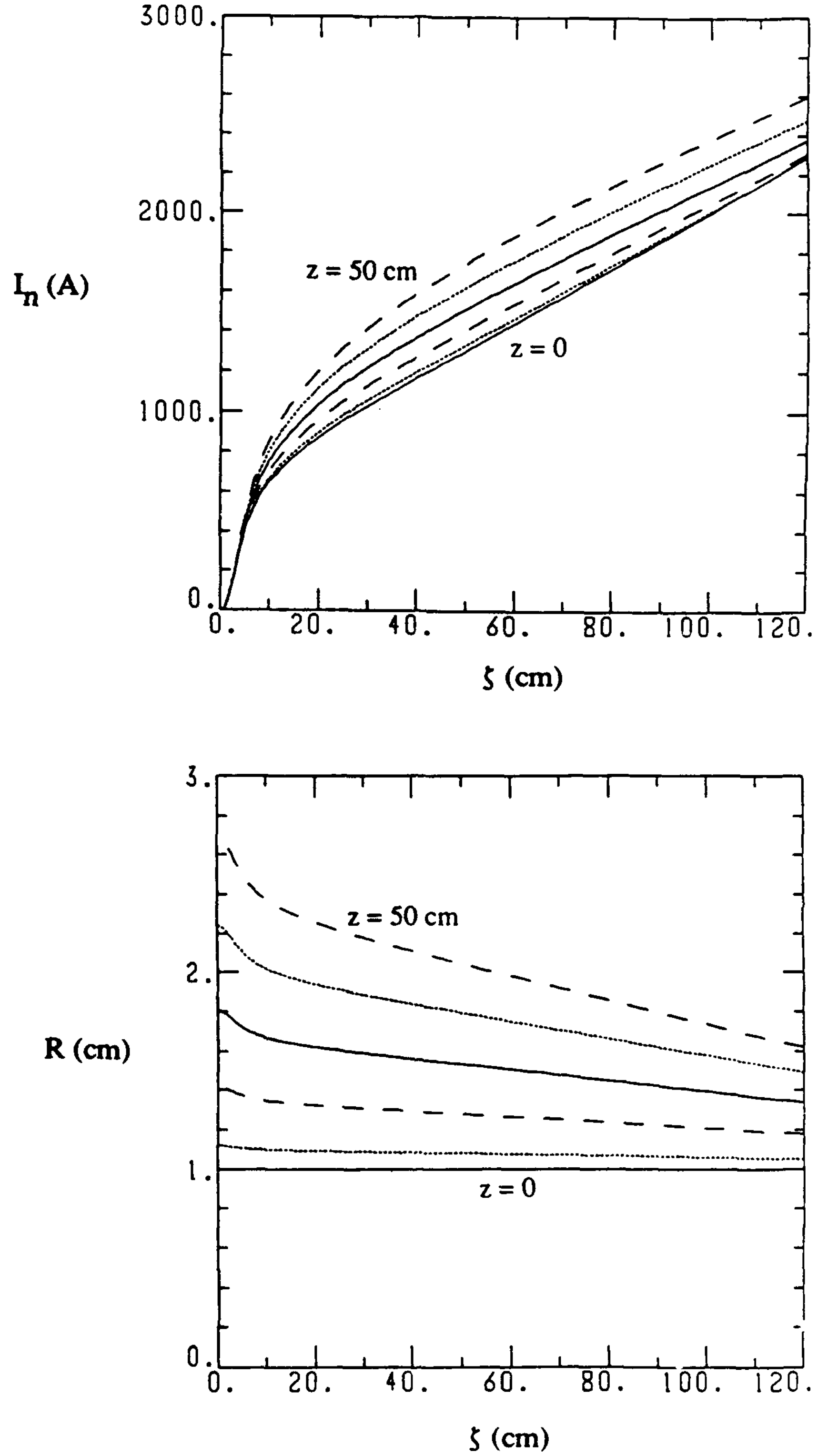

Fig. 4. $I_n(\zeta)$ and $R(\zeta)$ for a DYNAPROP simulation with the peak beam current raised from 10 kA to 100 kA. The peak net current is only a factor of two higher than in Fig. 1. Individual curves are for z = 0, 10, 20, 30, 40 and 50 cm.

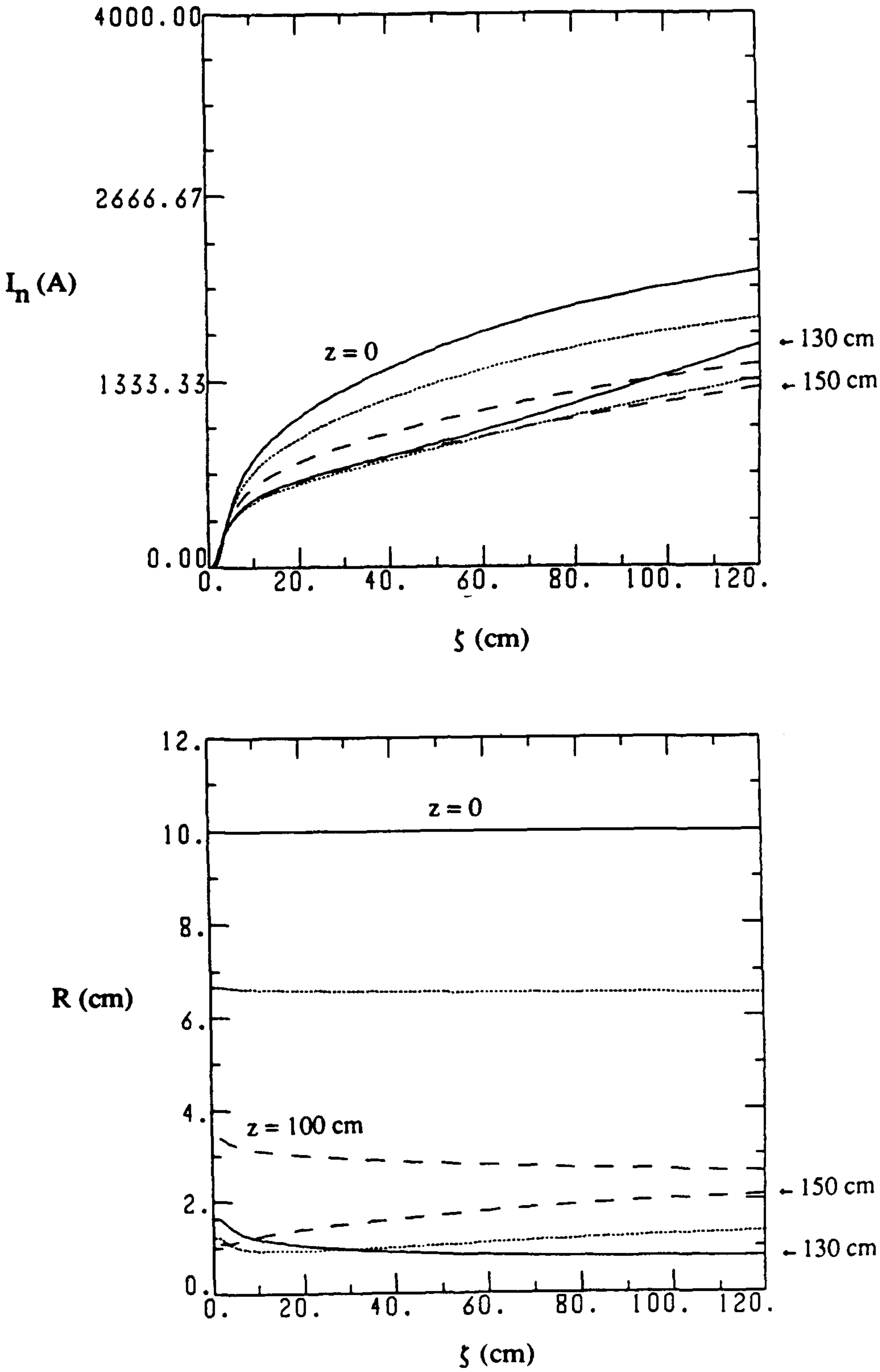

FIG. 5. $I_n(\zeta)$ and $R(\zeta)$ for a converging beam case with the nominal GAMBLE beam parameters except that R_o = 10 cm and the beam is focused at a nominal focus distance L = 150 cm. The net current is similar to that seen in Fig. 1. $I_n(\zeta)$ is sufficiently large to shift the focal point for much of the beam to ~130 cm. Individual curves are for z = 0, 50, 100, 130, 140 and 150 cm.

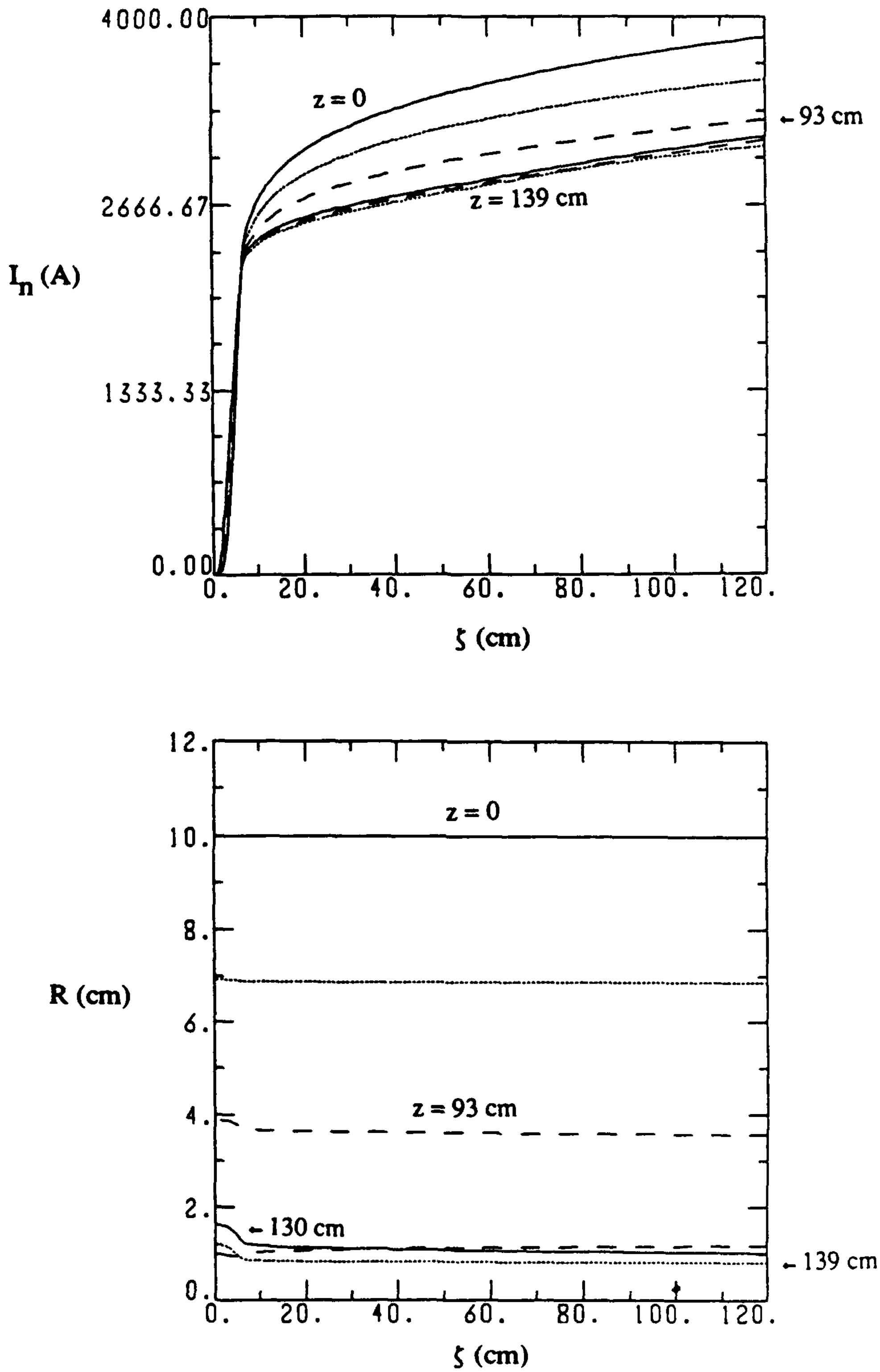

FIG. 6. $I_b(\zeta)$ and $R(\zeta)$ for a 300 kA Li^{+3} beam with other parameters similar to those expected for LMF. The net current rises very rapidly in the beam head and then freezes in at 3-4 kA. The shift in the focus is less than seen in fig. 5. Individual curves are for z = 0, 46, 93, 130, 139 and 148 cm.

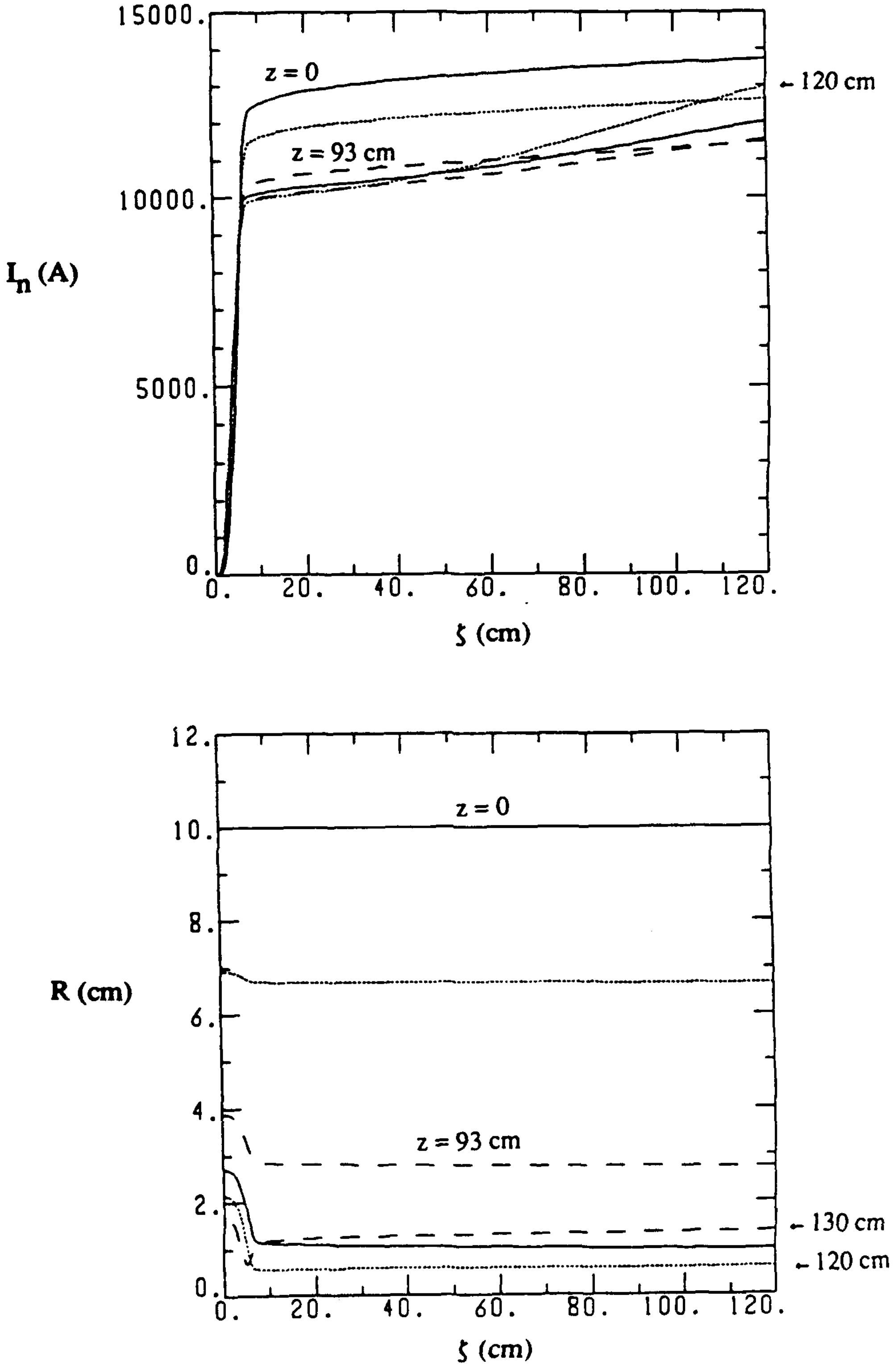

FIG. 7. $I_n(\zeta)$ and $R(\zeta)$ for a 1500 kA LMF beam beam with other parameters identical to those used in Fig. 6. The net current behavior is similar to that seen in Fig. 6 except that it is a factor of 3-4 higher. This is sufficient to cause a substantial shift in the beam focus. Individual curves are at z = 0, 46, 93, 111, 120 and 130 cm.