IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

METHOD OF ACTIVE CHARGE AND CURRENT NEUTRALIZATION OF INTENSE ION BEAMS FOR ICF*

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Summary

Intense ion beam neutralization by sufficiently cold, co-moving and co-injected electrons is crucial to Light Ion and important to Heavy Ion Inertial Confinement Fusion (ICF) drivers for the ballistically focused propagation onto ∿ 5 mm radius targets located some 10 m downstream. Methods of generating the beam neutralization electrons with required properties are given in the context of a Light Ion Fusion Experiment (LIFE) designed[1] accelerator. Recently derived envelope equations[2] for neutralized and ballistically focused intense ion beams are applied to the LIFE geometry in which 10 MeV He^+ multiple beamlets coalesce and undergo 45:1 radial compression while beam pulses experience a 20:1 axial compression in the propagation range of 10 m. For these representative conditions, the theoretical analysis produces a requirement of the initial electron temperature neutralizing the ions as $T_{eo} \leq 35$ eV where also the initial ion temperature T_{io} is correlated. Both active and auto[4]-neutralization methods are examined and found to produce initial electron temperatures consistent with the requirement of the envelope equation for both radial and axial adiabatic beam pulse compressions. The stability of neutralized beam propagation is also examined concerning the Pierce type electrostatic instability and for the case of LIFE beams it is found to have insignificant effect. A scaled experimental setup is presented which can serve to perform near term tests on the ballistically focused propagation of neutralized light ion beams.

Neutralized Ballistic Propagation of Intense Ion Beams

The key properties of a 2 MJ Light Ion ICF driver which relies on neutralized and ballistically focused

Table I

L.I.F.E. SINGLE BEAM PARAMETERS FOR A 2 MJ, 150 TW, 95 TW/cm^2, 40 BEAM-LINE ICF DRIVER SYSTEM

INTENSE PULSED COLD PLASMA	CHANNEL FOCUSING MULTI-GRID MULTI-APERTURE		
SOURCE →	ACCELERATOR →	NEUTRALIZER →	BALLISTIC TRANSPORT →
• He^+	• 23 kA/BEAM LINE	• He PLASMA	• 10^{-3} torr, Li
• $n_i = 10^{13}$ cm^{-3}	• 400 ns	• PULSED FILAMENTS	• 10 m
• $T_i \sim 0.1$ eV	• 3 → 10 MeV	• $n_e = 3 \times 10^{12}$ cm^{-3}	• $R_T = 0.5$ cm
• 10^{-3} torr	• 20:1 AXIAL COMPRESSION	• CO-MOVING e	• 50 kJ/BEAM LINE
• 1A/cm^2	• 45:1 RADIAL COMPRESSION	• CO-LOCATED e	
	• 200:1 GEOMETRIC RADIAL FOCUSING	• $T_{eo} \approx 40$ eV	

propagation are listed in Table I. The developed source[5] and accelerator design[1] are presented in these proceedings; features of the neutralizer and ballistic transport are given in the following. Two-dimensional numerical simulations[6] have indicated the necessity of launching electrons which are co-located with the ions, otherwise side-injected electrons heating rapidly attain an initial temperature which is prohibitive to the ballistic focusing of neutralized intense ion beams. A method of producing co-injected electrons with ions is shown in Figure 1. This neutralizer cell is located immediately adjacent to the output optics of a multi-aperture accelerator[1] from which 1 A He^+ beamlets at 3-10 MeV are emerging for a total of 23 kA current in 400 ns pulses. The ballistically focused beamlets pass through the neutralizer cell in which He^+ plasma is pre-pulsed at a density of n(plasma)/n(beam) ∿ 100 and

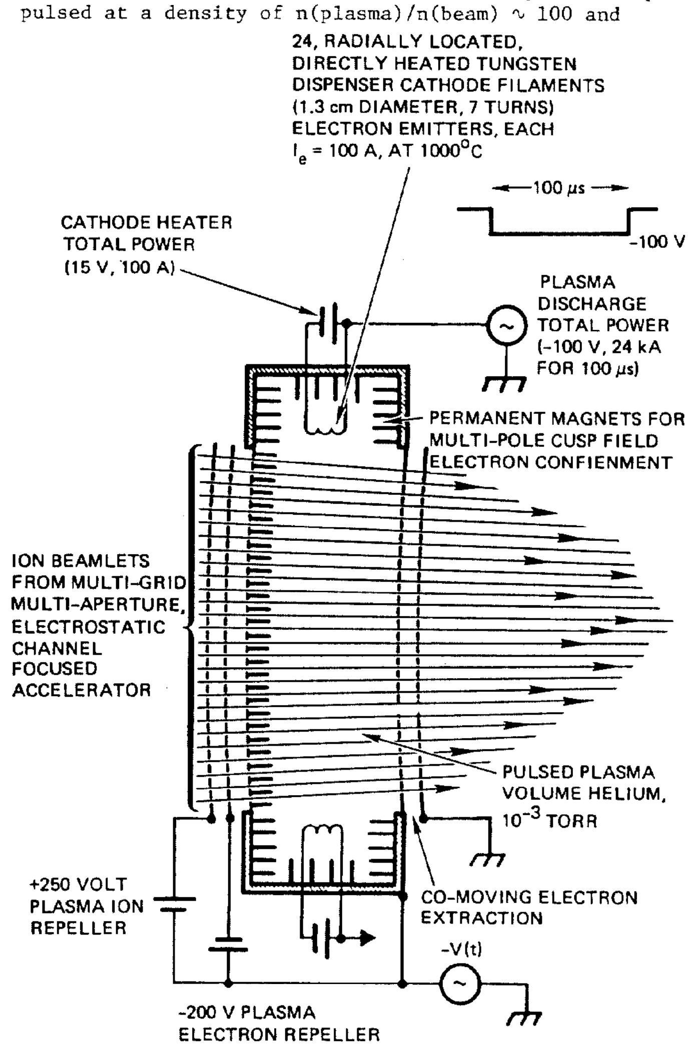

Figure 1. Method of Active Neutralization of Multiple Ion Beams.

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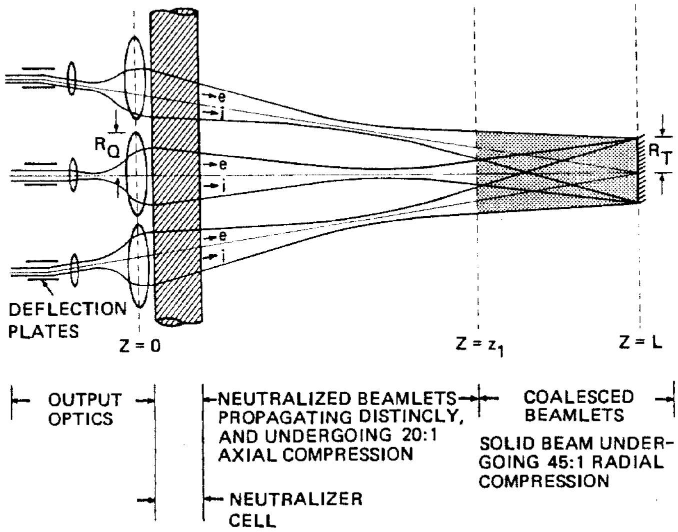

Figure 2. Stages in Ballistically Focused and Neutralized Multiple Ion Beam Propagation.

electron emission is continually supplied by radially located filaments. Ion beam charge neutralization occurs rapidly in the cell. In emerging beams, electrons are either accelerated by the moving space potential of ions (auto-neutralization)[4] or by an applied potential at the downstream gap of the cell. The stages entering in the ballistically focused and neutralized propagation of multiple ion beams are conceptually displayed in Fig. 2 showing the beam output optics section of the accelerator system, the adjacent neutralizer cell, the free propagation zone where distinct neutralized beamlets undergo some axial pulse compression and the critical propagation zone starting at z_1 where combined beamlets undergo both axial and radial adiabatic compressions in the course of ballistically focusing on targets. Considered in the LIFE geometry, the propagation range L is 10 m, z_1 = 8 m, $R(z_1)/R_F = 45$, $\ell_o/\ell_F = 20$ where ℓ_o and ℓ_F are the initial and final beam pulse lengths, $R_F\sqrt{f} = R_T$, R_F is the focused beam radius, R_T = 5 mm is a target radius and f is the fractional area of the beam incident on targets.

For intense and well neutralized ion beams where Debye length $\lambda_D \ll R(z)$ or $\ell(z)$, the neutralizing electrons are trapped within the ion beam potential well, same as a neutral gas is confined within a closed volume, and adiabatically are heated as the volume shrinks by radial and axial beam pulse compressions; in order for the beam to focus, the directed forces associated with the beam's radial and axial ballistic focusing must be large enough to overcome the pressures exerted by the heated electrons. An envelope equation describing the simultaneous occurrence of both axial and radial compressions is obtained by assuming that axial compression is occurring in the absence of external or internal forces at a constant rate and that both electrons and ions are heated adiabatically. At the onset of beam radial compression it is found that inequalities of initial $T_{e\perp}$ and $T_{e\parallel}$ are quickly isotropized so that electrons are adiabatically heated in three dimensions characterized by a specific heat ratio of $\gamma_e = 5/3$. Because the axial directed energy of ions is very large compared to any temperature $T_{i\parallel}$, the axial motion of ions is not significantly perturbed by the pressure of electrons or the thermal ion expansion so that the rise in transverse ion temperature $T_{i\perp}$ occurs by adiabatic heating in two dimensions which is characterized by the value of $\gamma_i = 2$. The associated envelope equation and these conditions are given by Eq. (1), (2) and (3), where E_b is the kinetic energy of ions and θ is the maximum convergence angle in the ballistic focusing of beamlets,

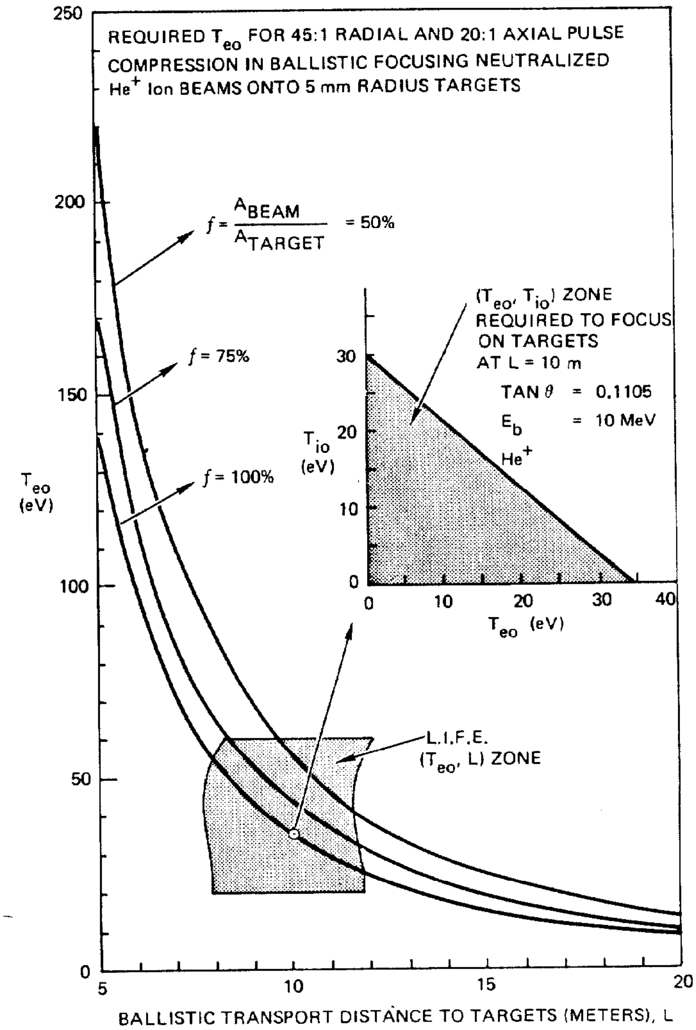

Figure 3. Required Initial Electron Temperature for Ballistically Focused and Neutralized Light Ion Beams.

$$\frac{1}{2} E_b\tan^2\theta = \frac{3}{2} z_i T_{eo}\left[\left(\frac{R_o}{R_F}\right)^{4/3}\cdot\left(\frac{\ell_o}{\ell_F}\right)^{2/3} - 1\right] + T_{io}\left[\left(\frac{R_o}{R_F}\right)^2 - 1\right] \quad (1)$$

$$T_e = T_{e\perp} = T_{e\parallel} = T_{eo}\left(\frac{R_o^2\ell_o}{R_F^2\ell_F}\right)^{\gamma_e - 1} \; ; \; \gamma_e = 5/3 \quad (2)$$

$$T_i = T_{i\perp} = T_{io}\left(R_o^2/R_F^2\right)^{\gamma_i - 1} \; ; \; \gamma_i = 2. \quad (3)$$

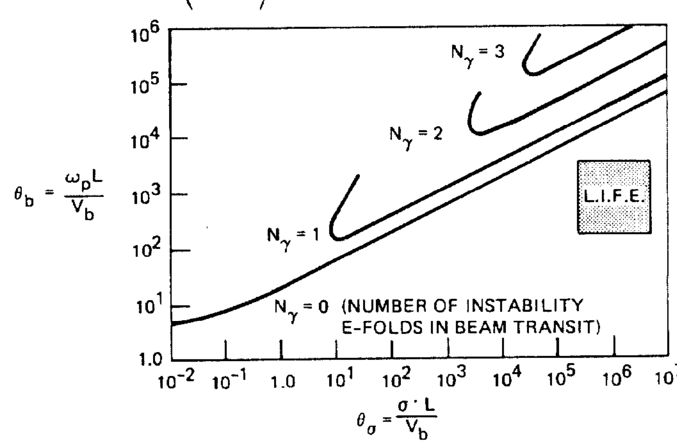

Figure 4. Pierce Instability Analysis for Neutralized Ion Beam Propagation.

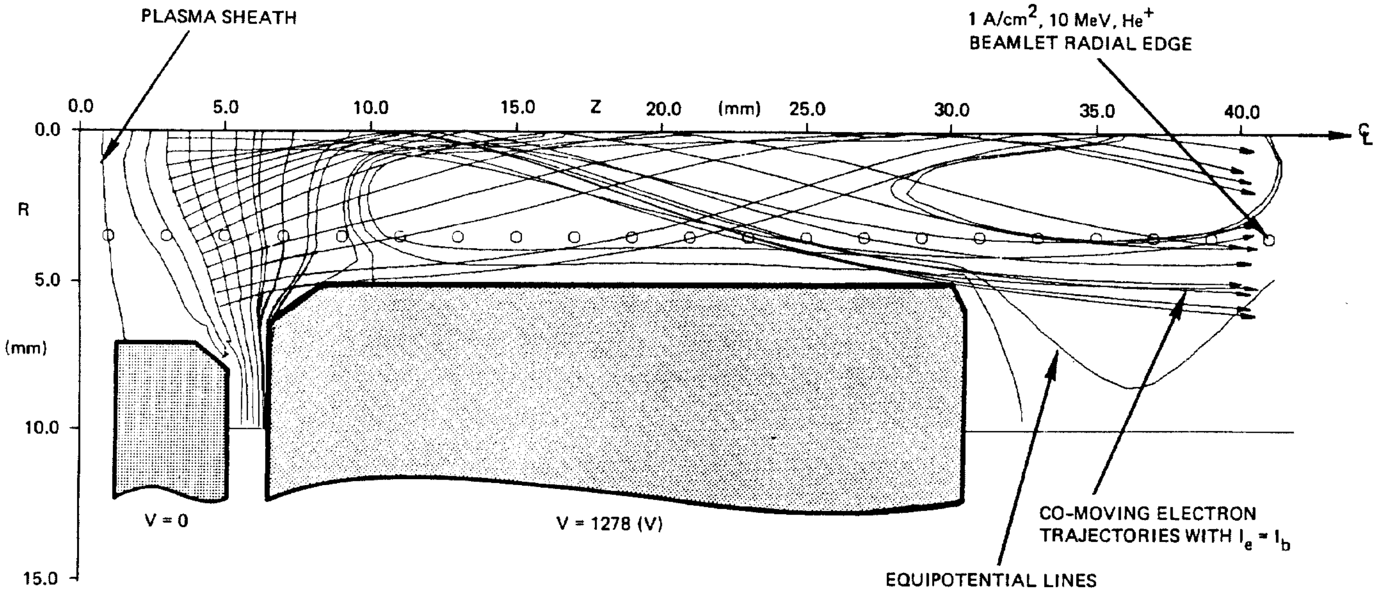

Figure 5. Production of Co-Moving Electrons Co-Injected with Ion Beamlets.

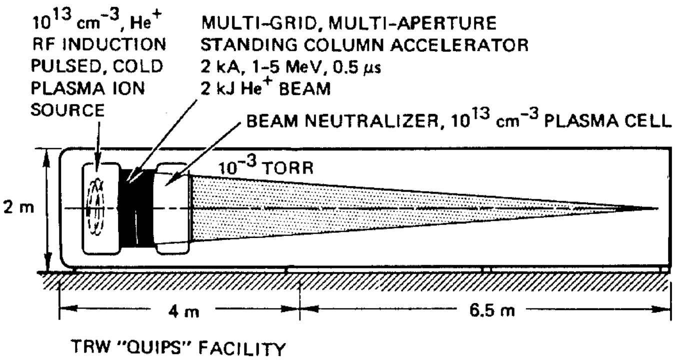

Figure 6. Experimental Setup to Test Ballistically Focused Propagation of Neutralized Light Ion Beams.

$\tan\theta = a_o/L$. Equation 1 can be used with $T_{io} = 0$ to obtain the limiting tolerable T_{eo} as a function of radial and axial compressions, the propagation range, the convergence angle and E_b, for a given initial beam overall radius a_o. These calculations are shown in Fig. 3 for the case of LIFE beams, demonstrating that a $T_{eo} \leq 35$ eV will be required to ballistically focus 100% of the beam onto 5 mm radius targets from a range of 10 m. The correlated requirement in terms of initial T_{eo} and T_{io} is also obtained from Eq. 1 and shown in Fig. 3, so that values of $T_{io} \sim 4$ eV are acceptable. A recent analysis appropriately made for this ICF ion propagation concerning the Pierce type electrostatic instability[3] is also applied for the case of LIFE beams and found to have an insignificant effect, as shown in Fig. 4. We note that the 3-D heating of electrons also enhances the validity of Eq. (1) for well neutralized beams; this is because in 3-D the Debye length scales as $\lambda_D \sim T_{eo}^{1/2} (a(z))^{1/3}$ and the required inequality of $a(z)/\sqrt{2} >> \lambda_D$ is preserved down to mm spot size beams. Moreover, T_{ii} cannot rise by equilibration with T_e during μs propagation times since $\sim$ 20 ms is needed for this.

In auto-neutralization thermal electrons are accelerated to co-move with ions influenced by the space charge of co-located traversing ion beams. In 1-D numerical simulations Humphries[4] et al have observed that initially the potential experienced by electrons oscillates between $\phi = 0$ and $\phi = 4\ E_e$ with periodicity of $\lambda = 2\pi v_b/\omega_{be}$ where $E_e = (m_e/M_i)E_b$, and after a few oscillations settles to $\phi \simeq E_e$, producing both current and charge auto-neutralization. A measure of the resulting T_{eo} is numerically deduced to be $T_{eo} = 0.043\ E_e$, so that T_{eo} = 20-60 eV for 3-10 MeV He^+ beams. By actively accelerating electrons in the manner shown in Fig. 5 a T_{eo} = 10 eV is deduced in a 2-D electrostatic simulation for 10 MeV 1 A/cm² beams. The T_{eo} from auto-neutralization could be reduced by initiating the motion of co-located electrons at higher than thermal speeds, say at $E_e \sim 300$ eV directed energy, by employing the method given in Figures 1 and 5. A scaled experimental setup is displayed in Fig. 6 which is designed to address the critical issues in the ballistically focused propagation of neutralized light ion beams. This field of research is so far lacking significant inputs from appropriate experiments which would be relevant to both this light ion and the heavy ion ICF drivers.

*Work performed in part under the auspices of U.S. DOE contract DE-AC08-79DP40109 and W-7405-ENG.36.

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