The collective effects of intense ion and electron beams propagating through background plasma

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Applications:
- HIF, FI,
- collisionless shocks in astrophysics.

Issues:
- Controlling degree of neutralization by plasma;
- Mitigation of plasma instabilities;
  - Generation of strong magnetic field, beam filamentation, collisionless beam stopping and plasma heating.
Controlling degree of neutralization by dense plasma

- **Practical consideration:** What plasma sources are needed for 100000 times simultaneous neutralized drift compression.

- **Theoretical consideration:** Basic problem is not considered in textbooks. Need solid foundation instead of phenomenological (1-f) approach.

Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation direction. For long beams canonical momentum is conserved: \[ mV_{ez} = eA_z / c = e\int_0^r Bdr / c \]

\[ \phi = mV_{ez}^2 / 2e \quad V_{ez} \sim V_b n_b / n_p \quad \phi_{\nu_p} = mV_b^2 \left( \frac{n_b}{n_p} \right)^2 / 2 \]

Having \( n_p \gg n_b \) strongly increases the neutralization degree.
Influence of magnetic field on beam neutralization by a background plasma

Small radial electron displacement generates fast poloidal rotation according to the conservation of azimuthal canonical momentum:

$$V_\phi = \frac{e}{m c} (A_\phi + B_{sol} \delta r)$$

The poloidal rotation twists the magnetic field and generates the poloidal magnetic field and large radial electric field.


$$E_r \sim \frac{1}{c V_{e\varphi}} B_{sol}; \quad B_{e\varphi} = B_{ez} \frac{V_{e\varphi}}{V_{bz}}$$

Self-magnetic field; perturbation in the solenoidal magnetic field; and the radial electric field in a perpendicular slice of the beam pulse: $n_{b0} = n_p/2 = 1.2 \times 10^{11} \text{cm}^{-3}$; $V_b = 0.33c$,

$B_{z0}$: (b) 300G; and (e) 900G.
Plasma response to the beam pulse is drastically different depending on whether $\omega_{ce}/2\beta\omega_{pe} < 1$ or $> 1$

Gaussian beam:
$r_b = 2c/\omega_{pe}$,
$l_b = 5r_b$, $\beta = 0.33$

$\omega_{ce}/2\beta\omega_{pe}$
Left: 0.5
Right: 4.5

Electrostatic field is defocusing;
The response is paramagnetic.

Electrostatic field is focusing;
The response is diamagnetic.

Application of a solenoidal magnetic field allows control of the radial force acting on the beam particles.

\[ F_r = e(E_r - V_b B_\phi / c) \]

Normalized radial force acting on beam ions in background plasma for different values of \( (\omega_{ce} / \omega_{pe} \beta_b)^2 \). The green line corresponds to a gaussian density profile. System parameters are: \( r_b = 1.5 \delta_p \); \( \delta_p = c / \omega_{pe} \).

Electromagnetic Field Radiation by a Moving Beam in a Magnetized Plasma

Beam excites/radiates Helicon (electron) branch

$$\alpha = \omega_{ce}/2\beta$$

$$V_b = V_{gz} \quad V_{gx} = 0$$

No waves ($\alpha < 1$)

Waves are excited ($\alpha > 1$)

$$\omega_h = \omega_{ce} k k_z \left( k^2 + \frac{\omega_{pe}^2}{c^2} \right)$$

assumed $\omega_{ce} \ll \omega_{pe}$ for simplicity

Long wavelength Whistler (electromagnetic)

Short wavelength (quasi-electrostatic)

Generation of large radial electric field near the focus due to excitation of quasi-electrostatic wave

Gaussian beam with $\beta = 0.33$, $l_b = 17 r_b$, $r_b = \omega_p/c$, $n_b = 0.05 n_p$, $\omega_{ce}/2\beta \omega_{pe} = 1.37$
Complicated electrodynamics of beam-plasma interaction would make J. Maxwell proud!

Artist: E.P. Gilson
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Mitigation of plasma instabilities

- **Two-stream**
  - fast, can lead to electron heating.
  - mitigated by gradients of the plasma density and beam velocity variation.

- **Weibel (filamentation)**
  - slow, can lead to the formation of the beam filaments.
  - mitigated by the beam transverse thermal velocity.
Three Stages of Electron Beam Filamentation

1) Linear growth and saturation via magnetic particle trapping
2) Nonlinear coalescence of current filaments
3) Coalescence of super-Alfvenic current filaments.

Beam current is absent in the center of filament and localized at the edges of the filament.
Conclusions

- Developed nonlinear 2-3D theory of charge and current neutralization of intense ion and electron beam pulses propagating in plasma.
  - Presence of the magnetic field clearly makes the collective processes of beam-plasma interactions rich in physics content.
- Linear and nonlinear analysis of the two-stream and Weibel instabilities taking into account nonuniform profiles of the plasma density and beam velocity.
- Many results of the PIC simulations remain to be explained by analytical theory, especially in 3D.
Movie of the filamentation

\[ n_p = 8 \times 10^9 \text{cm}^{-3} \]
\[ n_b = 2 \times 10^9 \text{cm}^{-3} \]
\[ \gamma_b = 3.3 \]
Analytic solution for filament structure

\[ \mathbf{B} = -e_z \times \nabla \psi \]  
Vector potential, magnetic flux

Conservation of canonical momentum for beam and plasma electrons:

\[ m\gamma_b v_{bz} - \frac{e}{c} \psi = m\gamma_b v_{b0} \]
\[ m v_{be} - \frac{e}{c} \psi = 0 \]

Quasineutrality: \[ n_i = n_b + n_e \]

Amphere's law:

\[ \nabla^2 \psi - \frac{4\pi e^2}{mc} n_i \psi = 4\pi e n_b \beta_{b0} \]

The beam part of the solution has the form of the Hammer-Rostoker beam equilibrium.
Magnetic energy decrease as a result of merger of large filaments, $I > I_A$

In small filaments, the current flows throughout the entire beam cross section $\rightarrow$ the current doubles $\rightarrow$ the magnetic energy doubles.

In large filaments, the current flows only at the periphery of the beam $\rightarrow$ the magnetic energy decreases.

Current I: $2.4I_A$, Current II: $2.7I_A$, Resulting current IV: $4.5I_A$
Super-Alfvenic filaments, $I > I_A = \gamma mc^3/e$

Beam density is equal to the background ion density in the filament and sharply decreases at the periphery of the filament.

Ambient plasma is fully expelled from the filament.

Beam current is absent in the center of filament and localized at the edges of the filament.