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

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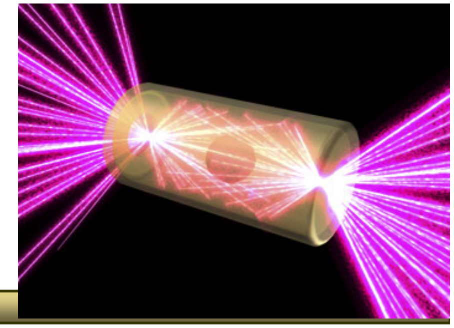
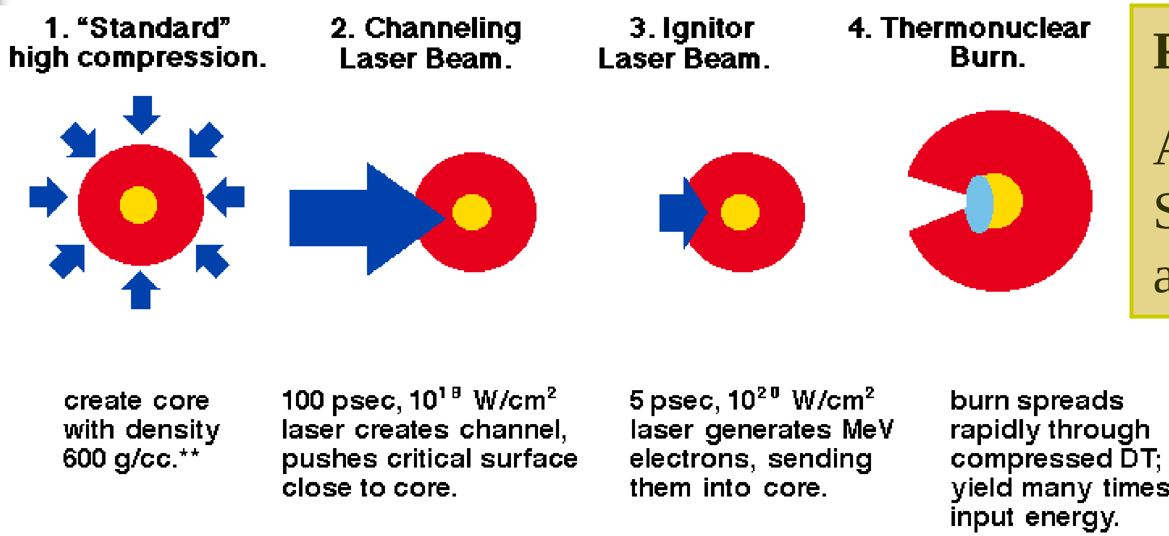
Outline

- **Applications:**
  - **Fast Ignition Scheme of Laser Driven Inertial Fusion**
  - **Neutralized Drift Compression Scheme of Ion Beam Driven Inertial Fusion**
  - **Collisionless shocks in astrophysics**
  - **Collective effects in intense particle beams in accelerators**

Electron MHD with electron inertia and kinetic effects

Applications: Fast Ignition Scheme of Laser Driven Inertial Fusion



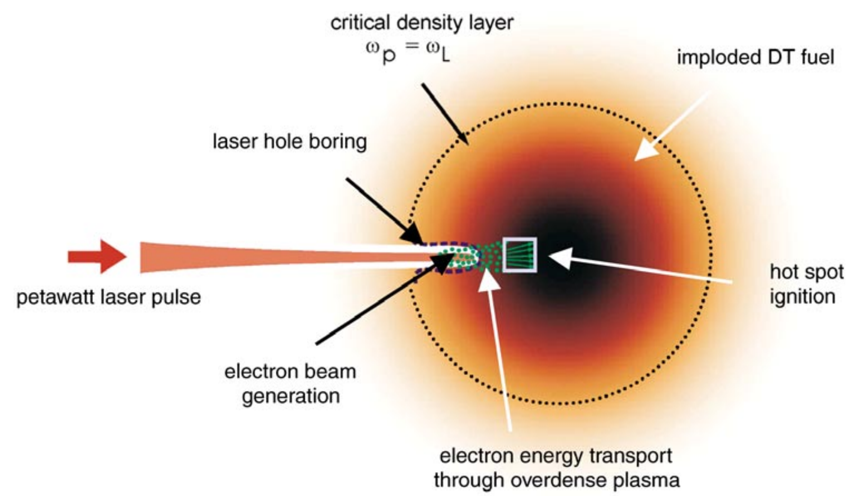


*Tabak, Hammer, Glinsky, Kruer, Wilks, Woodworth, Campbell, & Perry *Phys. Plasmas* **1** 1626 (1994)
** H. Azechi, et al. Laser Part. Beams **9**, 2 (1991).

Fast Ignition:

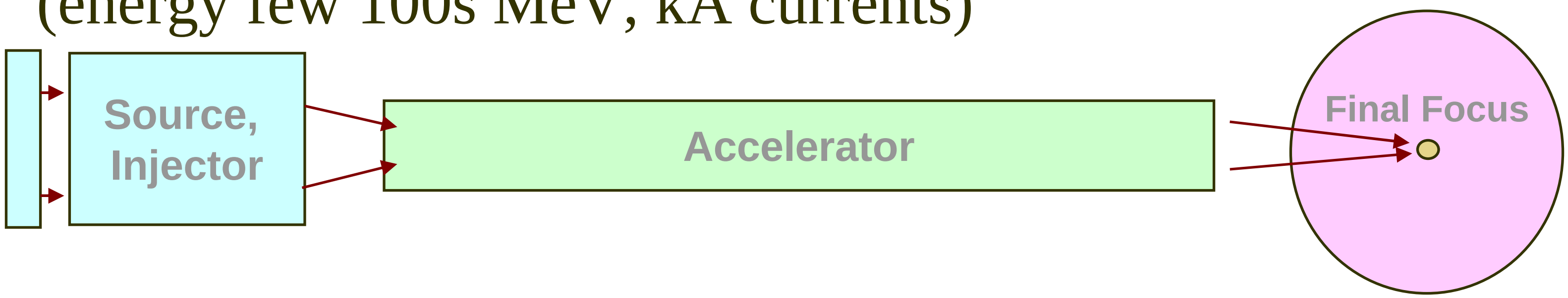
Assemble cold dense plasma, Small region is ignited using a petawatt laser

- **Collisional stopping of 1-2 MeV beams: what if the energy is much higher?**
- **Electrons have to travel through long "tenuous" coronal plasma: what happens to them on the way to the dense core?**

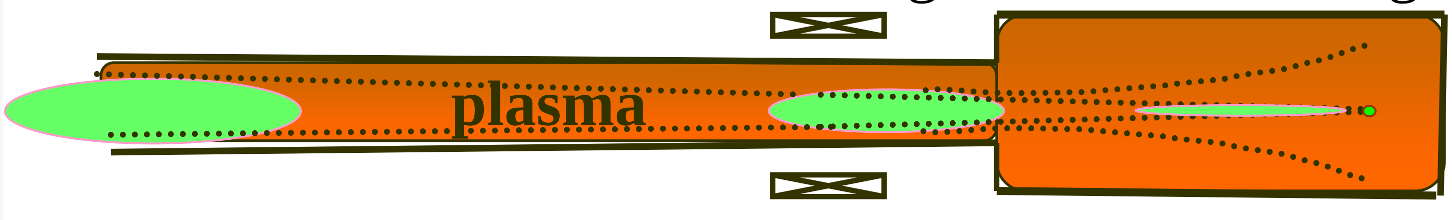


Applications: Neutralized Drift Compression Scheme of Ion Beam Driven Inertial Fusion

Instead of lasers intense ion beam pulses are used as a driver (energy few 100s MeV, kA currents)



Plasma Neutralizes Ion Beam Charge and Provides Tight Focus

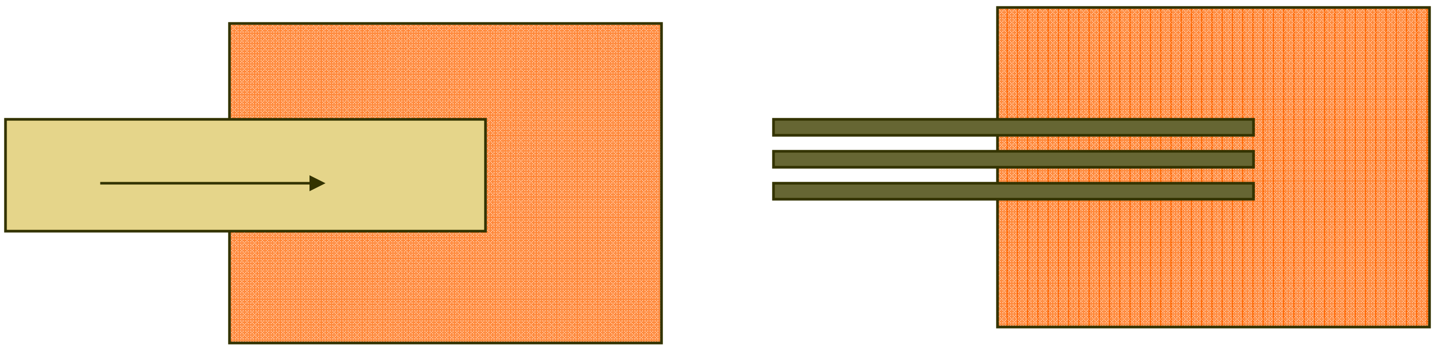


- Issues:
  Controlling degree of neutralization by plasma;
  Mitigation of plasma instabilities;
  Generation of strong magnetic field, beam filamentation, collisionless beam stopping and plasma heating.

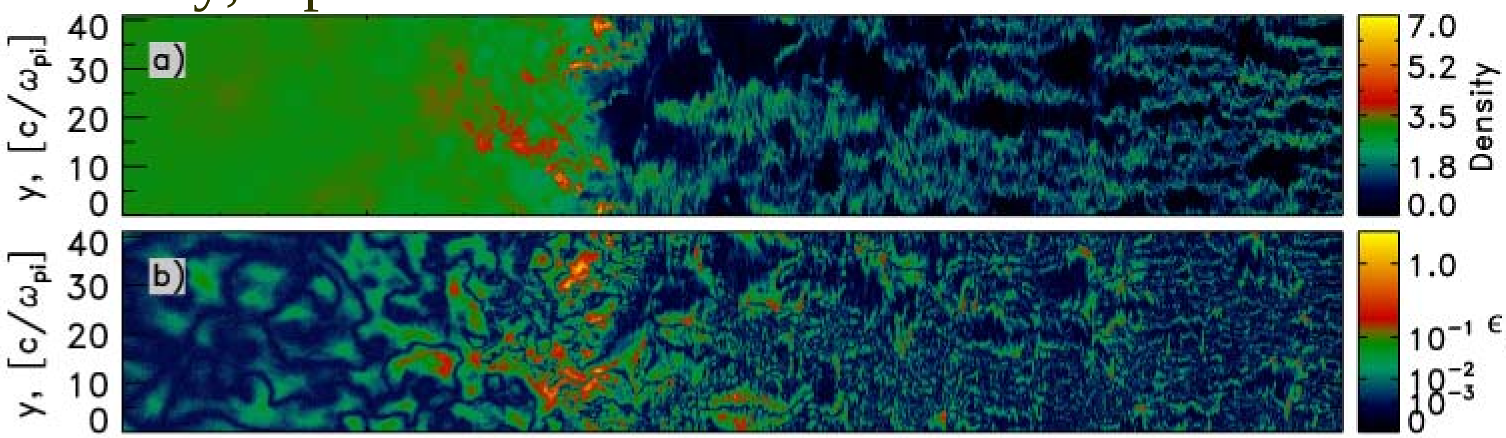
Applications: Collisionless shocks in astrophysics

Study mechanisms of collisionless energy transfer from intense electron beam to plasma during filamentation process.

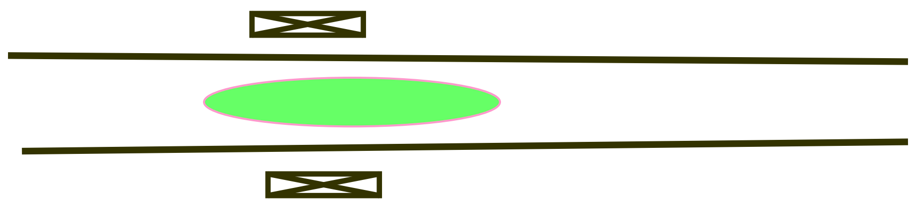
Electron beam or plasma stream penetrating to another plasma



Colorplots of density and magnetic energy in collisionless shock, A. Spitkovsky, Ap.J 2008



Collective effects in intense particle beams in accelerators



Intense nonneutral fast particle beam pulses have with self-potential of 100V-10kV and are subject to collective instabilities, Harris, Weibel, resistive wall, two-stream…

Tools: electron fluid and *full* Maxwell equations are solved numerically and analytically.

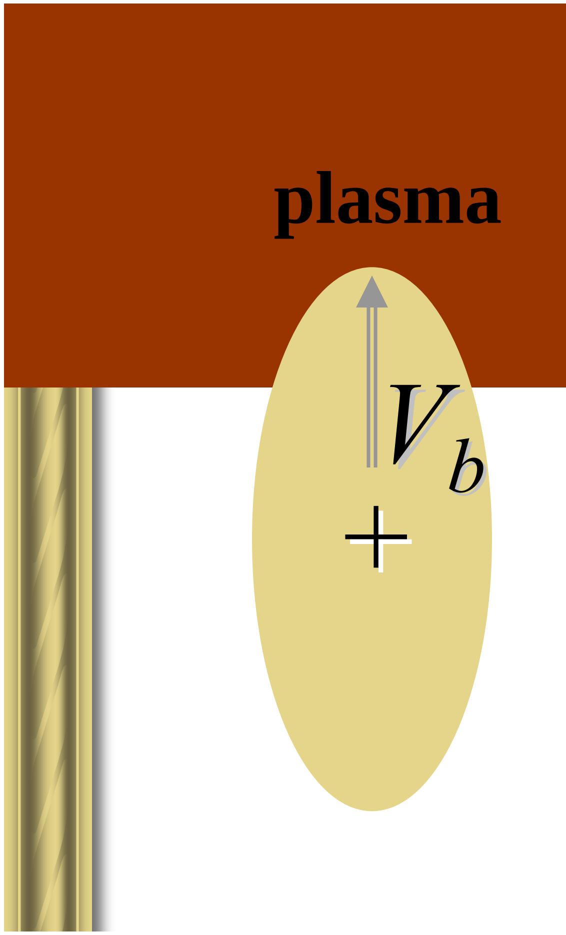
$$\frac{\partial \vec{p}_e}{\partial t} + (\vec{V}_e \bullet \nabla)\vec{p}_e = -\frac{e}{m}(\vec{E} + \frac{1}{c}\vec{V}_e \times \vec{B}), \quad \frac{\partial n_e}{\partial t} + \nabla \bullet \left(n_e \vec{V}_e\right) = 0,$$

$$\nabla \times \vec{B} = \frac{4\pi e}{c}\left(Z_b n_b V_{bz} - n_e V_{ez}\right) + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}, \qquad \nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}.$$

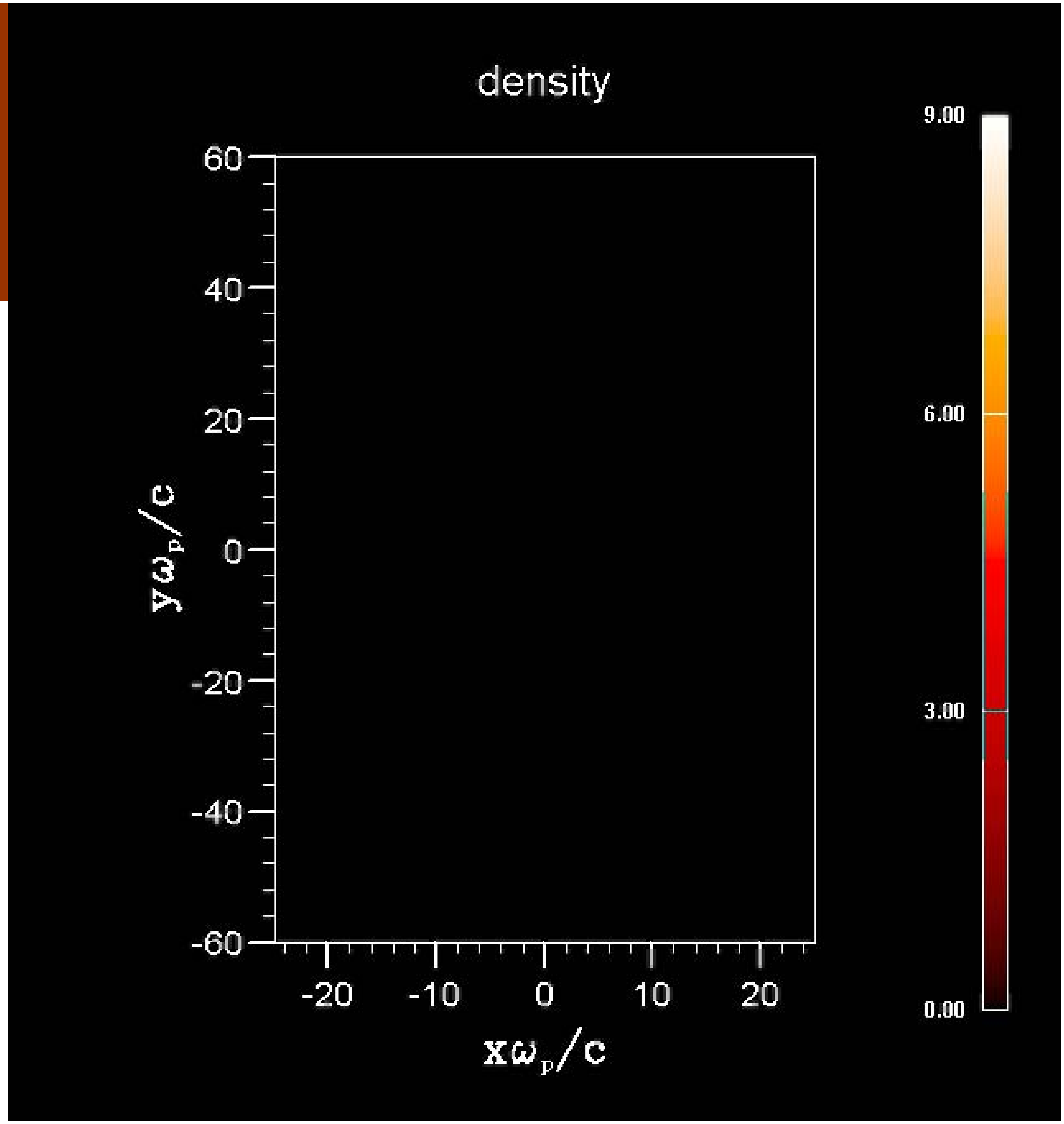
Explicit and implicit solvers, moving frames

For slow beams or dense plasmas (compared to the beam density) displacement current and radiation can be neglected => Darwin scheme.

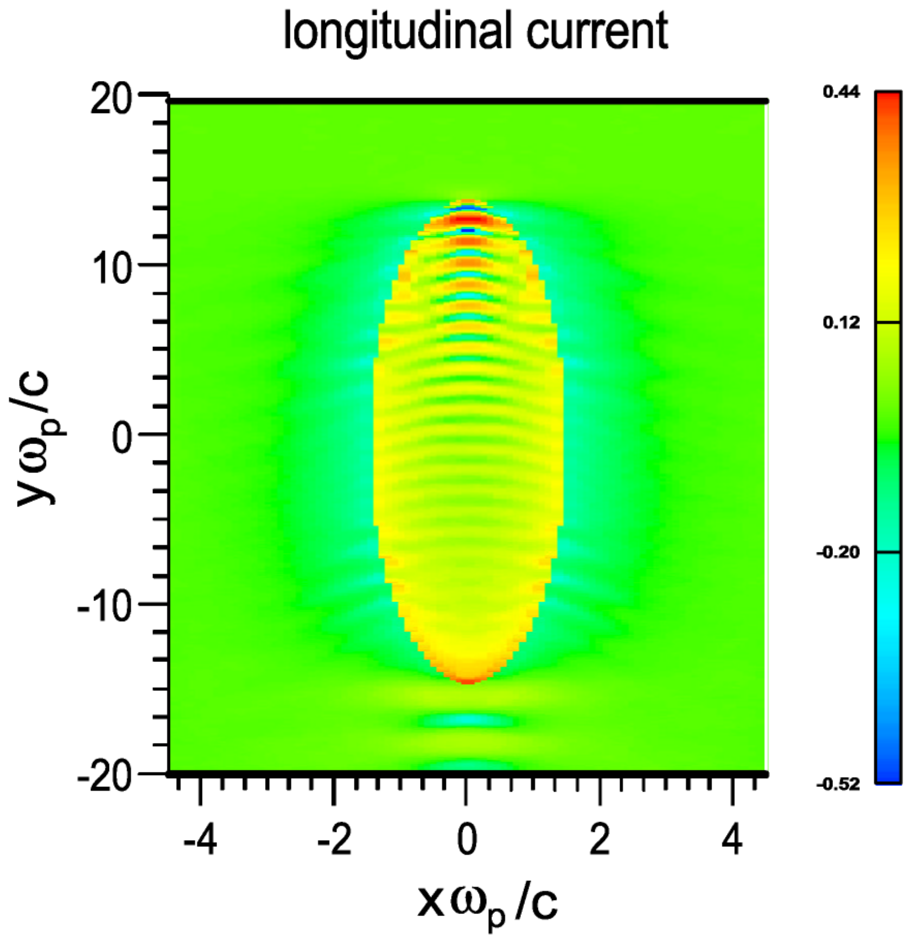
Analytical approaches: conservation of the canonical momentum or the generalized vorticity.



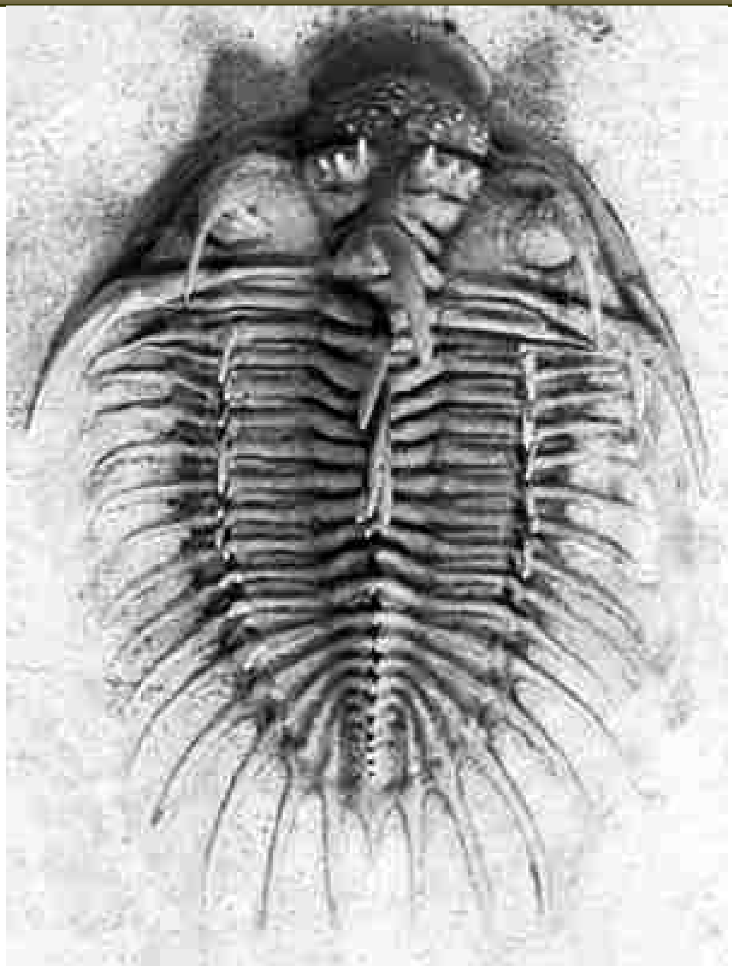
beam length $30c/\omega_p$
beam radius $0.5c/\omega_p$
beam density is 5 of
plasma density;
beam velocity $0.5c$.



Steady- State Results



normalized electron current $j_y/(ecn_p)$



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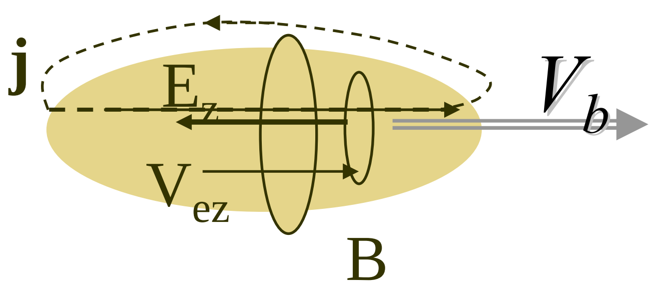
Controlling degree of neutralization of intense ion beam pulse by dense plasma

- **Practical consideration: what plasma sources are needed for effective neutralization.**



$$\frac{\partial \int Bds}{\partial t} => E_z$$

$$eE_r = \frac{1}{c} V_{ez} B_\theta = -mV_{ez} \frac{\partial V_{ez}}{\partial r}$$

Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation direction.

For long beams canonical momentum is conserved $mV_{ez} = eA_z / c = e\int_0^r Bdr / c$

$\phi = mV_{ez}^{\ 2} / 2e \quad V_{ez} \sim V_b n_b / n_p \quad \phi_{vp} = mV_b^{\ 2} \left(n_b / n_p \right)^2 / 2$

Having $n_p >> n_b$ strongly increases the neutralization degree.

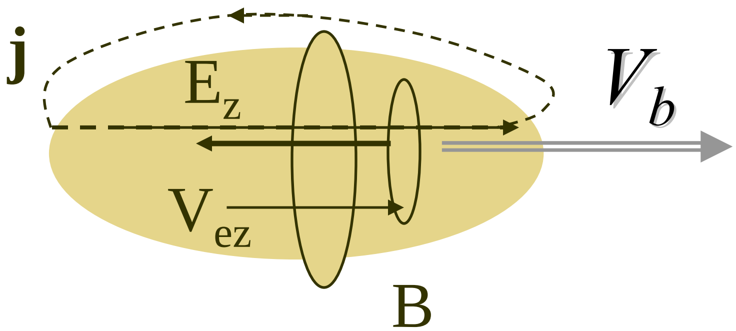
Electrons produced in the beam pulse carry away magnetic field

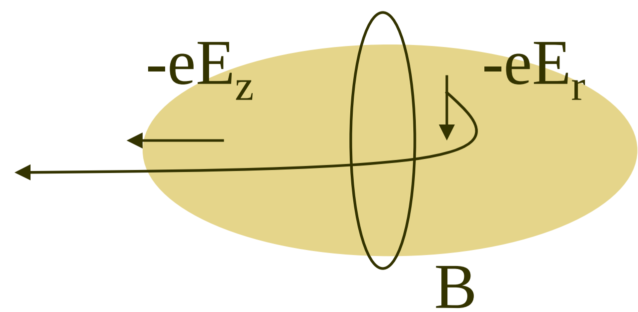
Electrons enter ahead of the beam pulse

$$v_{ez} = \frac{eA_z(z)}{mc}$$

Electrons originate inside the beam pulse

$$v_{ez} = \frac{e}{mc}\left[A_z(z) - A_z(z_b)\right]$$



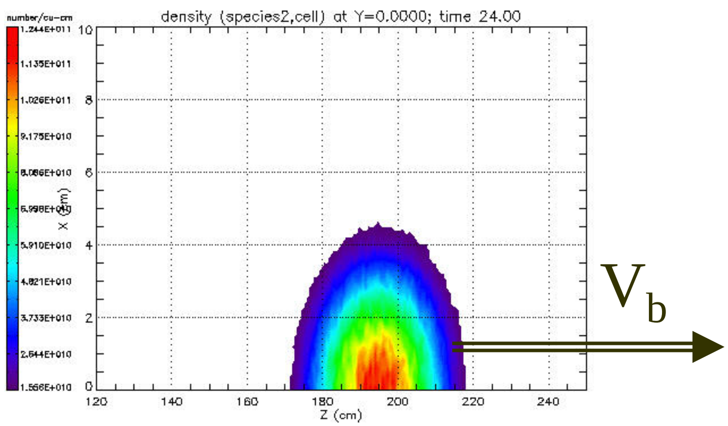


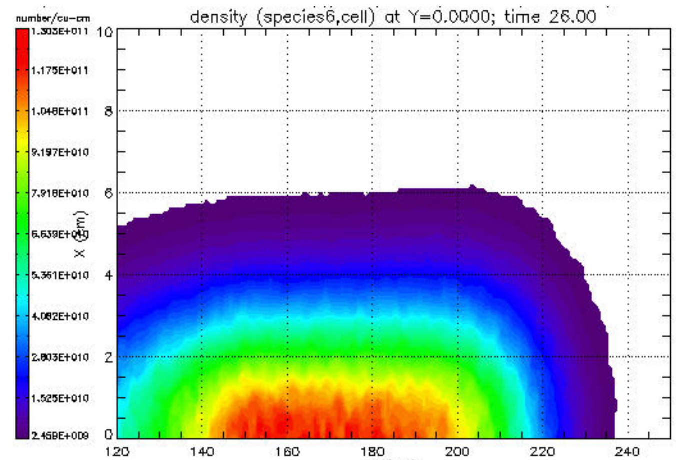
If an electron originates in the region of strong magnetic field, and later moves into a region of weaker magnetic field, then the electron flow velocity is in the direction opposite to the beam velocity; and the current of such electrons *enhances* the beam current rather than diminishes the beam current.

The return current becomes nonlocal.

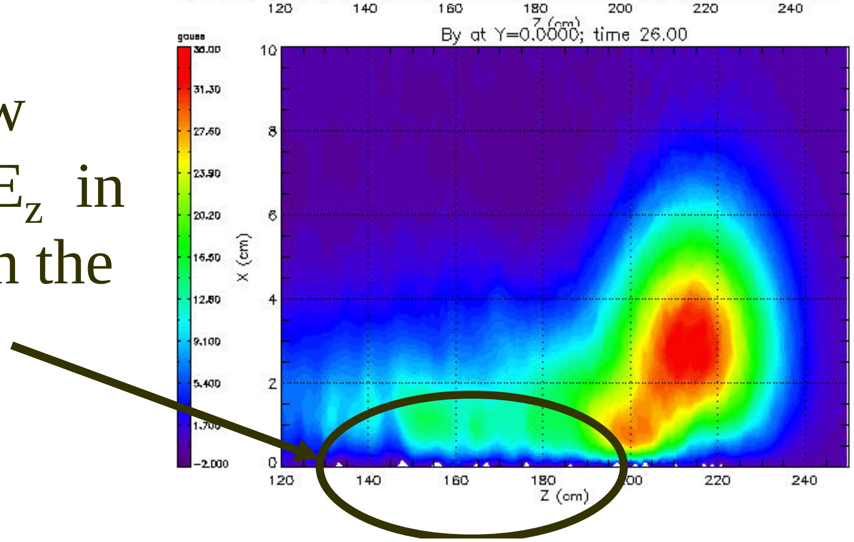
Long tail in the B profile is produced in the wake of the beam pulse due to ionization.

Beam pulse (left) produces plasma by gas ionization with comparable density (right), which generates a tail in the self-magnetic field.

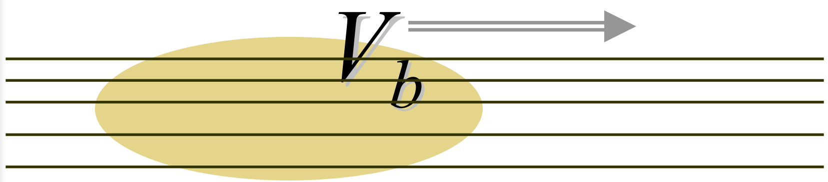




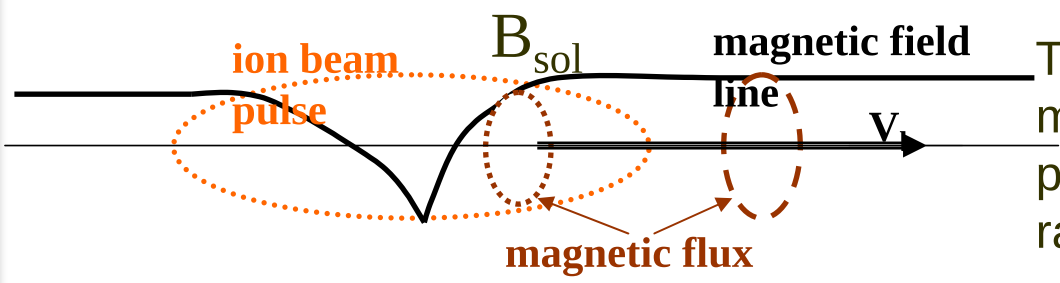
E_x in the beam pulse pushes new electrons into the beam center. E_z in the beam tail pushes electrons in the direction opposite to the beam velocity.



Influence of magnetic field on beam neutralization by a background plasma



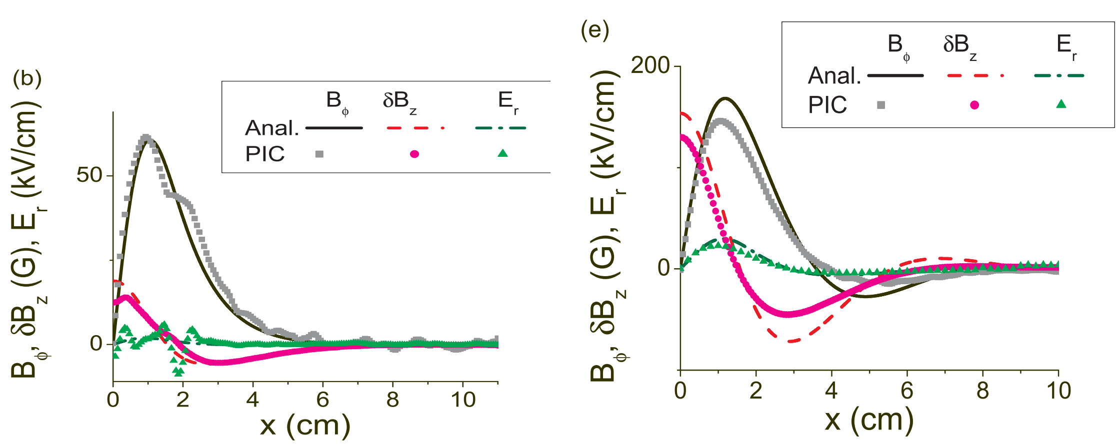
Small radial electron displacement generates fast poloidal rotation according to the conservation of azimuthal canonical momentum: $V_\phi = \frac{e}{mc}(A_\phi + B_{sol}\delta r)$



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

I. Kaganovich, et al, PRL **99**, 235002 (2007); PoP (2008).

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

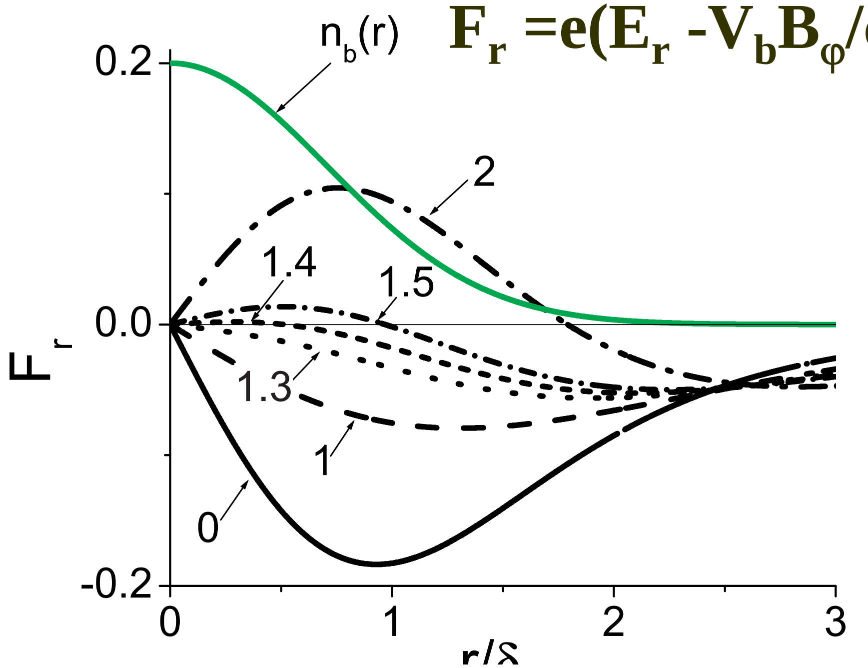


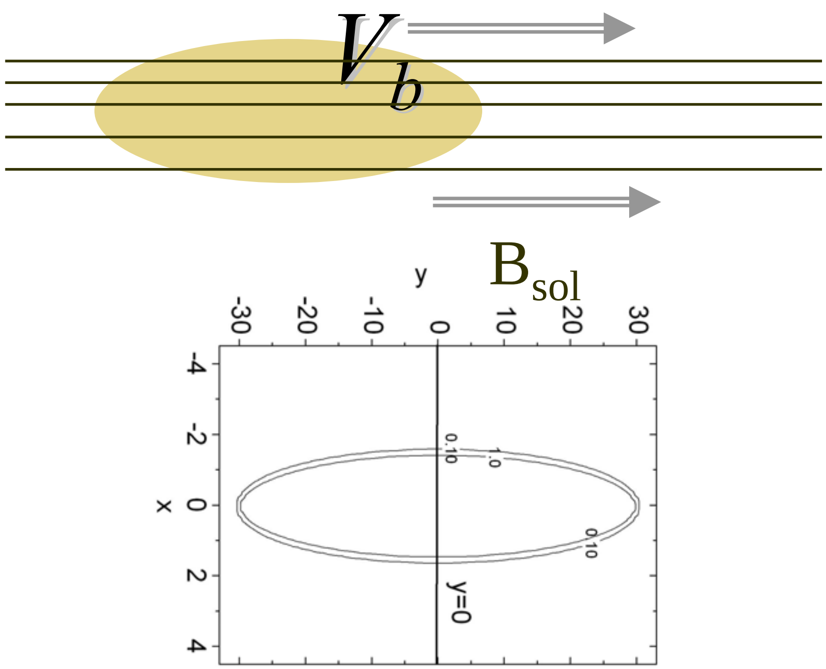
Self-magnetic field; perturbation in the solenoidal magnetic field; and the radial electric field in a perpendicular slice of the beam pulse: $n_{b0} = n_p/2 = 1.2 \times 10^{11} cm^{-3}$; $V_b = 0.33c$, B_{z0}: (b) 300G; and (e) 900G.

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

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 : $r_b = 1.5\delta_p$; $\delta_p = c/\omega_{pe}$.

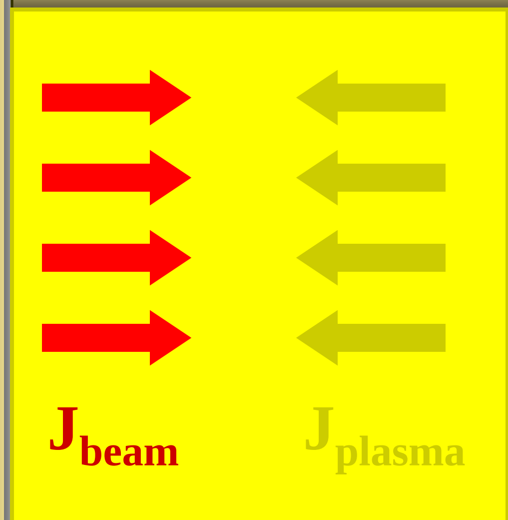
$$\mathbf{F_r = e(E_r - V_b B_\varphi / c)}$$



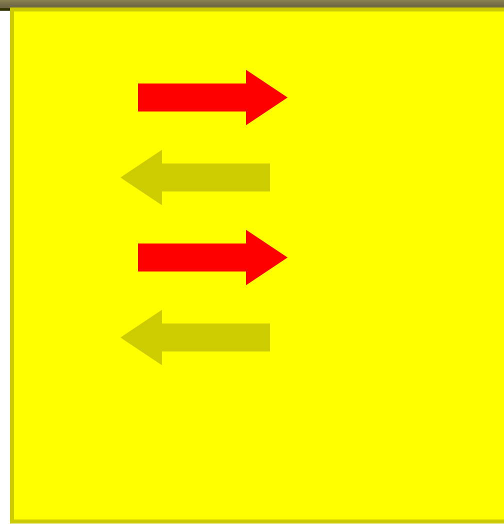


I. Kaganovich, et al, PRL **99**, 235002 (2007), M. Dorf, et al, PRL **103**, 075003 (2009).

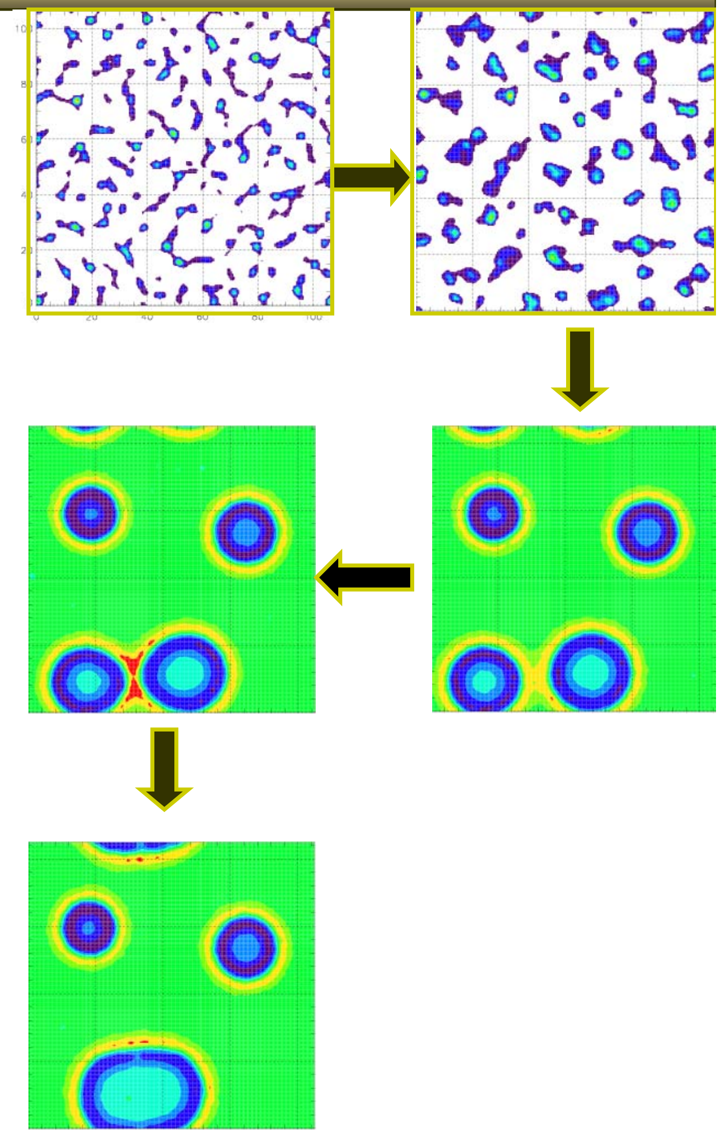
Weibel instability in relativistic beams



Beam enters the plasma, its current is neutralized

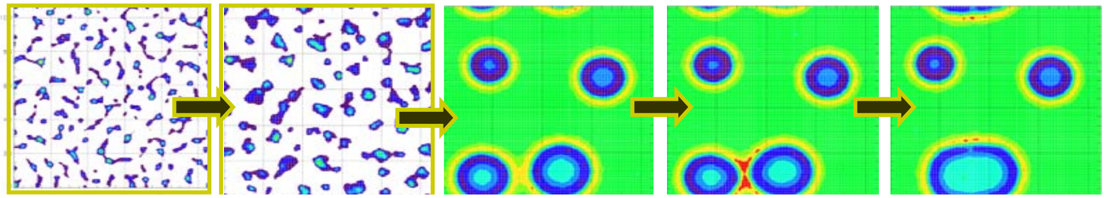


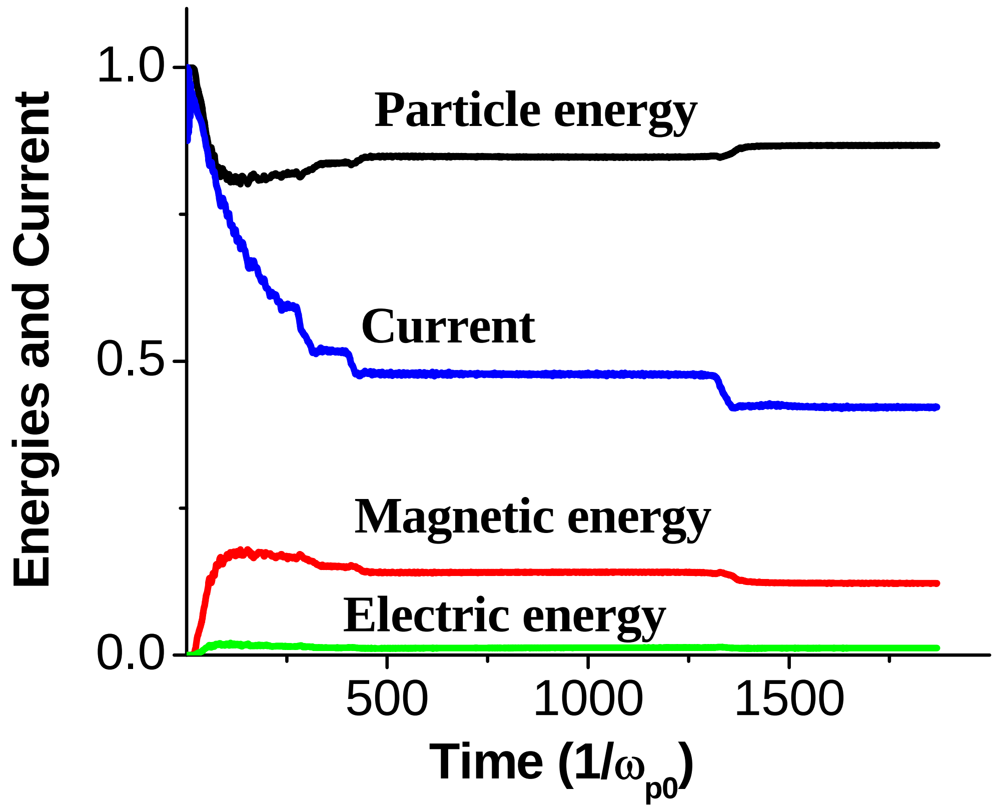
Opposite currents are repelled → filaments formation and interaction



Three Stages of Beam Filamentation

- **Linear growth and saturation via magnetic particle trapping**
  - small current filaments (c/ω_p), small energy extraction.
- **Nonlinear coalescence of current filaments**
  - each filament carries up to 17kA of current; significant energy conversion into magnetic fields.
- **Coalescence of super-Alfvenic current filaments**
  - beam current reduction, formation of "hollow" current filaments, decrease of the B-field energy.

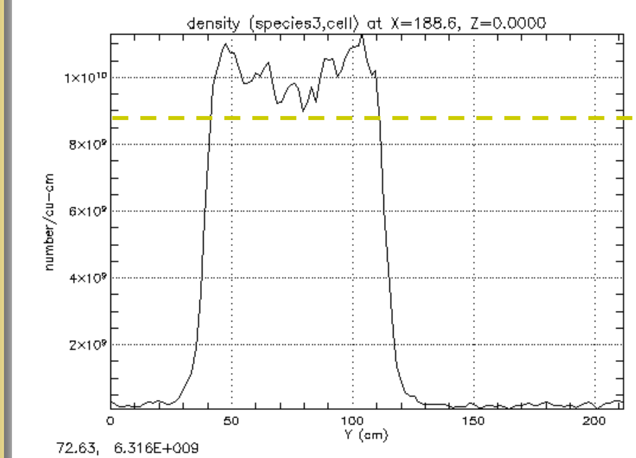




Movie of the beam density in 2D PIC simulations (fixed plasma ions)

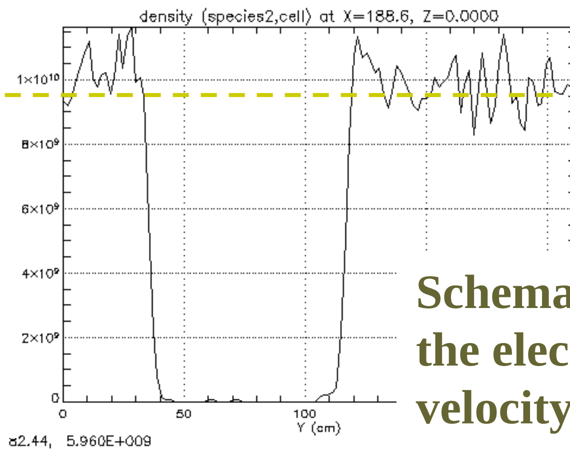
Super-Alfvenic filaments, $I > I_A = \gamma mc^3/e$

Beam density



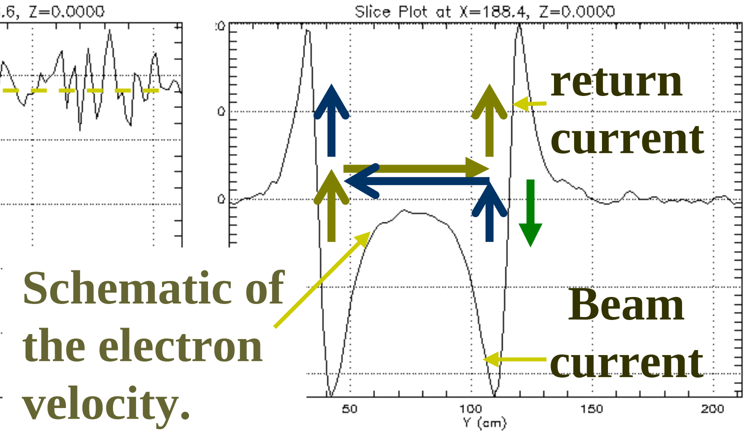
Beam density is equal to the back-ground ion density in the filament and sharply decreases at the periphery of the filament.

Plasma density



Ambient plasma is fully expelled from the filament.

Current density



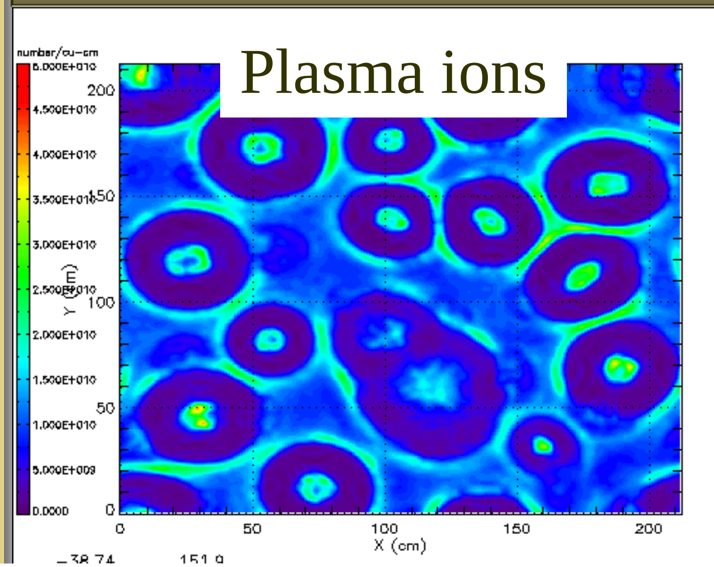
Beam current is absent in the center of filament and localized at the edges of the filament.

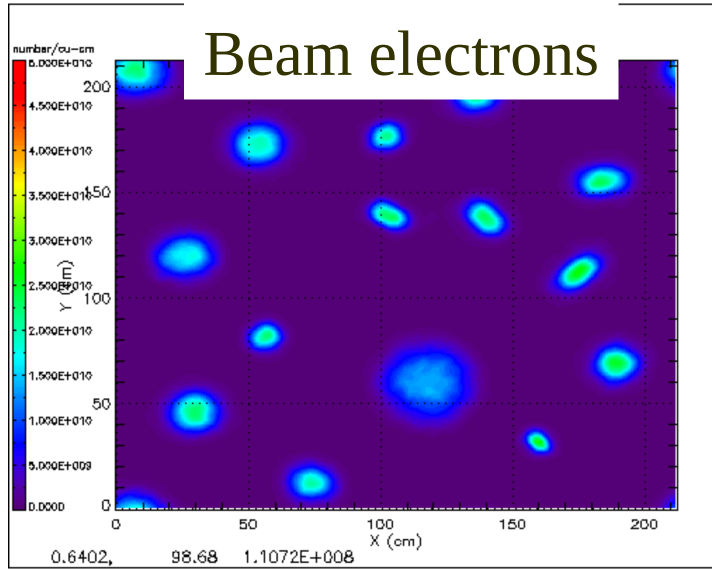
$$\nabla^2\psi - \frac{4\pi e^2}{mc} n_i \psi = 4\pi e n_b \beta_{b0}$$

Analytical solution making use of conservation of the canonical momentum, O. Polomarov, PRL 2008

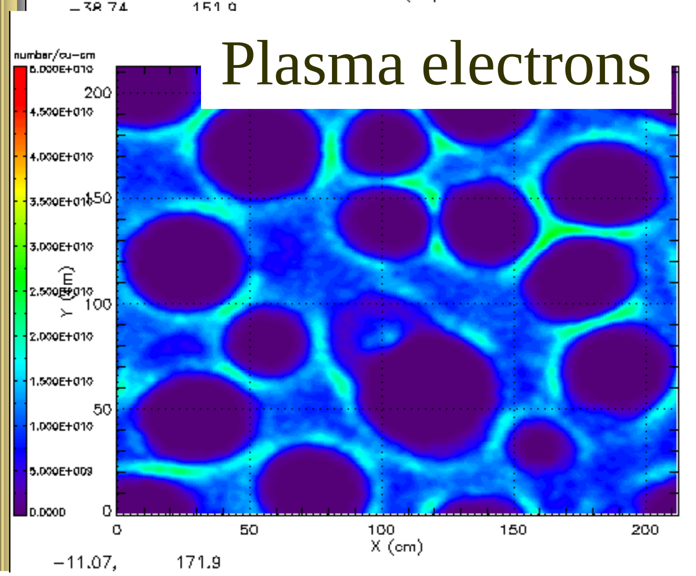
Movie of the plasma ion density in 2D PIC simulations moving plasma ions

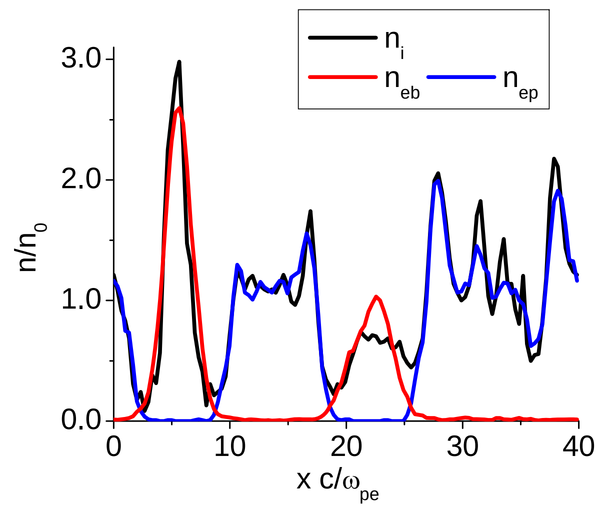
Density colorplots of beam electrons, plasma electrons, and plasma ions





Electric field pushes ions inwards inside filaments and outwards outside the filaments.

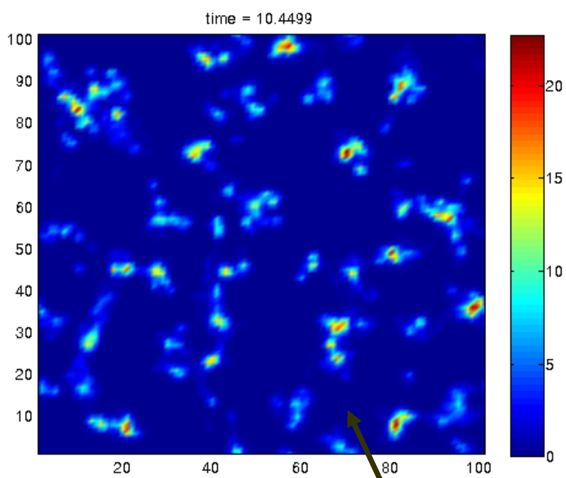


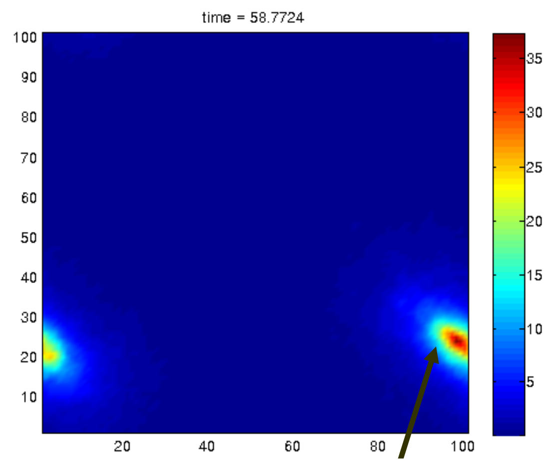


Slice of density profiles
electron beam
plasma electrons
plasma ions

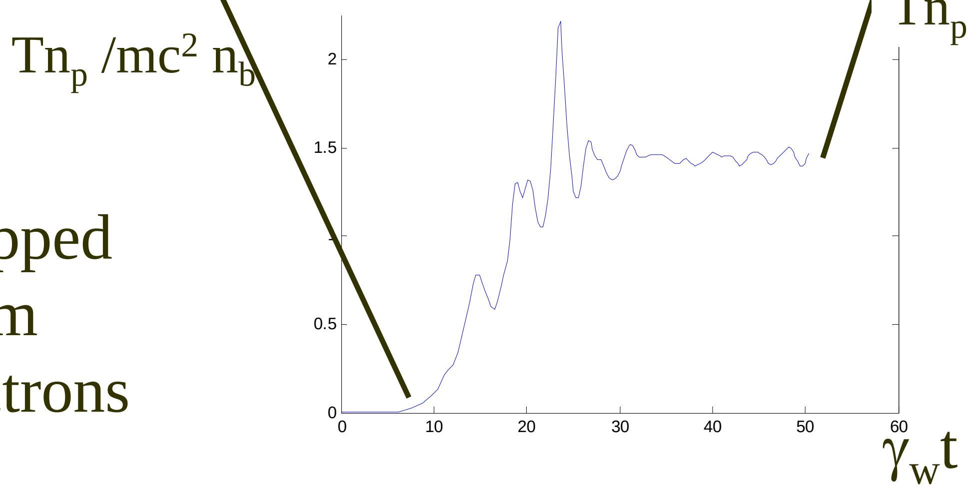
Electron beam temperature growth

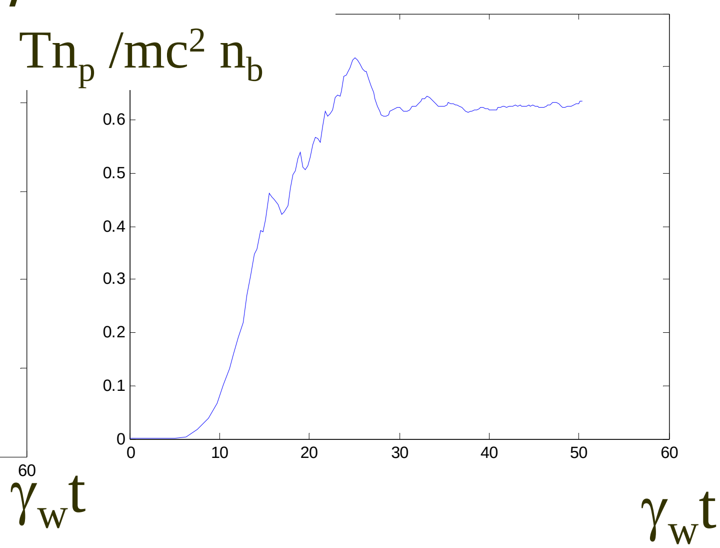
Distribution of the beam density normalized to the initial value, $n_{b0}/n_p=10^{-3}$





Untrapped beam electrons

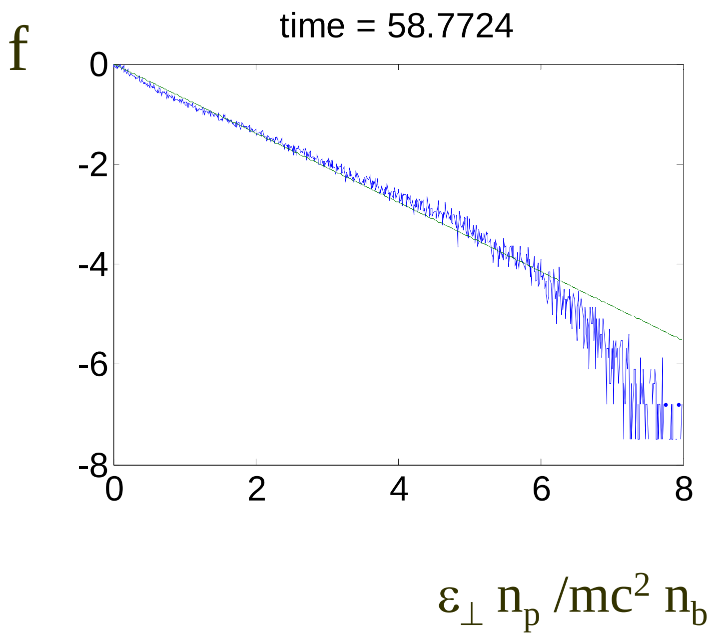




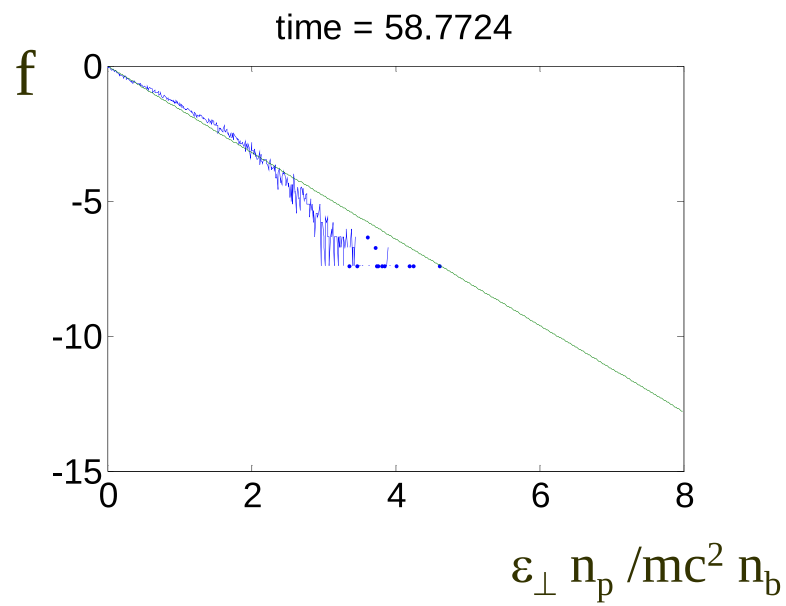
Trapped beam electrons

Trapped and untrapped particle form a Maxwellian distribution function

$Tn_p / mc^2 n_b = 1.45$



$Tn_p / mc^2 n_b = 0.62$



Conclusions

- Developed fast codes (Darwin scheme).
- Developed nonlinear 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.
- Developed an analytical model of the filaments structure of electron beams during the Weibel instability.