The Weibel Instability and Collisionless Shocks

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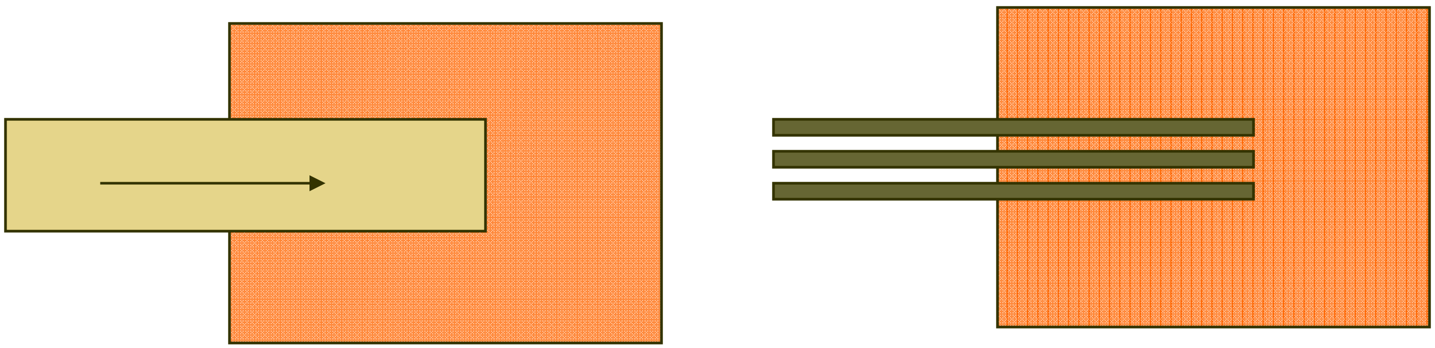
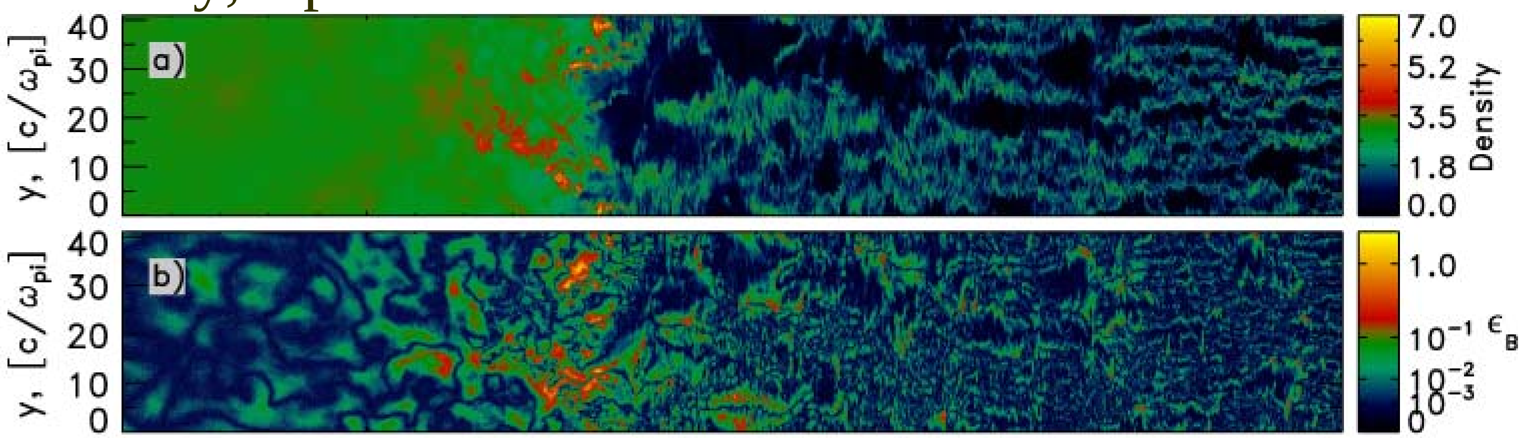
Applications: Collisionless shocks in astrophysics

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



Open Scientific Questions:

Transport of beam currents in access of one limiting Alfven Current (17kA*gamma) almost certainly occurs in astrophysical context.

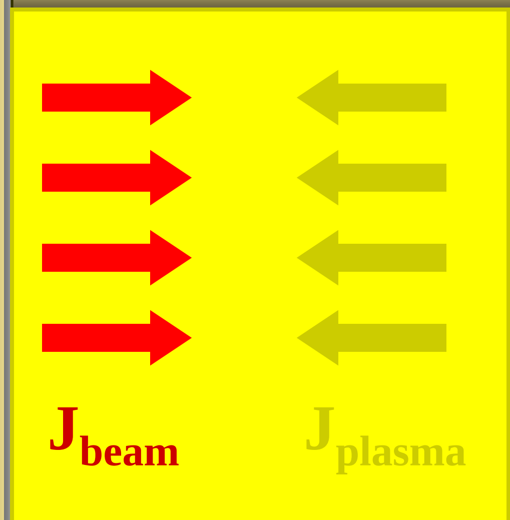
No laboratory experimental observations have been made.

Understanding how such beams naturally develop, interact with each other, and deposit their energy into the plasma is one of the outstanding problems in laboratory astrophysics.

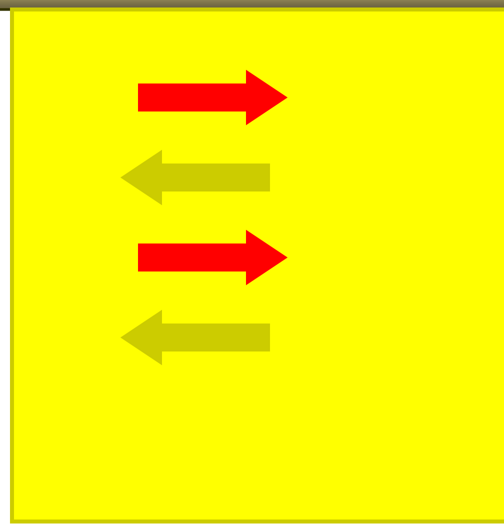
Open Scientific Questions:

- **Energy cascade during the Weibel instability: from collisionless skin depth to much greater spatial scales.**
- **Energy extraction efficiency from the relativistic beams to magnetic fields in the interstellar plasma.**
- **Interplay between the Weibel instability and magnetic reconnection: can the energy flow direction be reversed from B to beam?**
- **Experimental/computational issue: time-resolved imaging of highly relativistic objects such as shocks, filaments. Can we observe the evolution of such structures?**

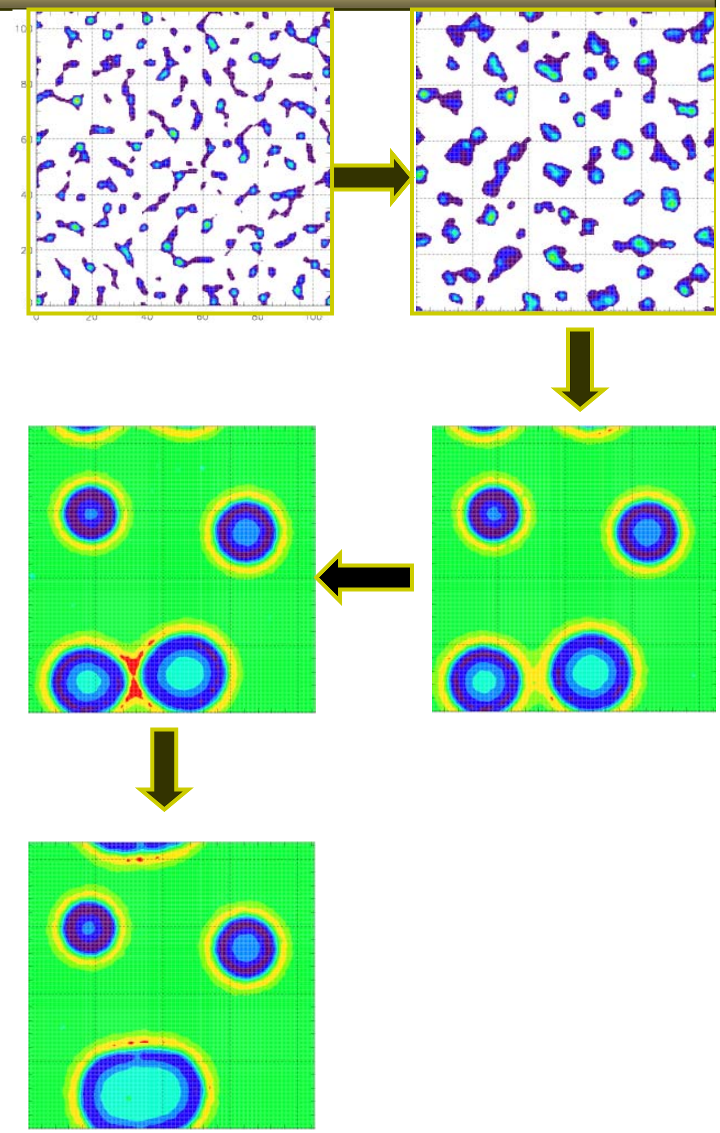
Weibel instability in relativistic beams



Beam enters the plasma, its current is neutralized

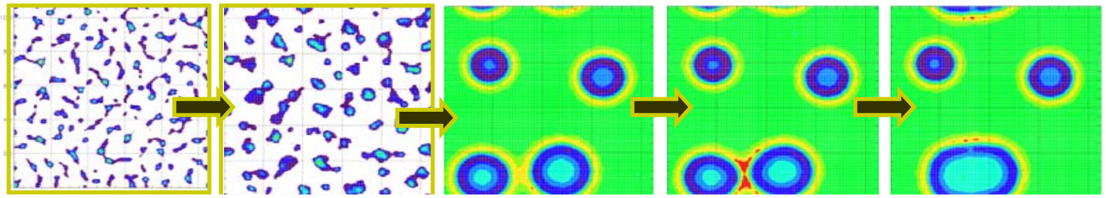


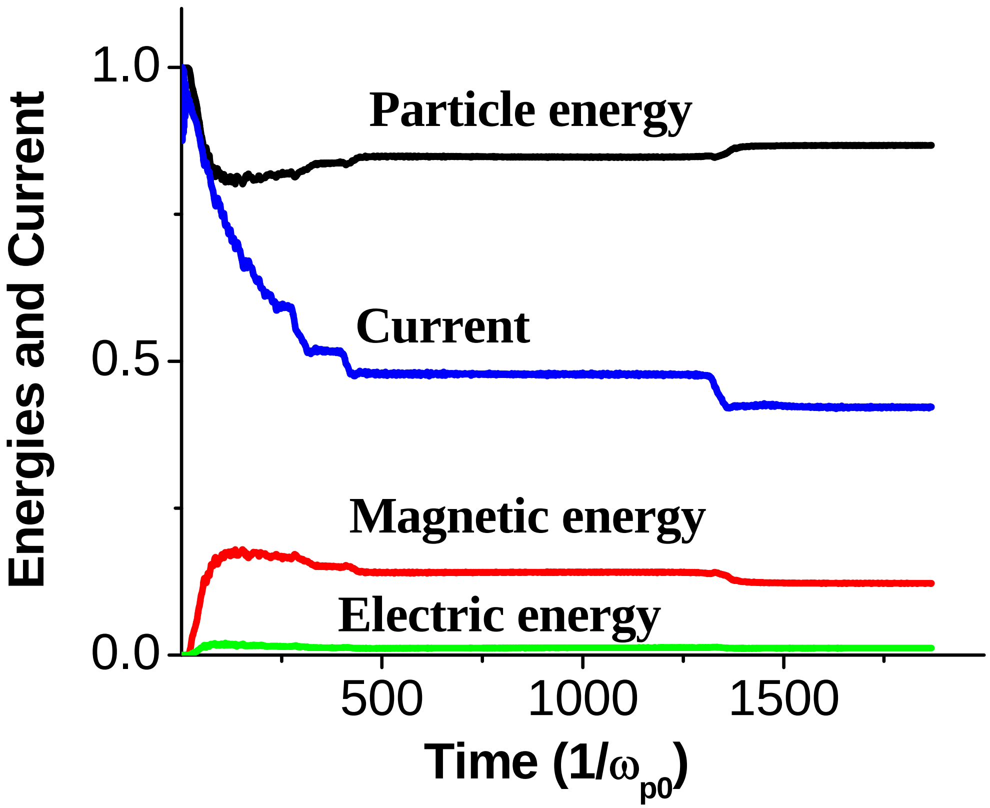
Opposite currents are repelled → filaments formation and interaction



Three Stages of Beam Filamentation

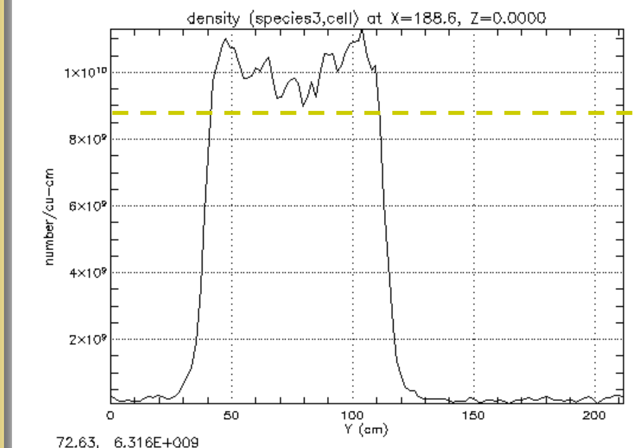
- **Linear growth and saturation via magnetic particle trapping**
  - small current filaments (c/ω_p), small energy extraction.
- **Nonlinear coalescence of current filaments**
  - each filament carries up to 17kA of current; significant energy conversion into magnetic fields.
- **Coalescence of super-Alfvenic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



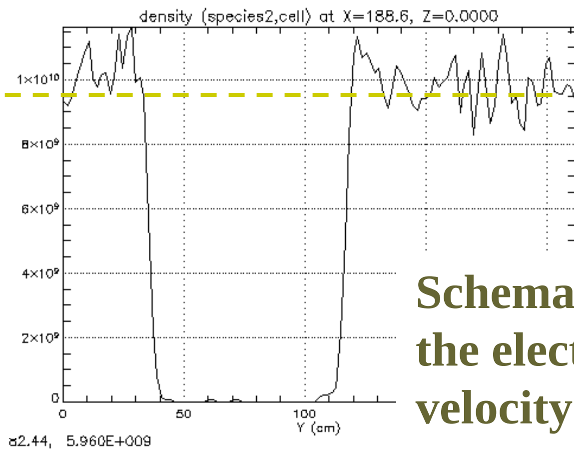


Super-Alfvenic filaments, $I > I_A = \gamma m c^3 / e$

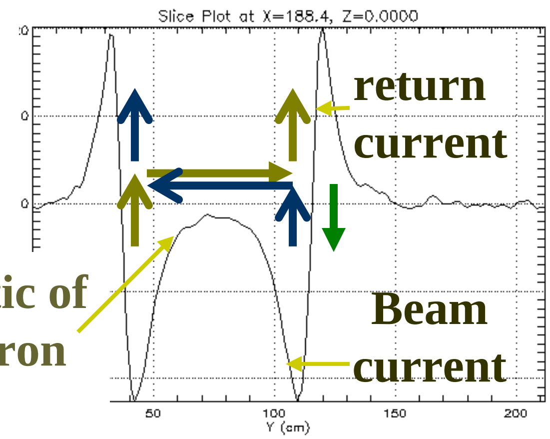
Beam density



Plasma density



Current density



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

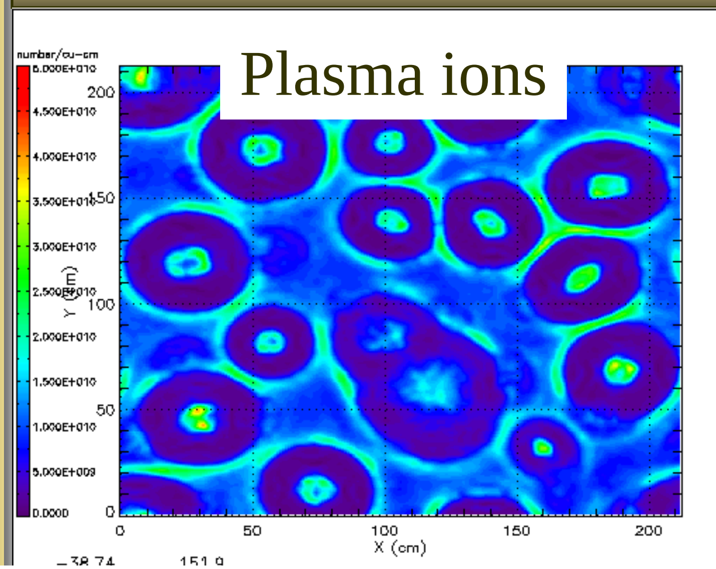
Ambient plasma is fully expelled from the filament.

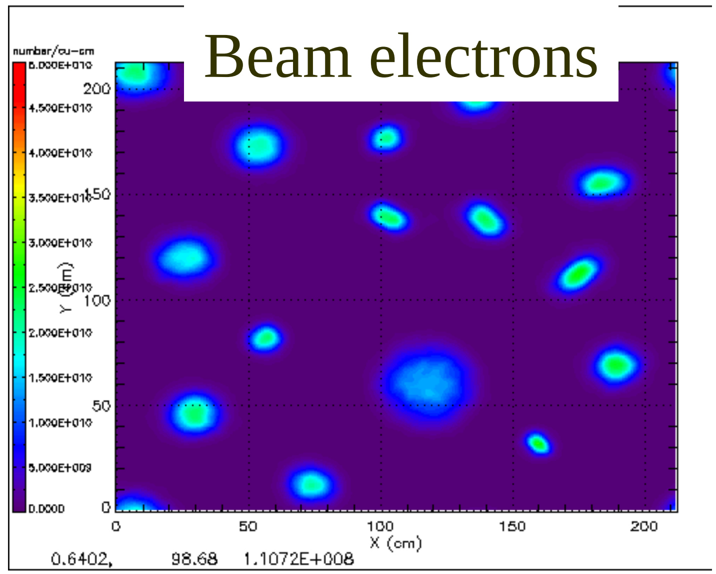
Beam current is absent in the center of filament and localized at the edges of the filament.

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

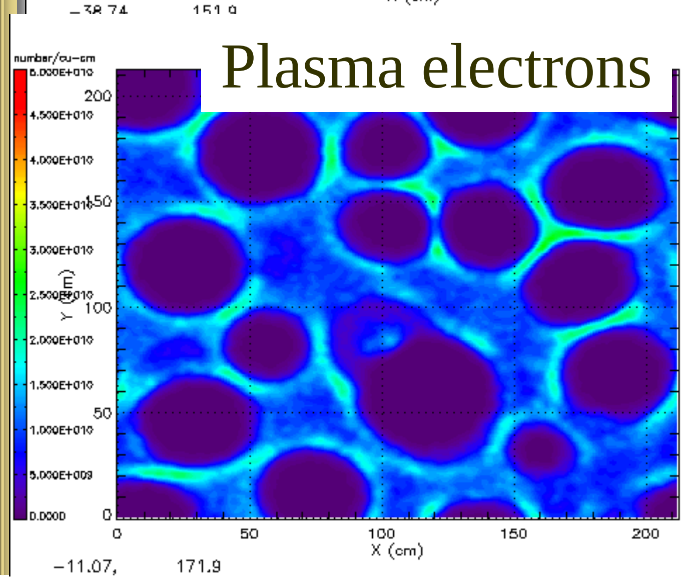
Analytical solution making use of conservation of the canonical momentum, O. Polomarov, PRL 2008

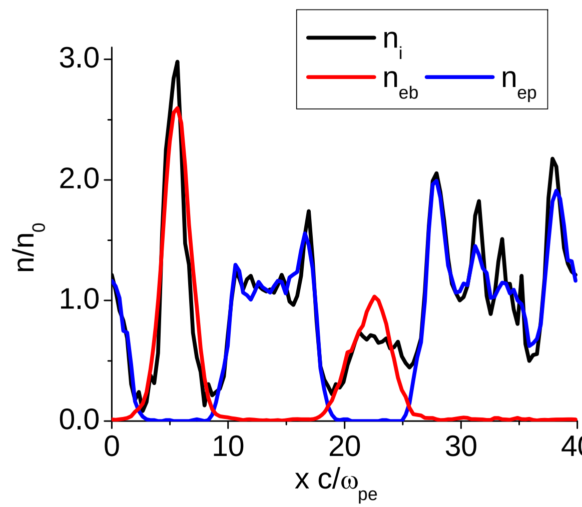
Density colorplots of beam electrons, plasma electrons, and plasma ions





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



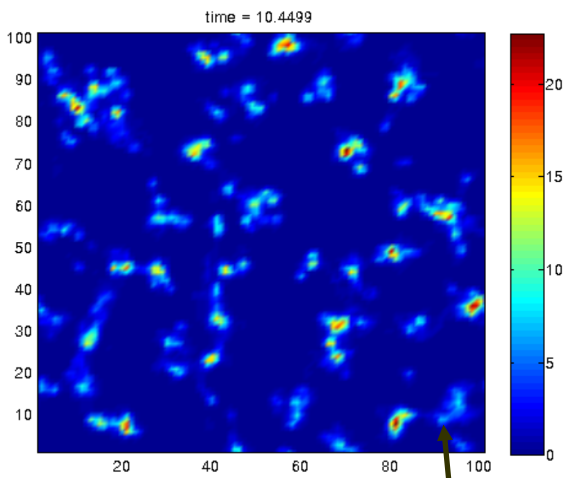


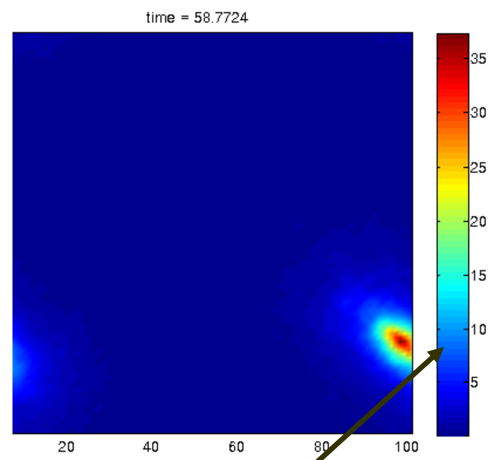
Slice of density profiles

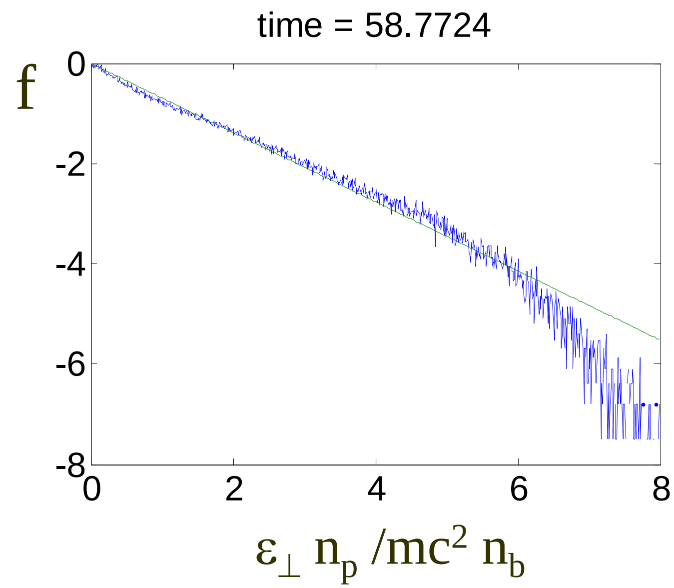
- electron beam (red)
- plasma electrons (blue)
- plasma ions (black)

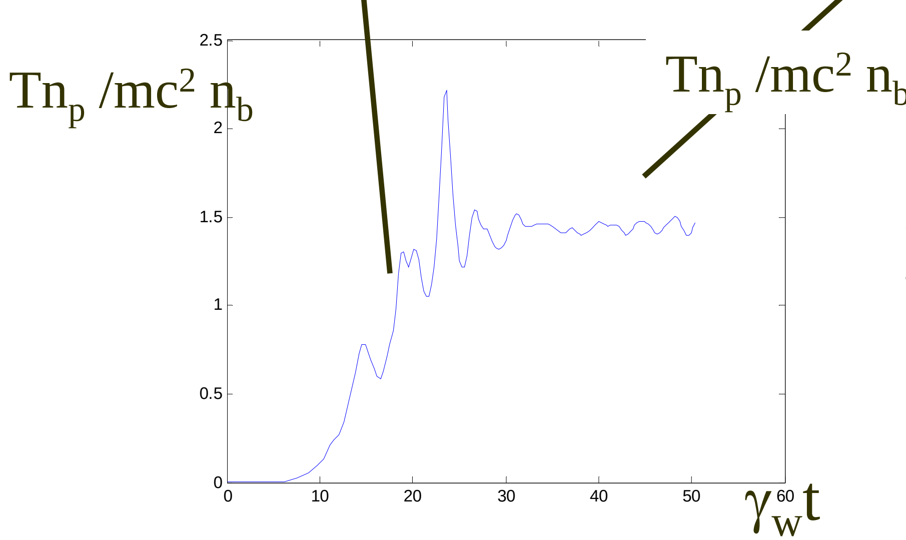
Electron beam temperature growth

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



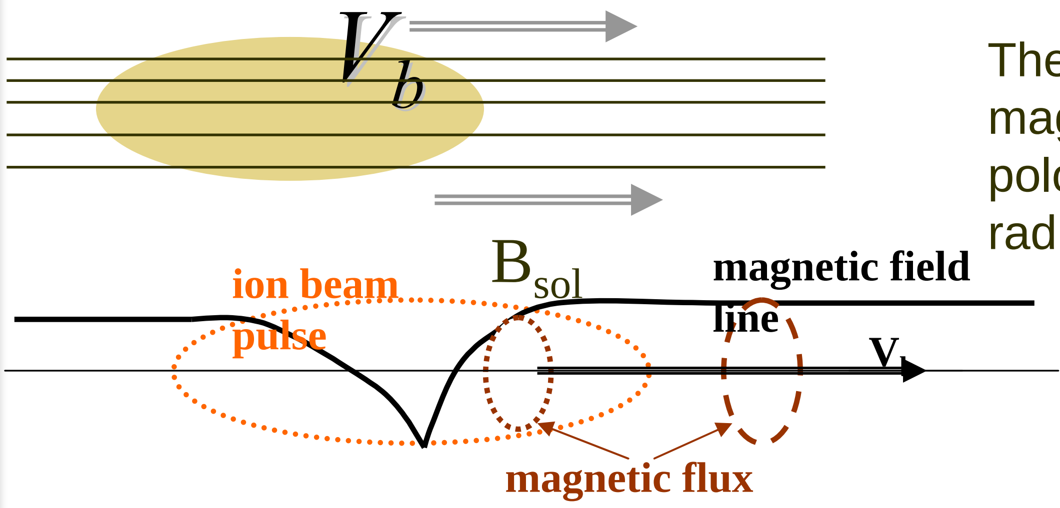






A Maxwellian distribution function in transverse kinetic energy if formed for initially cold electron beam due to the Weibel instability.

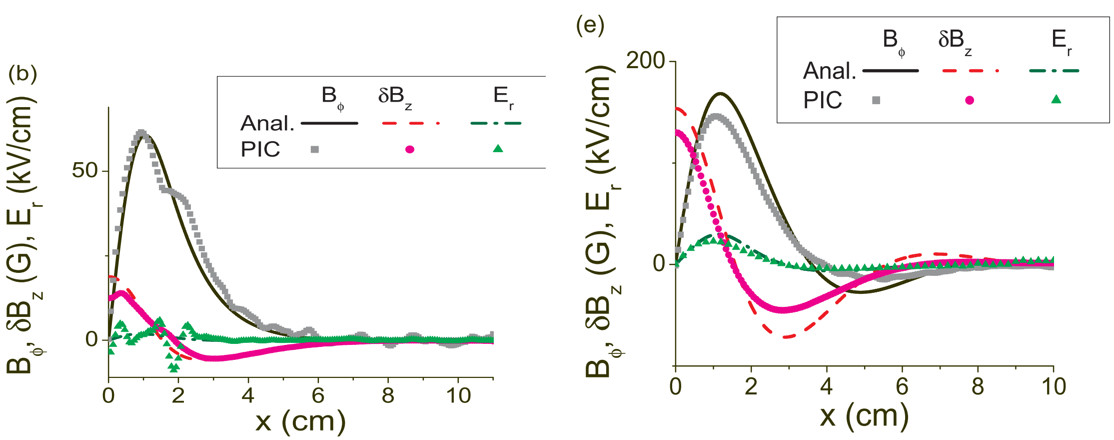
Magnetic dynamo effect for ion beam propagating through a background plasma in solenoidal magnetic field



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

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

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

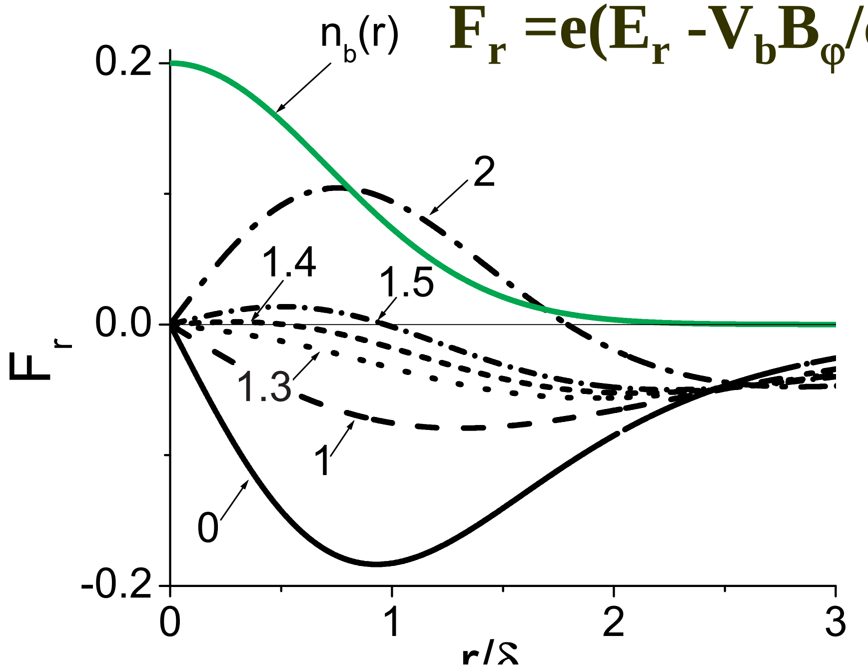


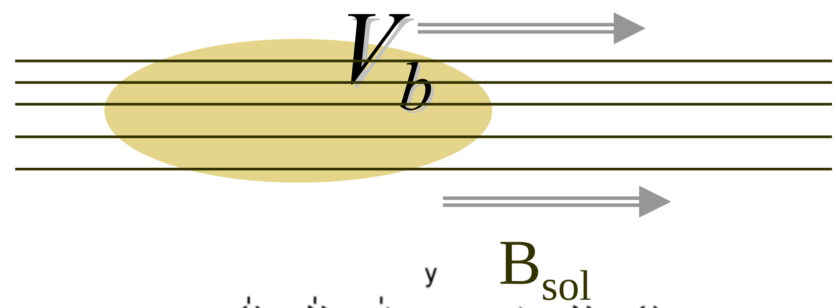
Self-magnetic field; perturbation in the solenoidal magnetic field; and the radial electric field in a perpendicular slice of the beam pulse: $n_{b0} = n_p/2 = 1.2 \times 10^{11} cm^{-3}$; $V_b = 0.33c$, B_{z0}: (b) 300G; and (e) 900G.

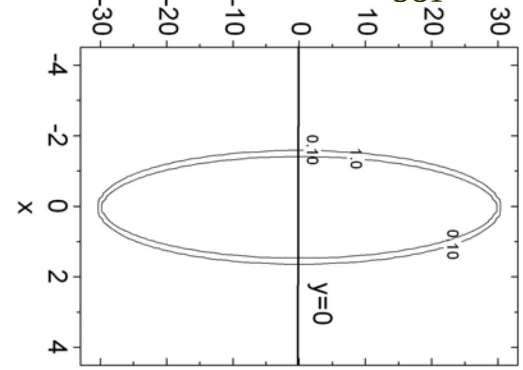
Self-focusing effect can be used to study self-field of intense particle beams

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).