Physics of ion beam pulse neutralization by background plasma

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PPPL

Outline

- Why volumetric plasma has to be used for intense ion beam focusing.
- Key plasma parameters for good charge and current neutralization in a background plasma.
- Effects of applied magnetic field on the degree of charge and current neutralization
  - solenoidal magnetic field,
  - dipole magnetic.
- Effects of gas ionization on self-magnetic field of ion beam pulse.

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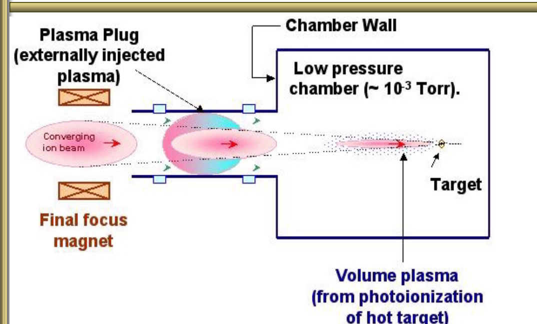
Plasma neutralization is the only practical way to focus intense ion beam pulses

- **Intense beam pulses produces electrons due to gas ionization or surface emission =>**
- **Incomplete neutralization results in incontrollable space charge forces =>**
- **Beams can not be ballisiticaly focused**

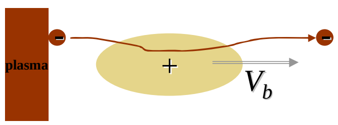
Schemes for beam space-charge neutralization

- **Electron emission**
- **Plasma plug**
- **Volumetric plasma**
- **Combination**

Schemes for beam space-charge neutralization



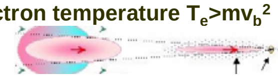
Space-charge potential in a plasma plug $\sim mV_b^2/2$?



- If electrons to move with the beam, i.e. their velocity ~ beam velocity V_b than
- $\varphi \sim mV_b^2/2 >> T_e$

Disadvantages of plasma plug scheme

- Electrons follow the beam with velocity v_b ; after extraction electron temperature $T_e > mv_b^2$ large ~keV;



- During compression T_e rapidly increases $T_e \sim 1/r_b^2$ *=>
- High T_e prevents focusing

* Lifschitz et al, NIMPR A 544, 202 (2005).

Measurements on NTX demonstrate achievement of smaller spot size using volumetric plasma

The Neutralized Transport Experiment*

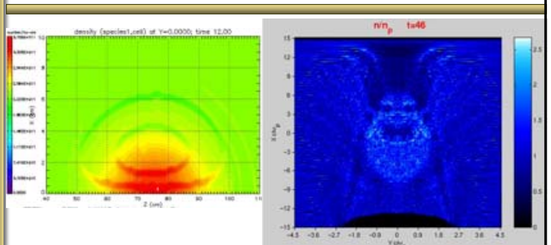
Neither plasma plug nor volumetric plasma. | Plasma plug. | Plasma plug and volumetric plasma.

*P. K. Roy, S. S. Yu et al., PRL **95,** 234801 (2005).

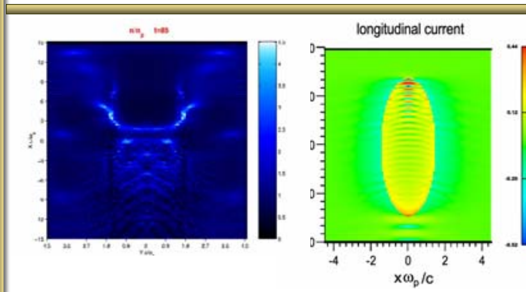
Why do theory of plasma neutralization?

- Benchmark codes
- Predict neutralization in wide range
- Intellectual challenge and fun

Which image is real physics, which is artifact of a code?



Which image is real physics, which is artifact of a code?



Theory provides solid foundation and reality check.

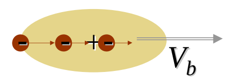
Theory addresses basic questions:

- **How well does the plasma neutralize the beam pulse?**
- **What determines the remnant self-electric and self-magnetic fields of the intense beam pulse?**
- **What collective instabilities are excited and how do they affect the beam pulse transport in the background plasma?**

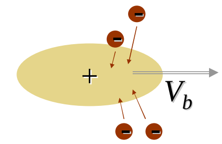
Two ways for the electrons to neutralize the beam pulse

Electrons can move into the beam pulse

Longitudinally => beam charge and current are neutralized.



Transversely => beam charge is neutralized, but not current neutralized; a large self-magnetic field can be generated.



Nonlinear Theory

- **Important issues:**
  - **Finite length of the beam pulse**
  - **General value of n_b/n_p (n_b>>n_p)**
  - **2D treatment**
- **Approximations:**
  - **Fluid approach**
  - **Conservation of generalized vorticity**
  - **Long dense beams l_b >> r_b .**
- **Exact analytical solution**

FOR MORE INFO... I. Kaganovich, *et. al*, Nuclear Instruments and Methods in Physics Research A 544, 383 (2005); Physics of Plasmas 8, 4180 (2001).

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- **Key plasma parameters for good charge and current neutralization in a background plasma.**
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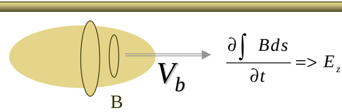
Current Neutralization



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

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

For long beams canonical momentum is conserved** $mV_{ez} = eA_z / c$

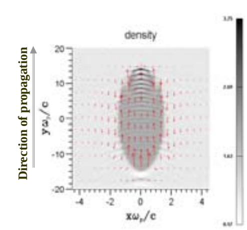
$$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c} \qquad -\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} V_{ez} = \frac{4\pi e}{mc^2}(Z_b n_b V_{bz} - n_e V_{ez}).$$

$$I_b > 4.25(\beta n_b / n_p) kA$$

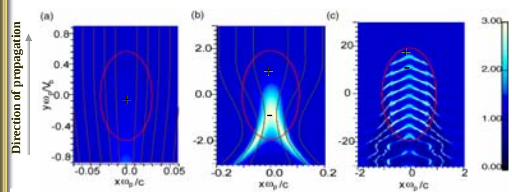
* K. Hahn, and E. PJ. Lee, FED **32-33** 417 (1996)
** I. D. Kaganovich, et al, LPB **20** 497 (2002).

Current Neutralization Depends on Beam Radius and Skin Depth ($\omega_p r_b/c$>>1)

Beam parameters:
l_b=15 c/ ω_p , r_b =1.5 c/ ω_p , n_b = n_p , V_b=c/2.
Shown are the normalized electron density n_e/n_p and the vector fields for the current.



Charge Neutralization Depends on Pulse Duration and Plasma Frequency ($\omega_p t_b/2\pi >> 1$)



Shown in the figures are contour plots of the normalized electron density (n_e/n_p) in (x,y) space. The beam density has a flat-top profile, and the red lines show the beam pulse edges. The brown contours show the electron trajectories in the beam frame. The beam density is n_b=0.5n_p.

The beam dimensions correspond to r_b/l_b =0.01 and $\omega_p t_b/2\pi$= (a) 0.19, (b) 0.64, (c) 6.4.

Self-Electric Field of the Beam Pulse Propagating Through Plasma

$$m\left[\frac{\partial \mathbf{V}_e}{\partial t} + (\mathbf{V}_e \cdot \nabla)\mathbf{V}_e\right] = -e\left(\mathbf{E} + \frac{1}{c}\mathbf{V}_e \times \mathbf{B}\right)$$

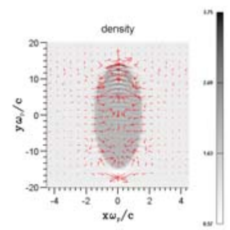
$$eE_y \sim mV_b/\tau_b$$

$$eE_x = \frac{1}{c}V_{ey}B = -mV_{ey}\frac{\partial V_{ey}}{\partial x}$$

- E_y is inductive
- E_x is electrostatic,
- potential is

$$\phi = -mV_{ez}^2/2 >> T_e$$

$$V_{ez} \sim V_b n_b/n_p$$



Shown are n_e/n_p and the vector fields for the electric force on electrons.

Summary: key plasma parameters for good charge and current neutralization

- A nonlinear fluid theory for the quasi-steady-state propagation of an intense ion beam pulse in a background plasma.
  - provide benchmark for numerical codes.
  - Robust analysis of beam propagation in the target chamber.
- The simulations of current and charge neutralization performed for conditions relevant to heavy ion fusion showed:
  - very good charge neutralization: key parameter $\omega_p l_b/V_b$,
  - very good current neutralization: key parameter $\omega_p r_b/c$.
- Plasma wave breaking heats electrons $n_b > n_p$.

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- Why volumetric plasma has to be used for intense ion beam focusing.
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  - **solenoidal magnetic field,**
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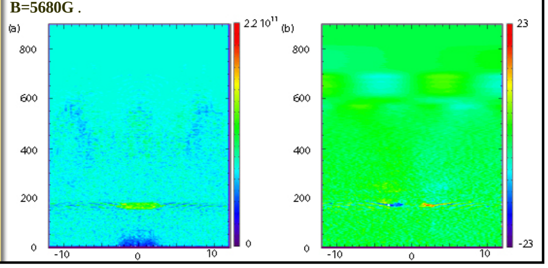
Generation of waves at beam entry into plasma due to presence of solenoidal magnetic field

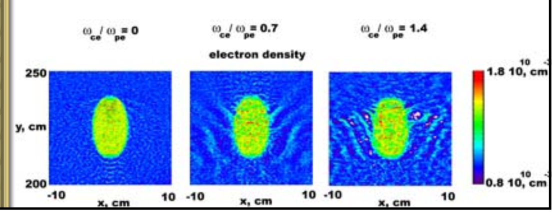
Shown are color plots of the electron density (a) and the magnetic field component (b) generated by the ion beam pulse. The plasma density is n_p=10^{11} cm^{-3}; the beam velocity is V_b=0.2c; the beam current is 1.2kA, solenoidal field B=5680G .



Solenoidal magnetic field influences the neutralization by plasma if $\omega_{ce} > \beta\omega_{pe}$

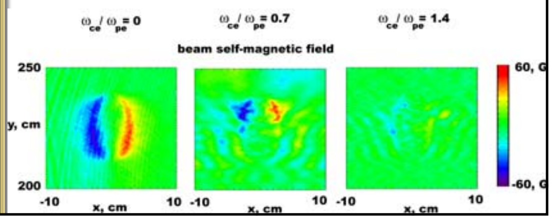
Plots of electron charge density contours in (x,y) space, calculated in 2D slab geometry using the LSP code with parameters:

Plasma: n_p=10^{11}cm^{-3}; Beam: V_b=0.2c, 48.0A, r_b=2.85cm and pulse duration τ_b=4.75 ns. A solenoidal magnetic field of 1014 G corresponds to ω_{ce}=ω_{pe}.

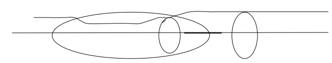


Analytical studies show that the beam self-magnetic field greatly diminishes if $\omega_{ce} >> \beta\omega_{pe}$

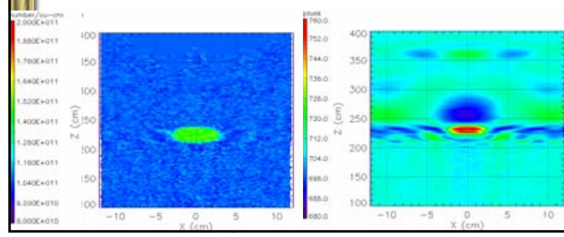
Beam self magnetic field contour plots in (x,y) space, calculated in 2D slab geometry using the LSP code.



Plasma acts as paramagnetic inside ion beam pulse!



dB=-BdS/S



Summary: of effects of solenoidal magnetic field on plasma neutralization

- **Solenoidal magnetic field inhibits the current $\omega_{ce} >> \beta\omega_{pe}$.**
- **Due to solenoidal magnetic field, waves are generated at the angle to magnetic field for $\omega_{ce} > \beta\omega_{pe}$.**
- Application of an external solenoidal magnetic field clearly makes the collective processes of ion beam-plasma interactions rich in physics content. Many results of the PIC simulations remain to be explained by analytical theory.

See four recent papers by I. Kaganovich, et al. at http://nonneutral.pppl.gov.

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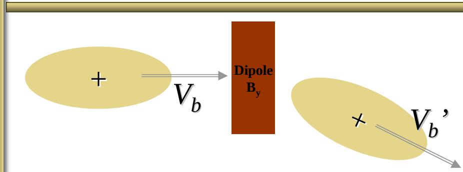
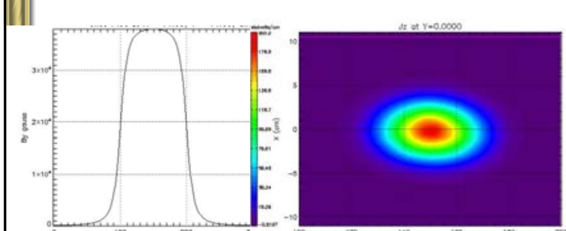
Dipole magnetic field can be used to bend ion beam motion



- **Can plasma still neutralize the beam in strong magnetic field?**
- **3D simulations needed!**

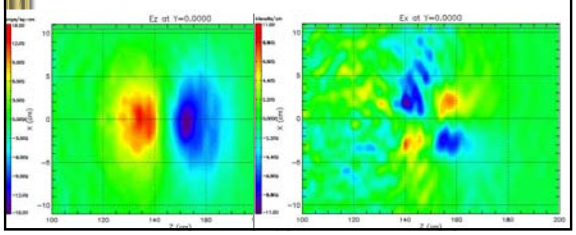
3D simulations show no current neutralization

Shown are the magnetic field of the dipole, B_y and the current density in the dipole region, j_z;



3D simulations show good charge neutralization and quadruple structure of E_x

Shown are the longitudinal, inductive electric field, E_z *and* the transverse electric field E_x.



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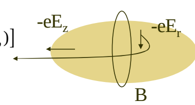
- **Effects of gas ionization on self-magnetic field of ion beam pulse.**

Electrons produced in the beam pulse carry away magnetic field

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

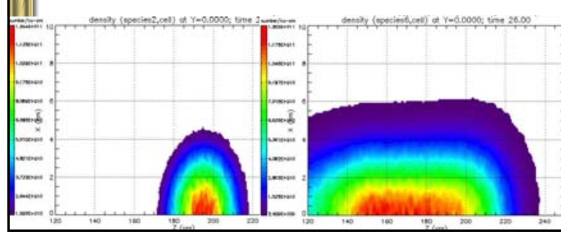


If an electron originates in the region of strong magnetic field, and later moves into region of weaker magnetic field then the electron flow velocity is in the direction opposite to the beam velocity; and the current of such electrons *enhances* the beam current rather than diminish the beam current.

The return current becomes nonlocal.

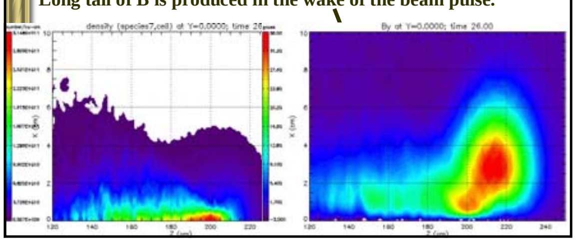
Color plots of the ion density produced by beam ionization

Beam pulse (left) produces plasma by gas ionization (right) with comparable density



Color plots of the electron density and magnetic field due to gas ionization

E_x in the beam pulse pushes new electrons into the beam center, E_z in the beam tail pushes is in the direction opposite to the beam velocity.
Long tail of B is produced in the wake of the beam pulse.



Results and Conclusions (1/2)

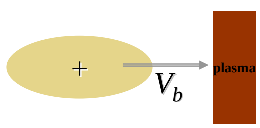
- **A nonlinear fluid theory has been developed that describes the quasi-steady-state propagation of an intense ion beam pulse in a background plasma.**
  - **Provides benchmark for numerical codes and experiments.**
  - **Provides robust analysis of beam propagation through background plasma.**
- **Simulations of current and charge neutralization performed for conditions relevant to intense ion beams shows:**
  - **Very good charge neutralization: key parameter is $\omega_p l_b/V_b$,**
  - **Very good current neutralization: key parameter is $\omega_p r_b/c$.**
- **Plasma wave breaking heats the electrons whenever $n_p < n_b$.**

Results and Conclusions (2/2)

- **Effects of solenoidal magnetic:**
  - **solenoidal magnetic inhibits the self-magnetic field whenever $\omega_{ce} >> \beta\omega_{pe}$.**
  - **collective excitations are generated at an angle relative to the solenoidal magnetic field for $\omega_{ce} > \beta\omega_{pe}$.**
- **Effects of dipole magnetic field**
  - **no current neutralization**

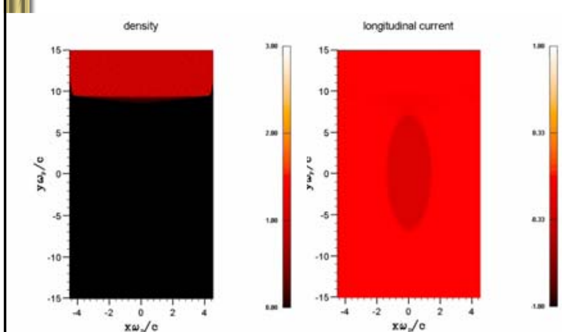
Additional slides

How long is the transition region to establish quasi-steady-state propagation?

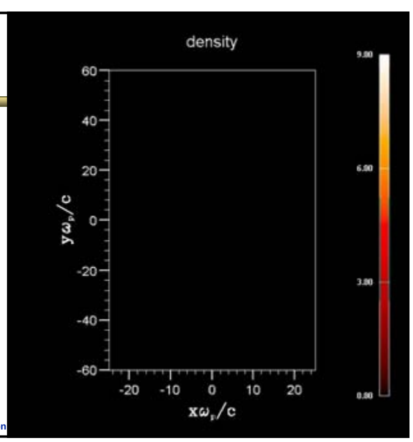


Movies show the results of 2D particle-in-cell simulations.
Shown are the evolution of the electron density and current density for two cases:
Beam density is equal to
(1) One-half of the plasma density;
(2) Five times the plasma density.

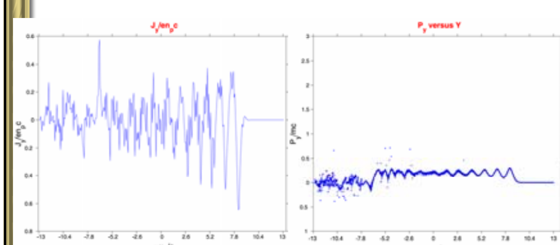
FOR MORE INFO... I. D. Kaganovich, E. A. Startsev and R. C. Davidson, Physica Scripta T107 54 (2004).



Beam length =30 c/ω_p; Beam radius =0.5 c/ω_p; Beam density = 5 times plasma density; Beam velocity = 0.5*c*.

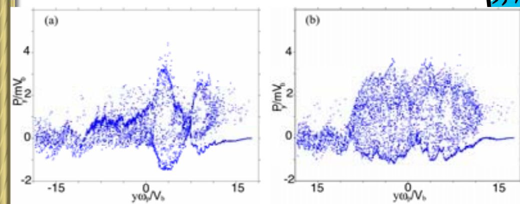


Fluid approximation is good if $n_b \leq n_p$



Electron current and phase space l_b=15c/ω_p; $n_b = n_p$; V_b =c/2.

Plasma Wave Breaking Heats the Electrons when $n_b > n_p$

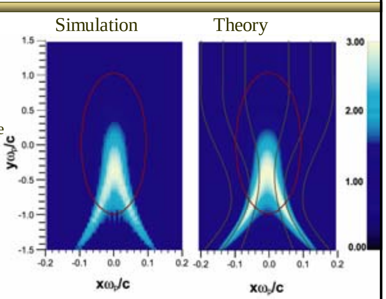


Electron phase space shown for $l_b=30V_b/\omega_p$; $n_b = 2n_p$.
Times after entering the plasma plug are: (a) 113 $/\omega_p$, and (b) 245$/\omega_p$.

Comparison of Theory and Simulation: Electron Density

Electron density
Left – PIC simulation
Right - fluid theory.

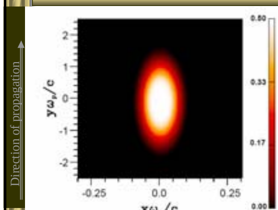
Red line: ion beam pulse boundaries. The brown contours show the electron trajectories in the beam frame.



FOR MORE INFO...

I. Kaganovich, E. A. Startsev and R. C. Davidson, Nuclear Instruments and Methods in Physics Research A 544, 383 (2005); Physics of Plasmas 11 3546 (2004).

Is $\varphi \sim mV_b^2/2$?

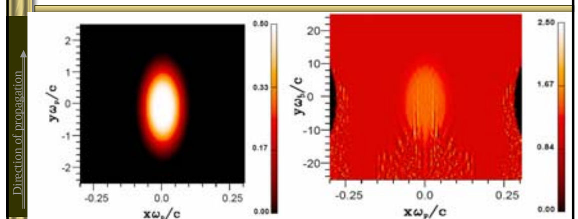


Take beam with $\varphi_b=2\pi e^2 n_b r_b^2 << mV_b^2/2$

Check if it is charge neutralized in plasma?

Neutralization of an ion beam pulse during steady-state propagation of the beam pulse through a cold, uniform, background plasma in planar geometry calculated using the EDPIC code. The beam propagates in the y-direction. Shown in the figure are color plots of the normalized beam density (n_b/n_p). $V_b=0.5c$, $n_b=0.5n_p$. The beam radius $r_b=0.1\ c/\omega_p$, and pulse duration $\tau_b\omega_p=60$.

Check of $\varphi \sim mV_b^2$



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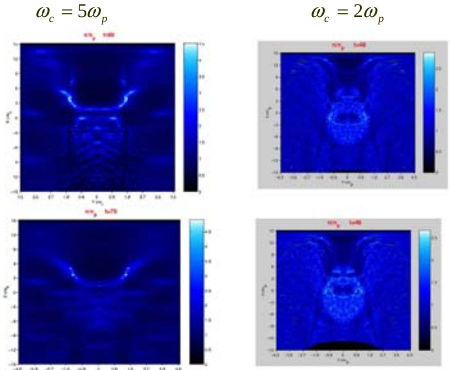
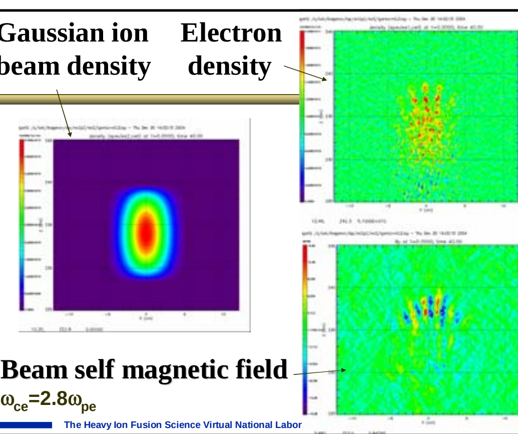
Beam Propagates Along Magnetic Field.

$\omega_c = 5\omega_p$ $\omega_c = 2\omega_p$



Gaussian ion beam density / Electron density



Beam self magnetic field

$\omega_{ce}=2.8\omega_{pe}$