

## Interaction of Intense Ion Beams with Background Plasma: Applications to Heavy Ion Inertial Fusion

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## Talk Outline

- Introduction into inertial ion fusion concepts
- Update on Heavy Ion Fusion Program
- Physics of Ion Beam Plasma Interaction

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## Heavy Ion Fusion Concept



## Drivers: Ion Beam Versus Laser

### Lasers Pros./ Ion Beam Con.:

Easy to focus one beam in vacuum  
 Much more money in program



### Lasers Con. /Ion Beam Pros.:

Protecting final optics  
 Protecting first wall  
 Conversion to X-rays  
 Beams cross talks  
 (Unwanted laser plasma interactions)  
 Low repetition rate (a few/day)  
 Low electrical efficiency (a few - 10%)

## Heavy Ion Fusion past Concepts

- **Electron beam based fusion**
  - Can not compress overheated target
- **Diode based light ion fusion**
  - Instability in magnetically isolated diode at MA currents leads to large ion temperature
- **Accelerator ring based ion fusion**
  - Lot of resonances in ring with collective modes
  - Requires GeV relativistic ions, which are difficult to stop in the target

## USA HIF Concept

Focusability  $\Rightarrow$  Multiple beams  $\sim 100$

Stability  $\Rightarrow$  Linear accelerator

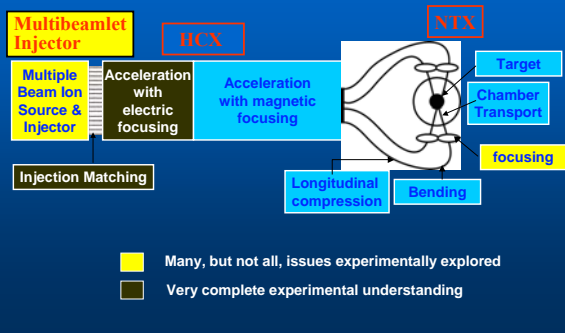
Efficiency  $\Rightarrow$  Induction/Helix acceleration

Cost  $\Rightarrow$  Modular approach

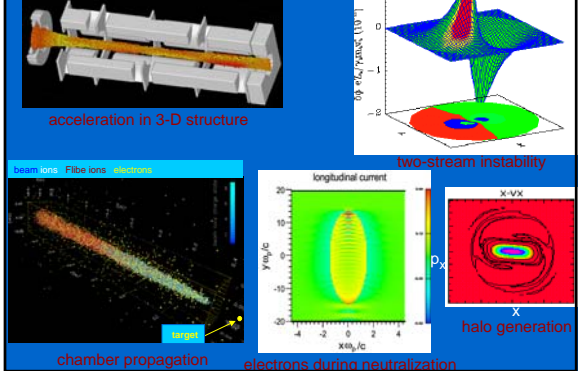
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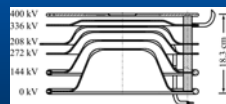
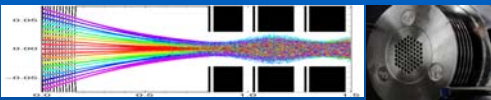
## The Present Experimental Program: HCX and NTX experiments



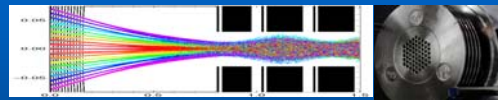
## Beam simulations and theory span a variety of processes



**Multibeamlet Injector** Merging high density beamlets is an innovative approach to build compact multi-beam HIF injector



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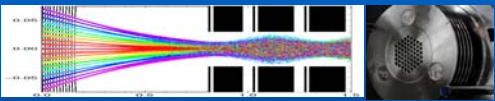


- Beat space-charge limit by compressing  $\Rightarrow$
- Use many metal plates to shield beamlets from one another and converge adiabatically to achieve high current, and high average current density with low emittance.
- Minimize the injector and matching section size for a compact multi-beam HIF driver system.

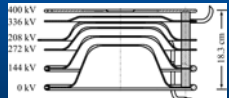


### Multibeamlet Injector

Merging high density beamlets is an innovative approach to build compact multi-beam HIF injector



- Beat space-charge limit by compressing =>
- Use many metal plates to shield beamlets from one another and converge adiabatically to achieve high current, and high average current density with low emittance.
- Minimize the injector and matching section size for a compact multi-beam HIF driver system.



Current density  $100 \text{ mA/cm}^2$  (5 mA)  
 Ion beam temperature  $T_{\text{eff}} < 2 \text{ eV}$   
 Charge states  $> 90\%$  in  $\text{Ar}^+$   
 Energy spread  $< \text{a few } \%$

Results: 61 beamlets

### HCX

## High Current Experiment (HCX)



Issues to be resolved:

- Dynamic aperture (usable aperture set by dynamics)
- Halo production
- Effect of desorbed gas on tail
- Electron production & orbits (magnetic transport)
- Mismatch, misalignment

Parameters:

- $\text{K}^+$  or  $\text{Cs}^+$
- $\sim 0.2 - 0.7 \text{ Amp}$ ,  $1 - 1.7 \text{ MeV}$
- $4.5 - 7 \mu\text{s}$ ,  $\epsilon_n = 0.9 \pi \text{ mm.mrad}$
- $\sigma_x = 44^\circ$ ,  $\sigma_y = 7^\circ$  tune depression,  $\sigma_x / \sigma_y = 0.2$

Quadrupoles:

- 10 (30-40 later) electrostatic
- 4 pulsed normal magnetic
- a few superconducting

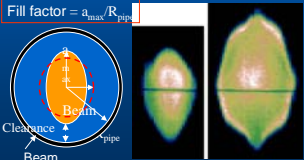
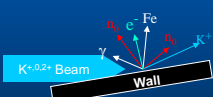
### HCX

## High Current Experiment (HCX)

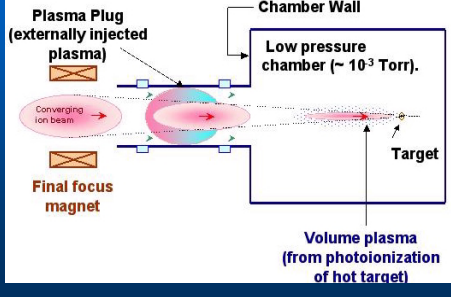
Striving for Large Filling Factor

Beam intensity profile for 60% (left) and 80% (right)

Beam hitting gas or walls creates electrons and gas

## Plasma Neutralizes Ion Beam Charge and Provides Tight Focus



Plasma Plug (externally injected plasma)

Chamber Wall

Low pressure chamber ( $\sim 10^{-3} \text{ Torr}$ )

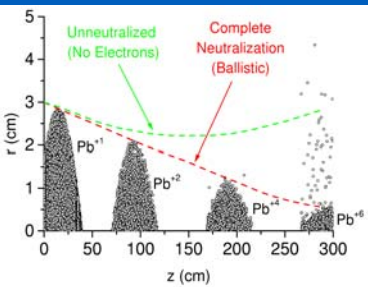
Converging ion beam

Final focus magnet

Target

Volume plasma (from photoionization of hot target)

## Plasma Electrons Neutralize Ion Beam Space Charge

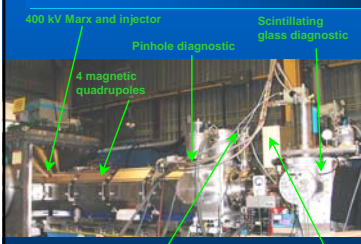


Unneutralized (No Electrons)

Complete Neutralization (Ballistic)

$\text{Pb}^{+1}$ ,  $\text{Pb}^{+2}$ ,  $\text{Pb}^{+3}$ ,  $\text{Pb}^{+4}$

## The Neutralized Transport Experiment (NTX)



400 kV Marx and injector

Pinhole diagnostic

Scintillating glass diagnostic

4 magnetic quadrupoles

MEVVA Source (plasma plug)

RF Source (Volumetric)

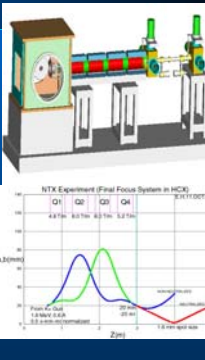
300kV, 25 mA

$\epsilon_n = 0.050 \pi \text{ mm-mr}$

Argon RF plasma source

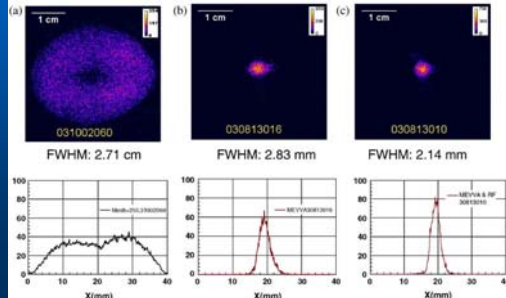
$3.75 < t < 4.0 \text{ ms}$

$n > 10^{11} \text{ cm}^{-3}$   $p < 10^{-5} \text{ Torr}$



## 100 Times Transverse Beam Focusing with Plasma

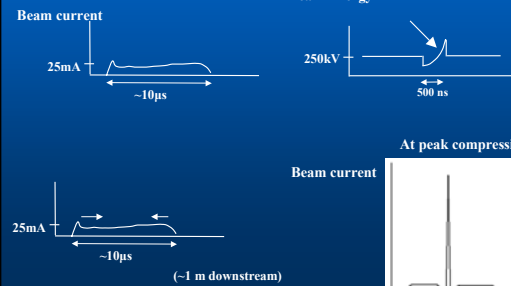
Beam images at the focal plane (a) non-neutralized, neutralized: (b) Plasma plug, and (c) plasma plug and volume plasma.



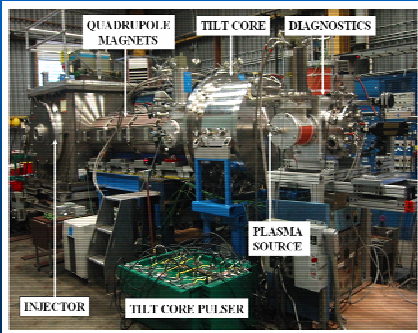
## 100 Times Longitudinal Beam Focusing with Plasma

At entry to Neutralized Drift Section NTX beam (25mA, 250kV)

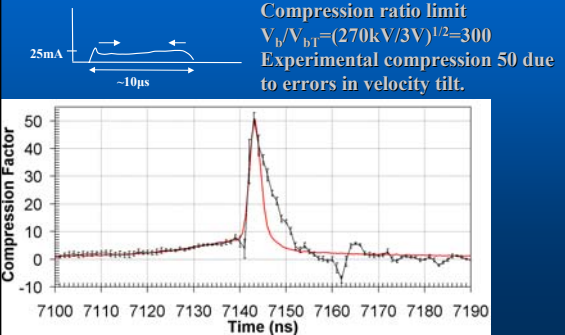
Tilt voltage from induction core  
Beam Energy



## Results of Longitudinal Beam Focusing with Plasma



## Results of Longitudinal Beam Focusing with Plasma



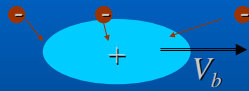
## Talk Outline

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## Theory addresses basic questions:

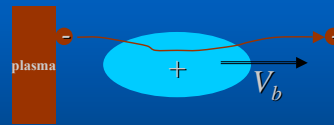
- How well plasma neutralizes the ion beam pulses?
- What determines remaining self electric and magnetic fields of the intense ion beam pulse?
- What are instabilities and how deteriorative is their action on the ion beam pulse transport in a background plasma?

## What is Degree of Space Charge Neutralization?



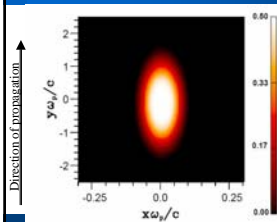
- Ion beam space charge has potential few keV (MeV in driver),
- whereas plasma temperature few eV.

## Space Charge Potential $\sim mV_b^2/2$ ?



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

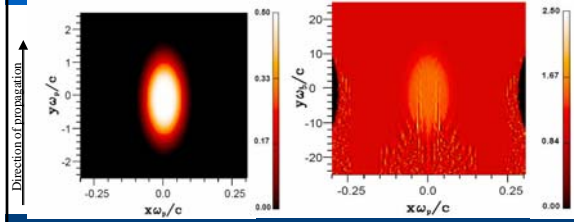
## Is $\phi \sim mV_b^2/2$ ?



Take beam with  $\phi_b = 2\pi e^2 n_b r_b^2 \ll mV_b^2/2$   
 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  $\tau_p \omega_p = 60$ .

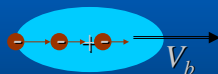
## Check of $\phi \sim mV_b^2$



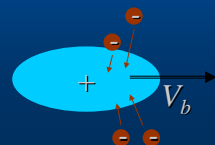
Neutralization of an ion beam pulse during steady-state propagation of the beam pulse through a cold, uniform, background plasma in planar geometry calculated using the EDPIC code. The beam propagates in the y-direction. Shown in the figure are color plots of the normalized beam density ( $n_b/n_p$ )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

## Two ways for ion beam pulse to grab electrons.

### Longitudinally



### Transversely



## System of Equations

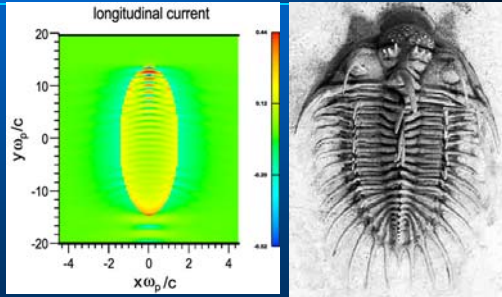
$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{V}_e) = 0,$$

$$\frac{\partial \mathbf{p}_e}{\partial t} + (\mathbf{V}_e \cdot \nabla) \mathbf{p}_e = -e(\mathbf{E} + \frac{1}{c} \mathbf{V}_e \times \mathbf{B}),$$

$$\nabla \times \mathbf{B} = \frac{4\pi e}{c} (Z_b n_b \mathbf{V}_b - n_e \mathbf{V}_e) + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t},$$

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}.$$

## Steady- State Results



normalized electron current  $j_z/(ec n_p)$

<http://www.trilobites.com>

## Conservation of Generalized Vorticity

$$\mathbf{\Omega}_e = \nabla \times \mathbf{p}_e - e\mathbf{B}/c,$$

$$\frac{\partial \mathbf{\Omega}_e}{\partial t} - \nabla \times (\mathbf{V}_e \times \mathbf{\Omega}_e) = 0,$$

$$\oint \mathbf{\Omega}_e \cdot d\mathbf{S} = \oint (\mathbf{p}_e - \frac{e}{c}\mathbf{A}) \cdot \delta\mathbf{r} = const.,$$

$$\mathbf{\Omega}_e = 0 \Rightarrow \nabla \times \mathbf{p}_e = e\mathbf{B}/c, \quad \mathbf{p}_e - e\mathbf{A}/c = \nabla f.$$

FOR MORE INFO... I. Kaganovich, *et.al.*, Physics of Plasmas 8, 4180 (2001).

## Nonlinear Theory

- Important issues:
  - Finite length of the beam pulse,
  - Arbitrary value of  $n_b/n_p$  ( $n_b \gg n_p$ ),
  - 2D.
- Approximations:
  - Fluid approach,
  - Conservation of generalized vorticity,
  - Long dense beams  $l_b \gg r_b, V_b/\omega_p$ .
- Exact analytical solution.

## Simplified Code

- Approximation of long beams:
  - Beam length is much longer than beam radius;
  - Therefore, beam can be described by a number of weakly interacting slices.
  - The electric field is found from radial Poisson's equation.
  - As a result of the simplification the second code is hundreds times faster than the first one and can be used for most cases, while the first code provides benchmarking for the second.

## Plasma Potential and Vector Potential

$$\mathbf{\Omega}_e = 0 \Rightarrow \nabla \times \mathbf{p}_e = e\mathbf{B}/c, \quad \mathbf{p}_e - e\mathbf{A}/c = \nabla f.$$

Convenient gauge  $f=0$  gives potential

$$\mathbf{p}_e = e\mathbf{A}/c$$

$$e\varphi = \mathbf{p}_e^2 / 2m_e$$

## Approximate System of Equations

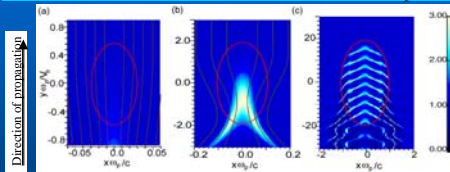
$$l_b \gg r_b, \quad (V_{ey} - V_b) \frac{\partial n_e}{\partial y} + \frac{\partial}{\partial x} (n_e V_{ex}) = 0,$$

$$\nabla \times \bar{\mathbf{p}}_e = \frac{e}{c} \bar{\mathbf{B}}, \quad \frac{\partial}{\partial x} E_x = 4\pi e (Z_b n_b + n_p - n_e),$$

$$K_e = m_e \bar{V}_e^2 / 2, \quad (V_{ey} - V_b) \frac{\partial p_{ex}}{\partial y} + \frac{\partial K_e}{\partial x} = -eE_x,$$

$$-\frac{\partial^2}{\partial x^2} p_{ey} = \frac{4\pi e}{c} (Z_b n_b V_{by} - n_e V_{ey}).$$

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

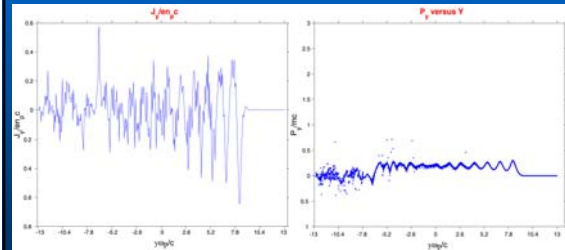


The beam propagates along the y-axis. The beam density has a flat-top profile, and the red lines show the beam pulse edges. Shown in the figures are contour plots of the normalized electron density ( $n_e/n_p$ ) in  $(x, y)$  space. The brown contours show the electron trajectories in the beam frame.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

Note  $\omega_p t_b > 1$  not  $l_b \gg \lambda_D$

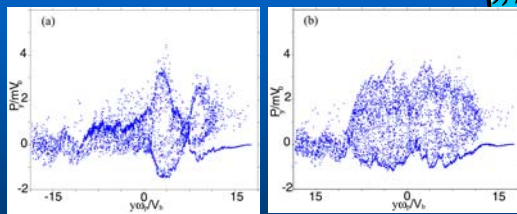
$l_b \gg V_b / \omega_p \gg V_t / \omega_p = \lambda_D$  since  $V_b \gg V_t$

## Fluid approximation is good if $n_b \leq n_p$



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

## 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)  $245/\omega_p$ .

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

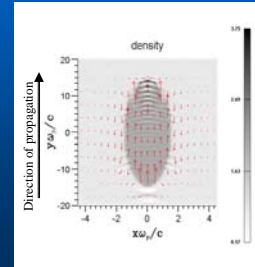
Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation

$$\vec{\Omega}_e = 0 \Rightarrow \nabla \times \vec{p}_e = e\vec{B}/c.$$

$$-\frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} V_{cy} = \frac{4\pi e}{mc^2} (Z_p n_p V_{by} - n_e V_{cy}).$$

$$n_e = n_b + n_i \Rightarrow \nabla \cdot \vec{j} = 0$$

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



## Self Electric Field of the Beam Pulse Propagating Through Plasma

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

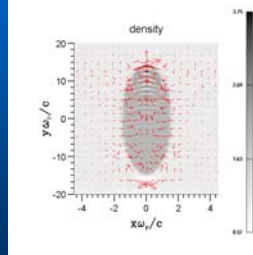
$$eE_y \sim mV_b / \tau_b$$

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

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

$$\phi = -mV_{ec}^2 / 2 \gg T_e$$

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



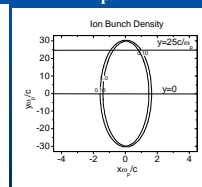
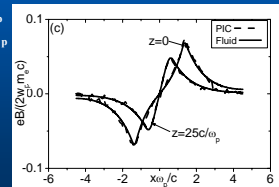
Shown are  $n_e/n_p$  and the vector fields for the electric force on electrons.

## Comparison of Theory and Simulation: Magnetic Field

Key parameter  $\omega_p r_b/c$ ,

Magnetic field neutralization  $r_b \gg c/\omega_p$ .

$l_b = 30c/\omega_p$   
 $r_b = 1.5c/\omega_p$   
 $n_b = n_p$   
 $V_b = 0.5c$



FOR MORE INFO... I. Kaganovich, et al., Physics of Plasmas 8, 4180 (2001).

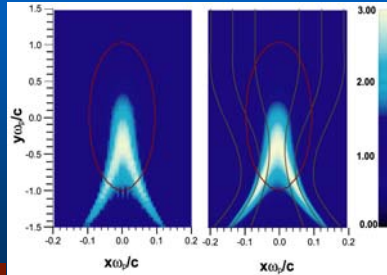
## Comparison of Theory and Simulation: Electron Density

Electron density  
Left - PIC,  
Right - fluid

$$I_b = 1c/\omega_p, \quad r_b = 0.1c/\omega_p$$

$$n_b = 0.5n_p, \quad V_b = 0.5c$$

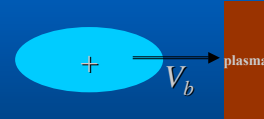
Brown lines: electron trajectory in the beam frame.  
Red line: ion beam size.



FOR MORE INFO...

I. Kaganovich, E. A. Startsev and R. C. Davidson, "Nonlinear plasma waves excitation by intense ion beams in background plasma", Phys. Plasmas 11 3546 (2004).

## How long is transition region?

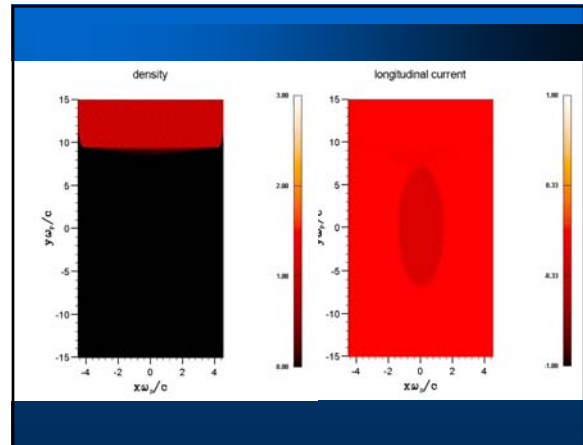


FOR MORE INFO...

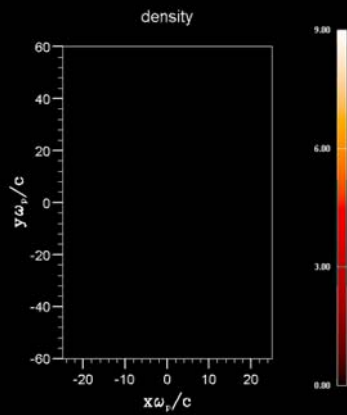
I. D. Kaganovich, E. A. Startsev and R. C. Davidson, "Analytical and numerical studies of the complex interaction of a fast ion beam pulse with a background plasma", Physica Scripta T107 54 (2004)

## Results of 2D PIC-MC Code

- Beam propagation in the y-direction,
  - beam length  $7.5 c/\omega_p$ ;
  - beam radius  $1.5 c/\omega_p$ ;
  - beam density equal to the half of the plasma density;
  - beam velocity  $c/2$ .
- Shown are electron density and the current.



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



## Results and Conclusions

- 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  $\omega_p I_b/V_b$ ,
  - very good current neutralization: key parameter  $\omega_p r_b/c$ .
- Plasma wave breaking heats electrons  $n_b > n_p$

# Beam Propagation in Plasma in External Magnetic Field

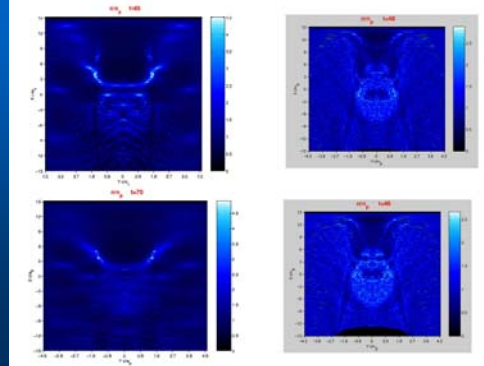
FOR MORE INFO...

I. D. Kaganovich, E. A. Startsev and R. C. Davidson, "Ion beam pulse neutralization by a background plasma in a solenoidal magnetic field", to be published in Nuclear Instruments and Methods in Physics Research (2005).

## Beam Propagates Along Magnetic Field.

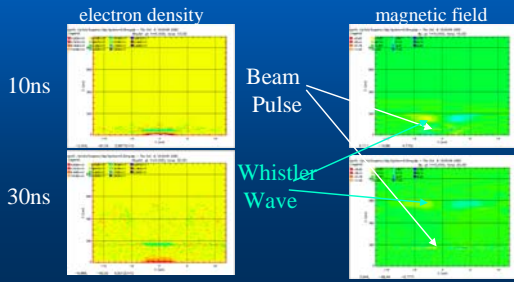
$$\omega_c = 5\omega_p$$

$$\omega_c = 2\omega_p$$



## Generation of Waves at Beam Entry Into Plasma

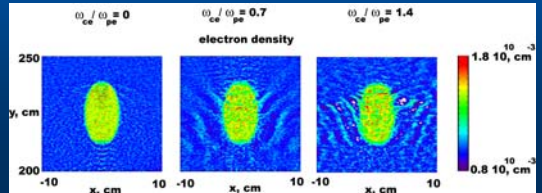
Results of LSP  $V=0.2c$   $\omega_c = 5.6\omega_p$



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

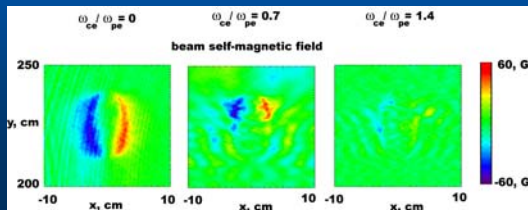
Plots of electron charge density contours in (x,y) space, calculated in 2D slab geometry using the LSP code with parameters:

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

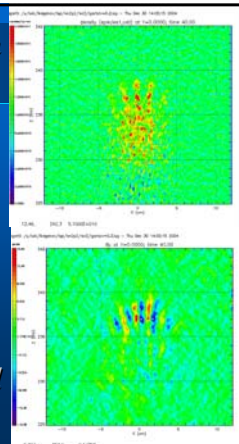
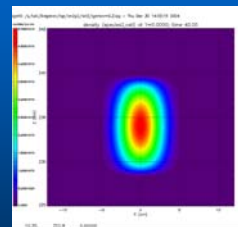


## Analytical studies show that the beam self magnetic field greatly diminishes in the limit $\omega_{ce} \gg \beta\omega_{pe}$

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

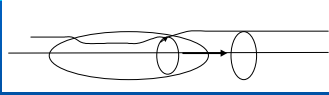


## Gaussian ion beam density Electron density

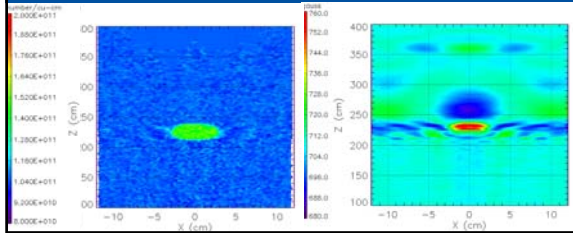


Beam self magnetic field  $\omega_{ce}=2.8\omega_{pe}$

Plasma inside ion beam acts as paramagnetic!



$$dB = -BdS/S$$



## Conclusions

- Solenoidal magnetic field inhibits the current  $\omega_{ce} \gg \beta\omega_{pe}$ .
- 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>.