Neutralization Physics of Intense, Compressed Beam

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Outline

- What degree of neutralization is needed for $>10^4$ simultaneous transverse (>100) and longitudinal (>50) beam compression.
- Key plasma parameters for beam focusing in a background plasma.
- Effects of applied magnetic field on the degree of charge and current neutralization

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**

Ballistic beam focusing on target neutralization requirements

$$\frac{d^2r}{ds^2} = \frac{Q_{eff}}{r} + \frac{\varepsilon^2}{r^3},$$

$$r'^2 + 2Q_{eff}\ln\frac{1}{r} + \frac{\varepsilon^2}{r^2} = const,$$

$$2Q_{eff}\ln\frac{r_0}{r} + \frac{\varepsilon^2}{r^2} = r_0'^2,$$

$$Q_{eff} = Q_0\left[(1-f) - \beta_b^2(1-f_m)\right],$$

$$(1-f) \ll \frac{r_0'^2}{2Q_0\ln\frac{r_0}{r_f}} \approx \frac{10^{-4}}{10^{-3}} \approx 0.1 = 10\%.$$

$$\omega_{pi}^2(1-f)t_f^2 \ll 1 \quad \Rightarrow \quad (1-f) < 3\%$$

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.

φ_b~100V φ_{pp} ~m$V_b^2/2$ =5.5V > φ_{vp} = φ_{pp} $(n_b/n_p)^2$=0.3eV

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

Combined radial and longitudinal beam focusing

$$\frac{d^2r}{ds^2} = \frac{Q_{eff}L_0}{rL(s)} + \frac{\varepsilon^2}{r^3},$$

Compression
$L_0/L(s)$~100

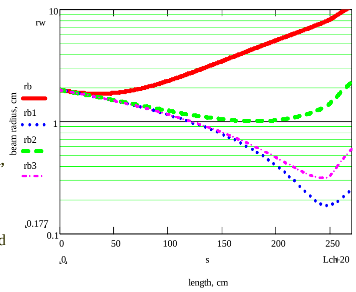
Combined focusing; neutralization requirements

$$\frac{d^2 r}{ds^2} = \frac{Q_{eff} L_0}{r L(s)} + \frac{\varepsilon^2}{r^3},$$

Compression
$L_0 / L(s) \sim 100$

NTX beam: I= 22mA, K^+, T_i=0.2eV

- f=0 unneutralized
- f=1 fully neutralized
- f=1-0.08 92%
- f=1-0.008 99.2%



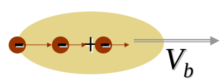
Why develop a theory of plasma neutralization?

- **Benchmark codes**
- **Predict neutralization over a wide range of parameters**
- **Intellectual challenge**

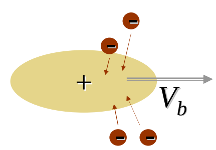
Two ways for the electrons to neutralize the beam pulse

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.

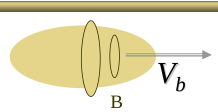


Nonlinear Theory

- **Important issues:**
  - **Finite length of the beam pulse**
  - **General value of n_b/n_p ($n_b \gg n_p$)**
  - **2D treatment**
- **Approximations:**
  - **Fluid approach**
  - **Long dense beams $l_b \gg r_b$.**
- **Exact analytical solution for scaling laws**

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

Current Neutralization



$$\frac{\partial \int Bds}{\partial t} \Rightarrow E_z$$

Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation*. For long beams canonical momentum is conserved** $mV_{ez} = \frac{e}{c} A_z$

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

$$r_b^2 > \frac{c^2}{4\pi e^2 n_p / m} \qquad r_b > \delta_p \qquad n_p = 2.5\times 10^{11} cm^{-3};\ \delta_p = 1cm$$

* K. Hahn, and E. PJ. Lee, Fusion Engineering and Design **32-33** 417 (1996)
** I. D. Kaganovich, et al, Laser Particle Beams **20** 497 (2002).

Self-Electric Field of the Beam Pulse Propagating Through Plasma

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

$$e\vec{E} = -\frac{\partial \vec{A}}{c\partial t} - \frac{\partial \phi}{\partial \vec{x}} \qquad A_z = cmV_{ez}/e \qquad B_\theta = -\frac{\partial A_z}{\partial r} \qquad V_{ez} \gg V_{er}$$

$$\phi = mV_{ez}^2/2e$$

$$eE_z = -mV_b \frac{\partial V_{ez}}{\partial z}$$

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

- E_z is inductive
- E_x is electrostatic

Self-Electric Field of the Beam Pulse Propagating Through Plasma

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

$$\phi = mV_{ez}^2/2e$$

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

$$\phi_{vp} = \frac{1}{2}mV_b^2\left(\frac{n_b}{n_p}\right)^2 = 5eV\left(\frac{n_b}{n_p}\right)^2$$ NTX K^+ 400keV beam

φ_b~100V $(1-f) = \phi_{vp}/\phi_b = 5\%\left(\frac{n_b}{n_p}\right)^2$

Summary of neutralization effects with out applied magnetic field

Electron velocity is accelerated by an inductive electric field.
Radial electric field is mostly electrostatic with effective potential

$$\phi_{vp} = \frac{1}{2}mV_{ez}^2 < \frac{1}{2}mV_b^2\left(\frac{n_b}{n_p}\right)^2$$

Having $n_b \ll n_p$ strongly increases the neutralization degree.

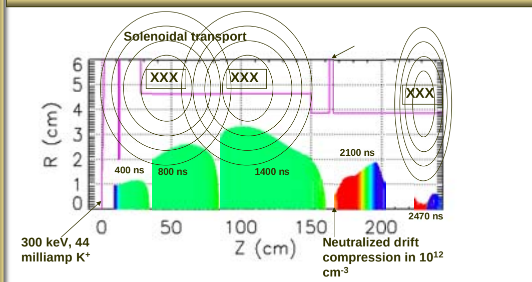
Effects of applied solenoidal magnetic field on degree of charge current neutralization

$$(1-f) \ll \frac{(r_0/L_f)^2}{2Q_0 \ln\frac{r_0}{r_f}} < 1\%.$$

$$\omega_{pi}^2(1-f)t_f^2 \ll 1 \quad\Rightarrow\quad (1-f) < 1\%$$

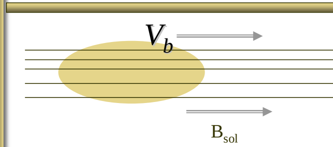
Solenoidal field provides shorter focus far from tilt core.

Solenoidal magnetic field for focusing



Courtesy of D. Welch

Role of magnetic field on neutralization

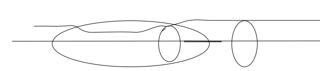


$$m\left[\frac{\partial \mathbf{V}_e}{\partial t} + (\mathbf{V}_e\cdot\nabla)\mathbf{V}_e\right] = -e\left(\mathbf{E} + \frac{1}{c}\mathbf{V}_e \times \mathbf{B}\right)$$

$$E_r \sim \frac{1}{c}V_{e\phi}B_{sol}$$

- **Strong solenoidal magnetic field:**
- **Pushes electrons along B only =>**
- **Good for current neutralization**
- **Bad for charge neutralization.**

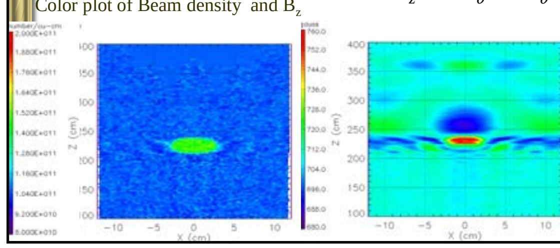
Electrons spin and plasma acts as paramagnetic inside the ion beam pulse!



$$\delta B_z = -B_z\delta S/S$$

$$\delta B_z \Rightarrow E_\theta \Rightarrow v_\theta$$

Color plot of Beam density and B_z



Examples of neutralization with B_{sol}

K^+ ions

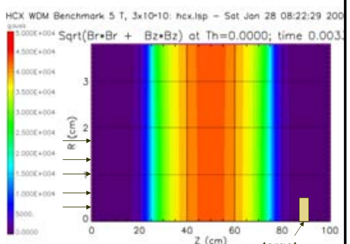
r_b=2 cm

728 mA, 25-ns pulse

Te 3eV

Uniform plasma density

$3x10^{10}$, $3x10^{11}$, $3x10^{12}$ cm^{-3}

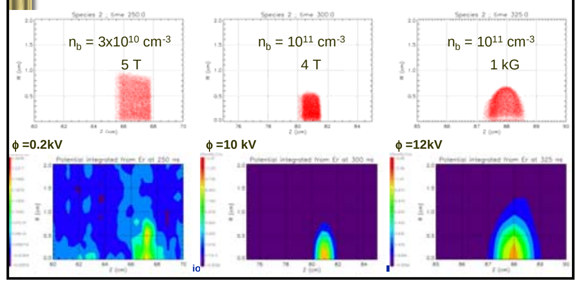


5-T solenoidal focus for HCX between 40-80 cm

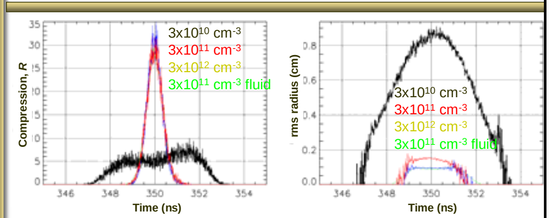
Courtesy of D. Welch

Potentials develop just as the beam emerges from the solenoid where $n_p \sim n_b$

- $3x10^{11}$ cm-3 density plasma case show 15 kV unneutralized potential
- Good neutralization with solenoid where $n_p >> n_b$



High electric fields prevent focusing



- **Focus for $3x10^{12}$ cm^{-3} is that of ballistic**
- **For $3x10^{10}$ cm^{-3} density much larger spot size**

Courtesy of D. Welch

Developed analytical theory in B_{sol}

- Linear full 2D and nonlinear 2D slice cases.
- The 2D slab linear problem is solved analytically in Fourier space.
- For a strong enough applied magnetic field, poles emerge in Fourier space. These poles are an indication that whistler and low-hybrid waves have been excited by the beam pulse.

E(k) of an ion beam

$$k^2\mathbf{E} - \mathbf{k}(\mathbf{k}\cdot\mathbf{E}) - \frac{\omega^2}{c^2}\epsilon\cdot\mathbf{E} = \frac{4\pi i\omega}{c^2}\mathbf{j}_b$$

$$\epsilon = \begin{pmatrix} \epsilon_\perp & i\epsilon_\vdash & 0 \\ -i\epsilon_\vdash & \epsilon_\perp & 0 \\ 0 & 0 & \epsilon_\parallel \end{pmatrix}$$

$$\epsilon_\perp = 1 - \frac{\omega_p^2}{\omega^2-\omega_c^2}$$

$$\epsilon_\parallel = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\epsilon_\vdash = \frac{\omega_c\omega_p^2}{\omega(\omega^2-\omega_c^2)}$$

Newton’s Second Law, Ohm’s Law, and Maxwell’s Equations can be combined in Fourier space to produce a set of equations that describes the electromagnetic fields produced by the ion beam,

B(k) of the beam

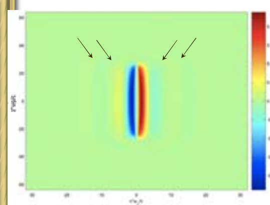
$$B_y = -\frac{4\pi i j_b}{c}\frac{k_x}{\left(-\frac{1}{G}\beta^2 k_z^2\epsilon_\parallel + k_x^2\right)}$$

$$G = 1 - \frac{1}{\left(1-\beta^2\epsilon_\perp - \frac{(\beta^2 k_z \epsilon_\vdash)^2}{(-\beta^2 k_z^2\epsilon_\perp + k^2)}\right)}$$

- **Poles in B_y correspond to waves**

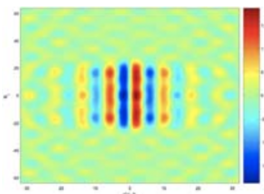
Two kind of waves are excited by the beam

(i) $\omega_c = 1.0\ \omega_p$



Ripples around beam corners

(ii) $\omega_c = 1.32\ \omega_p$

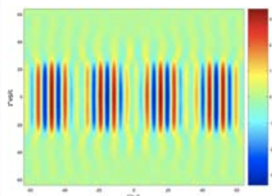


Globular structure within wavefronts and evidence of longitudinal waves

Criteria for Wave Propagation

(iii) $\omega_c = 1.35\ \omega_p$

$$\omega_c > \frac{2\beta}{1-\beta^2}\omega_p$$

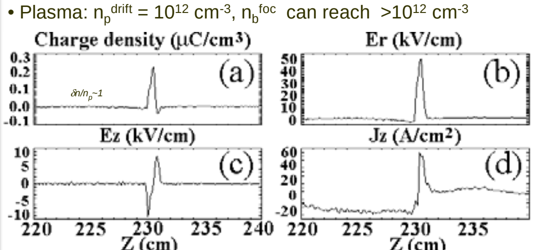


Note that this approximation gives a criterion only for radial waves. Our simulations have used $\beta = 0.5$, so we expect to see waves for $\omega_c > 1.33\omega_p$.

Undamped radial waves. Modulated in wave packets. Longitudinal "leaking".

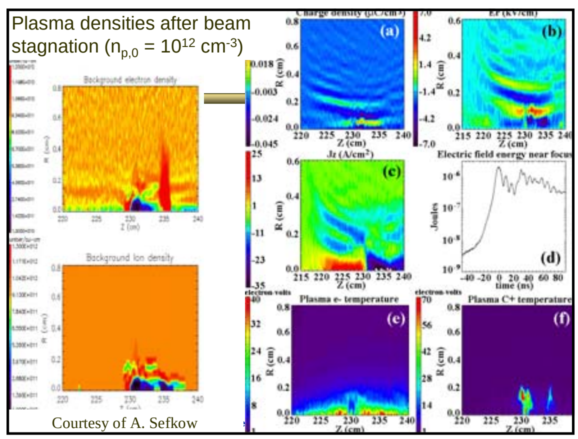
Example of wave excitation during focusing when $n_{beam} > n_{plasma}$

- 400 keV K^+, 80 mA, r = 1.9 cm, T = 0.2 eV,
- 2.50 m focal length
- Plasma: $n_p^{drift} = 10^{12}$ cm^{-3}, n_b^{foc} can reach $>10^{12}$ cm^{-3}



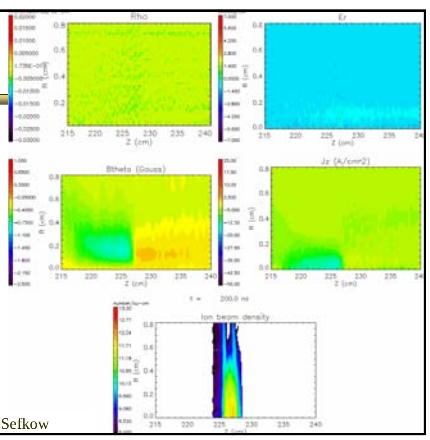
Courtesy of A. Sefkow

Plasma densities after beam stagnation ($n_{p,0} = 10^{12}$ cm^{-3})



Courtesy of A. Sefkow

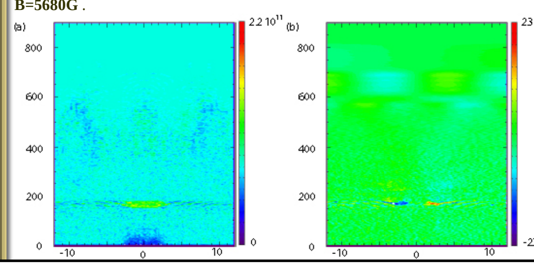
Movies



Courtesy of A. Sefkow

Generation of waves at beam entry into plasma due to presence of solenoidal magnetic field

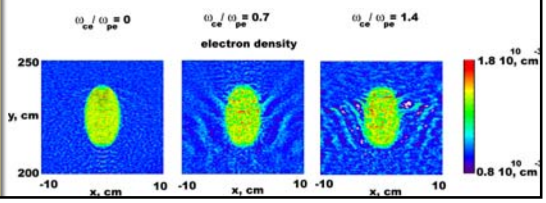
Shown are color plots of (a) the electron density and (b) the magnetic field component generated by the ion beam pulse. The plasma density is $n_p=10^{11}$ cm^{-3}; the beam velocity is $V_b=0.2c$; the beam current is 1.2kA; solenoidal field B=5680G .



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

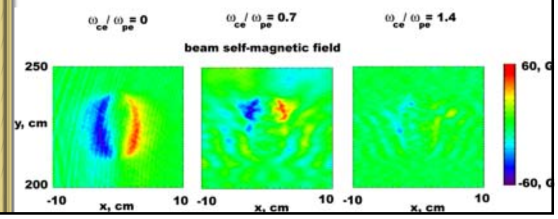
Plots of electron charge density contours in (x,y) space, calculated in 2D slab geometry using the LSP code with parameters:

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



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.



Summary of effects of solenoidal magnetic field on plasma neutralization

- **Solenoidal magnetic field inhibits the current when $\omega_{ce}>>\beta\omega_{pe}$ *but may strongly increase radial electric field.***
- **Due to solenoidal magnetic field, waves are generated at an angle to the 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.

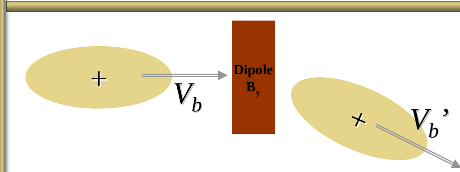
See four recent papers by I. Kaganovich, et al. at http://nonneutral.pppl.gov.

Additional slides

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 degree of charge current neutralization**
  - solenoidal magnetic field,
  - **dipole magnetic.**
- Effects of gas ionization on self-magnetic field of ion beam pulse.

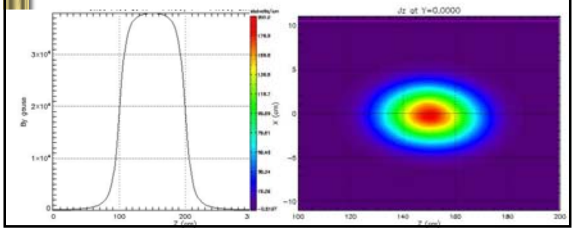
Dipole magnetic field can be used to deflect ion beam motion



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

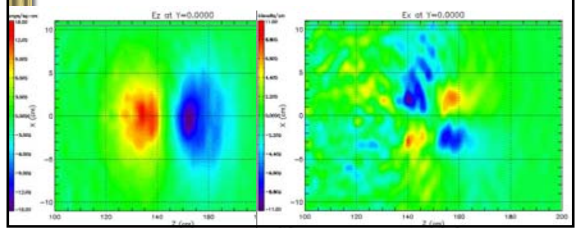
3D simulations show no current neutralization

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 neu-tralization and quadrupole structure of E_x

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



Outline

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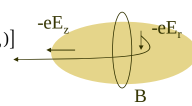
- Key plasma parameters for good charge and current neutralization in a background plasma.
- Effects of applied magnetic field on degree of charge current neutralization
  - solenoidal magnetic field,
  - dipole magnetic.
- **Effects of gas ionization on self-magnetic field of ion beam pulse.**

Electrons produced in the beam pulse carry away magnetic field

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



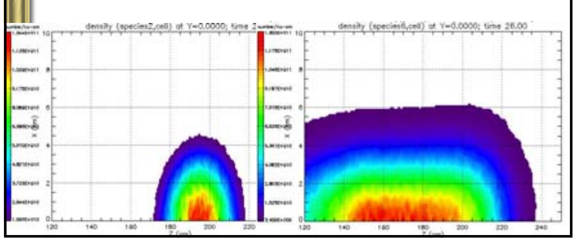
If an electron originates in the region of strong magnetic field, and later moves into a region of weaker magnetic field, then the electron flow velocity is in the direction opposite to the beam velocity; and the current of such electrons *enhances* the beam current rather than diminishes the beam current.

The return current becomes nonlocal.

The Heavy Ion Fusion Science Virtual National Laboratory PPPL

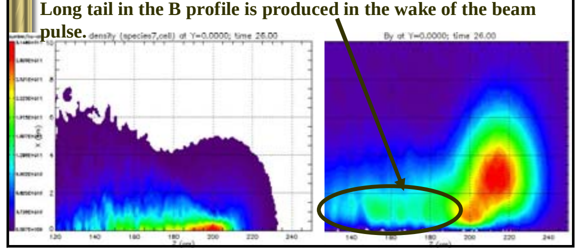
Color plots of the ion density produced by beam ionization

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 electrons in the direction opposite to the beam velocity.
Long tail in the B profile 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
  - good charge neutralization; quadruple structure of E_x
- **Effects of gas ionization**
  - Self-electric field in the beam pulse tail pushes new electrons in the direction opposite to the beam velocity, which *enhances* the beam current.
  - Long tail of current and magnetic field are produced in the wake of the beam pulse.

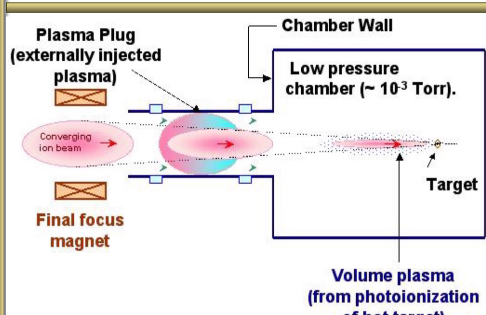
How to achieve high degree of neutralization?

What plasma parameters and plasma set up to use?

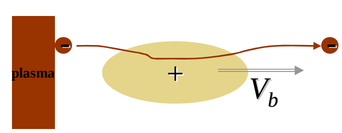
Schemes for beam space-charge neutralization

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

Schemes for beam space-charge neutralization



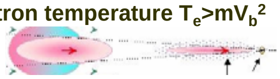
Is the space-charge potential in a plasma plug $\sim mV_b^2/2$?



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

Disadvantages of plasma plug scheme

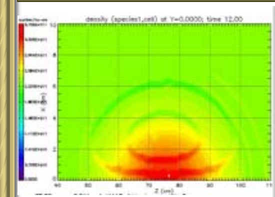
- Electrons follow the beam with velocity V_b ; after extraction electron temperature T_e>mV_b^2 is large (~keV)

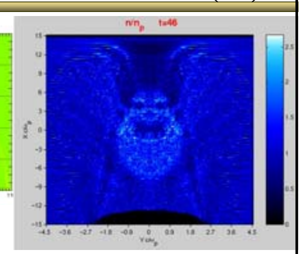


- During compression T_e rapidly increases T_e~1/r_b^2 *=>
- High T_e prevents focusing

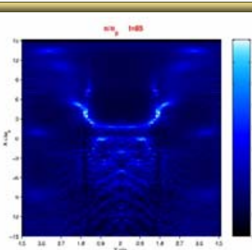
* Lifschitz et al, NIMPR A 544, 202 (2005).

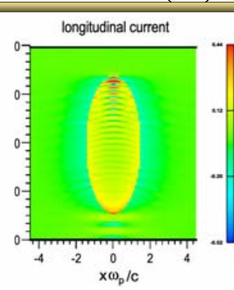
Which image is real physics, which is the artifact of a code? (1/2)





Which image is real physics, which is artifact of a code? (2/2)

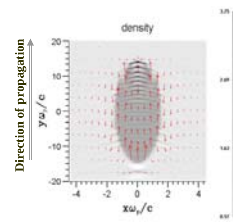




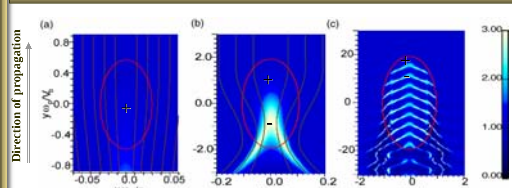
Theory provides a solid foundation and reality check.

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.



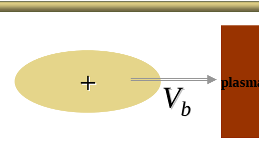
Charge Neutralization Depends on Pulse Duration and Plasma Frequency ($\omega_p t_b/2\pi$>>1)



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.

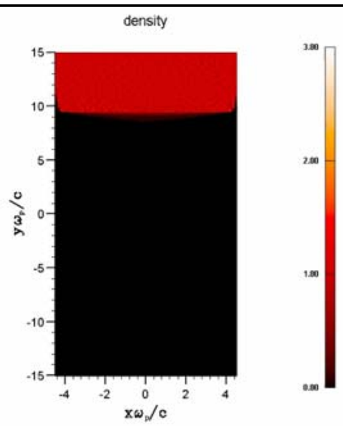
The beam dimensions correspond to r_b/l_b =0.01 and $\omega_p t_b/2\pi$= (a) 0.19, (b) 0.64, (c) 6.4.

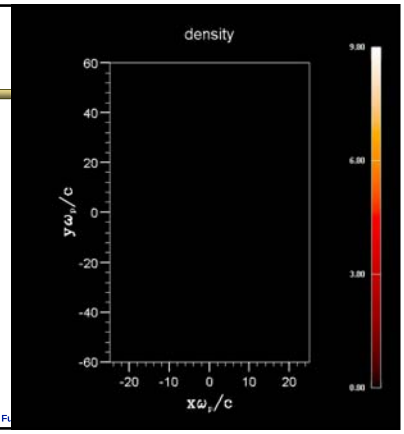
How long is the transition region to establish quasi-steady-state propagation?



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.

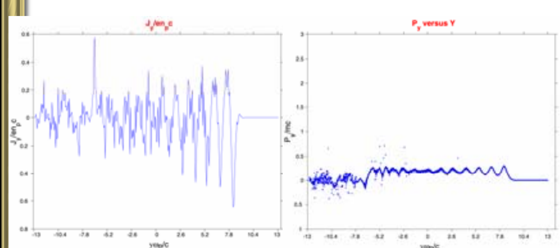
FOR MORE INFO... I. D. Kaganovich, E. A. Startsev and R. C. Davidson, Physica Scripta T107 54 (2004).





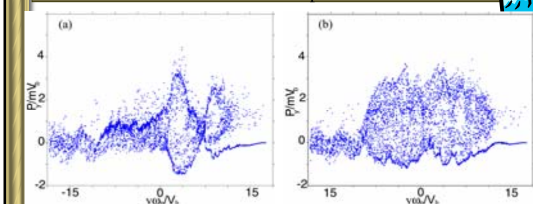
Beam length $=30\ c/\omega_p$; Beam radius $=0.5\ c/\omega_p$; Beam density = 5 times plasma density; Beam velocity = 0.5*c*.

Fluid approximation is good if $n_b \le n_p$



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 $n_b > n_p$

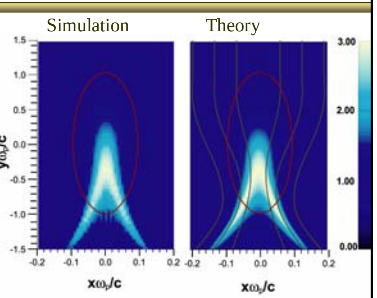


Electron phase space shown for $l_b=30V_b/\omega_p$; $n_b = 2n_p$.
Times after entering the plasma plug are: (a) 113 $/\omega_p$, and (b) 245$/\omega_p$.

Comparison of Theory and Simulation: Electron Density

Electron density
Left – PIC simulation
Right - fluid theory.

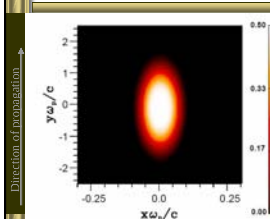
Red line: ion beam pulse boundaries. The brown contours show the electron trajectories in the beam frame.



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

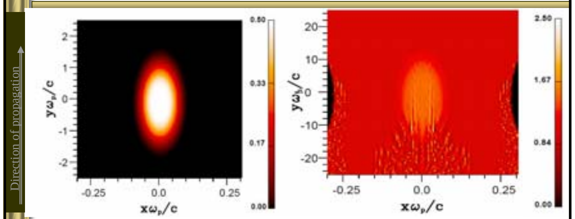


Take beam with $\varphi_b=2\pi e^2 n_b r_b^2 \ll mV_b^2/2$

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 $\tau_b\omega_p=60$.

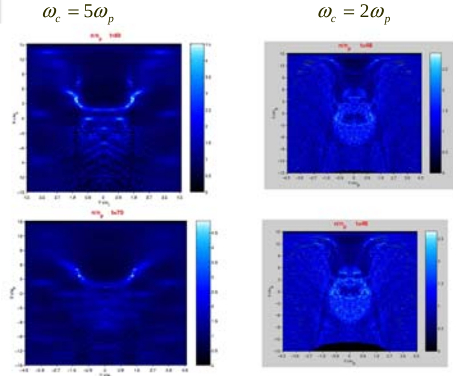
Check of φ ~mV_b^2



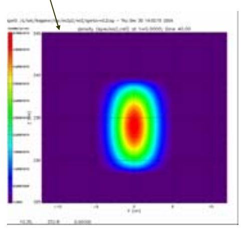
Neutralization of an ion beam pulse during steady-state propagation of the beam pulse through a cold, uniform, background plasma in planar geometry calculated using the EDPIC code. The beam propagates in the y-direction. Shown in the figure are color plots of the normalized beam density (n_b/n_p) (left)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

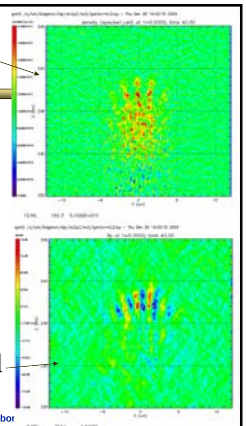
Beam Propagates Along Magnetic Field.

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



Gaussian ion beam density **Electron density**





Beam self magnetic field

ω_{ce}=2.8ω_{pe}