Designing Neutralized Drift Compression for Focusing of Intense Ion Beam Pulses in Background Plasma

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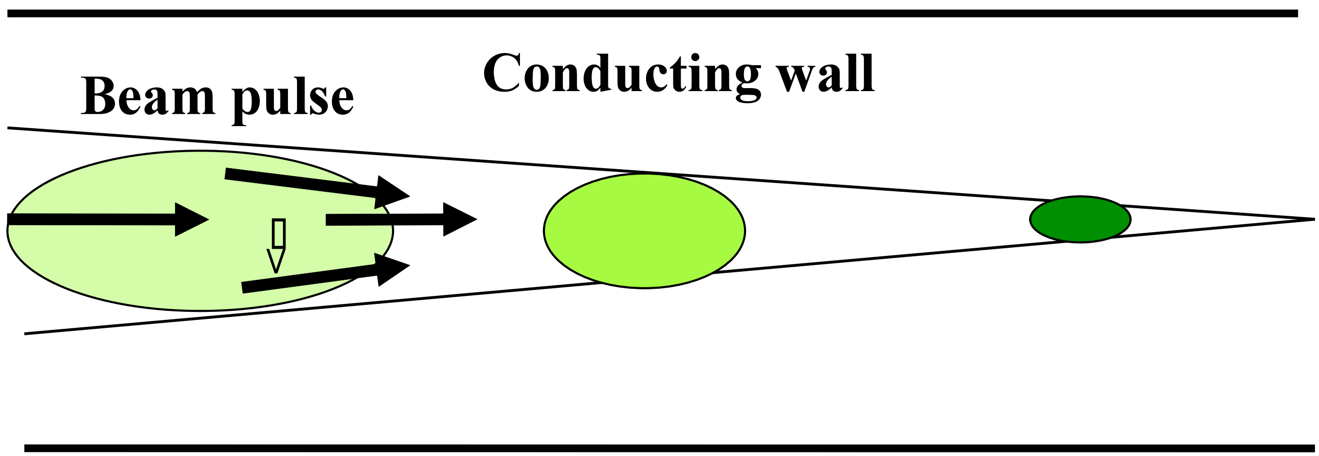
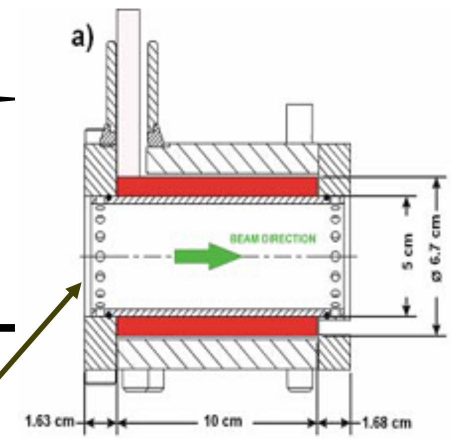
Voss Scientific

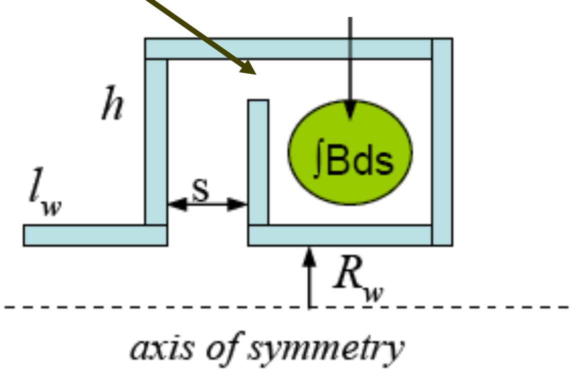
Neutralized drift compression can reach 300x300 = 10^5 combined longitudinal and transverse compression of ion beam pulse.





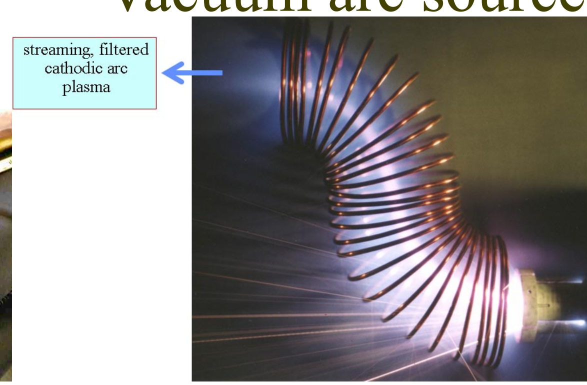
Radial velocity tilt is applied by magnetic lenses

Longitudinal velocity tilt – by inductive tilt core



Ferroelectric plasma source

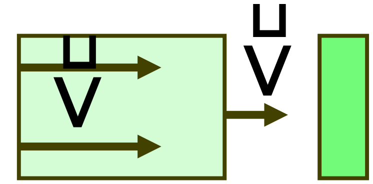
Vacuum arc source



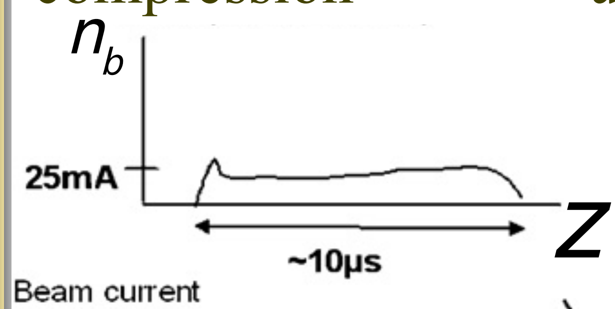
Outline

- **Longitudinal compression**
- **Radial compression**
- **Simultaneous longitudinal and radial compression**
- **The physics of the neutralization process and requirements for plasma sources.**

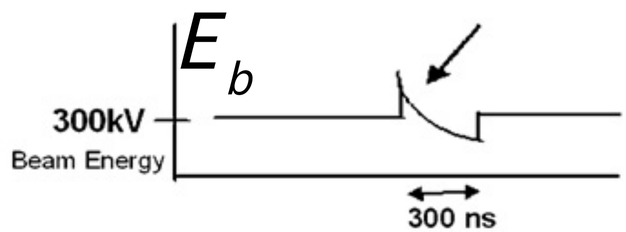
Longitudinal Compression



beam pulse before compression

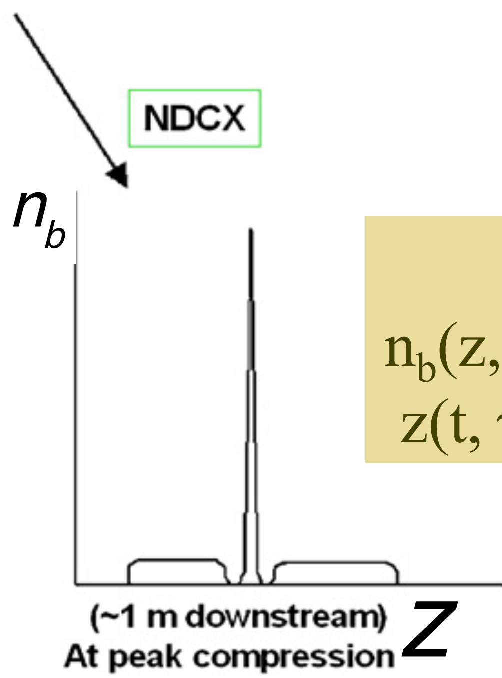


tilt core voltage waveform applied to uncompressed beam pulse



Z, τ

compressed beam current.



Analytical solution

$n_b(z,t)=n_{b0}v_{b0}/[v_b(\tau)-(t-\tau)dv_b(\tau)]$

$z(t, \tau)= v_b(\tau)\ (t-\tau)$

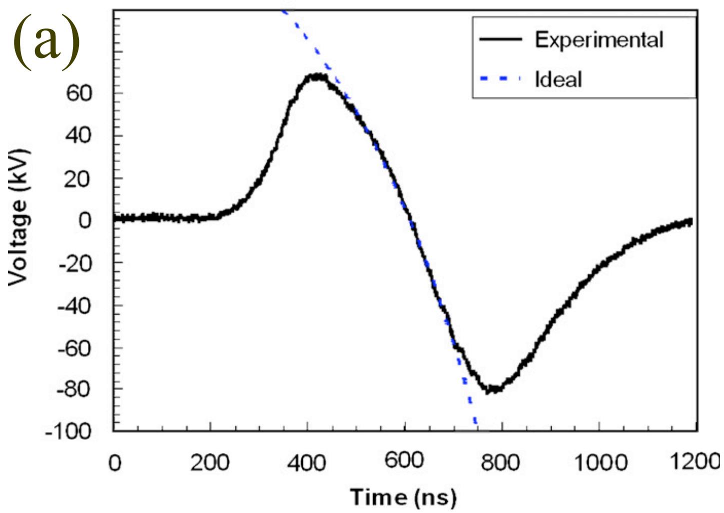
P.K. Roy et al, NIMPR. A **577,** 223 (2007).

Longitudinal compression is limited by errors in applied velocity tilt.

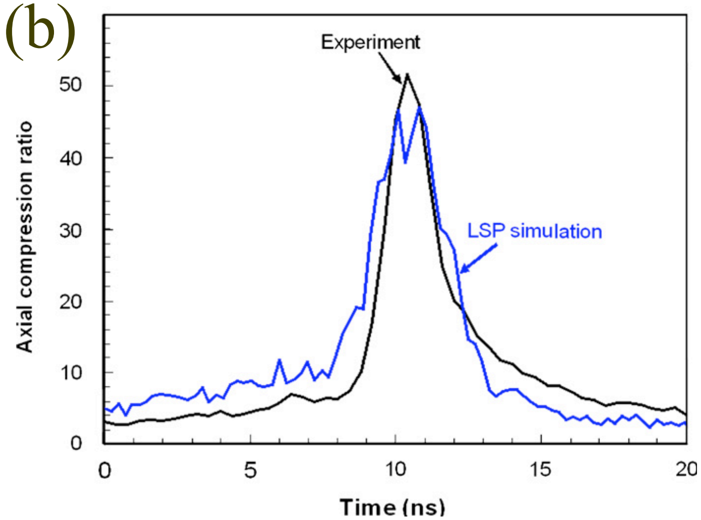
$Max(n_b/n_{b0}) = \Delta v_b/\delta v_b$

(a) Experimental and ideal voltage waveforms.
(b) Beam compression (experiment and simulation).
P.K. Roy et al, NIMPR. A **577** 223 (2007).

(a)



(b)

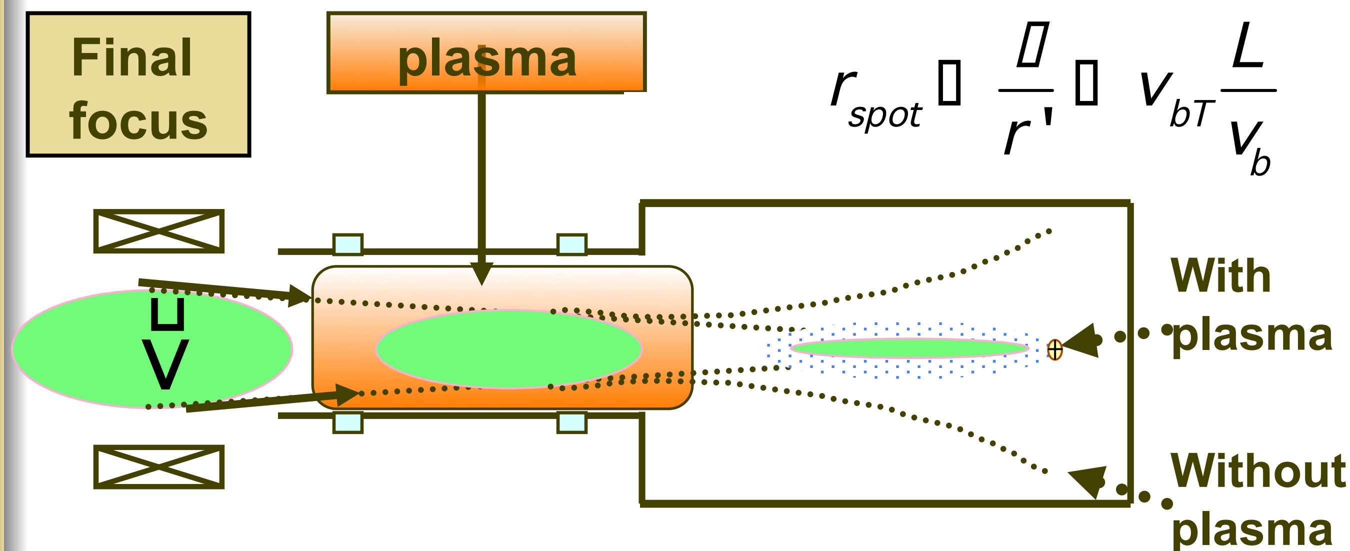


Analytical solution

$n_b(z,t) = n_{b0} v_{b0} / [v_b(\tau) - (t-\tau) dv_b(\tau)]$

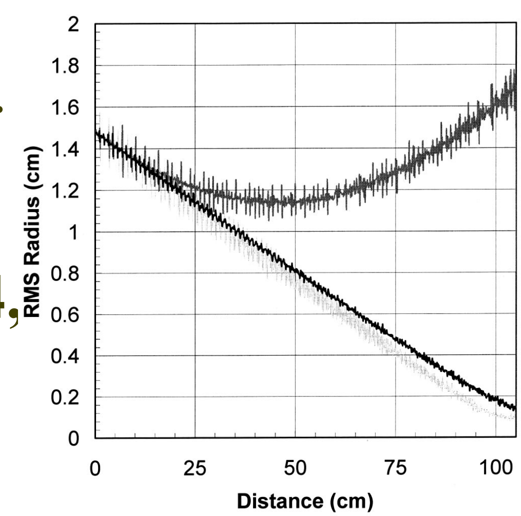
$z(t, \tau) = v_b(\tau)\,(t-\tau)$

Radial Compression is emittance limited, degree of neutralization >99%.



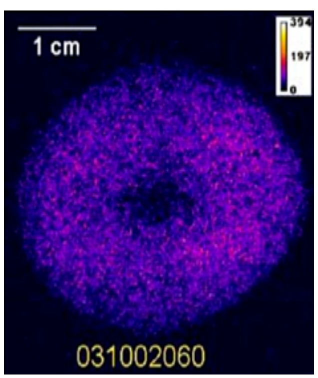
$$r_{spot} \approx \frac{\varepsilon}{r'} \approx v_{bT}\frac{L}{v_b}$$

Beam envelope with and without taking into account beam space charge.

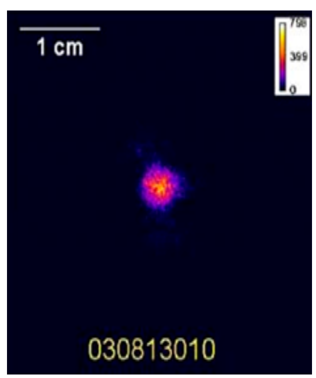


Beam images at the focal plane 24mA, 254 keV K+ ion beam: (a) without plasma (b) with plasma.

(a)

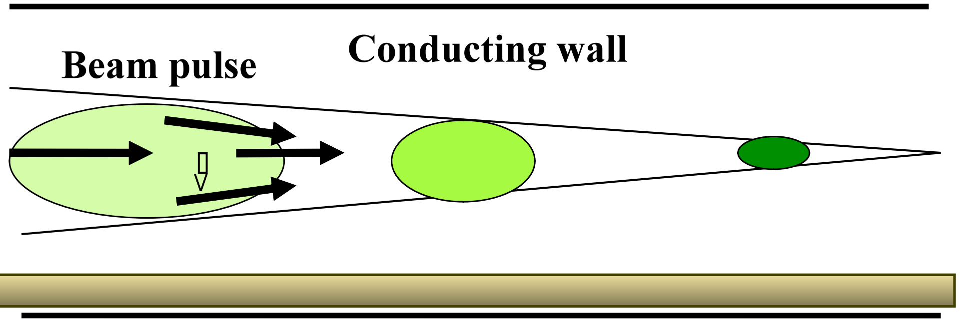


(b)



P.K. Roy et al, NIMPR. A **544**, 225 (2005).

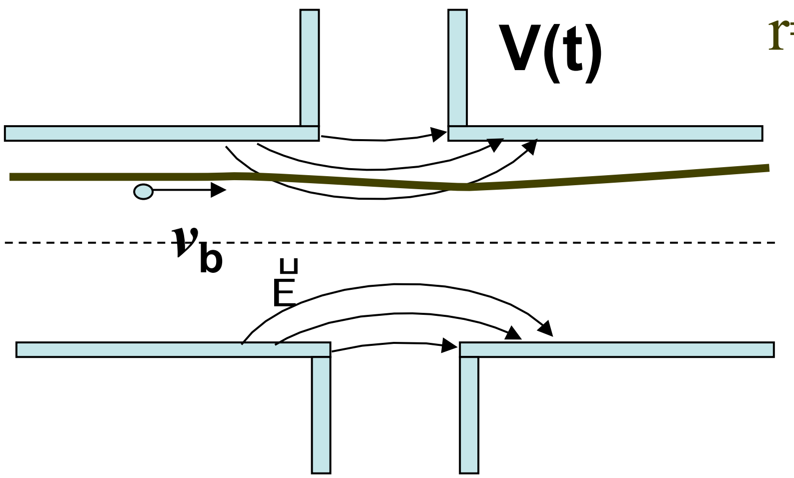
Outline



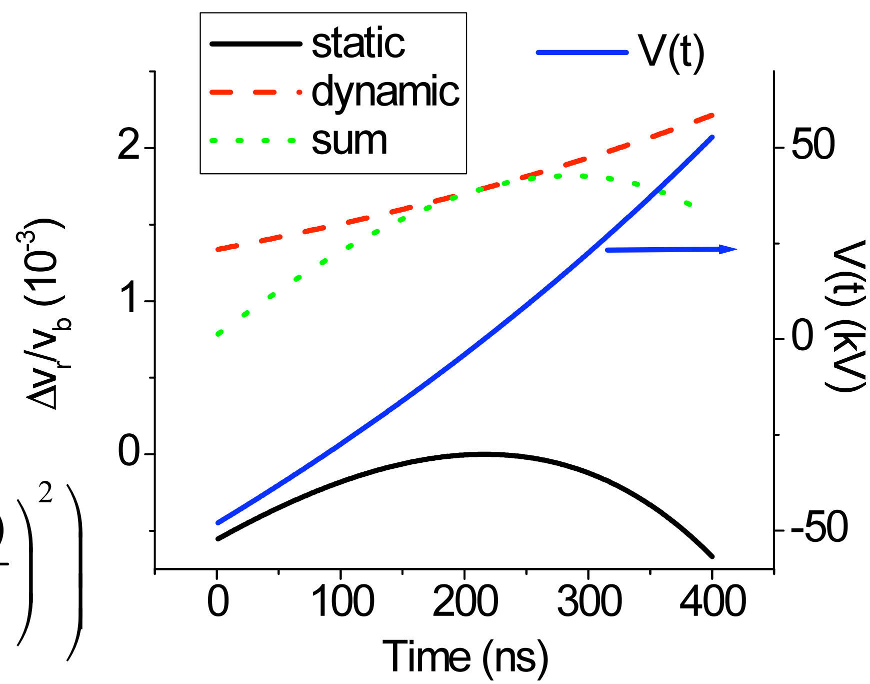
- Longitudinal compression
- Radial compression
- **Simultaneous longitudinal and radial compression**
- The physics of the neutralization process and requirements for plasma sources.

Aberration in the bunching module

acceleration gap of the induction bunching module.



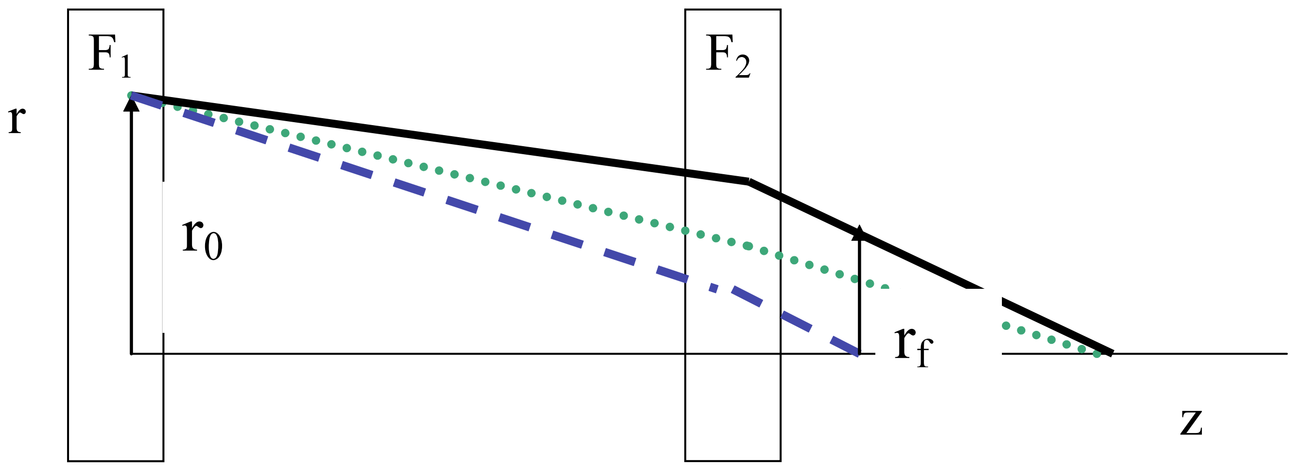
The static and dynamic aberrations for NDCX-I. Pulse t_p=400ns, E_b=300keV, r=1cm, R_w=3.8cm.



$$\frac{\Delta v_{br}}{v_{b0}} \cong \frac{r}{R_w}\left(-\frac{R_w}{4v_{b0}}\frac{e\dot{V}(t)}{E_b} - 0.082\left(\frac{eV(t)}{E_b}\right)^2 \right)$$

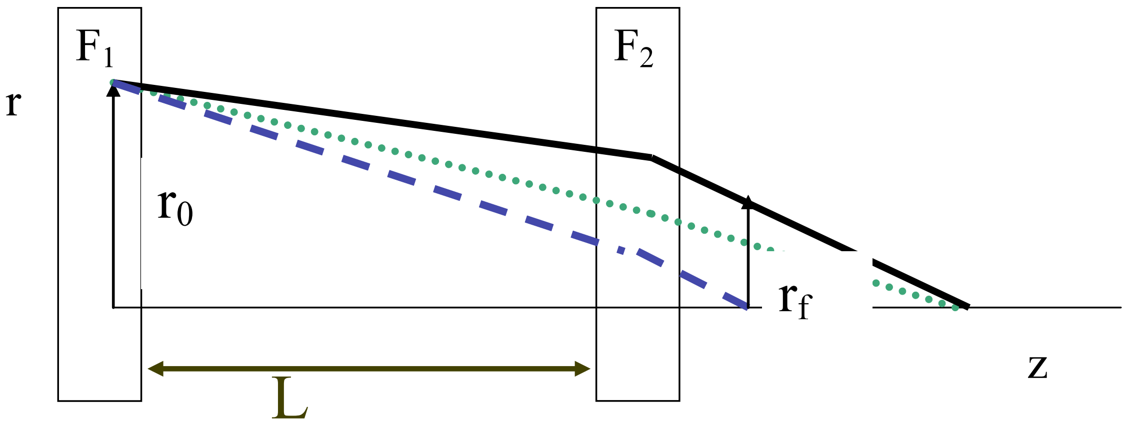
Strong final focusing element is utilized to reduce spot size at target.

Utilizing a time-dependent Einzel lens for correcting aberrations in the gap and chromatic effects in focusing system is the best. E.P. Lee, private communication (2008).
Placing a strong focusing element is the second best.



$r_{sp} \sim r_f\, 2\Delta v_b / v_b$ chromatic effects in the final focusing element

Optimization of the final focus system to achieve minimum of the spot size.



The beam spot radius at the target for two solenoids is given by

$$r_{sp} \sim \frac{r_b \Delta v_b}{v_b} \frac{F_2 F_1 + 2(F_1 - L)^2}{(F_2 + F_1 - L)F_1}$$

Minimizing the final spot size with respect to L,

$$r_{sp,\min} = \frac{r_b \Delta v_b}{v_b} \sqrt{\frac{8F_2}{F_1}} \qquad = 1\text{mm}$$

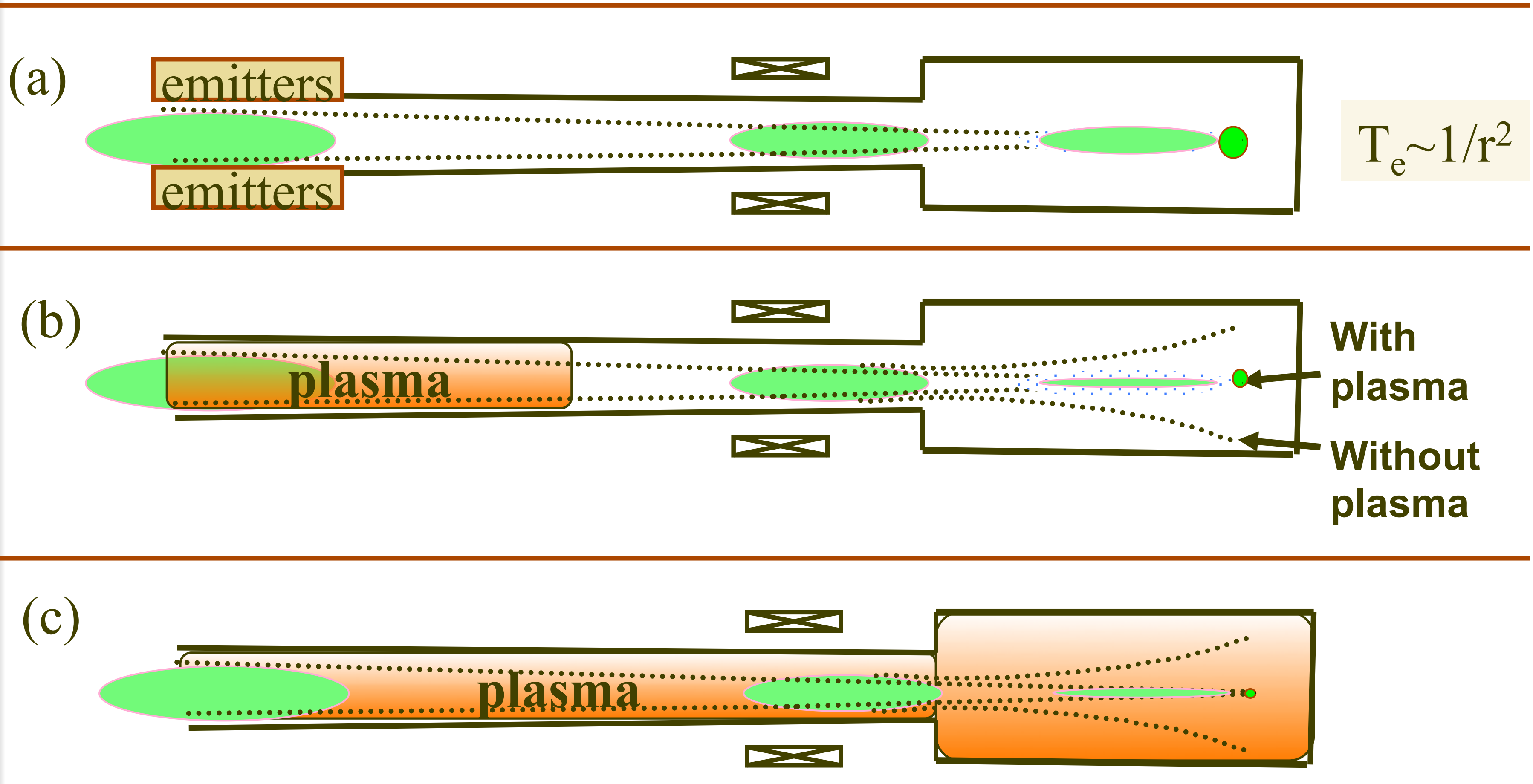
Outline

- Longitudinal compression
- Radial compression
- Simultaneous longitudinal and radial compression
- **The physics of the neutralization process and requirements for plasma sources.**
  - Is it possible to achieve better than 99% neutralization?!

Methods to neutralize intense ion beam

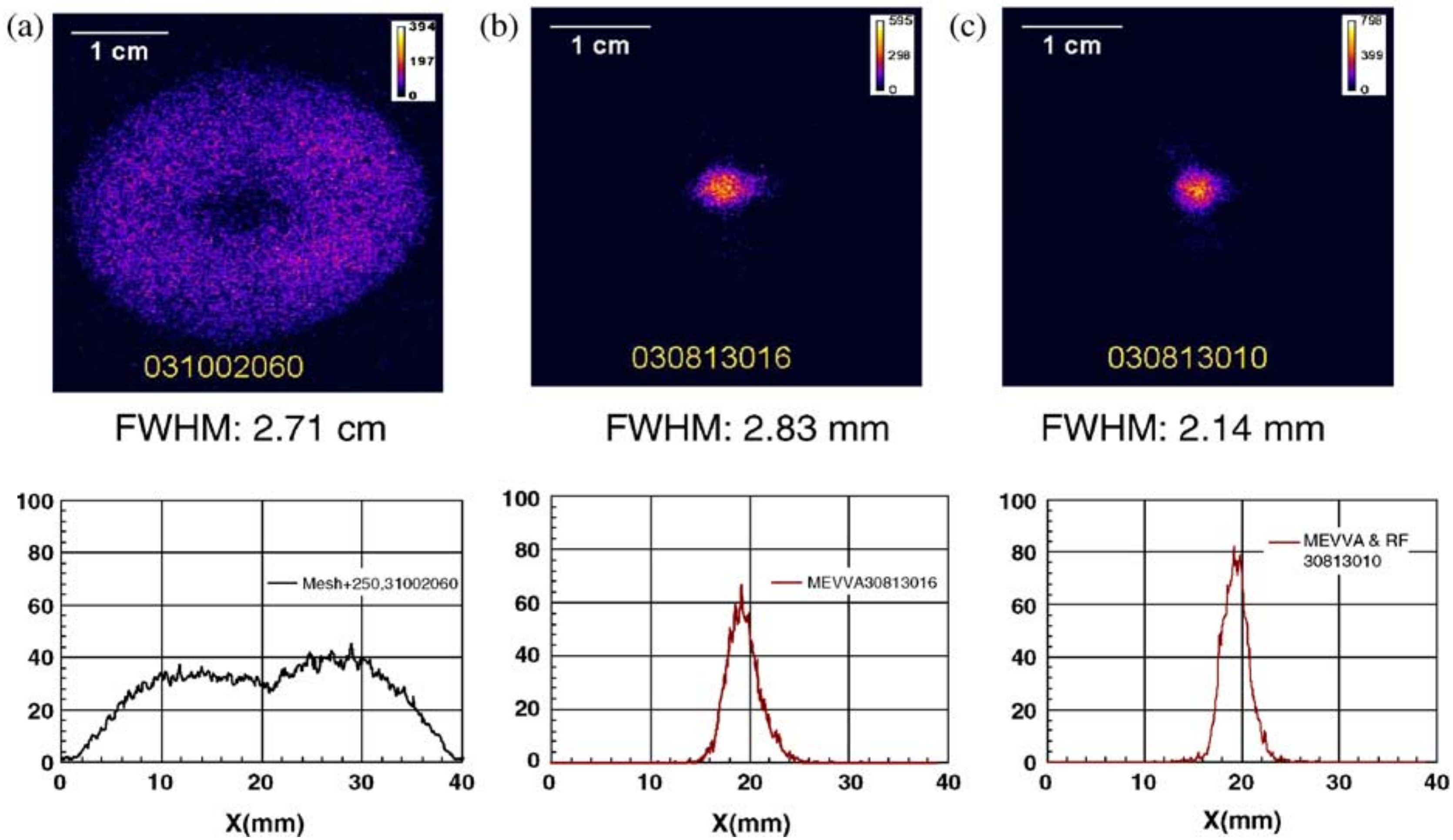
It's better to light a candle than curse the darkness:
It is better to use electrons than fight their presence.

(a) emitters, (b) plasma plug, and (c) plasma everywhere



Plasma plug cannot provide sufficient neutralization compared with plasma filling entire volume.

Beam images at the focal plane non-neutralized (a), neutralized plasma plug (b), and volumetric plasma everywhere (c).



P.K. Roy et al, NIMPR. A **544,** 225 (2005).

To determine degree of neutralization electron fluid and *full* Maxwell equations are solved numerically and analytically.

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

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

Solved analytically for a beam pulse with arbitrary value of n_b/ n_p, in 2D, using approximations: fluid approach, conservation of generalized vorticity.

I. Kaganovich, *et al.*, Phys. Plasmas **8**, 4180 (2001); Phys. Plasmas **15**, 103108 (2008); Nucl. Instr. and Meth. Phys. Res. A **577**, 93 (2007).

Results of Theory for Self-Electric Field of the Beam Pulse Propagating Through Plasma

Self-electric field is determined by electron inertia ~ electron mass

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

$$\phi_{vp} = m V_{ez}^2 / 2e$$

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

$$\phi_{vp} = \frac{1}{2} m V_b^2 \left(\frac{n_b}{n_p} \right)^2 = 5eV \left(\frac{n_b}{n_p} \right)^2$$

NTX K^+ 400keV beam **φ_b~*100V***

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

Degree of neutralization

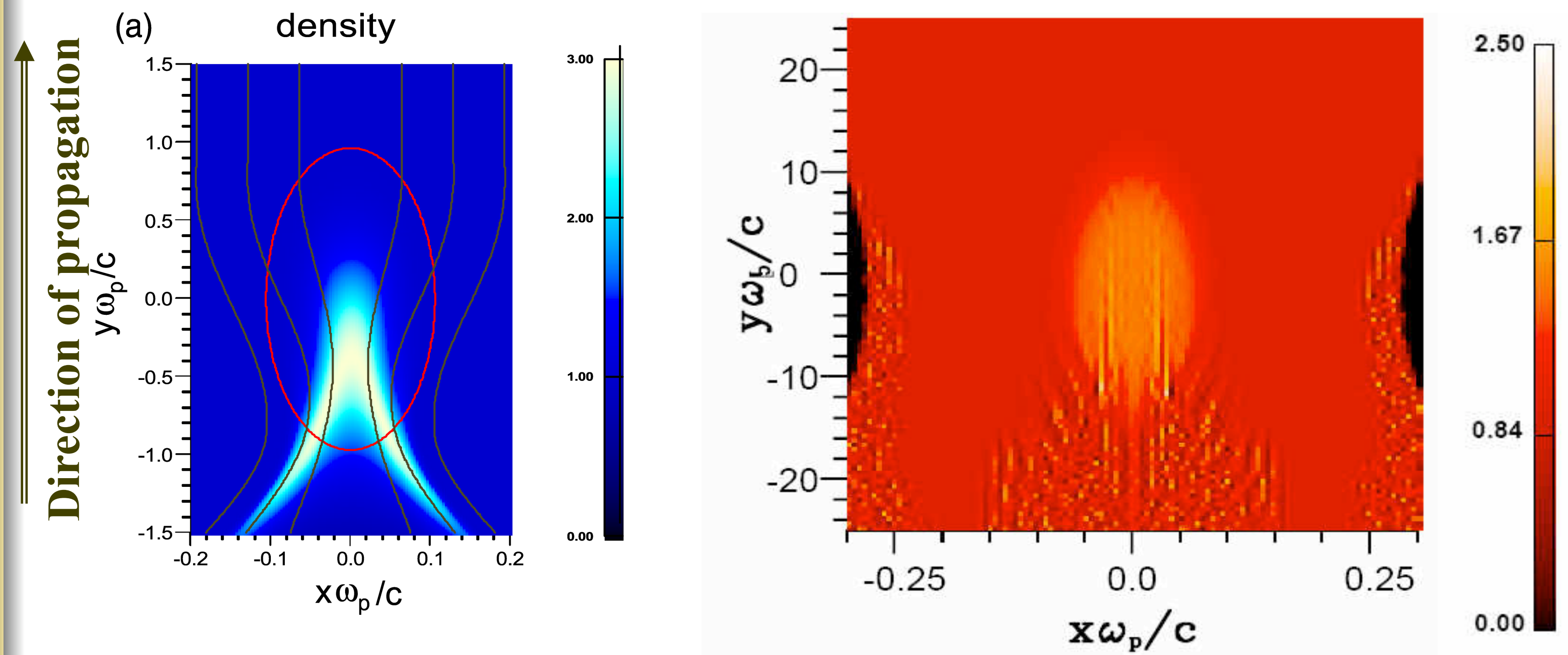
Having $n_b \ll n_p$ strongly increases the neutralization degree.

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

$$F_r = -m V_b^2 \frac{1}{n_p} \left| \frac{\partial n_b}{\partial r} \right|$$

Magnetic force dominates the electrical force and it is focusing!

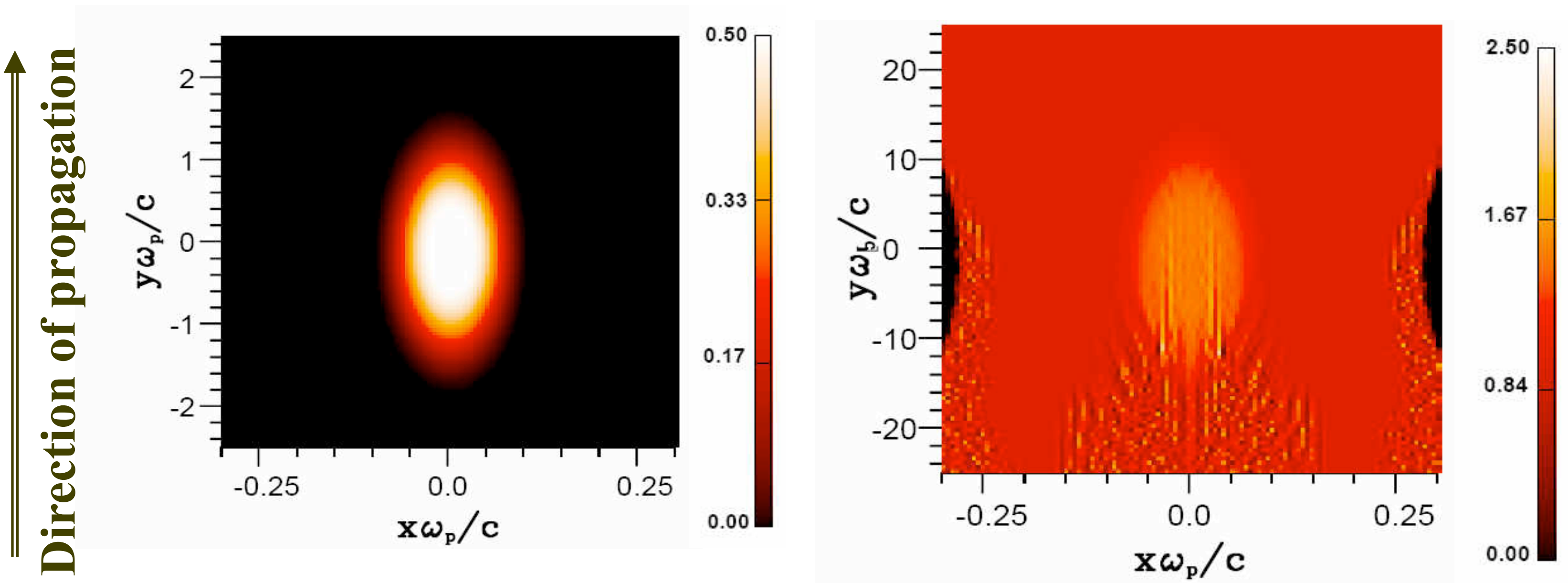
Analytic theory of chamber transport: neutralization and excitation of plasma waves by beam depends on bunch duration and plasma frequency, $\omega_p \tau_b$.



$\omega_p \tau_b$: a) 4 , (b) 60.

Shown in the figure are color plots of the normalized electron density (n_e/n_p), Red line: ion beam size, brown lines: electron trajectory in beam frame, β_b=0.5, l_b/r_b =10, n_b/n_p=0.5 .

Beam pulse is well neutralized even if its unneutralized potential $\varphi_b \ll mV_b^2$

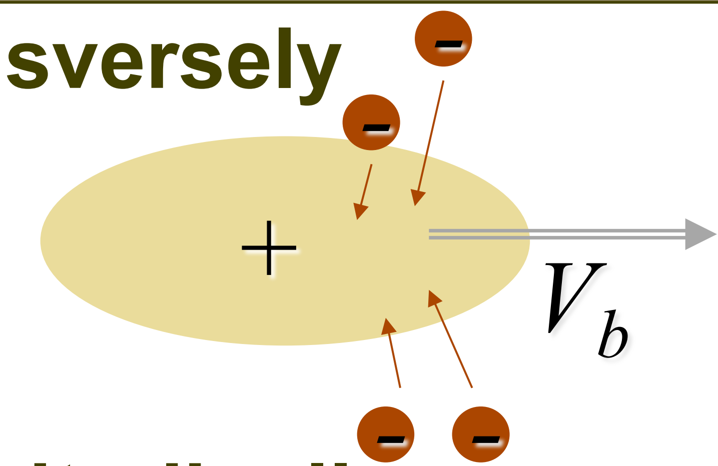


Neutralization of an ion beam pulse. Shown in the figure are color plots of the normalized beam density (n_b/n_p) (left) and the electron density (n_e/n_p), pulse duration $\boldsymbol{\tau_b\omega_p=60}$.

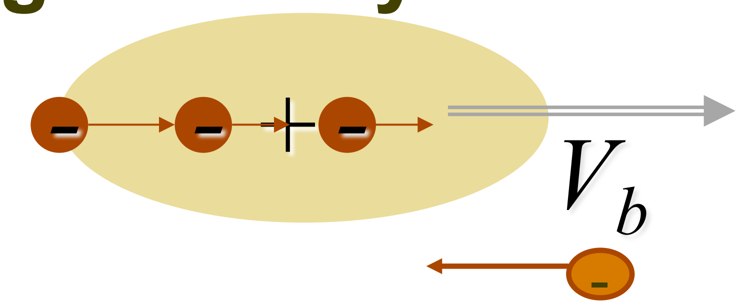
Criterion for neutralization is long pulse duration $\boldsymbol{\tau_b\omega_p\gg 1}$.

Two ways for ion beam pulse to grab electrons to insure full neutralization.

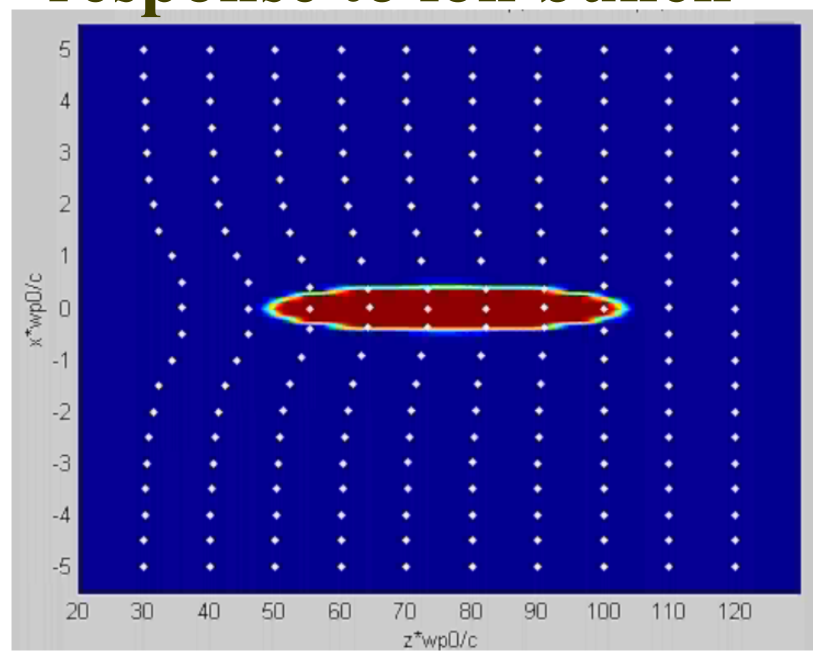
Transversely



Longitudinally



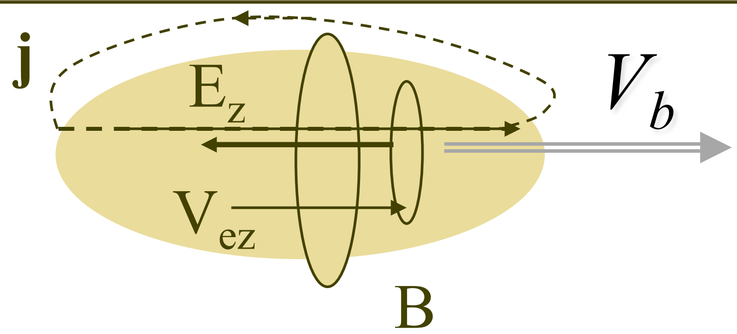
Electron positions in response to ion bunch



Note in unneutralized beam pulses, electrons accelerate into the beam attracted by space potential: indicating the inductive field is important even for slow beams!

#19

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** $mV_{ez} = \frac{e}{c} A_z$

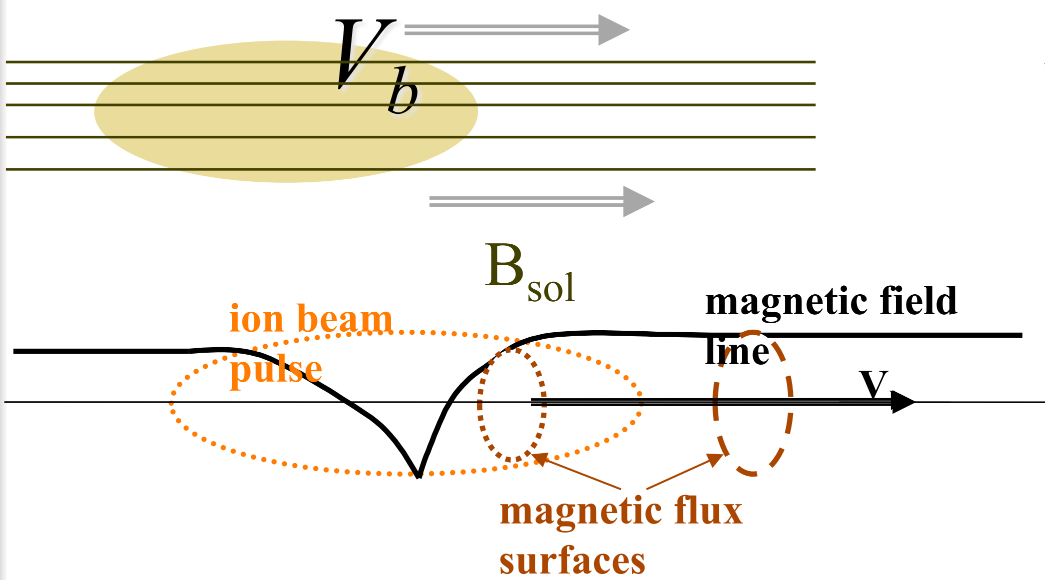
$$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c} \qquad -\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} V_{ez} = \frac{4\pi e}{mc^2}\left(Z_b n_b V_{bz} - n_e V_{ez}\right).$$

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

* 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).

Influence of magnetic field on beam neutralization by a background plasma



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

Small radial electron displacement generates fast poloidal rotation according to conservation of azimuthal canonical momentum:

$$V_\phi = \frac{e}{mc}(A_\phi + B_{sol}\delta r)$$

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

$$B_{e\varphi} = B_{ez}\frac{V_{e\varphi}}{V_{bz}}$$

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).

Equations for Vector Potential in the Slice Approximation.

$$-\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}A_z = \frac{4\pi}{c}j_{bz} - \frac{\omega_{pe}^2}{c^2}A_z - \frac{\omega_{ce}}{V_b}\frac{1}{r}\frac{\partial}{\partial r}(rA_\phi).$$

$$-\left(1+\frac{\omega_{ce}^2}{\omega_{pe}^2}\right)\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(rA_\phi)\right] = \frac{4\pi}{c}j_{b\phi} - \frac{\omega_{pe}^2}{c^2}A_\phi - \frac{\omega_{ce}}{V_b}\frac{\partial}{\partial r}A_z.$$

The electron return current

New term accounting for departure from quasi-neutrality.

Magnetic dynamo

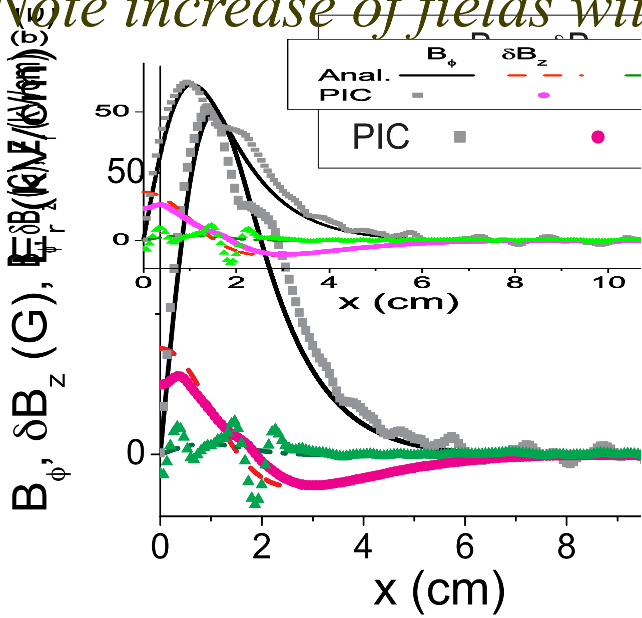
Electron rotation due to radial displacement

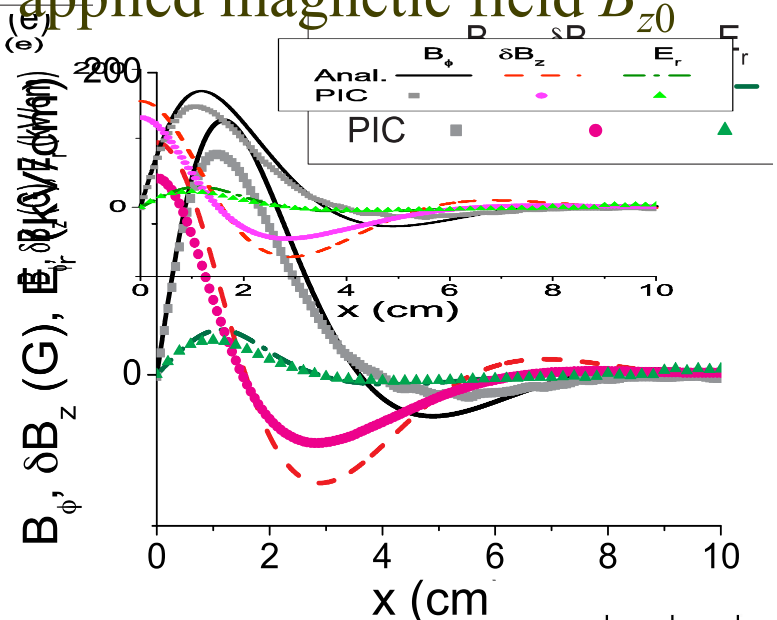
$$\omega_{ce} = \frac{eB_z}{mc}$$

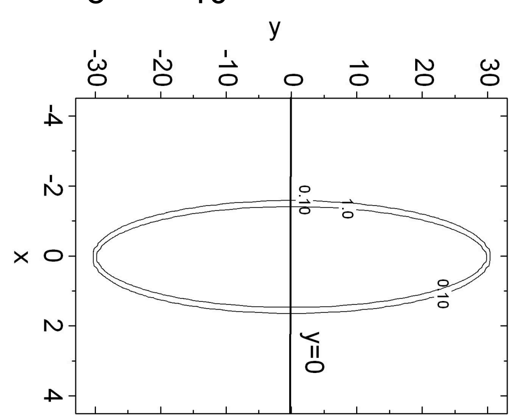
I. Kaganovich, et al, PRL **99**, 235002 (2007).

Applied magnetic field affects self-electromagnetic fields when $\omega_{ce}/\omega_{pe} > V_b/c$

Note increase of fields with applied magnetic field B_{z0}

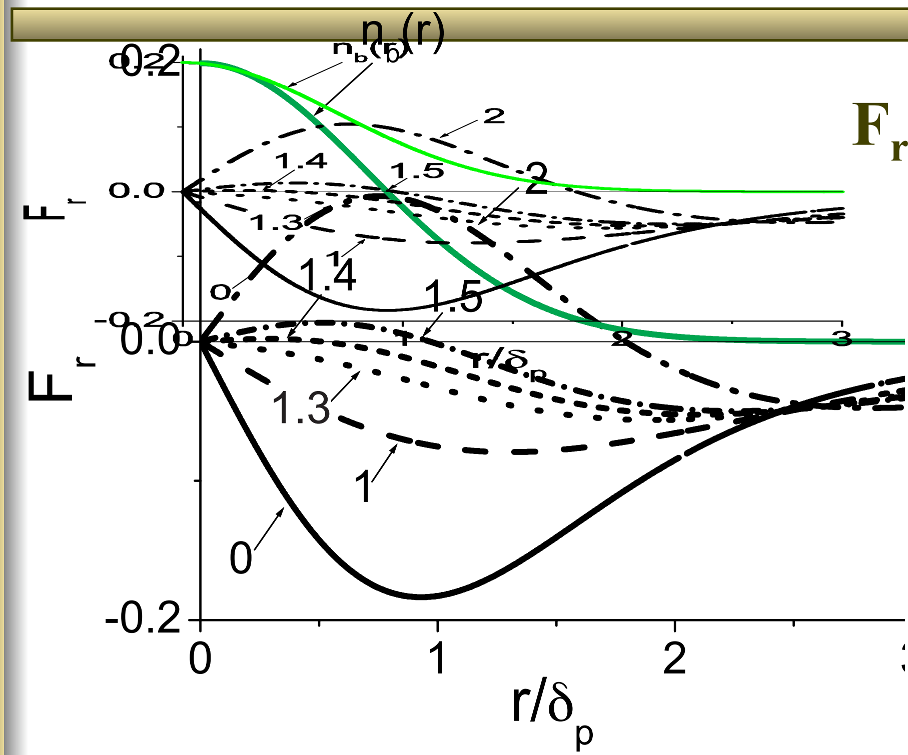




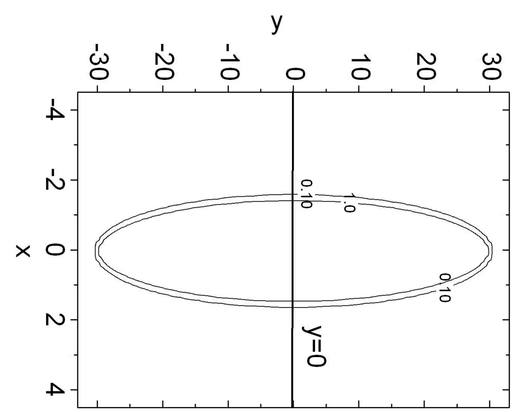


The self-magnetic field; perturbation in the solenoidal magnetic field; and the radial electric field in a perpendicular slice of the beam pulse. The beam parameters are (a) $n_{b0} = n_p/2 = 1.2 \times 10^{11} cm^{-3}$; $V_b = 0.33c$, the beam density profile is gaussian. The values of the applied solenoidal magnetic field, B_{z0} are: (b) 300*G;* and (e) 900*G* corresponds to $c\omega_{ce}/V_b \omega_{pe}$= (b) 0.57 ; and (e) 1.7.

Application of the solenoidal magnetic field allows control of the radial force acting on the beam ions.



$$F_r = e(E_r - V_b B_\varphi / c),$$



Normalized radial force acting on beam ions in plasma for different values of $(\omega_{ce} / \omega_{pe} \beta_b)^2$. The green line shows a gaussian density profile. $r_b = 1.5\delta_p$; $\delta_p = c/\omega_{pe}$.

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

Plasma response to the beam is drastically different depending on $\omega_{ce}/2\beta_b\omega_{pe}$ <1 or >1

Gaussian beam:
r_b=2c/ω_{pe}, l_b=5r_b,
β_b =0.33.

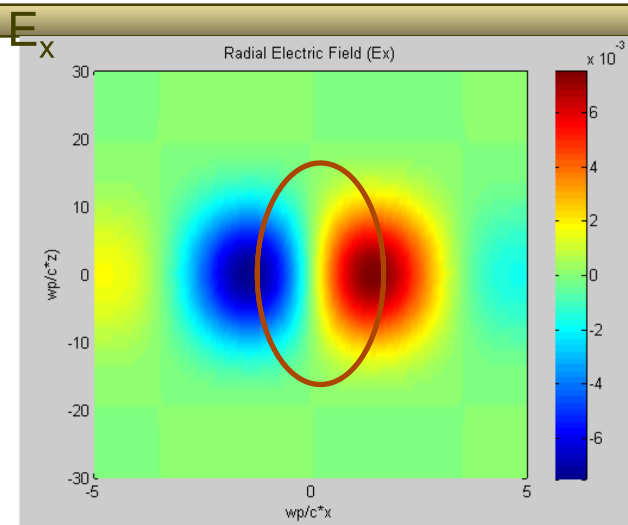
Brown line indicate the ion beam pulse.

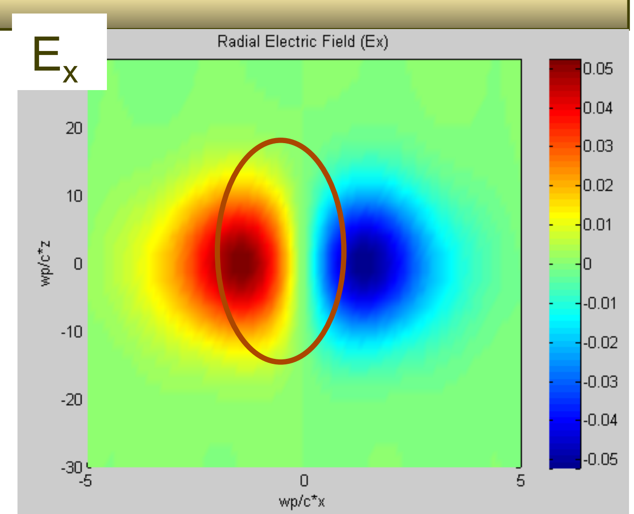
$\omega_{ce}/2\beta_b\omega_{pe}$

Left: 0.5

Right: 4.5

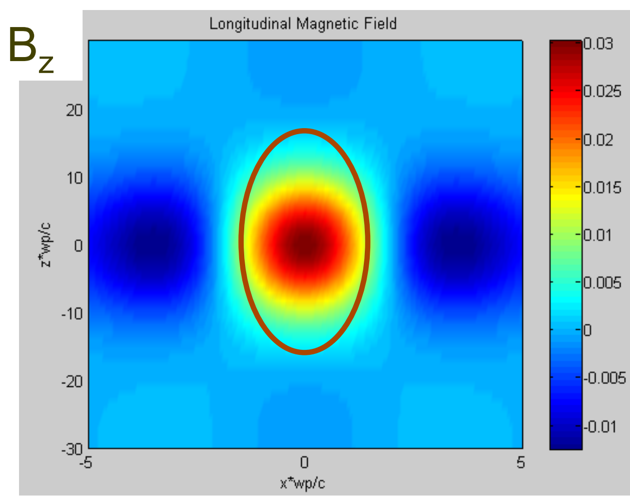
M. Dorf, et al, to be submitted PoP (2009).

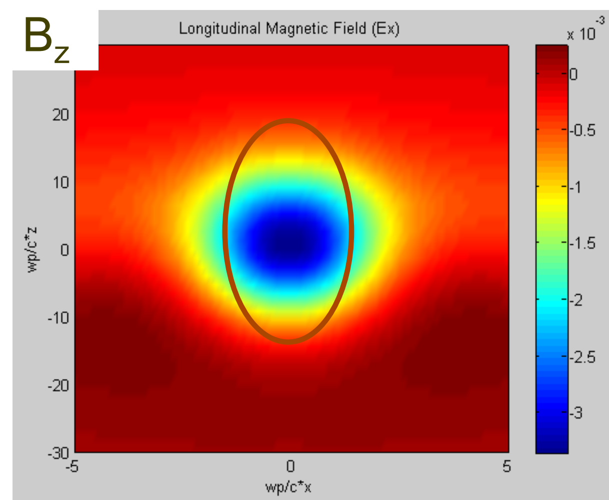




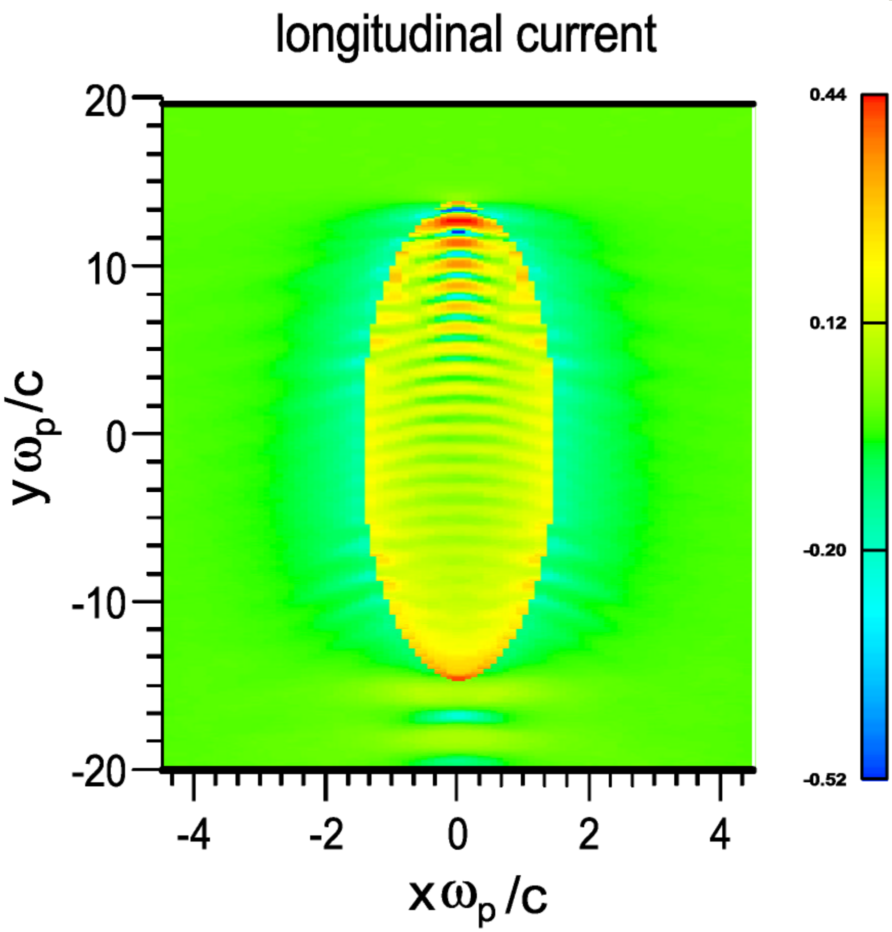
Electrostatic field is defocusing
The response is paramagnetic

Electrostatic field is focusing
The response is diamagnetic

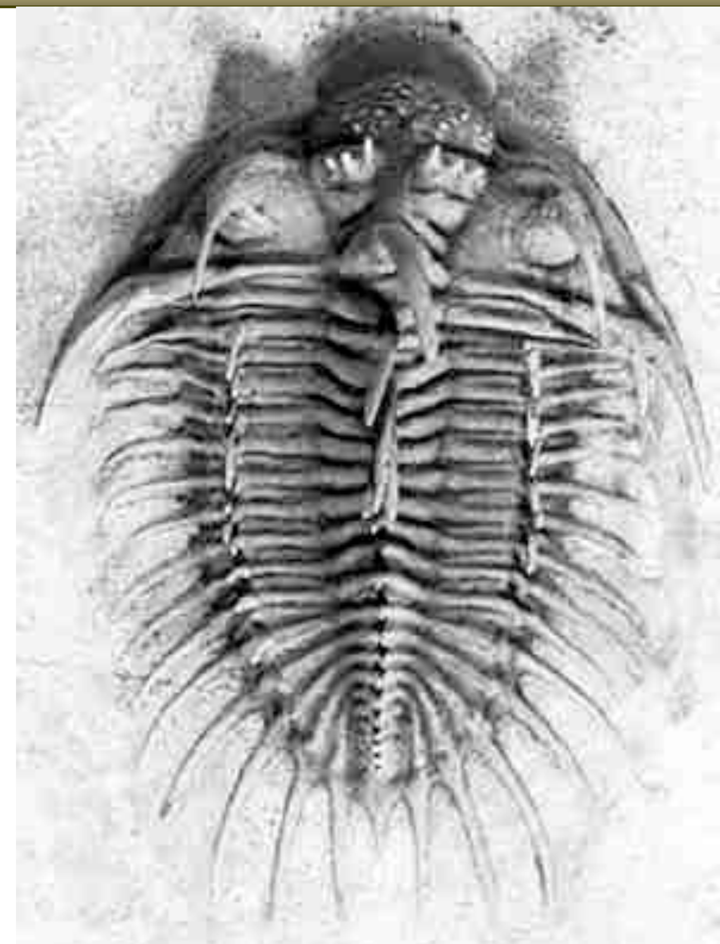




Excitation of plasma waves by the short rise in the beam head.



normalized electron current $j_y/(ecn_p)$

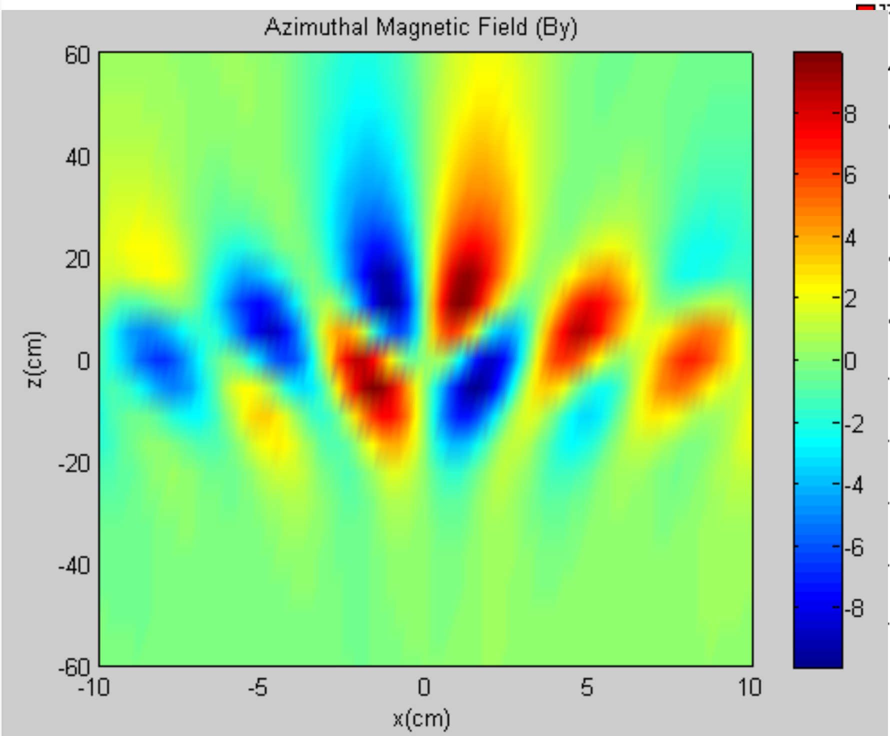


http://www.trilobites.com

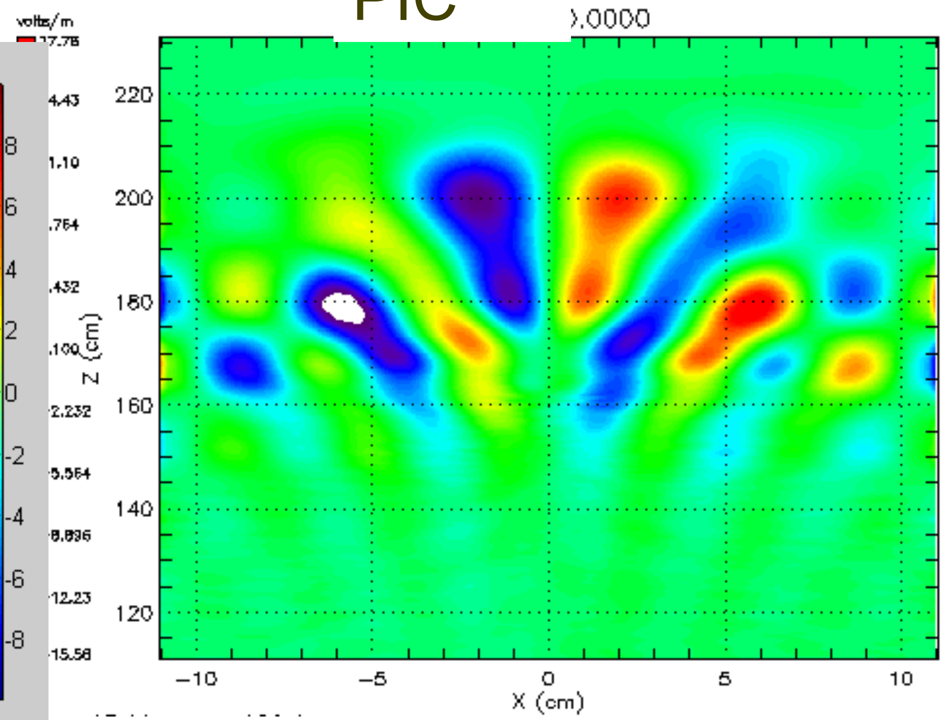
Beam pulse can excite whistler waves.

Gaussian beam with $\beta=0.33$, $l_b=17r_b$, $r_b=\omega_p/c$ $n_b=0.05n_p$, $\omega_{ce}/2\beta_b\,\omega_{pe}=1.37$

Analytical theory



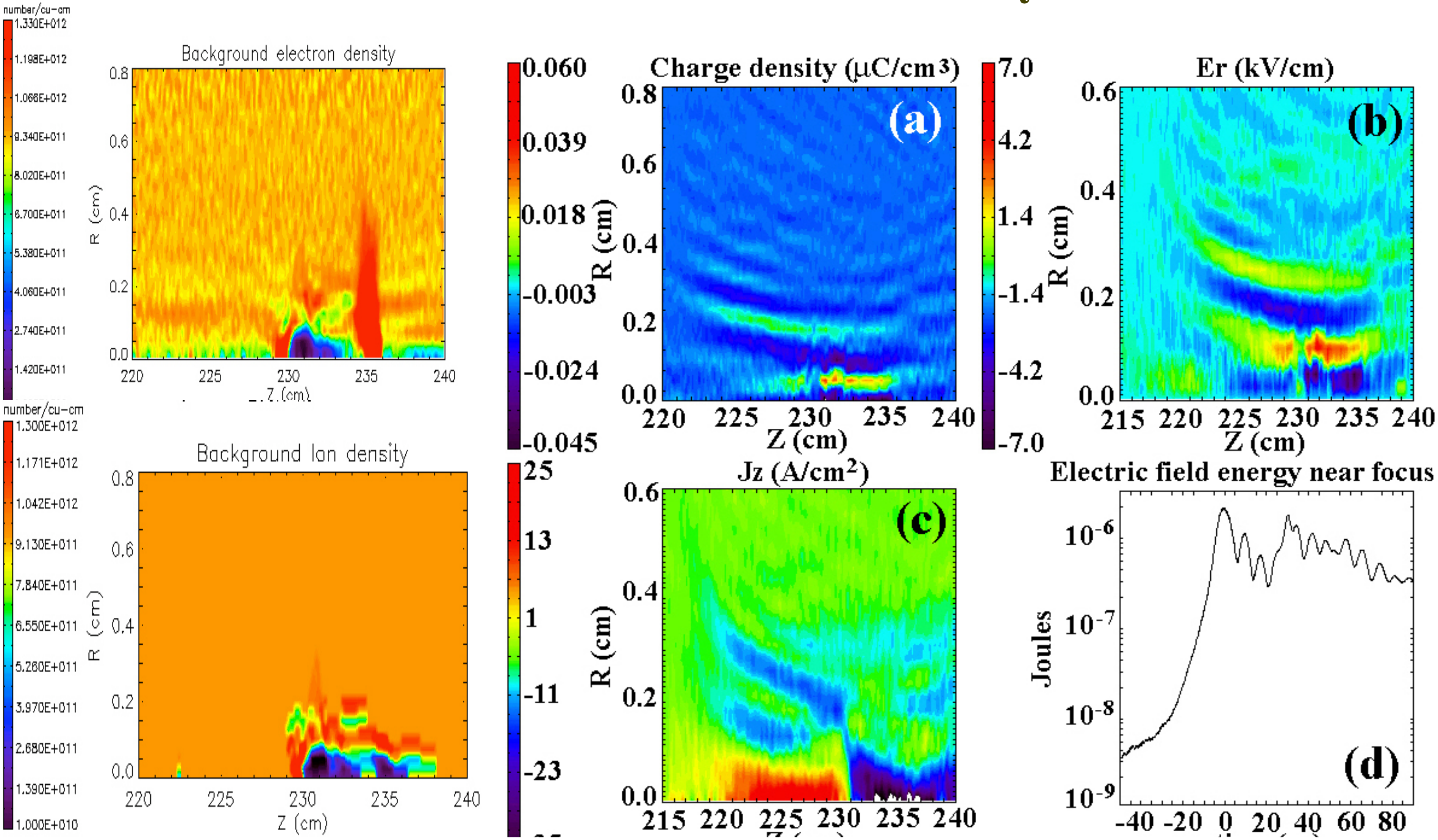
PIC



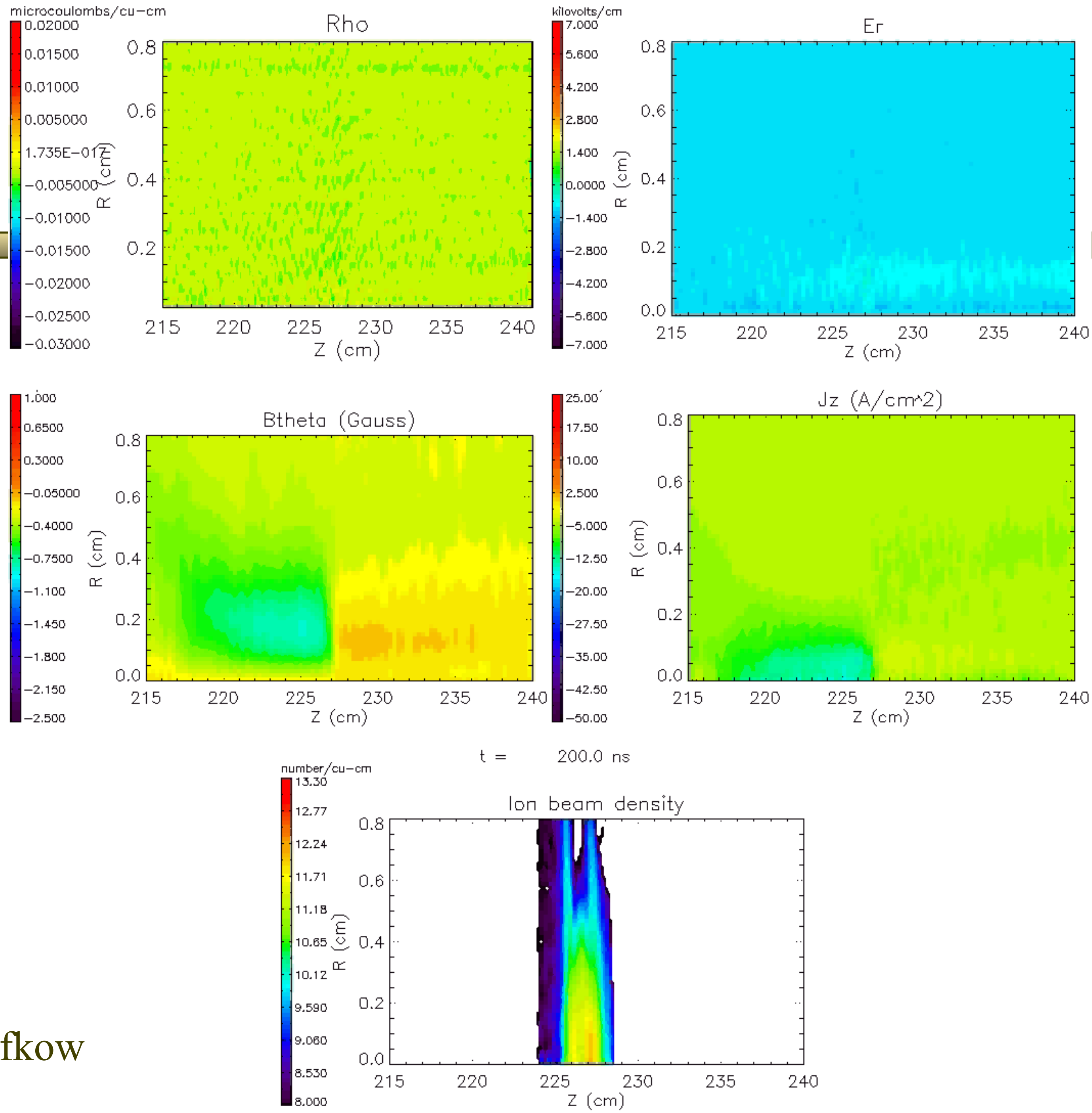
Courtesy of J. Pennington and M. Dorf

During rapid compression at focal plane the beam can excite lower-hybrid waves if the beam density is less than the plasma density.

Courtesy of A. Sefkow



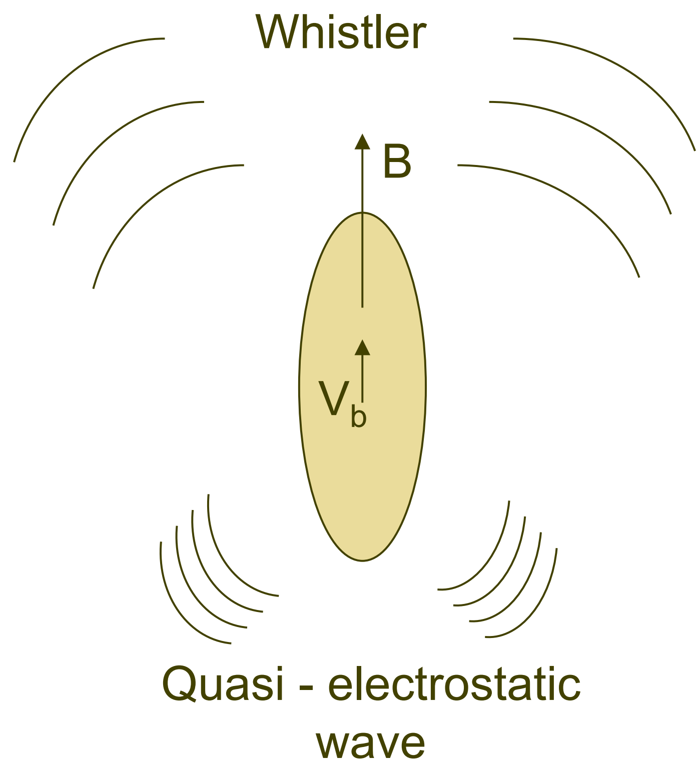
Movies



Courtesy of A. Sefkow

Complicated electrodynamics of beam-plasma interaction would make J. Maxwell proud!

Artist: E.P. Gilson 2008



Conclusions for simultaneous longitudinal and transverse neutralized compression

Identified limiting factors:

errors in the applied velocity tilt compared to the ideal velocity tilt limits the longitudinal compression to 50-100 times.

radial compression is limited by chromatic effects in the focusing system which can be corrected by time-dependent focusing element.

the background plasma can provide the necessary neutralization for compression, provided the plasma density exceeds the beam density everywhere along the beam path, i.e., $n_p > n_b$.

Conclusions for neutralization

Developed a nonlinear theory for the quasi-steady-state propagation of an intense ion beam pulse in a background plasma

- very good charge neutralization: key parameter $\omega_p l_b/V_b$,
- very good current neutralization: key parameter $\omega_p r_b/c$.

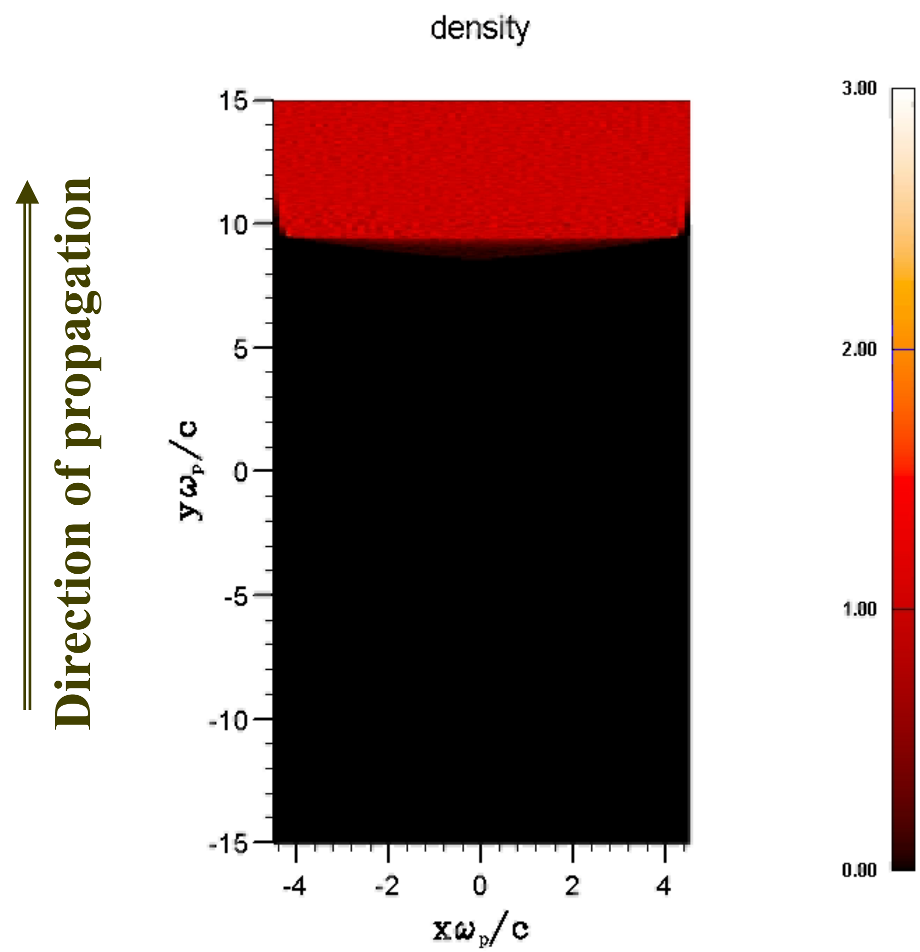
Application of a solenoidal magnetic field can be used for active control of beam transport through a background plasma.

- Theory predicts that there is a sizable enhancement of the self-electric and self-magnetic fields where $\omega_{ce} \sim \beta\omega_{pe}$.
- Electromagnetic waves are generated oblique to the direction of the beam propagation where $\omega_{ce} > \beta\omega_{pe}$.

Results of neutralization from 2D PIC Code

Shown are electron density.

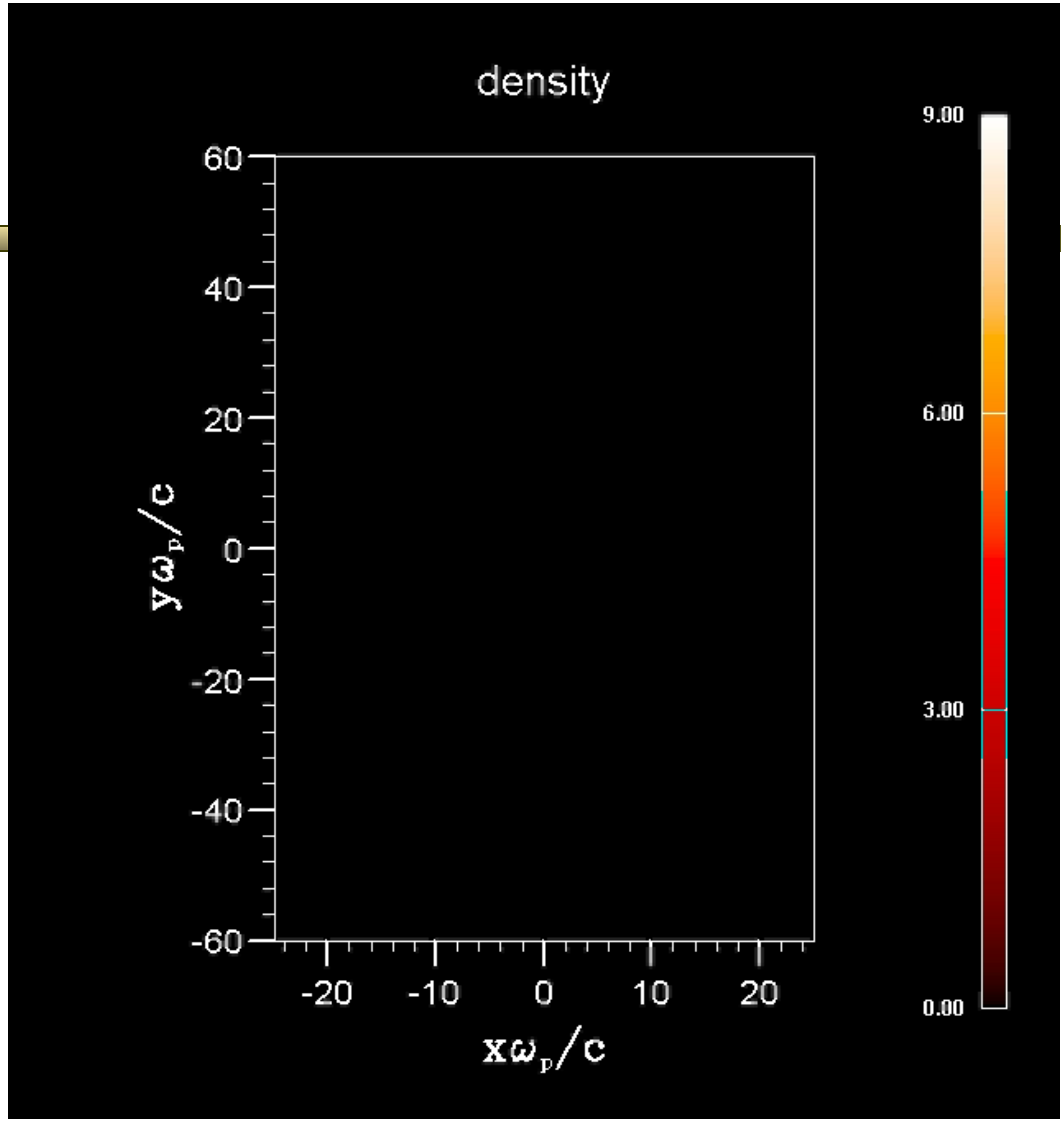
Beam propagation in the y-direction,
beam length 7.5 c/ω_p;
beam radius 1.5 c/ω_p;
beam density equals to the half of the plasma density;
beam velocity $c/2$.



beam length 30. c/ω_p; beam radius 0.5 c/ω_p;

•beam density is 5 of plasma density;

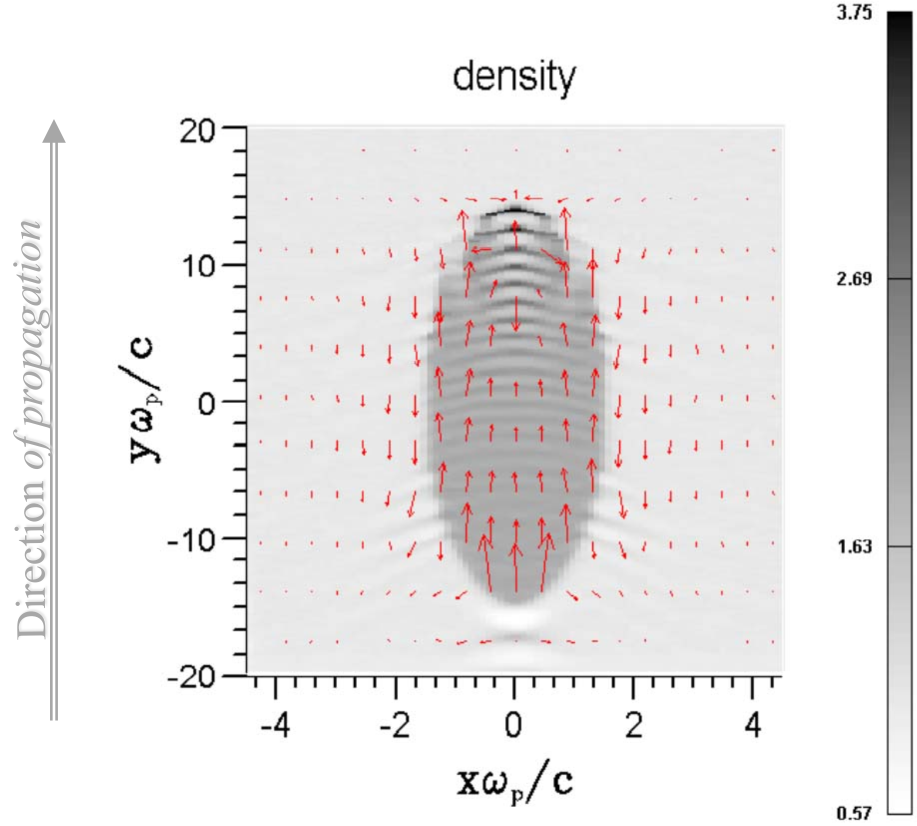
•beam velocity 0.5c.



Steady- State Results (current flow)

Beam propagates in the y-direction,
beam half length l_b=15 c/ω_p ;
beam radius r_b =1.5 c/ω_p ;
beam density n_b is equal to the background plasma density n_p;
beam velocity V_b=$c/2$.

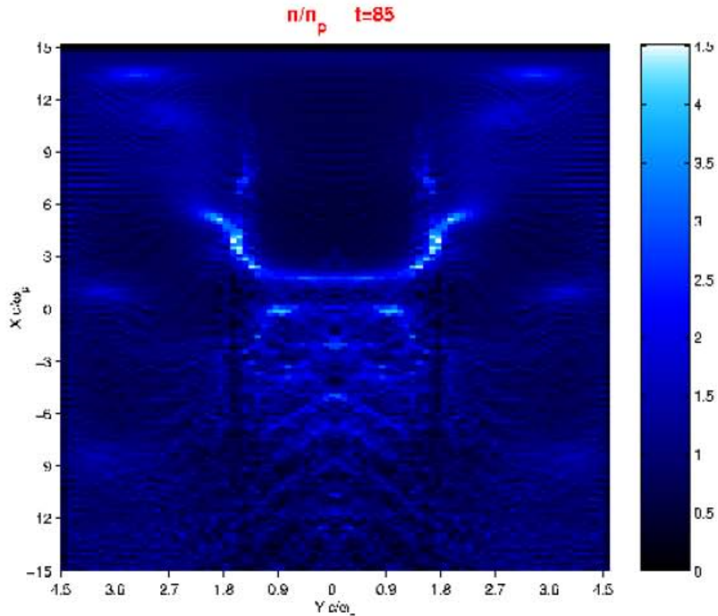
Shown are the normalized electron density n_e/n_p and the vector fields for the current.

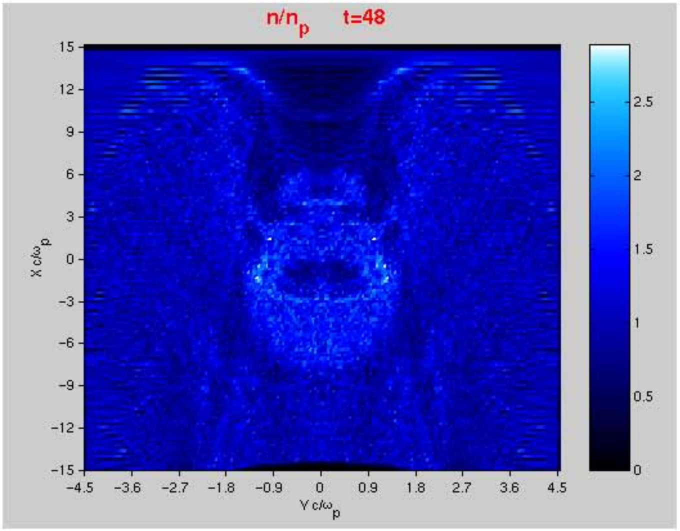


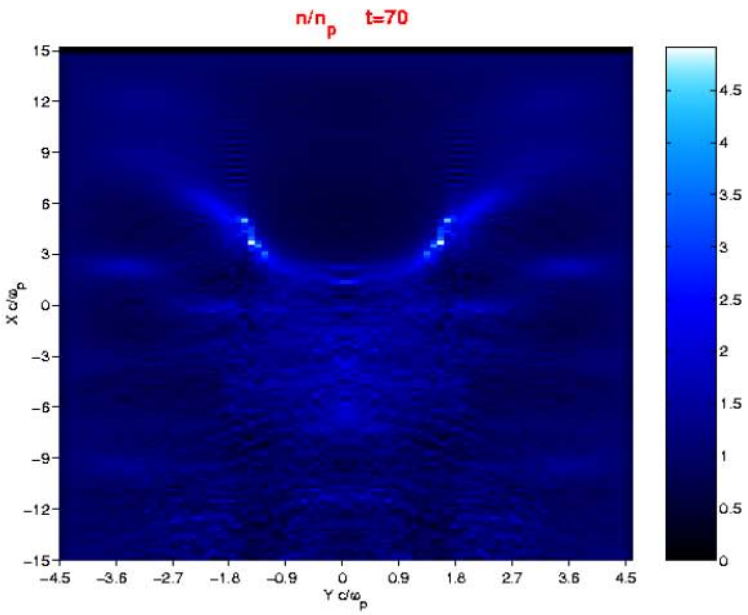
FOR MORE INFO...

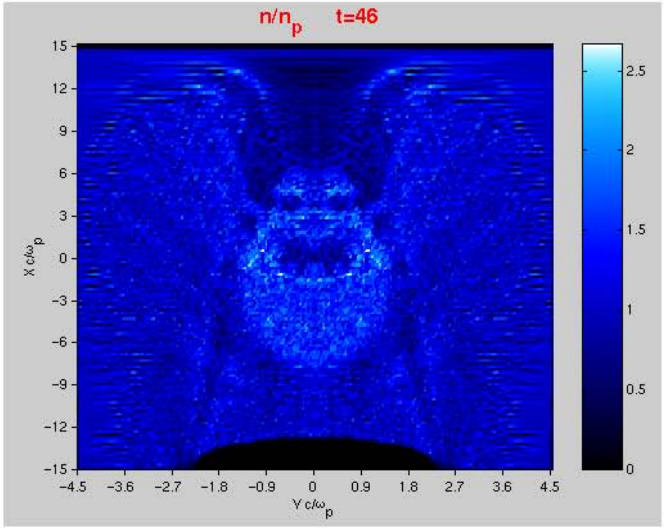
http://hifnews.lbl.gov/hifweb08.html

Beam Propagates Along Magnetic Field.









Comparison of Theory and Simulation: Electron Density

Key parameter $\omega_p l_b/V_b$,

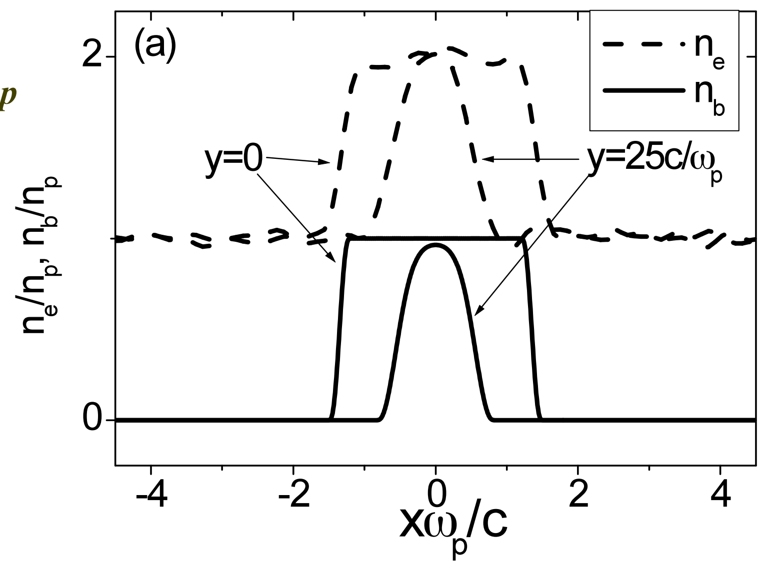
Quasineutrality $l_b >> V_b / \omega_p$.

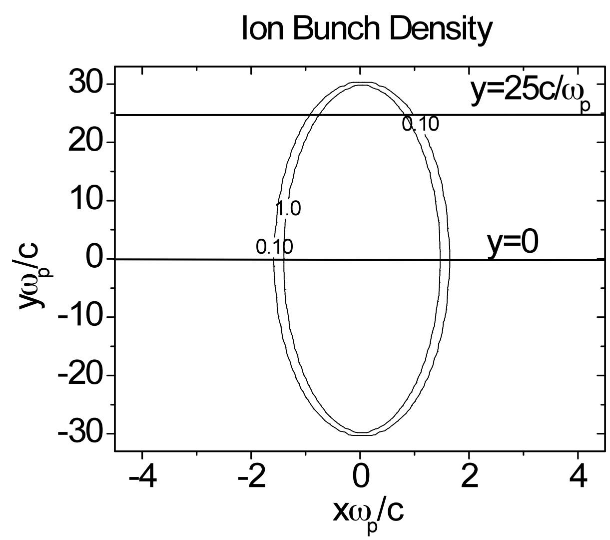
$l_b = 30c/\omega_p$

$r_b = 1.5c/\omega_p$

$n_p = n_b$

$V_b = 0.5c$





Comparison of Theory and Simulation: Magnetic Field

Key parameter $\omega_p r_b/c$,

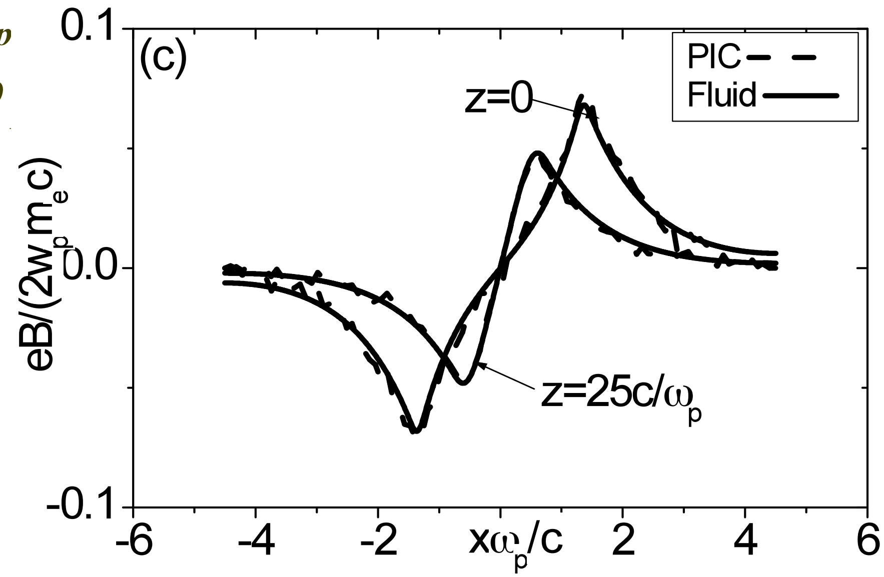
Magnetic field neutralization $r_b >> c/\omega_p$.

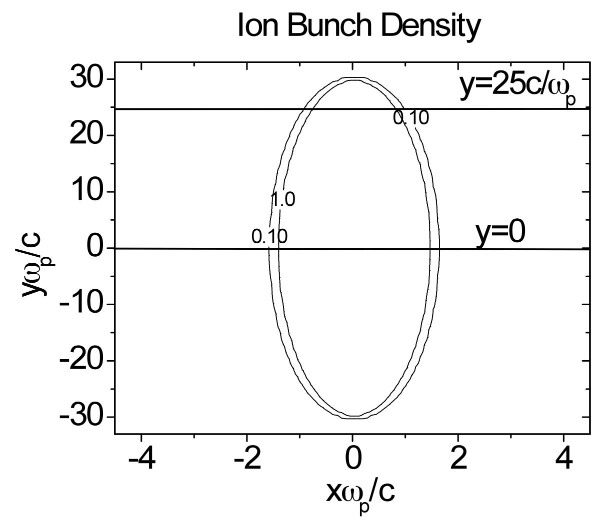
$l_b = 30c/\omega_p$

$r_b = 1.5c/\omega$

$n_p = n_b$

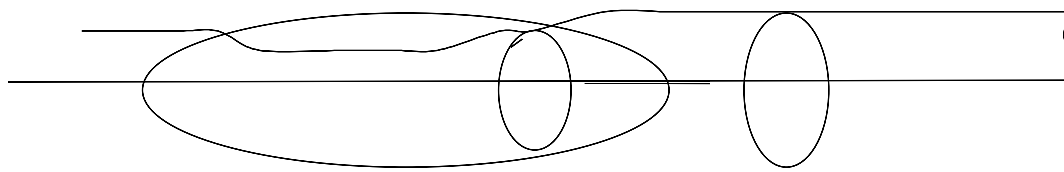
$V_b = 0.5c$





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

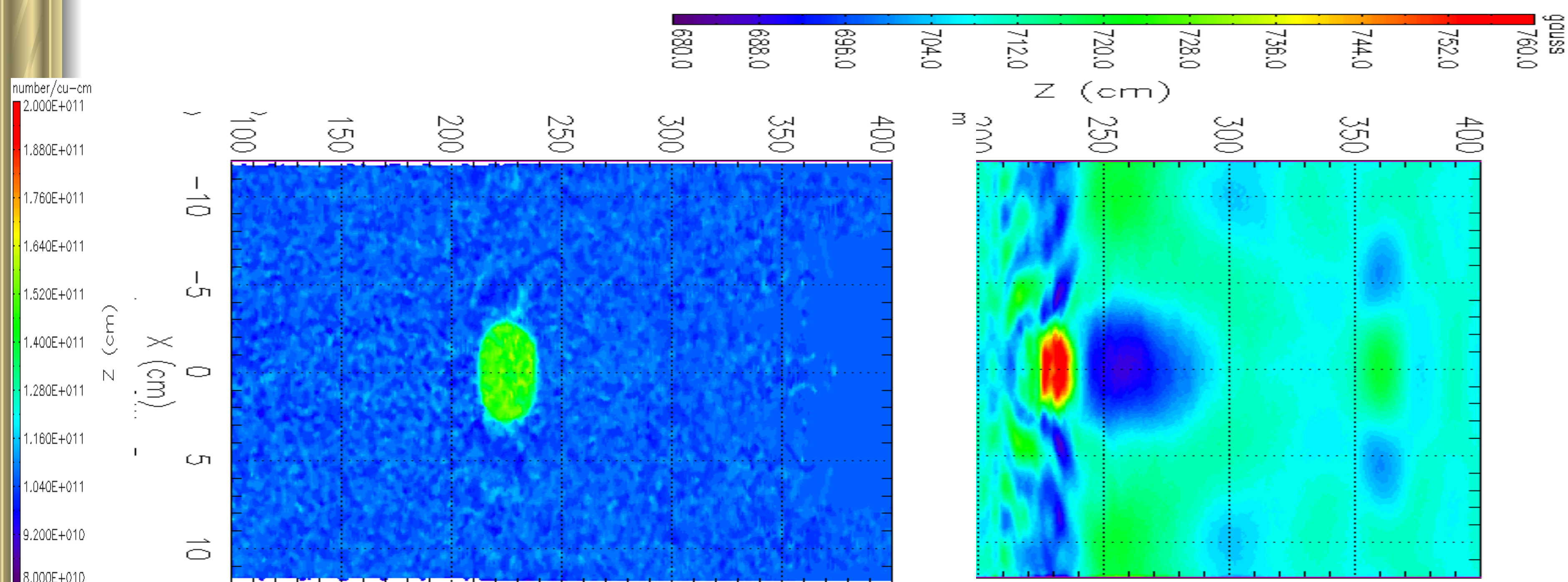
Plasma acts as a paramagnetic medium inside the ion beam pulse due to induced electron rotation!



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

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

Color plot of Beam density and B_z



Comparison of Theory and Simulation: Electron Density

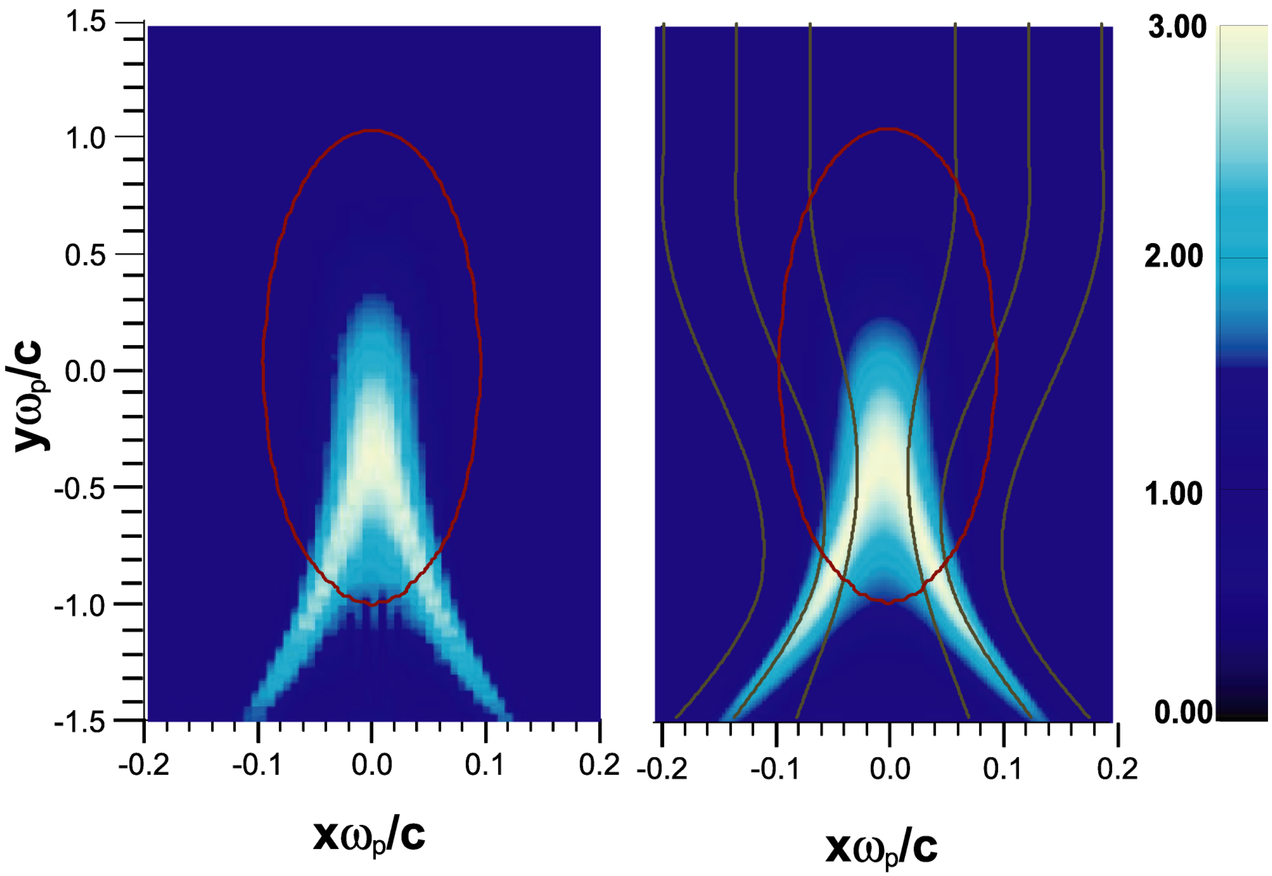
Electron density
Left – PIC,
Right - fluid

l_b *=1c/ω* $_{p,}$ r_b *=0.1c/ω* $_p$

n_b*=0.5*n_p *,* V_b*=0.5c*

Brown lines: electron trajectory in the beam frame.

Red line: ion beam size.



FOR MORE INFO...

I. Kaganovich e*t.al*, http://p
TPPH317.pdf