Neutralization of Ion Beams Propagating Along a Solenoidal Magnetic Field Through a Background Plasma

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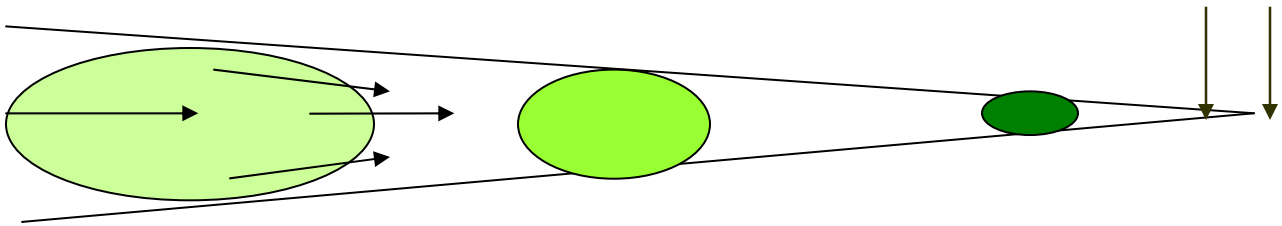
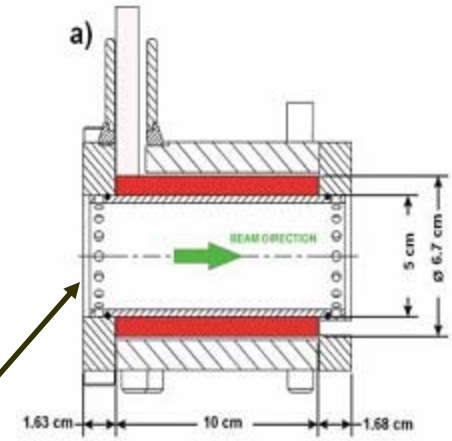
Motivation

- **Practical: what plasma source we need for 10000 times simultaneous neutralized drift compression.**

- **Theoretical: basic problem absent in textbooks. Solid foundation instead of phenomelogical (1-f) approach.**

Neutralized drift compression can reach 300x300 = 10^5 combined longitudinal and transverse compression



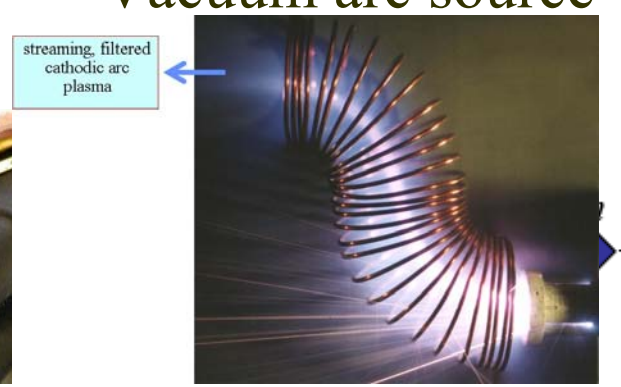


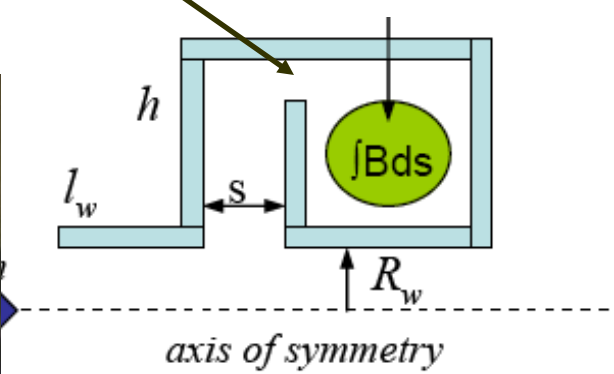
Radial velocity tilt is applied by magnetic lenses

Longitudinal velocity tilt – by inductive tilt core

Ferroelectric plasma source

Vacuum arc source





Outline

- **Neutralization of an ion beam by a plasma.**
  - **Self- electric and self-magnetic fields of an ion beam pulse propagating in a background plasma with and without B.**
  - **Control of self-electric and self-magnetic field by applying a small solenoidal magnetic field.**
  - **Excitation of whistler/helicon waves.**

Outline

- **Neutralization of an ion beam by a plasma.**
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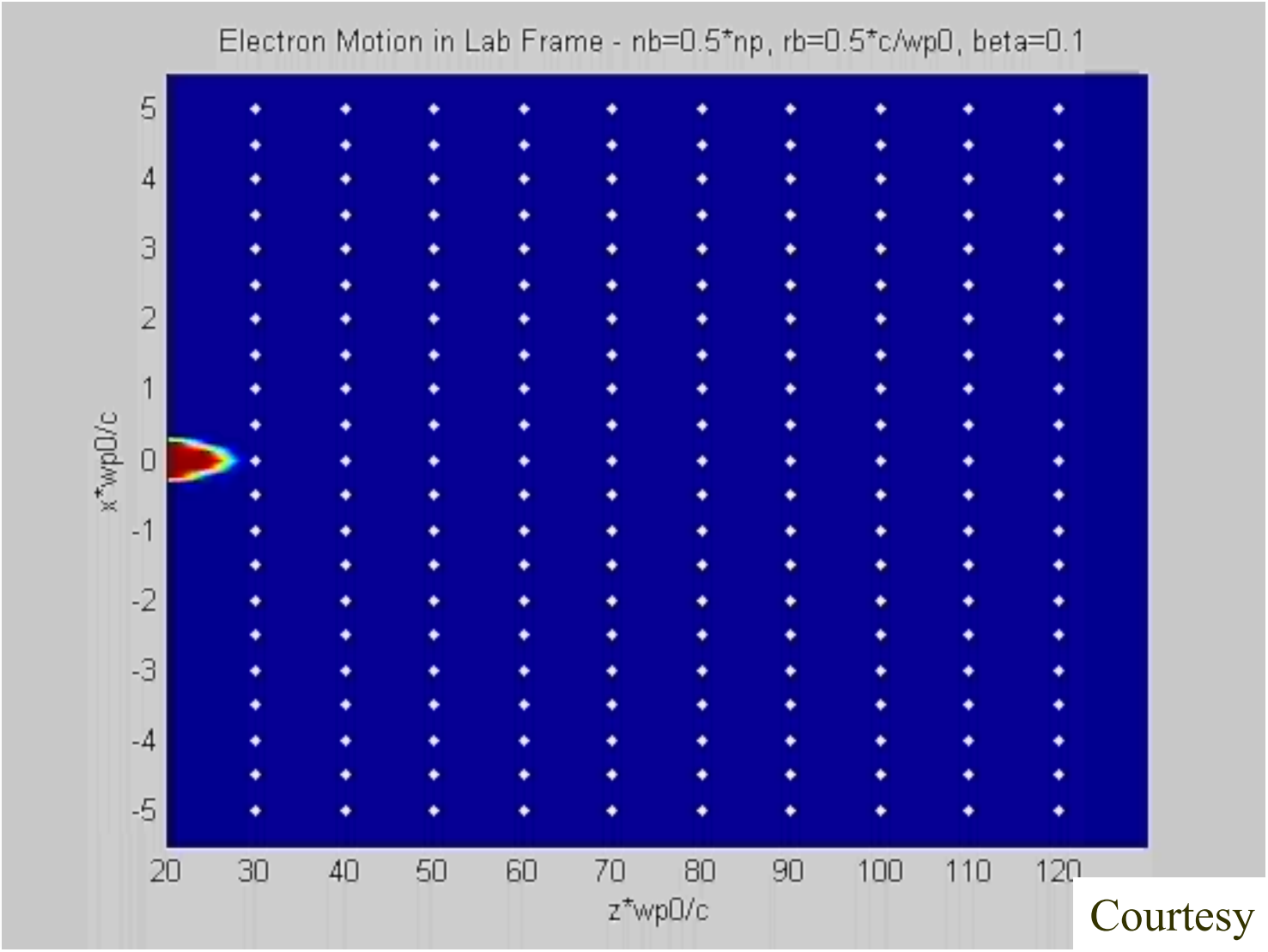
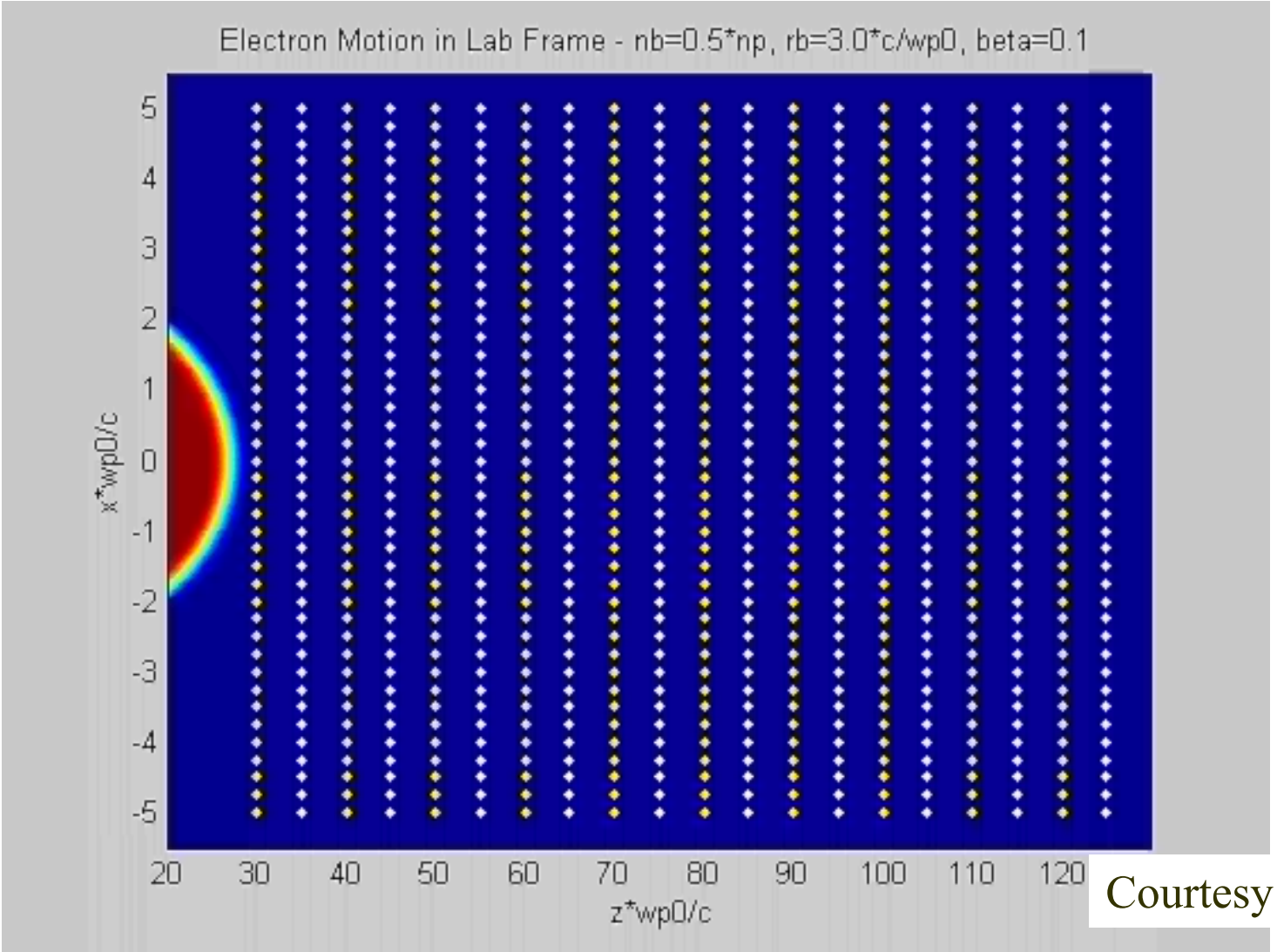
  - Excitation of whistler/helicon waves.

Visualization of Electron Response on an Ion Beam Pulse (thin beam)



Courtesy of B. C. Lyons

Visualization of Electron Response on an Ion Beam Pulse (thick beam)



Courtesy of B. C. Lyons

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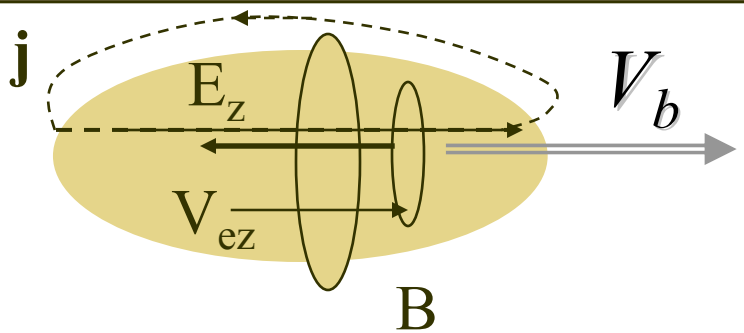
Current Neutralization



$$\frac{\partial \int B ds}{\partial t} => E_z$$

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

For long beams canonical momentum is conserved** $mV_{ez} = \frac{e}{c} A_z$

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

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

* 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

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

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

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

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

NTX K^+ 400keV beam φ_b***~100V***

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

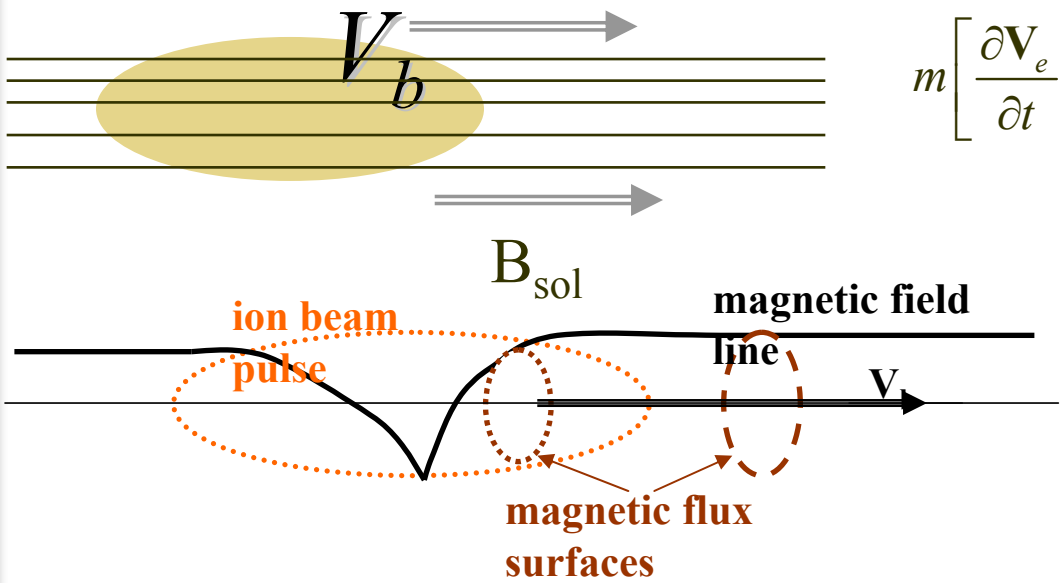
Degree of neutralization

Having $n_b << n_p$ strongly increases the neutralization degree.

Outline

- **Neutralization of an ion beam by a plasma.**
  - Self- electric and self-magnetic fields of an ion beam pulse propagating in a background plasma without B.
  - **Self- electric and self-magnetic fields of an ion beam pulse propagating in a background plasma in presence of applied solenoidal magnetic field.**

Influence of magnetic field on beam neutralization by a background plasma



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

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

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

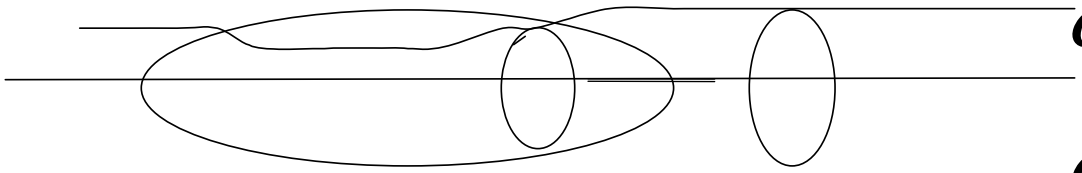
$$E_r \sim \frac{1}{c} V_{e\phi} B_{sol}$$

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

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).

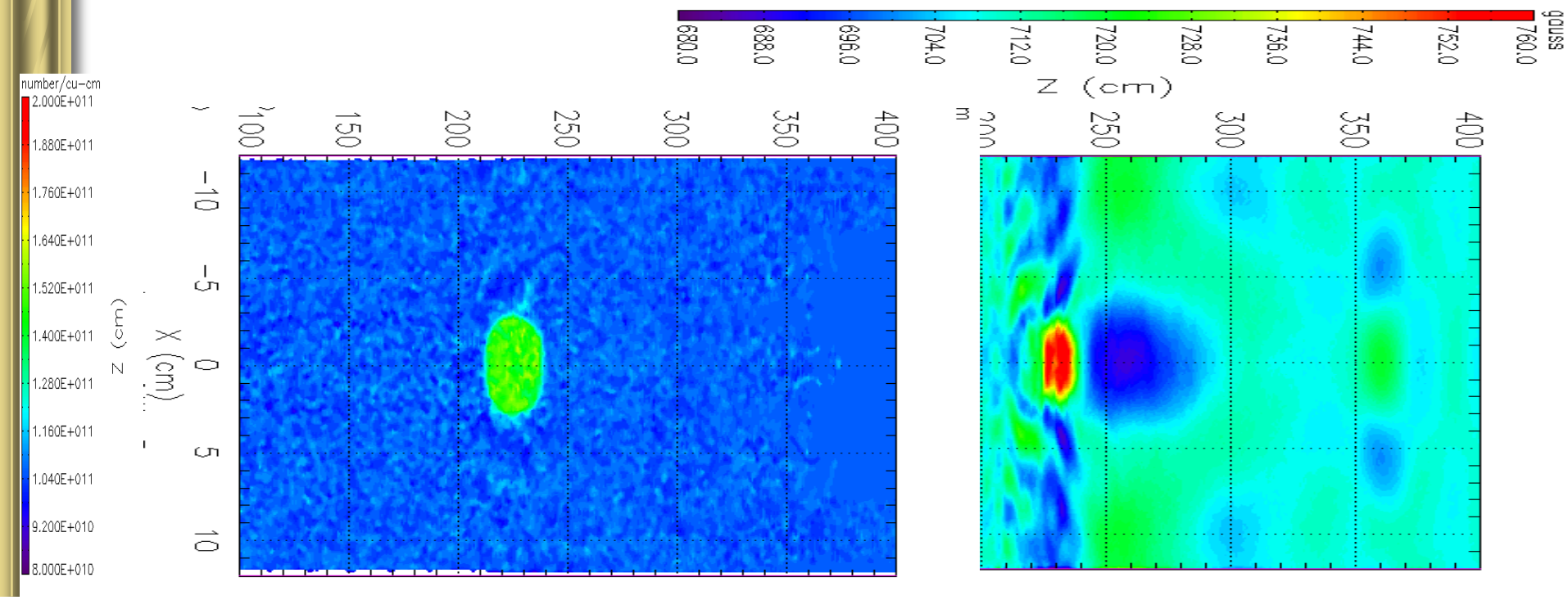
Plasma acts as a paramagnetic medium inside the ion beam pulse due to induced electron rotation!



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

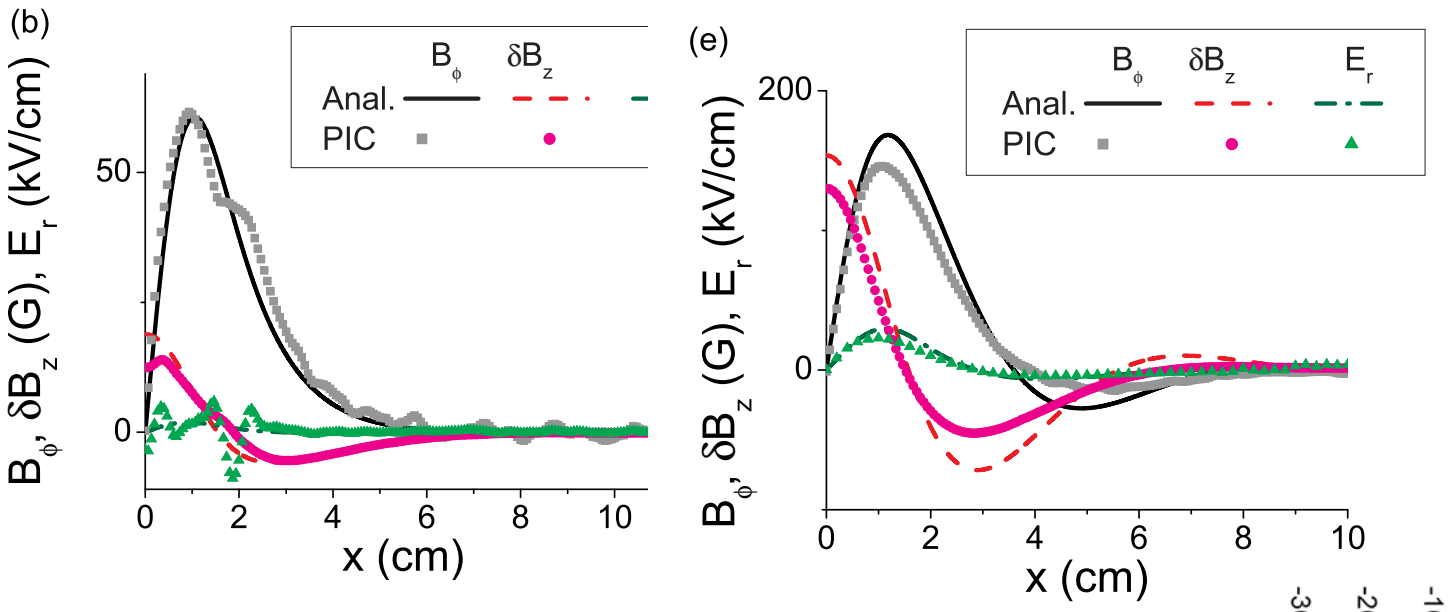
$$\delta B_z \Rightarrow E_\theta \Rightarrow v_\theta$$

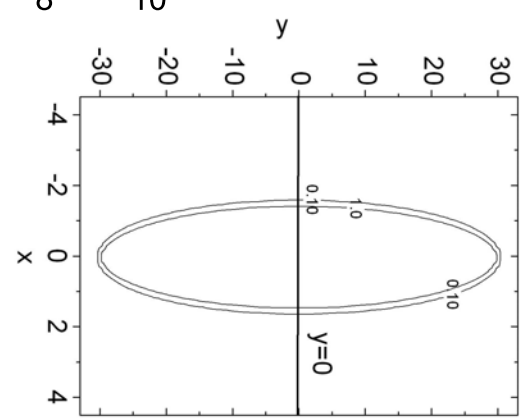
Color plot of Beam density and B_z



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

Note increase of fields with 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.

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

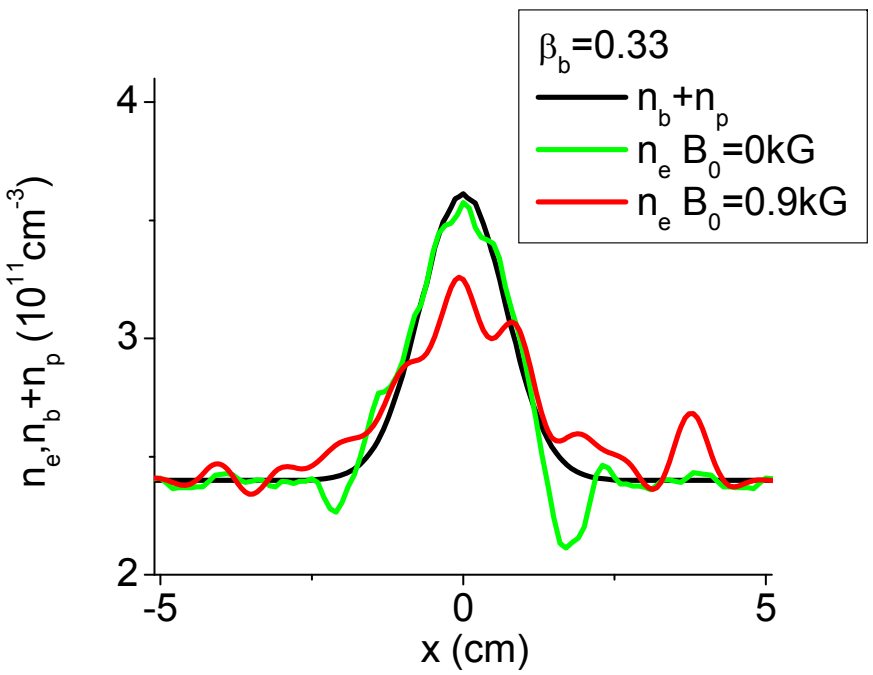
Electron rotation due to radial displacement

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

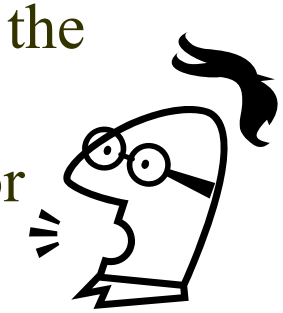
Breaking of the quasi-neutrality condition

- **$E_r \sim (\omega_{ce}/\omega_{pe}\beta_b)^2$.**
- **$dE_r/dr \sim 4\pi e n_b$, when $\omega_{ce} = \omega_{pe}$.**
  - Consistent with the plasma contribution into dielectric constant being comparable with the contribution by the displacement current.

$$\varepsilon_\perp = 1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2}$$



Need to account for the electron density perturbation even for $n_p >> n_b$!



Radial profile of the electron density perturbation by the beam. $\omega_{ce} = 0.5\omega_{pe}$ for B=0.9kG

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

Gaussian beam:
$r_b=2c/\omega_{pe}$,
$l_b=5r_b$, $\beta=0.33$

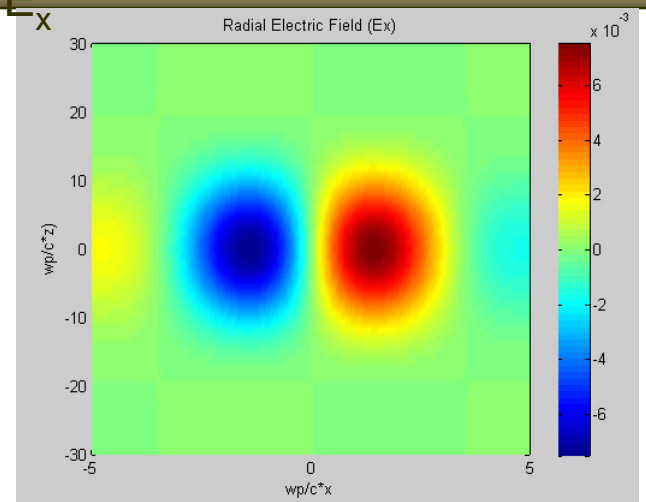
$\omega_{ce}/2\beta\omega_{pe}$

Left: 0.5

Right: 4.5

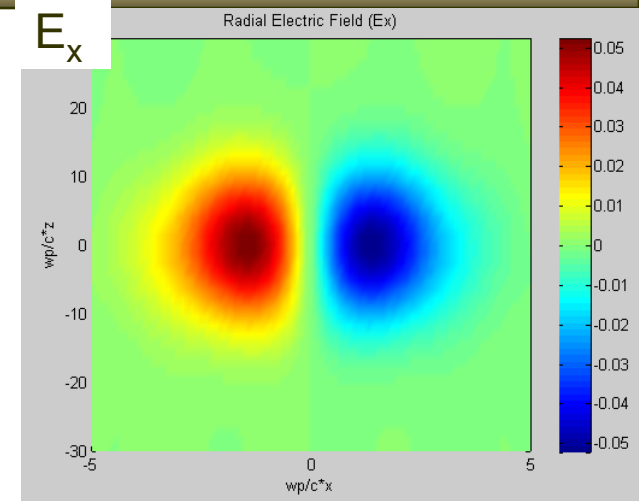
M. Dorf, et al, to be submitted PoP (2008).

E_x



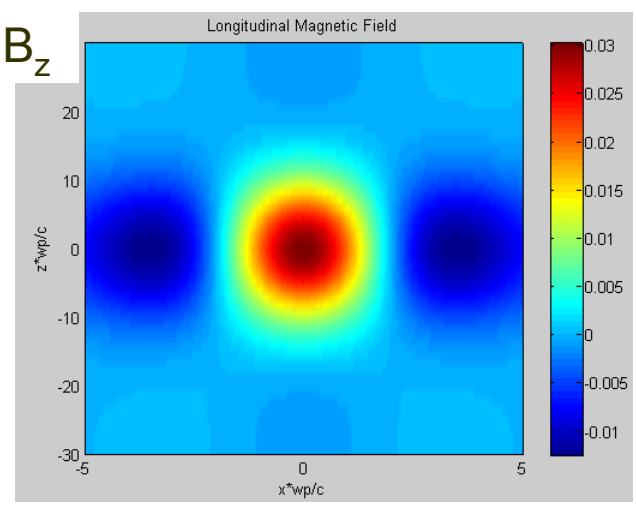
Electrostatic field is defocusing
The response is paramagnetic

E_x

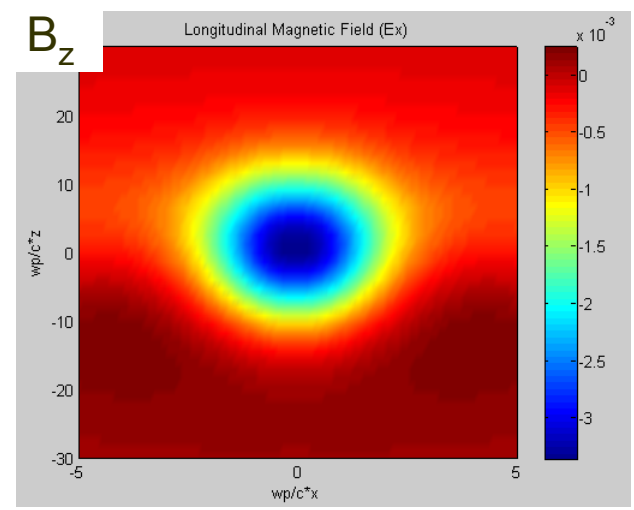


Electrostatic field is focusing
The response is diamagnetic

B_z



B_z



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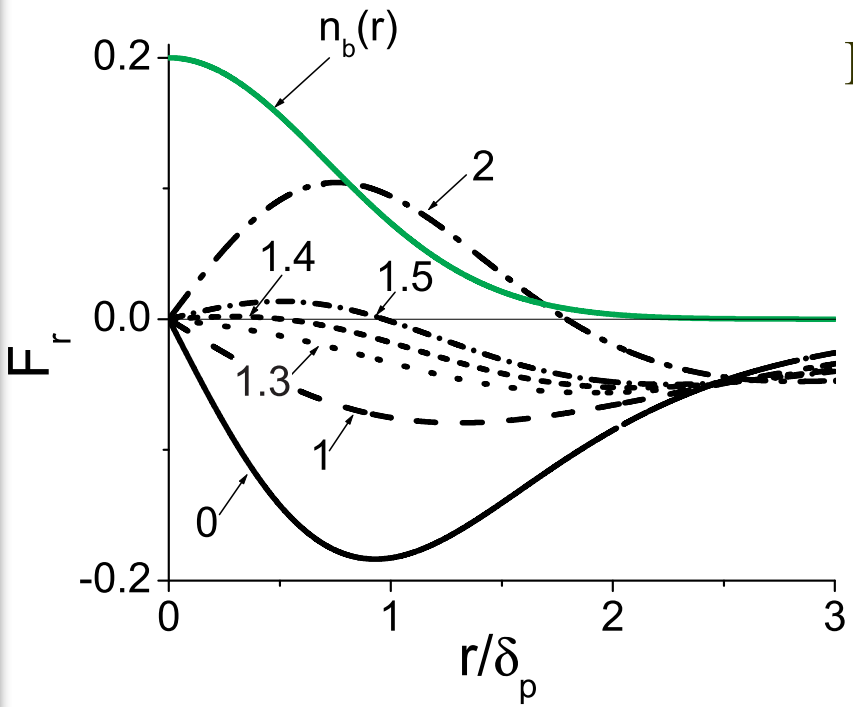
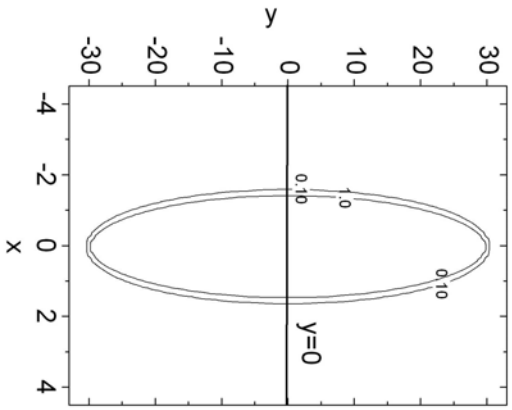
Application of the solenoidal magnetic field allows control of the radial force acting on the beam particles.



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



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).

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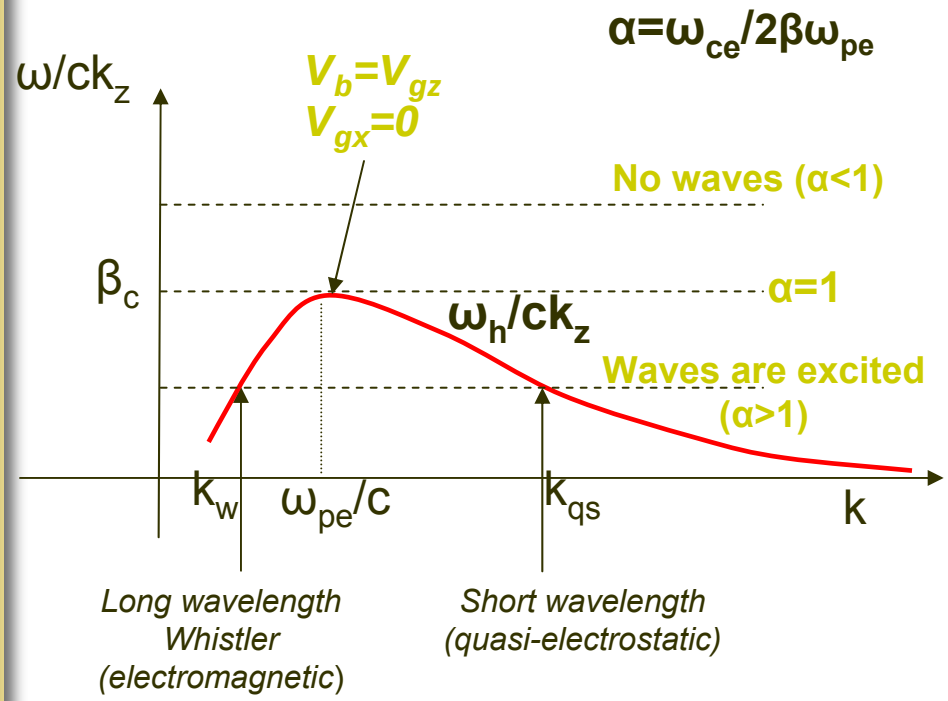
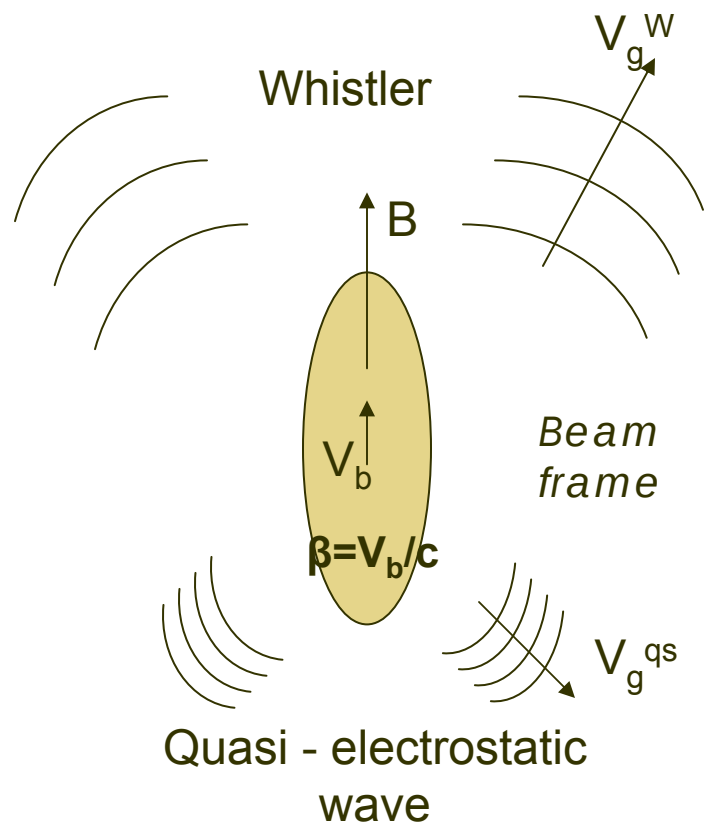
Electromagnetic Field Radiation by a Moving Beam in a Magnetized Plasma

- Beam excites/radiates Helicon (electron) branch $\omega_h = \omega_{ce} k k_z \Big/ \left(k^2 + \frac{\omega_{pe}^2}{c^2} \right)$ *assumed $\omega_{ce} << \omega_{pe}$ for simplicity*



$V_{gz} > V_b$ $\quad$ $V_{gz} < V_b$

$k_z V_{gx} > 0$ $\quad$ $k_z V_{gx} < 0$



Linear Analytical Theory: the Laplace Transform and Landau Contours

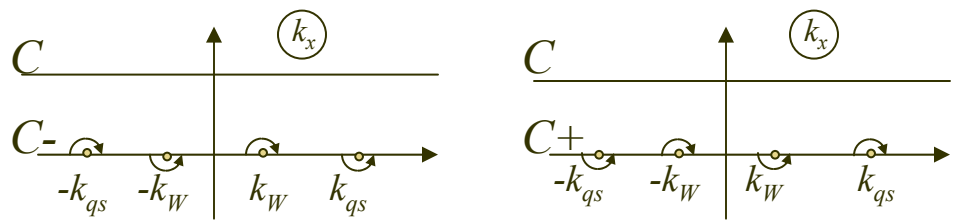
$$B_y = \frac{\omega_{ce}}{\omega_{pe}} \frac{n_p}{n_{b0}} = \int d\omega \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dk_z dk_x \frac{n_k}{(\omega - k_z V_b) D(\omega, k_x, k_z)} e^{-i\omega t + ik_x x + ik_z z}$$

Steady state
$\omega = k_z V_b$

$$\frac{1}{D(k_z V_b, k_x, k_z)} \cong -i\beta \frac{ck_x / \omega_{pe}\left(k_x^2 + \omega_{pe}^2 / c^2\right)}{4\alpha\sqrt{\alpha^2 - 1}} \left[\frac{1}{k_x^2 - k_{qs}^2} - \frac{1}{k_x^2 - k_W^2}\right]$$

$\alpha = 2\beta\omega_{pe}/\omega_{ce}$

Landau contours
(different for k_z>0 and k_z<0)



For a long beam with $n(x,z)=n_z(z)n_x(x)$

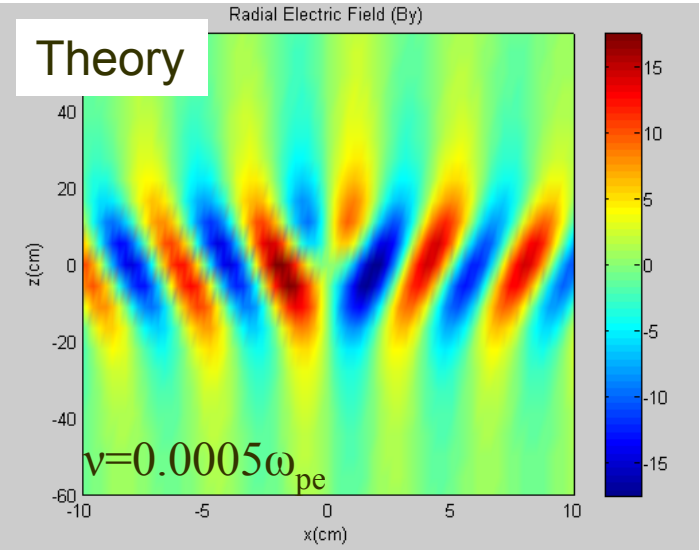
$$B_y = \underbrace{n_z(z)\int_C dk_x n_x(k_x) e^{ik_x x} b_k}_{\text{Local field}} + \underbrace{2\pi i \int_0^{\infty} dk_z n_z(k_z)\{res[-k_{qs}] + res[k_W]\} + 2\pi i \int_0^{\infty} dk_z n_z(k_z)\{res[k_{qs}] + res[-k_W]\}}_{\text{Excited wave field}}$$

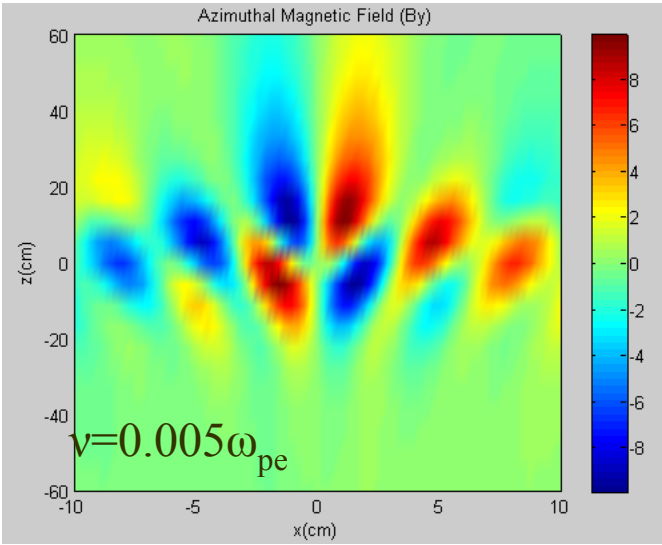
Local field (decays to zero for r>>r_b)

Excited wave field

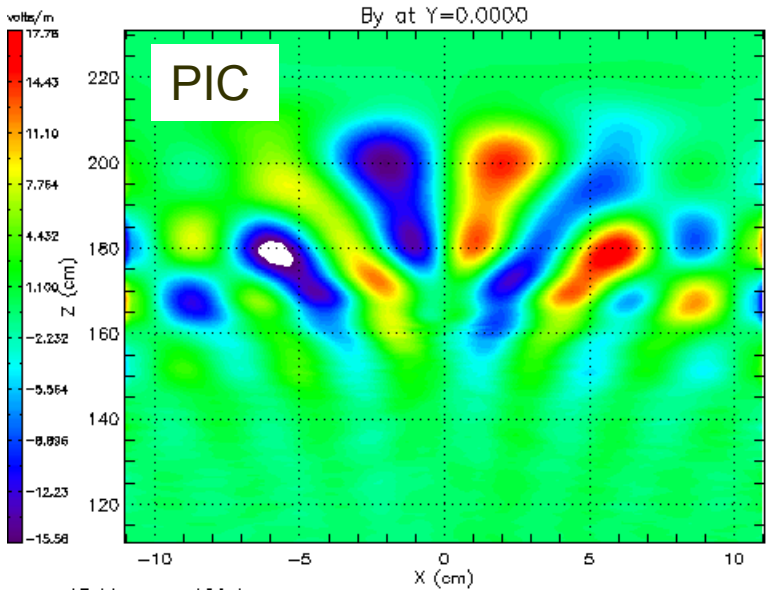
M. Dorf, et al, to be submitted PoP (2008).

Dissipation and numerical noise can modify wave profiles





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



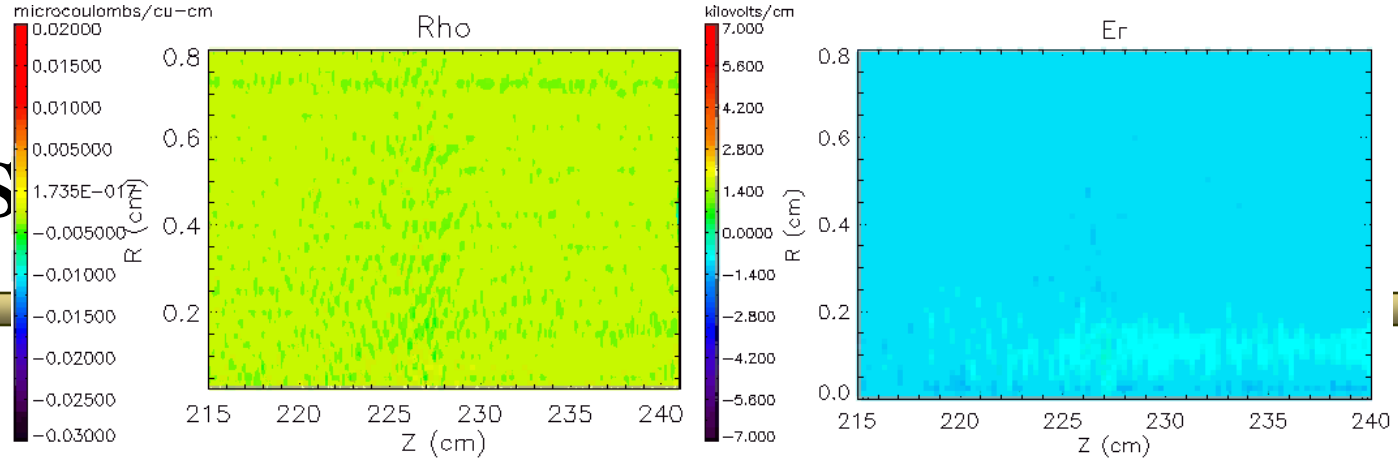
Noise in PIC simulations can lead to artificial damping of waves.

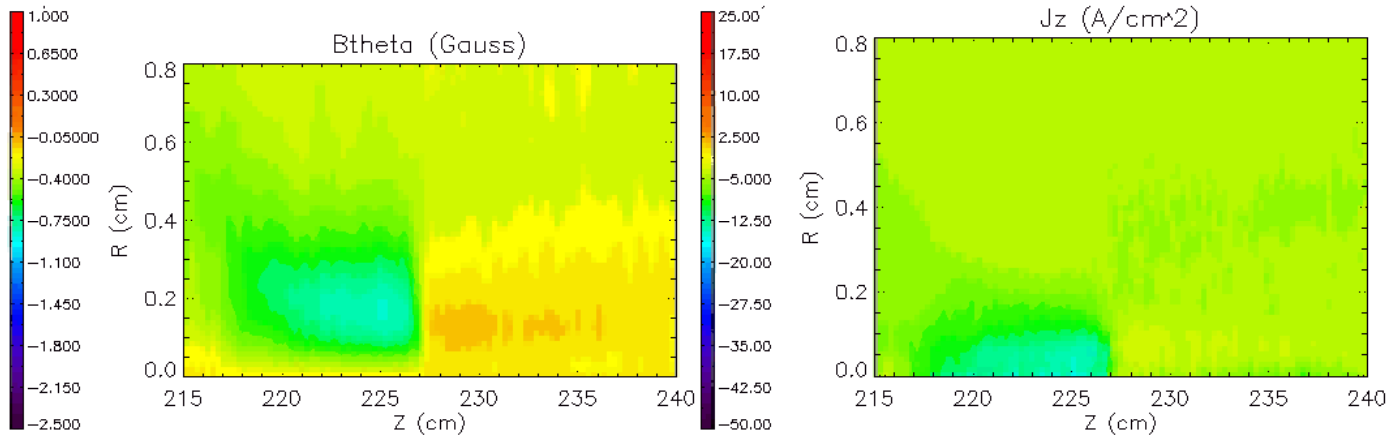
Courtesy of J. Pennington and M. Dorf

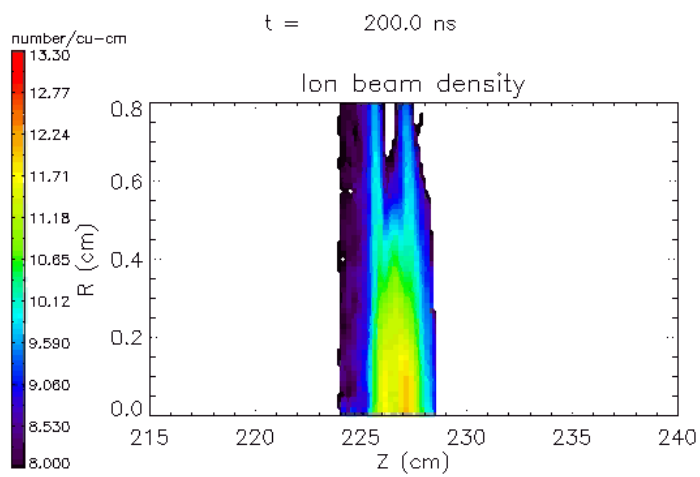
Complicated electrodynamics of beam-plasma interaction would make J. Maxwell proud!

Artist: E.P. Gilson 2008

Movies







Courtesy of A. Sefkow

#25

VOLUME 72, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1994

Whistler Wave Emission by a Modulated Electron Beam

C. Krafft,[1] P. Thévenet,[1] G. Matthieussent,[1] B. Lundin,[2] G. Belmont,[3] B. Lembège,[3] J. Solomon,[3] J. Lavergnat,[3] and T. Lehner[4,*]

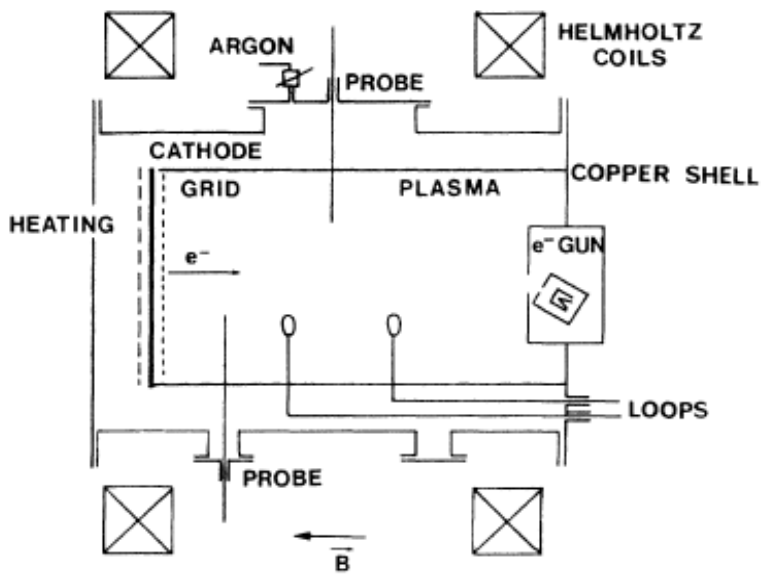


FIG. 2. Experimental setup: plasma production and modulated electron beam injection.

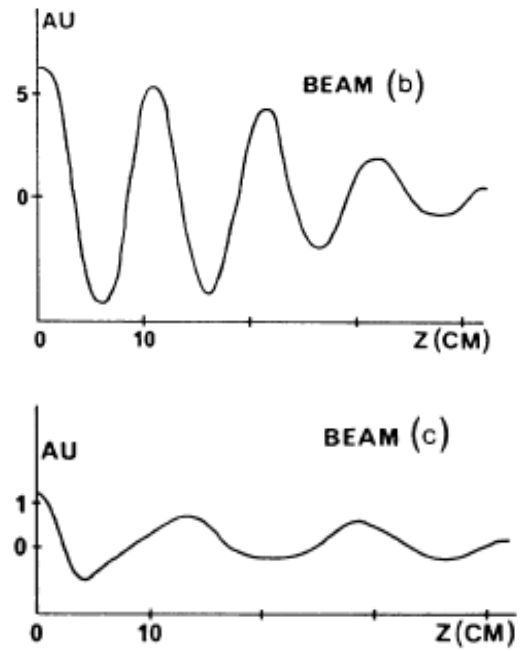
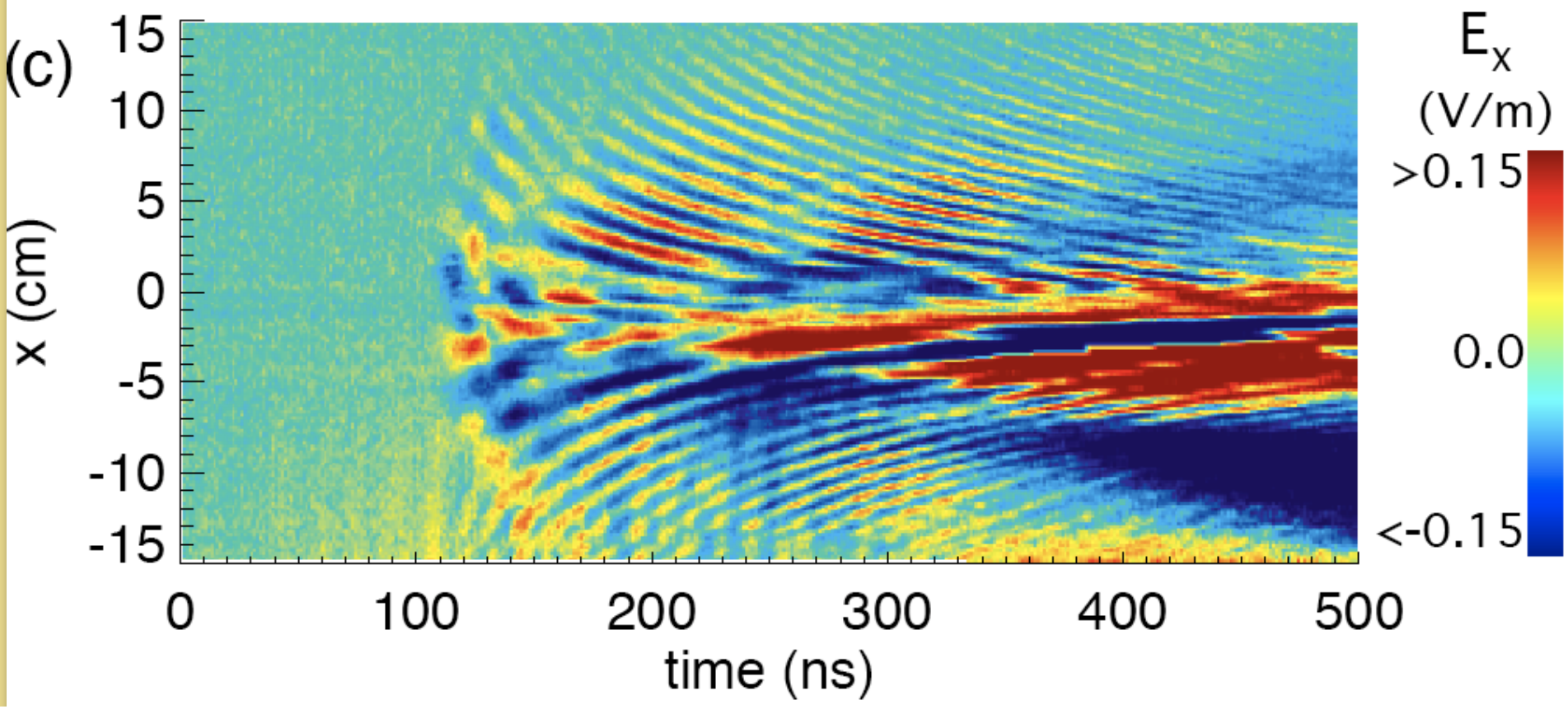


FIG. 4. Excitation of whistler by the modulated beam; (a) dispersion curve of whistler wave at different times in the afterglow; $I_{mod} = 1.8$ mA, $n_1 = 1.9 \times 10^{11}$ e/cm^3, $n_2 = 9.1 \times 10^{10}$ e/cm^3, $B = 100$ G, $E_b = 300$ eV, $\omega_0 = 90$ MHz; (b) and (c) interferometer output for a beam excited wave and a loop excited wave at frequency ω_0 [(b) $n = n_1$, double pole; (c) $n = n_2$, single pole].

Experimental observation of whistler waves.

W. Gekelman, LAPD, 10000 probe measurements of laser ablated plasmas colliding with background plasma.

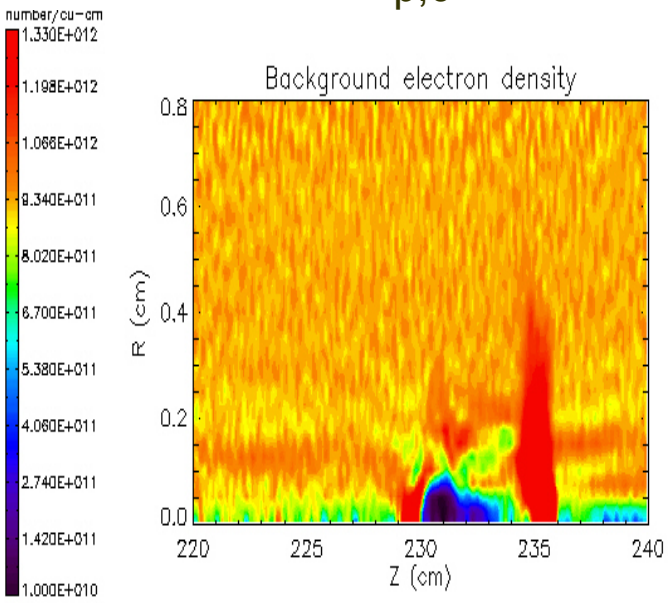


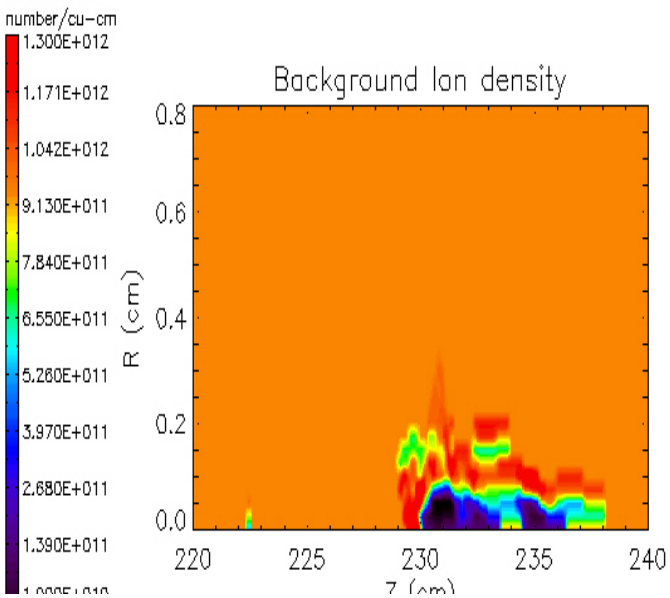
Conclusions

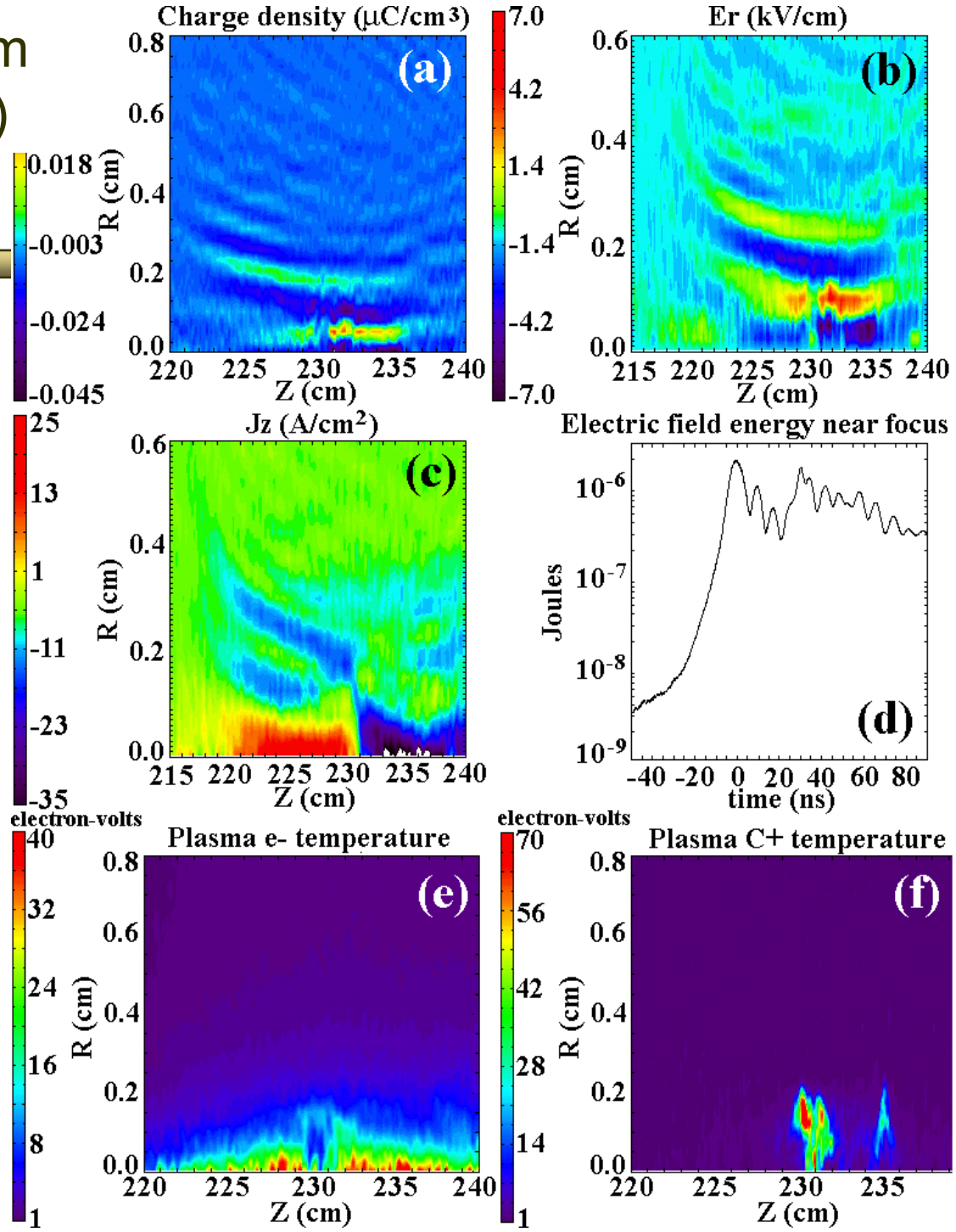
- Application of a weak solenoidal magnetic field can be used for active control of beam transport through a background plasma.

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

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







Courtesy of A. Sefkow