Technical Issues and Challenges of Neutralized Drift Compression for Focusing of Intense Ion Beam Pulses

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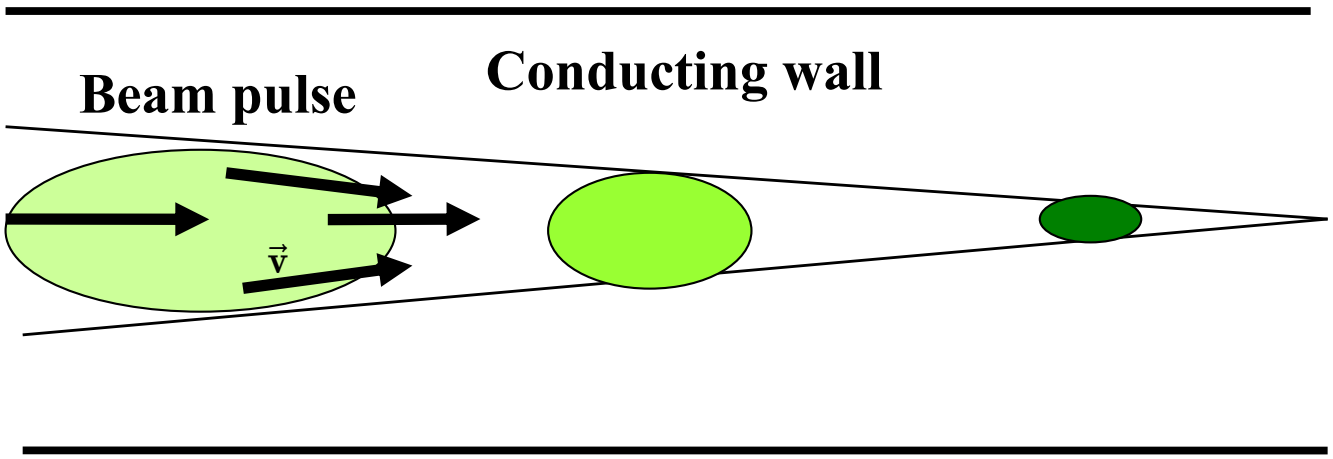
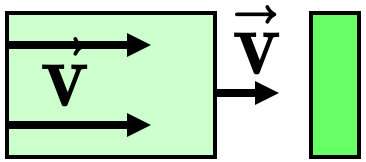
#2 Neutralized drift compression can reach 300x300 = 10^5 combined longitudinal and transverse compression of ion beam pulse.



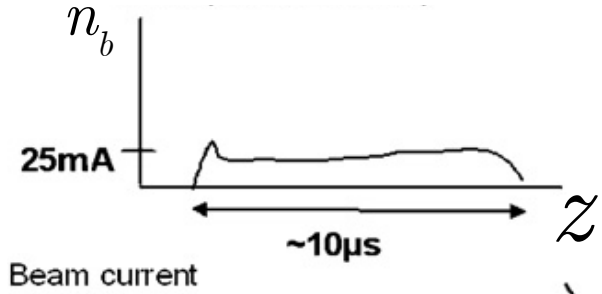
Outline

- Longitudinal compression
- Radial compression
- Simultaneous longitudinal and radial compression
- The physics of the plasma neutralization process and collective focusing schemes.

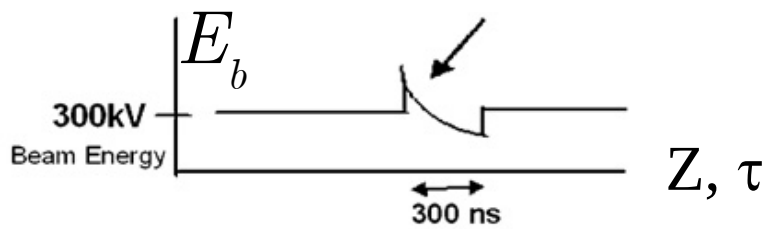
Longitudinal Compression

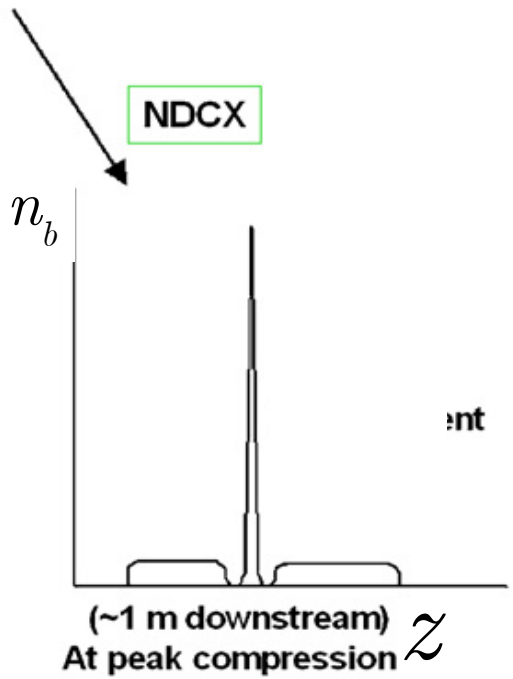


beam pulse before compression



tilt core voltage waveform applied to uncompressed beam pulse





compressed beam current.

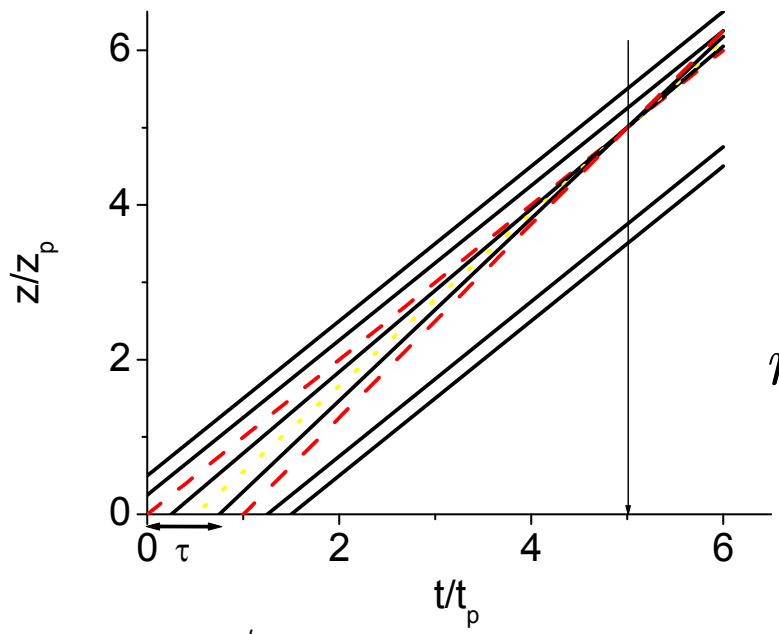
P.K. Roy et al, NIMPR. A **577,** 223 (2007).

Longitudinal compression is limited by errors in applied velocity tilt.

- ✓ We have performed analysis of errors in the applied velocity tilt on longitudinal compression *using full kinetic treatment.*
  - ✓ Analytical expression for the compression ratio was derived and can be used as a tool analyzing experimental data.
- ✓ The longitudinal compression ratio is inversely proportional to the relative error in the velocity modulation.
- ✓ However, a local value of compression ratio can be high even for the case of large errors if a fraction of the pulse compresses well.

Analytical solution for longitudinal compression

$$z(t,\tau) = v_b(\tau)(t-\tau) \quad z(t_f,\tau) = L_f \quad v_b^i(\tau) = v_{b0} t_f \,/\, \left(t_f - \tau\right)$$



$$C = dz_0 \,/\, dz \qquad z_0(\tau) = -v_{b0}\tau$$

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

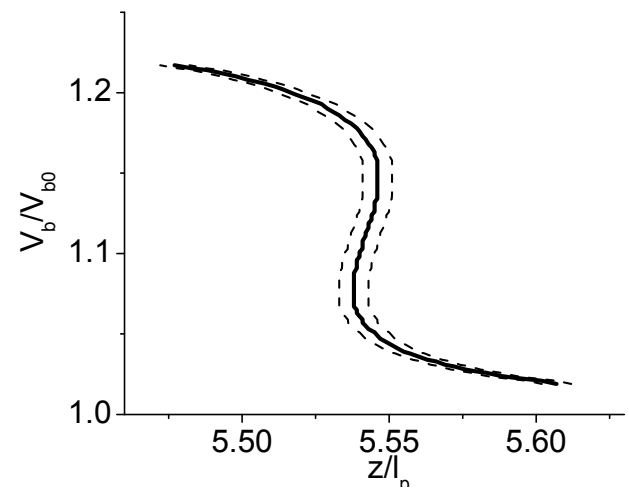
$$n_b(z,t) = \frac{n_{b0} v_{b0}}{v_b(\tau) - (t-\tau) dv_b(\tau) \,/\, d\tau}$$

(c)

$$n_b(z,t) = \int_{-\infty}^{t} v_{b0} d\tau \int_{-\infty}^{\infty} dv f(v) \delta\left(z - z_b(t,\tau) - vt\right)$$

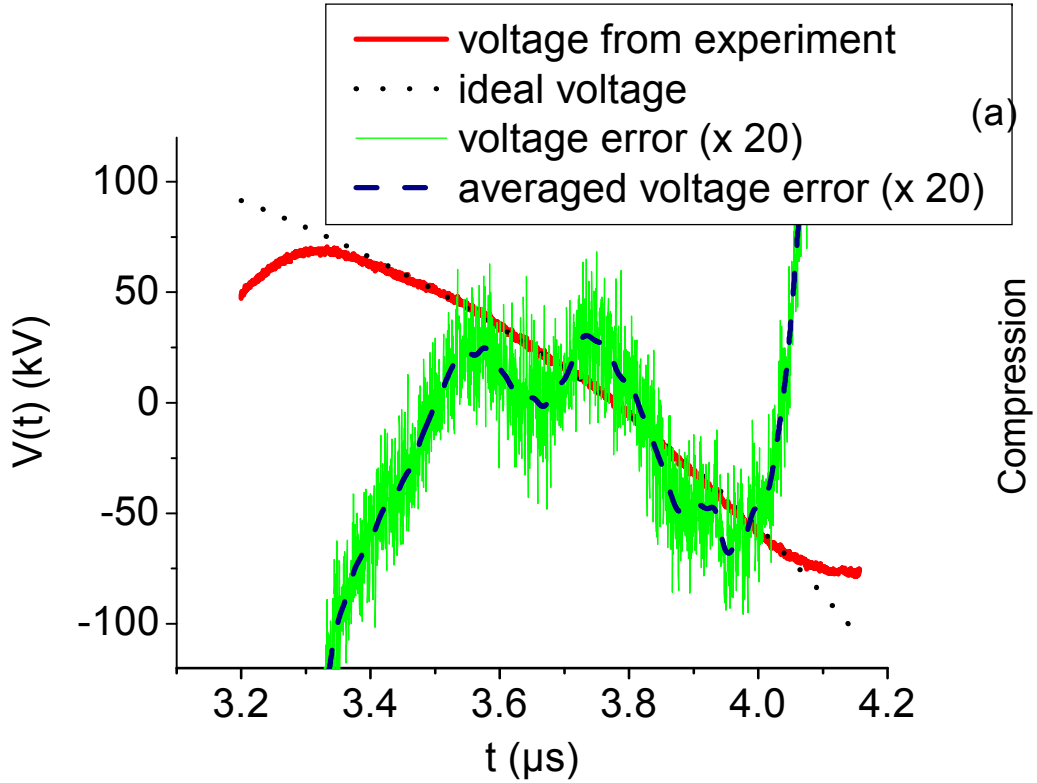
Number of beam particle arriving at given location

f(v) is initial velocity distribution function

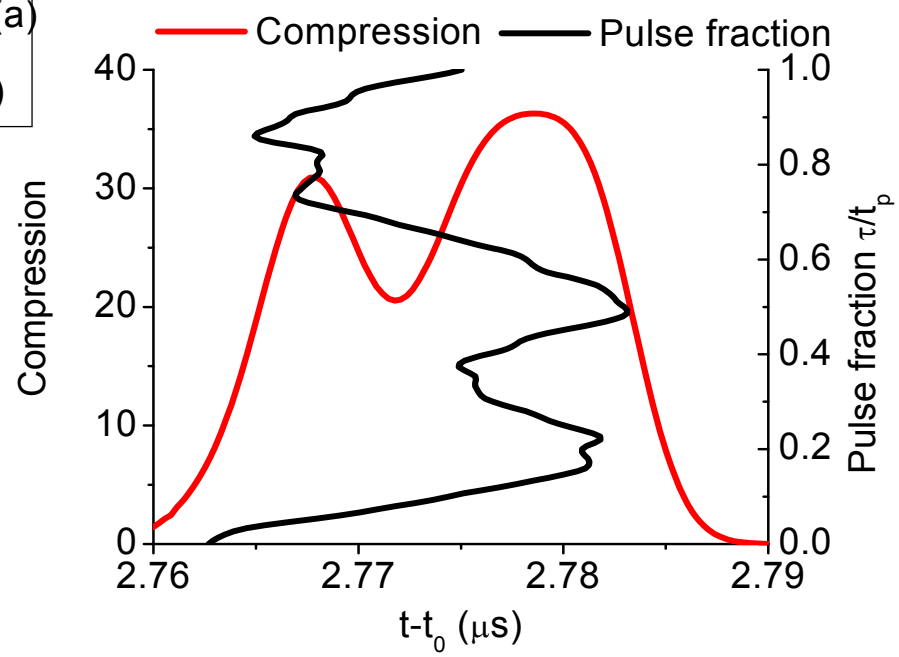


1-10% Voltage errors limit the longitudinal compression

Experimental voltage waveform of the NDCX-I induction bunching module from S.M. Lidia, 2009 PAC tu6pfp092.

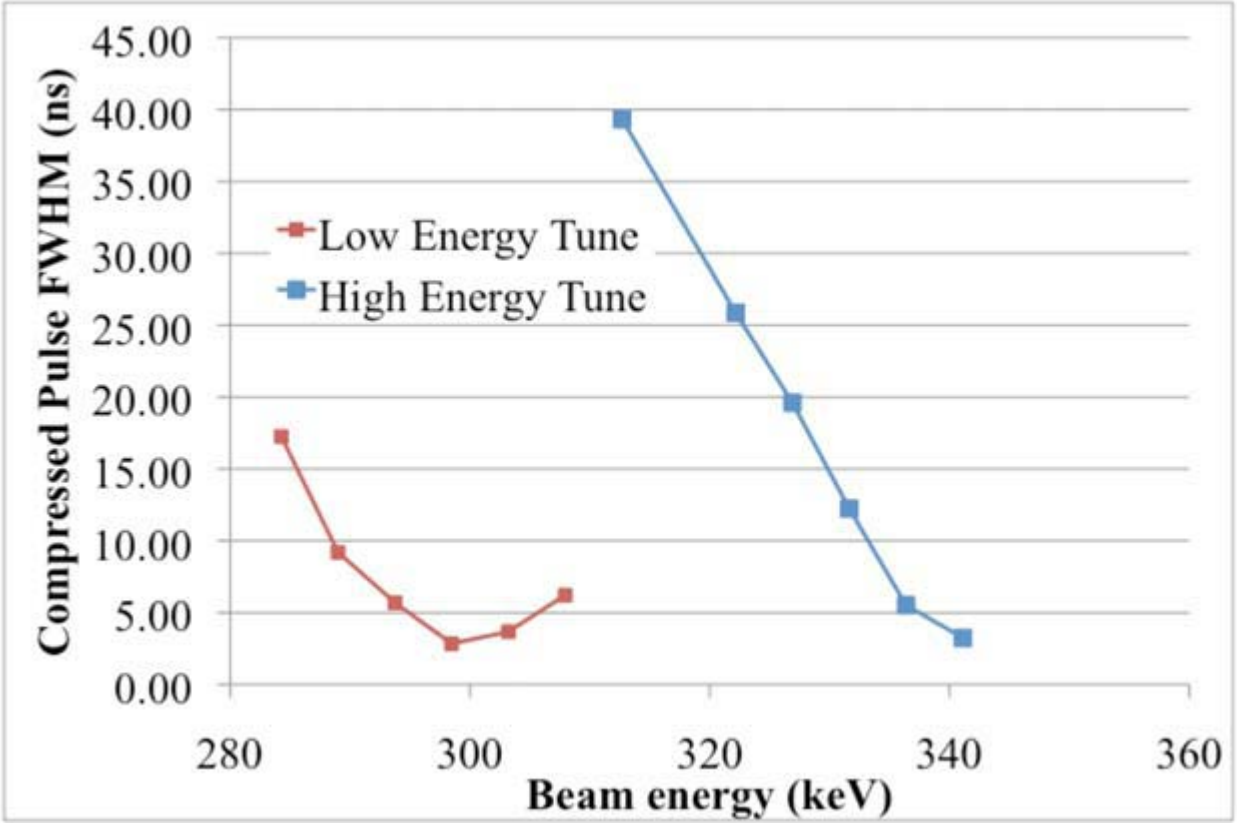


The simulated compressed pulse waveform at the target location z= 286.8 cm is plotted as a function of drift time.



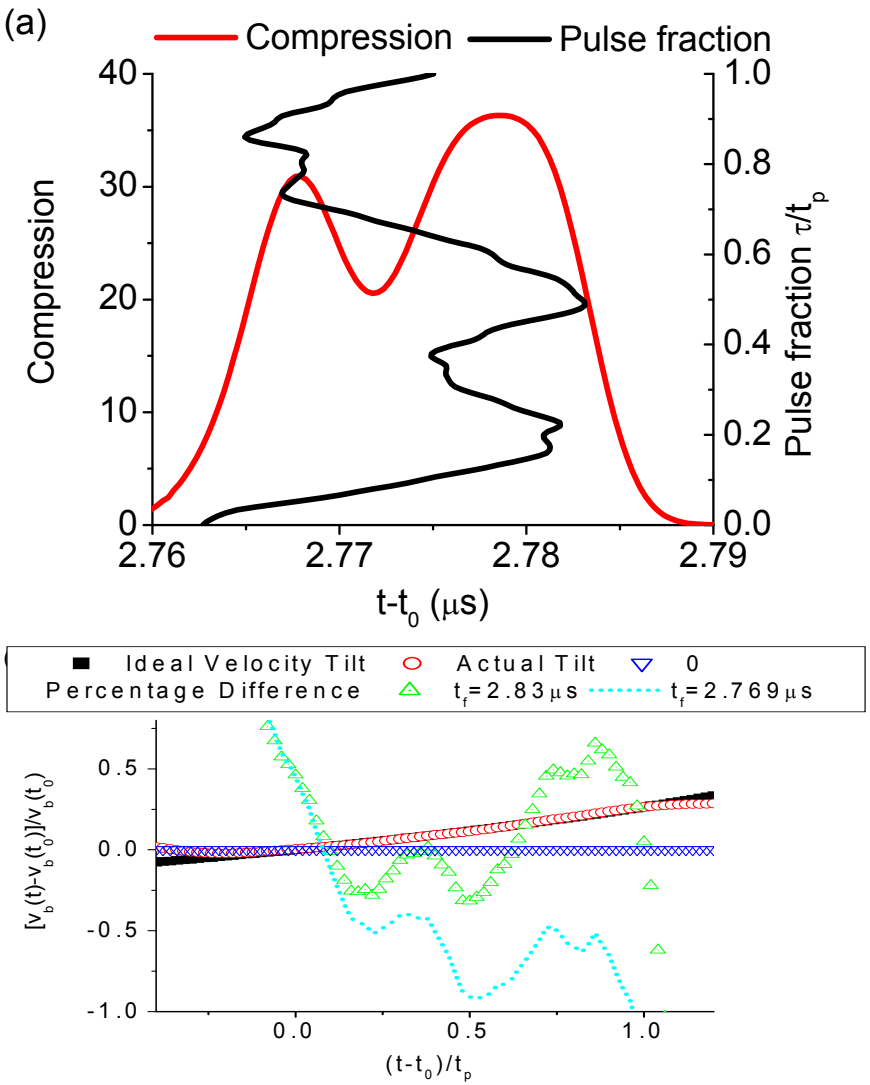
Optimal Beam Energy for compression

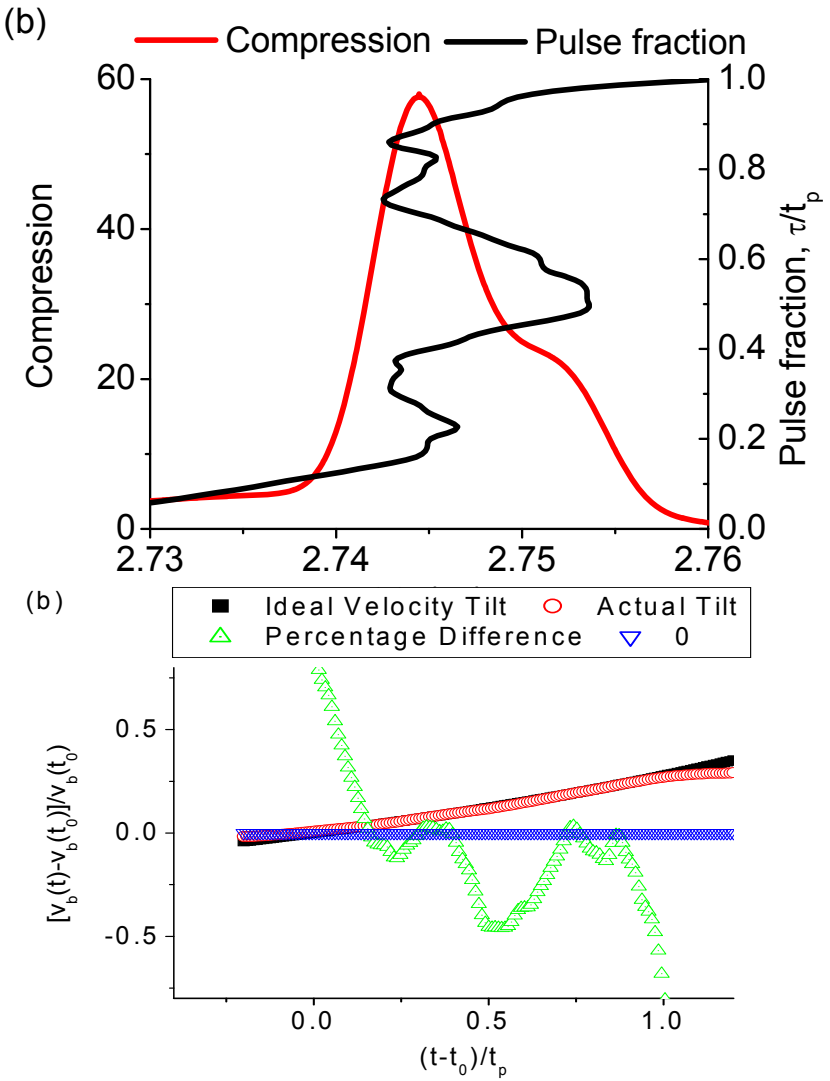
Variation of compressed pulse duration (FWHM) with beam energy for the low energy (280-300 keV) and high energy (330-340 keV) tunes. **F.M. Bieniosek et al.**



#9

The simulated compressed pulse waveform at the target for the beam energy (a) 270keV and **optimal** (b) 276 keV.

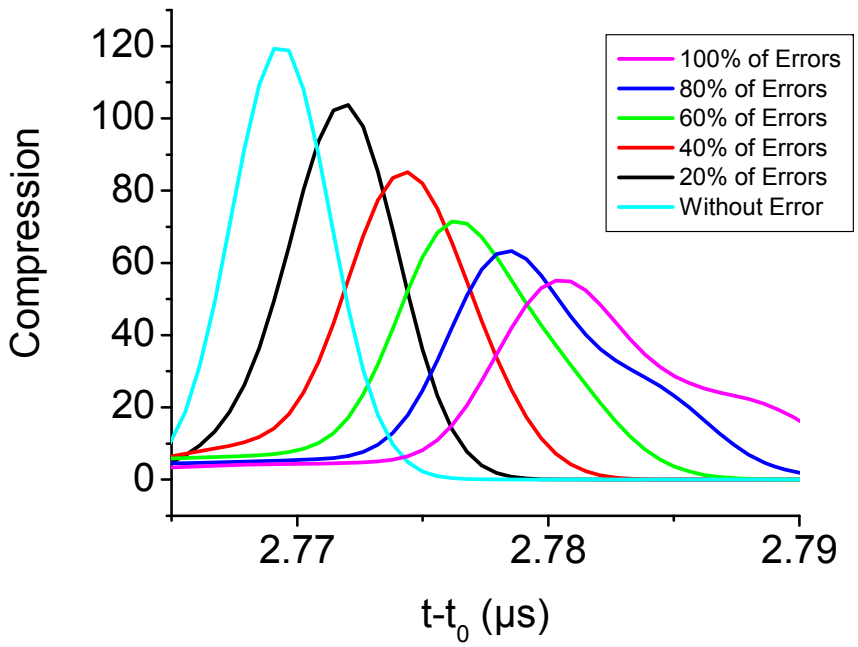


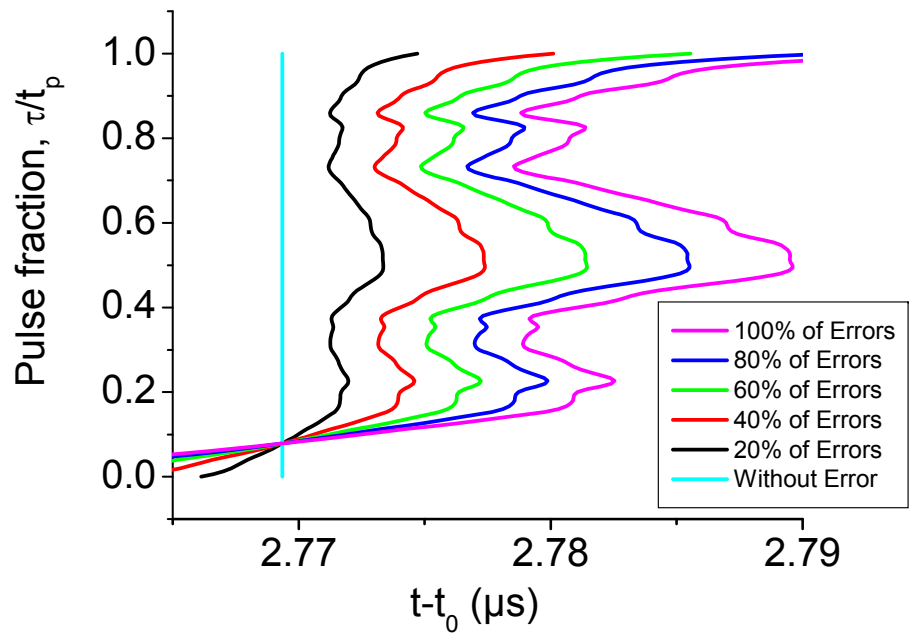


Compression ratio is a weak function of errors

$$C_{\max} \sim \left(\frac{\Delta U}{\Delta E_{bT}} \frac{\Delta U}{\delta U} \right)^{1/2}$$

Simulated compressed pulse waveform and pulse location at the target for reduced voltage errors as a function of time. The initial beam energy is 276keV, and the longitudinal temperature is T_z=0.27eV





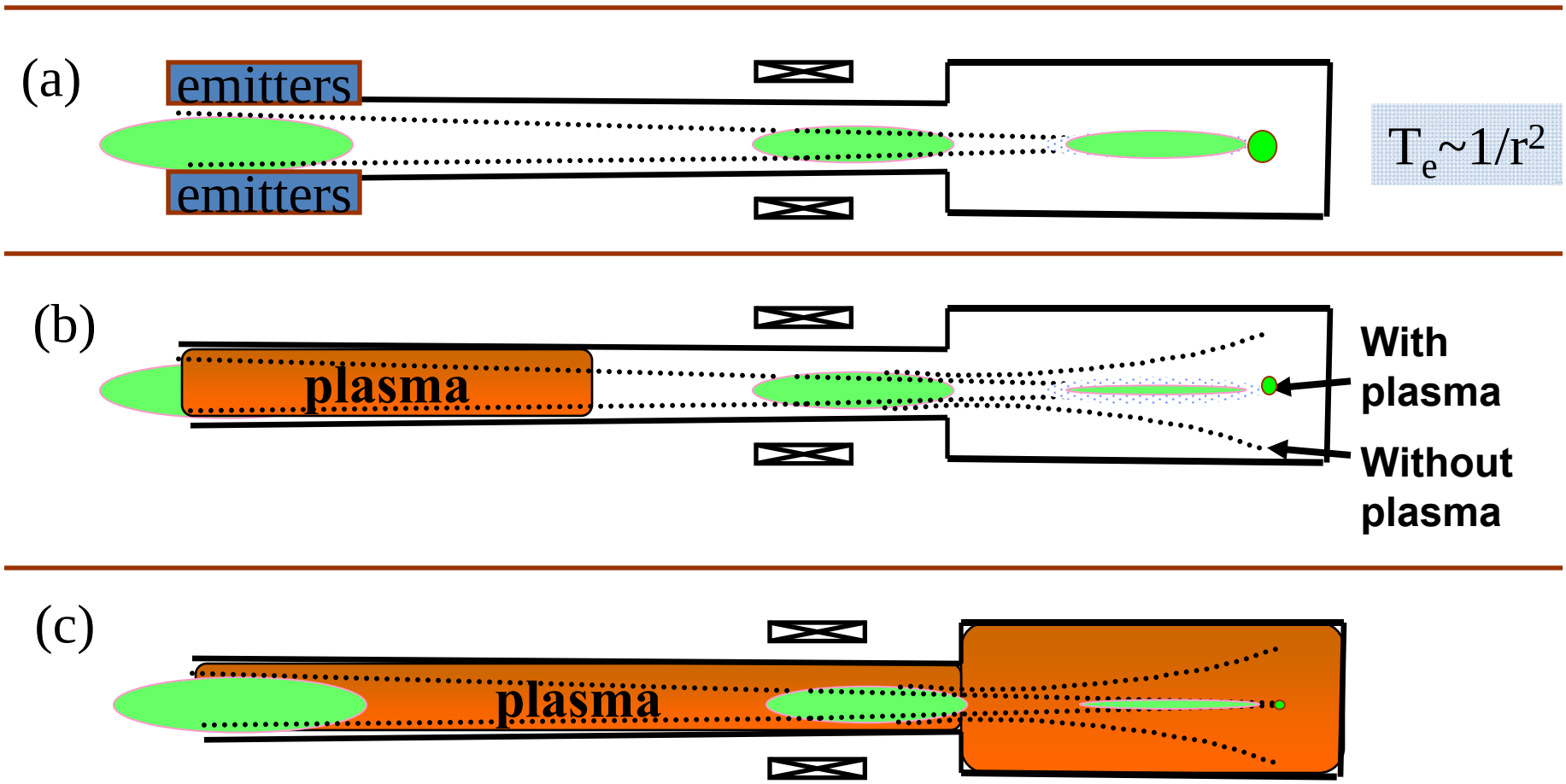
Outline

- 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?!

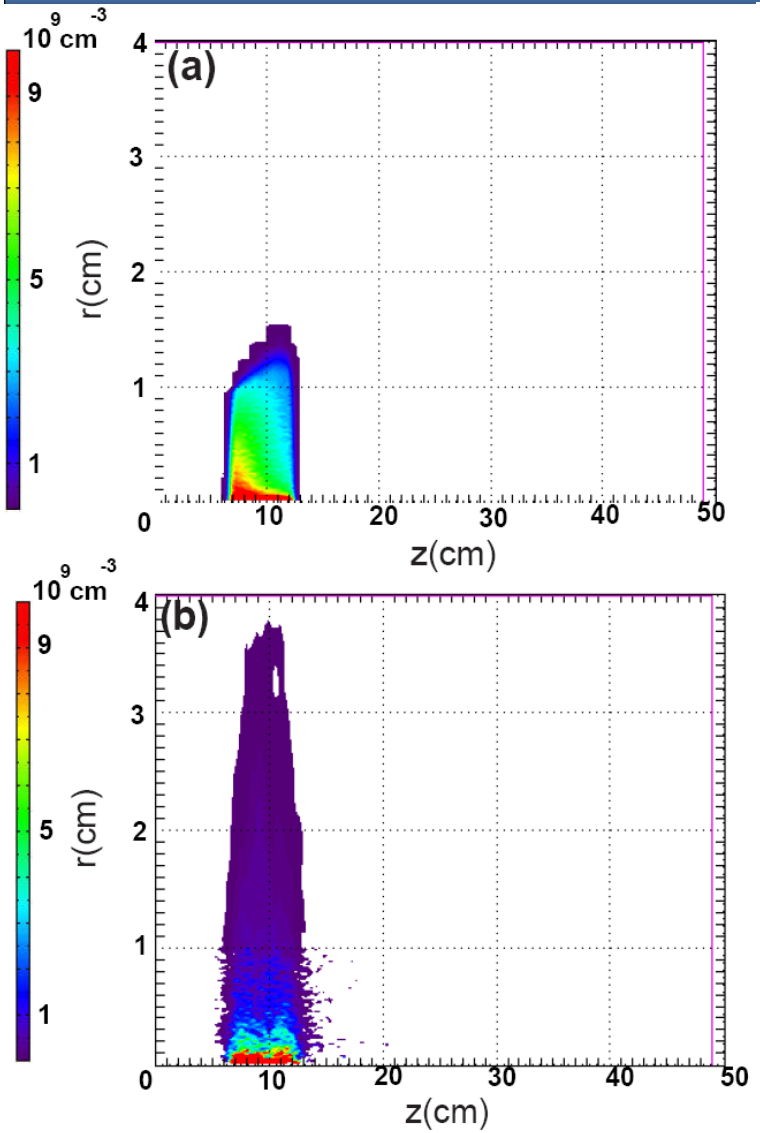
Methods to neutralize intense ion beam

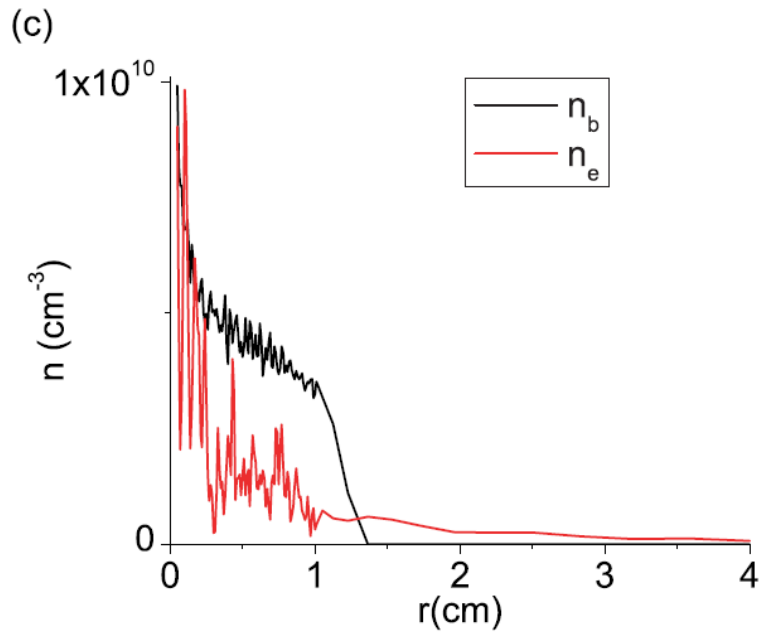
I. D. Kaganovich et al, Physics of neutralization of intense high-energy ion beam pulses by electrons, Phys. Plasmas **17**, 056703 (2010).

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



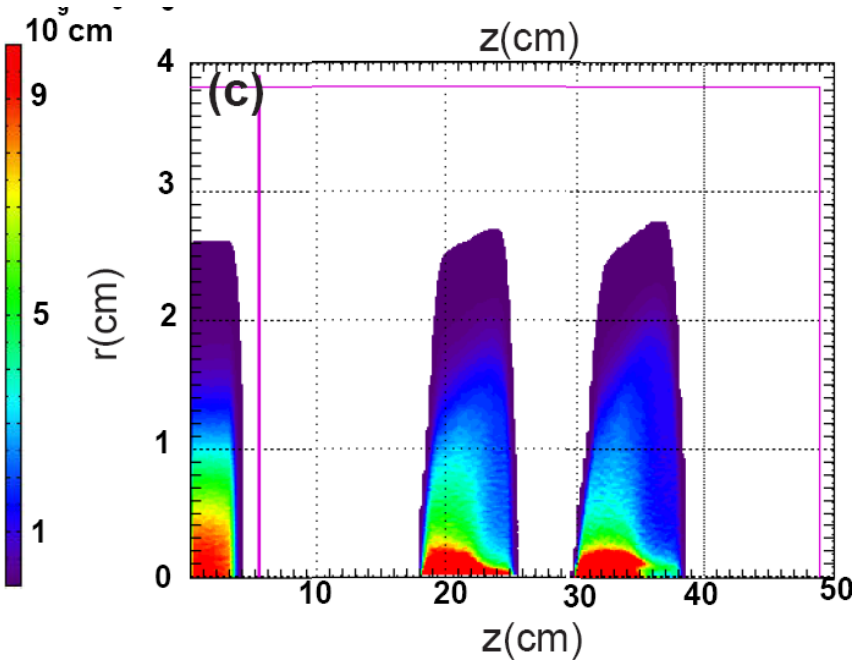
Neutralization by emitting filaments positioned near the beam sides is no good!

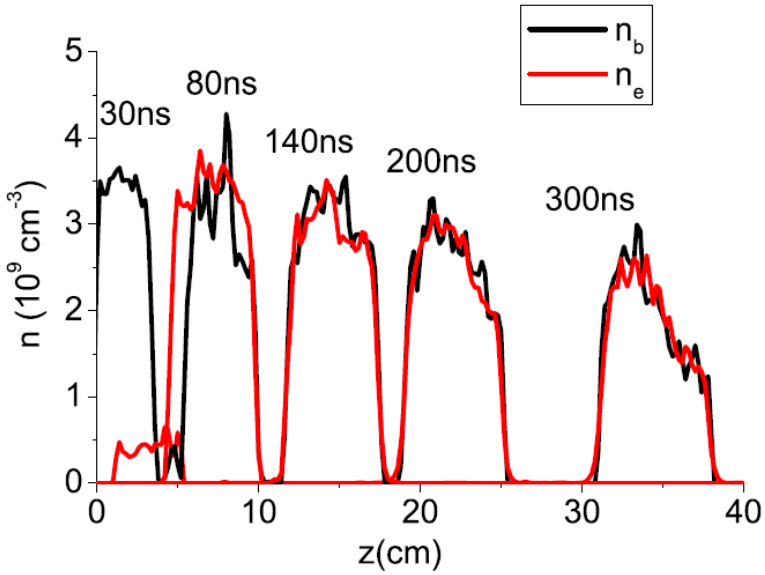




Color plots of (a) ion beam density, (b) electron density, and (c) 1D slice plot. K+ 320keV; 44ns pulse. The beam radial profile is a gaussian with r_b =1cm; and the maximum beam current density is 0.19A/cm^2.

Neutralization by emitting filaments immersed in the beam maybe good!

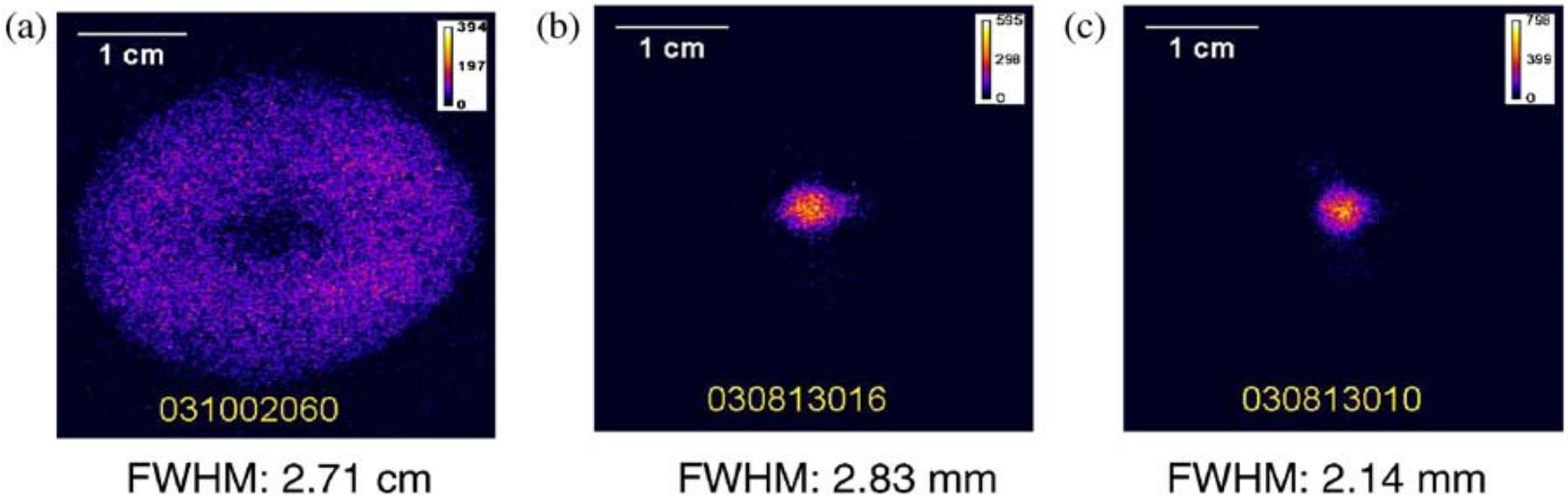




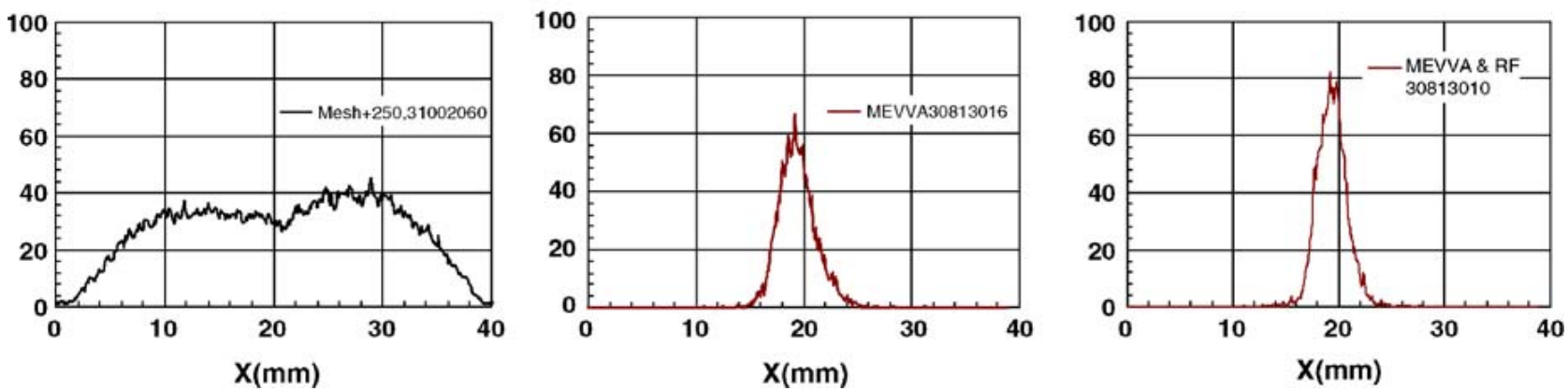
Color plots and one-dimensional plots of ion beam density at 30, 200, and 300 ns. Beam is neutralized with emission from a grid introduced into the beam path at *z=5 cm*.

Neutralization by volumetric plasma is the best!

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

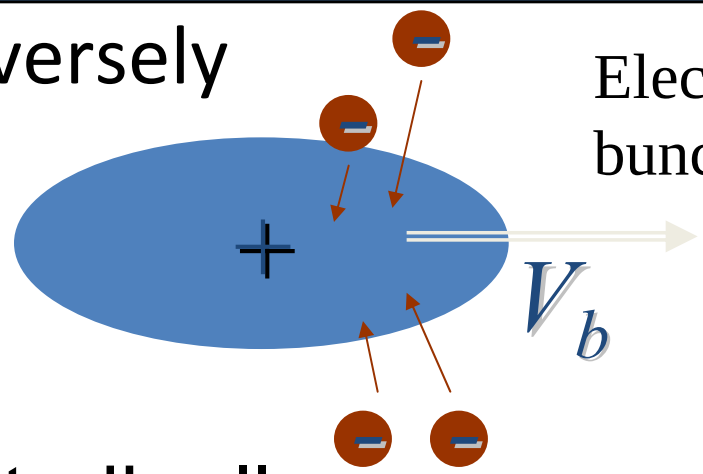


P.K. Roy et al, NIMPR. A **544,** 225 (2005).



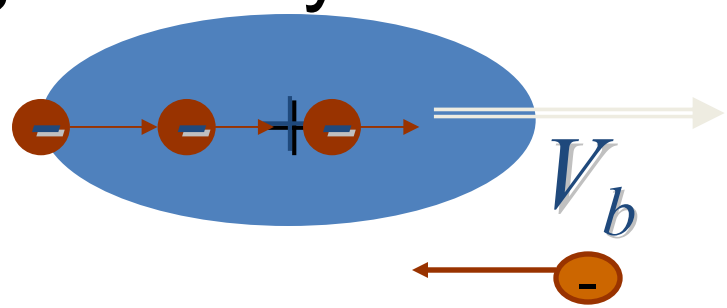
Two ways for ion beam pulse to grab electrons to insure full neutralization.

Transversely



Electron positions in response to ion bunch

Longitudinally



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

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

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

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

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

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

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

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

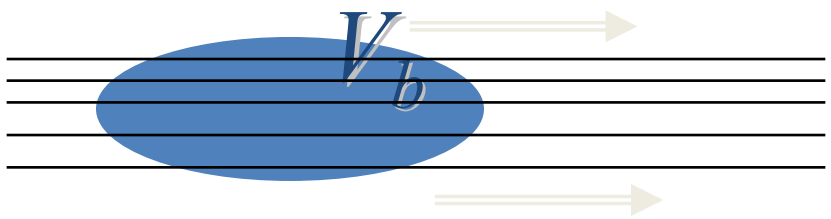
Having $n_b << n_p$ strongly increases the neutralization degree.

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

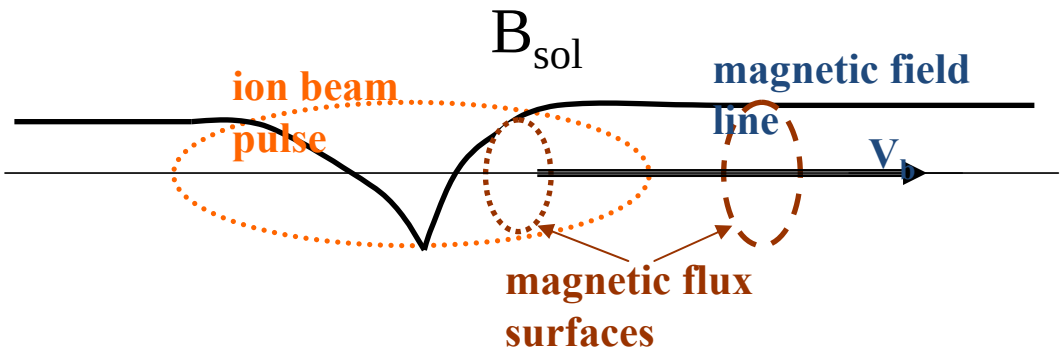
$$F_r = -mV_b^2 \frac{1}{n_p} \left| \frac{\partial n_b}{\partial r} \right|$$

Magnetic force dominates the electrical force and it is focusing!

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:

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

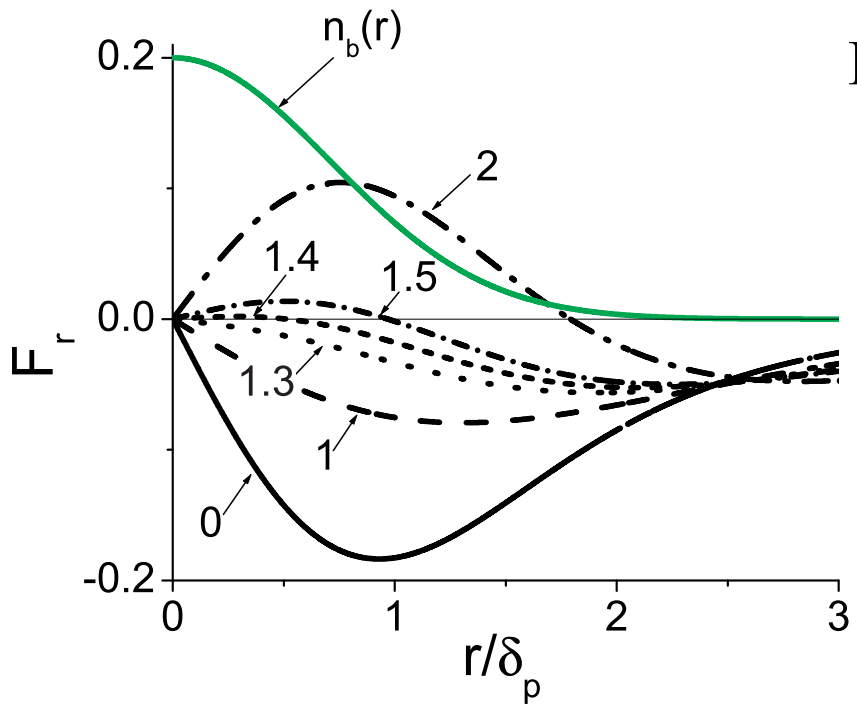
$$E_r \sim \frac{1}{c} V_{e\phi} B_{sol}$$

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

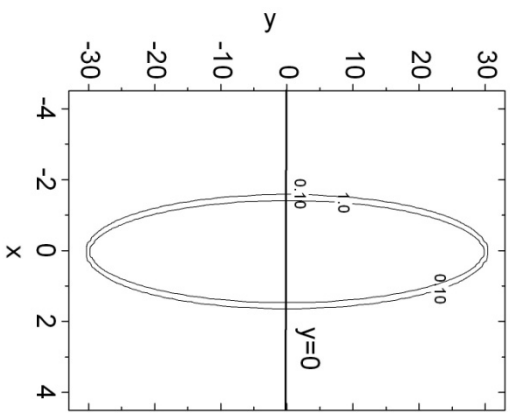
The poloidal rotation twists the magnetic field and generates the poloidal magnetic field and large radial electric field.

I. Kaganovich, et al, PRL **99**, 235002 (2007); PoP (2008).

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



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

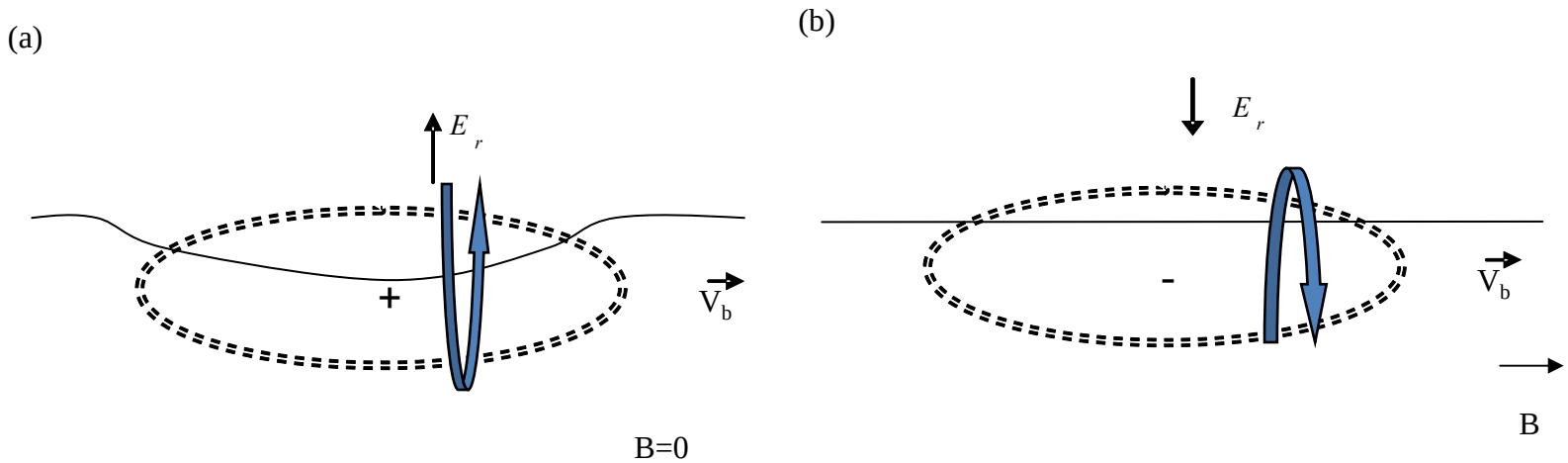


Normalized radial force acting on beam ions in plasma for different values of $(\omega_{ce}/\omega_{pe}\beta_b)^2$. The green line shows a gaussian density profile. $r_b = 1.5\delta_p$; $\delta_p = c/\omega_{pe}$.

I. Kaganovich, et al, Phys. Rev. Lett. **99**, 235002 (2007);

M. Dorf, et al, Phys. Rev. Lett. **103**, 075003 (2009).

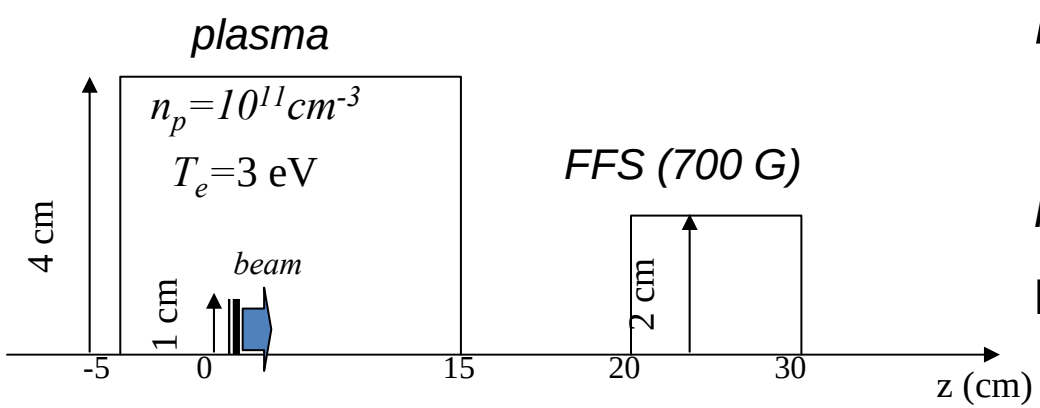
Plasma response to the beam is drastically different depending on $\omega_{ce}/2\beta_b\omega_{pe}$ <1 or >1



Schematic of an electron motion for the two possible steady-state solutions. (a) Radial self-electric field is defocusing for ion beam, rotation is paramagnetic; (b) Radial self-electric field is focusing for ion beam; rotation is diamagnetic.

M. Dorf, et al, Phys. Rev. Lett. **103**, 075003 (2009); PoP **17,** 023103 (2010).

Collective Focusing Lens Can be Used for NDCX Beam Final Focus instead of Strong Solenoid



Beam injection parameters

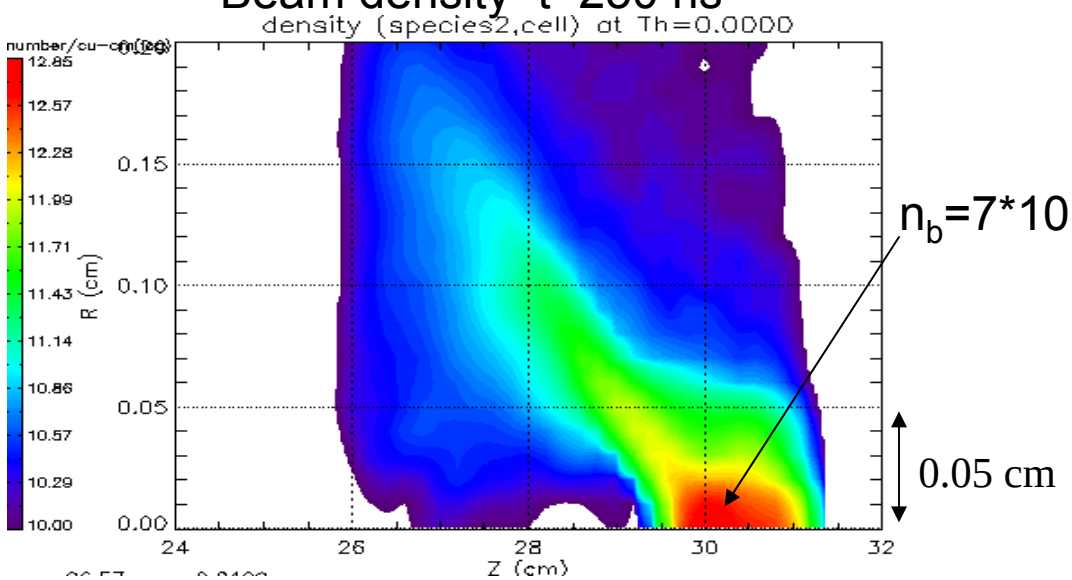
K^+ @ 320keV, $n_b=10^{10}cm^3$

r_b=1 cm, T_b=0.2 eV

beam pulse=40ns (5 cm)

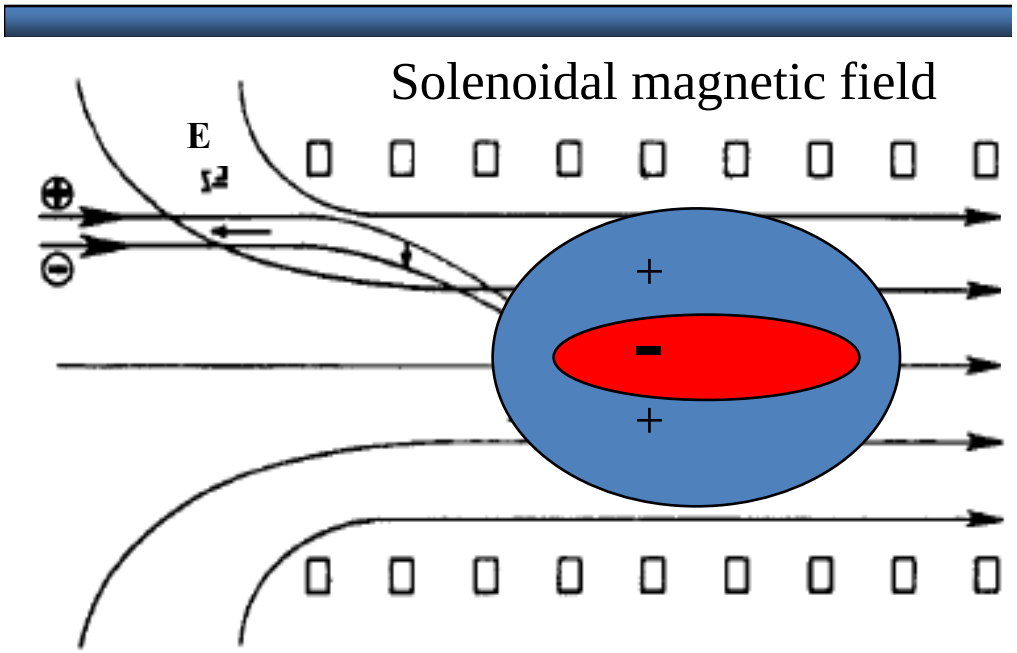
$\omega_{pe}(n_e=n_b)=0.46\omega_{ce}$

Beam density t=250 ns



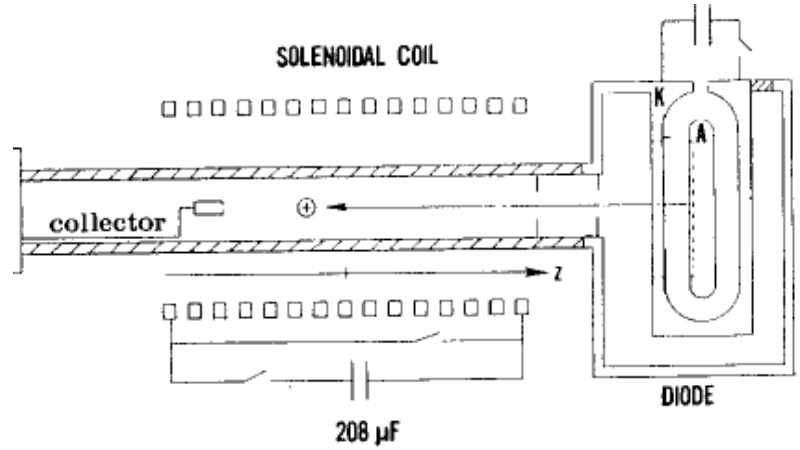
M. Dorf, et al, PoP submitted (2010).

Collective focusing schemes



S. Robertson, PRL, **48**, 149 (1982).
Thin collective lens

E_b~360 keV, r_b~2 cm, n_b~$1.5 \cdot 10^{11}$ cm^{-3}



. Experimental apparatus.

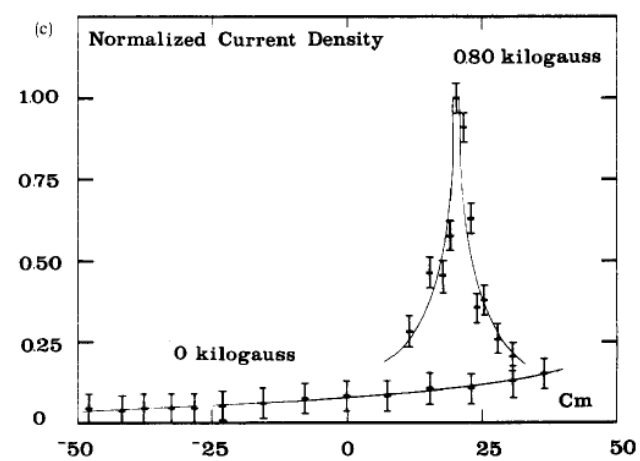


FIG. 8. Focused ion current. (a) Ion current density versus time ($B = 0$, 1.5 kG). (b) Peak ion current density versus axial position ($B = 0$, 1.5 kG). (c) Peak ion current density versus axial position ($B = 0$, 1.5 kG).

From R. Kraft, Phys. Fluids **30**, 245 (1987)

Conclusions: identified limiting factors

Errors in the applied velocity tilt compared to the ideal velocity tilt limits the longitudinal compression to 50-100 times. Compression ratio is inversely proportionally to square root of voltage errors and energy spread.

I. D. Kaganovich, et al., PRSTAB submitted (2010).

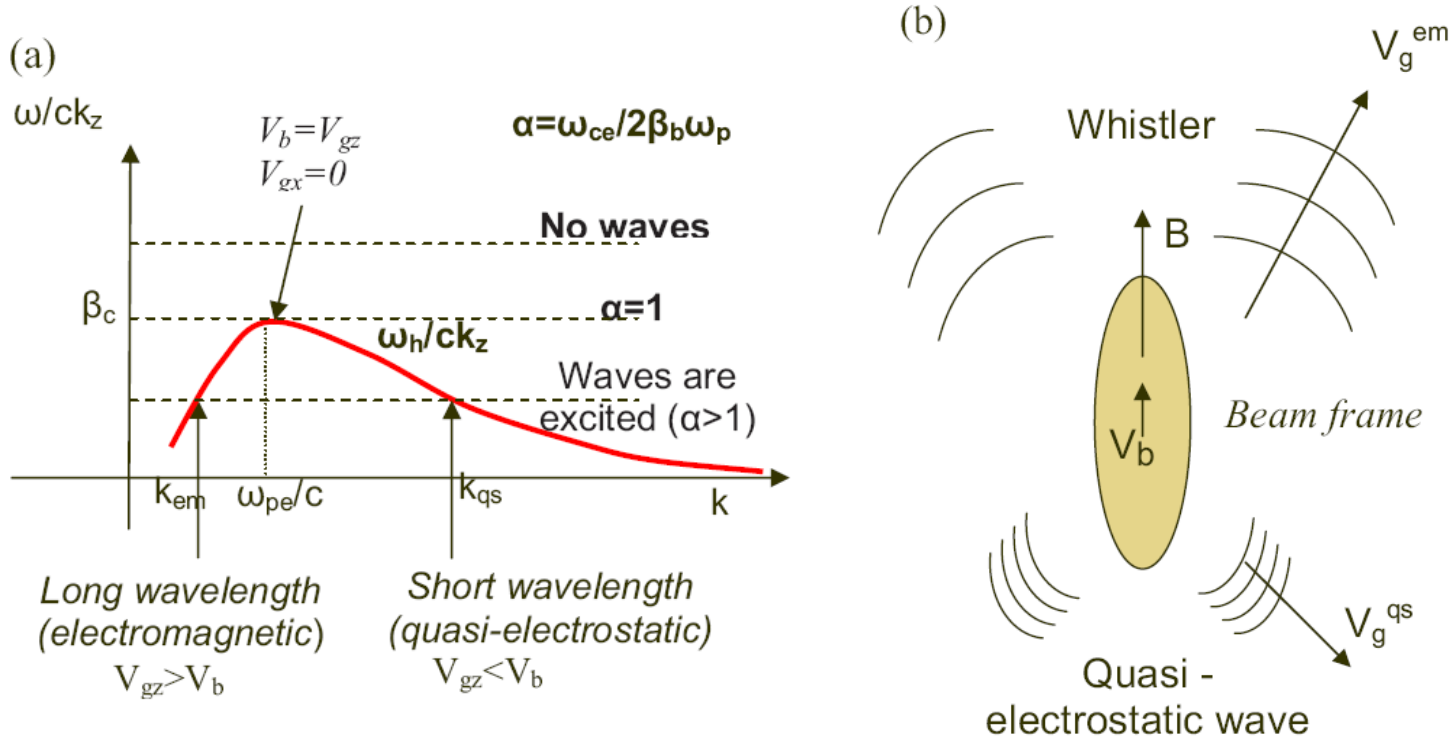
Plasma provides the necessary neutralization for compression, provided the plasma density exceeds the beam density everywhere along the beam path, i.e., $n_p > n_b$.

I. D. Kaganovich, et al, Phys. Plasmas **17**, 056703 (2010).

Collective focusing can provide tight focus for intense ions beams utilizing weak solenoidal magnetic field.

M. Dorf, et al, PoP submitted (2010).

The beam can excite whistler waves.



(a) The phase velocity of the whistler wave is plotted as a function of wave vector (solid curve) and is intersected by different values of the normalized beam velocity (dashed lines).

(b) Schematic illustration of the whistler waves excited by the ion beam pulse. M. Dorf et al., Phys. Plasmas **17,** 023103 (2010)**.**

Movies

Courtesy of A. Sefkow

Linear Analytical Theory Method: Laplace Transform and Landau Contours

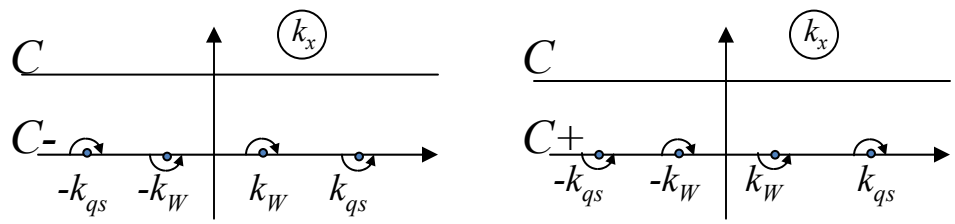
$$B_y = \frac{\omega_{ce}}{\omega_{pe}} \frac{n_p}{n_{b0}} = \int d\omega \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dk_z dk_x \frac{n_k}{(\omega - k_z V_b) D(\omega, k_x, k_z)} e^{-i\omega t + ik_x x + ik_z z}$$

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 $n(x,z)=n_z(z)n_x(x)$

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

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

Can be obtained in the slab approximation

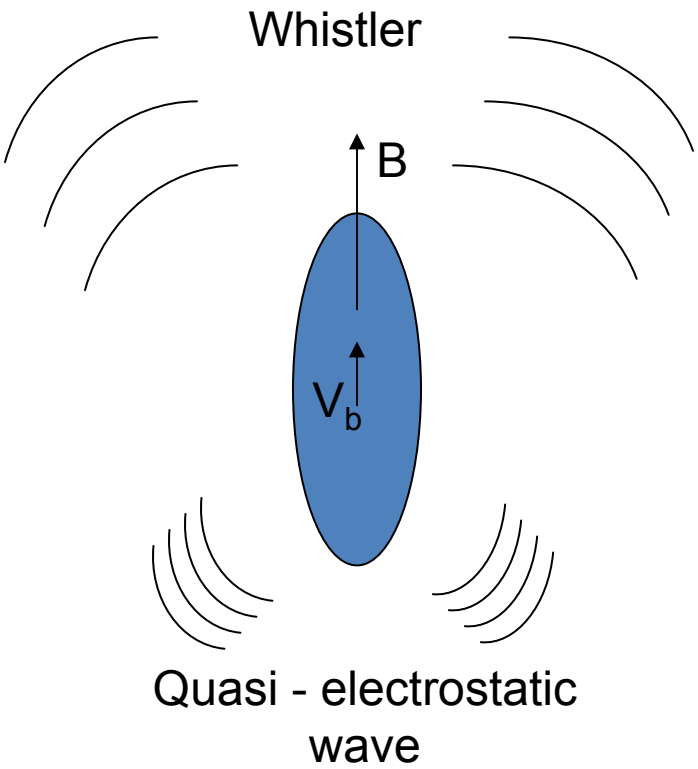
Excited wave field

– slab approximation does not work

Courtesy of
M. Dorf

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

Artist: E.P. Gilson 2008



Conclusions for neutralization

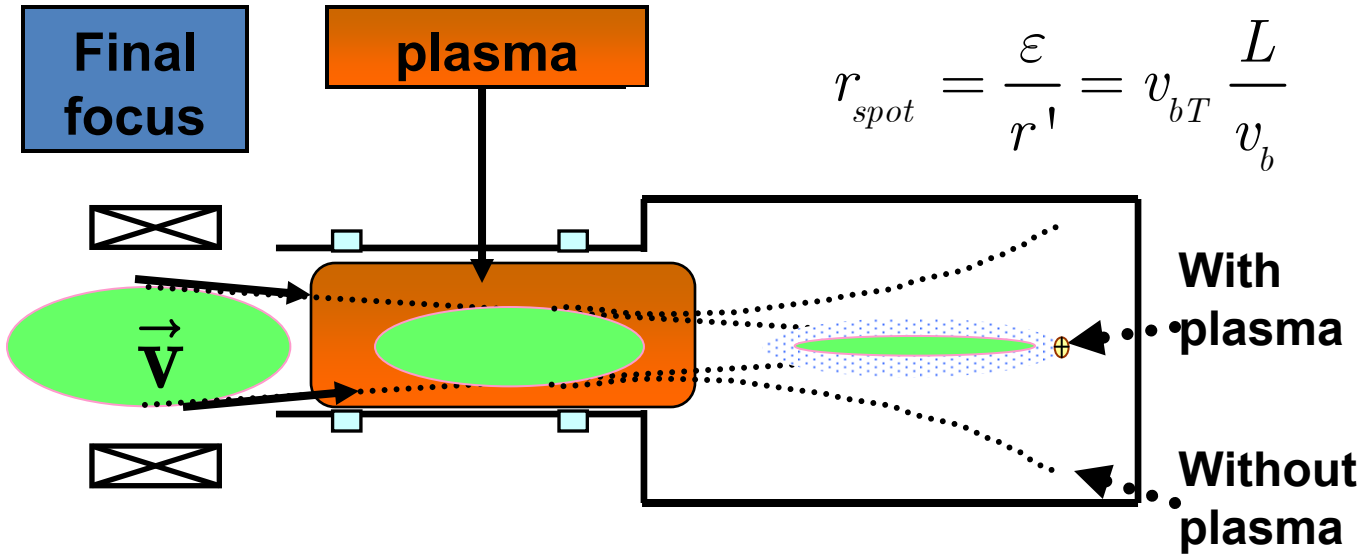
Developed a nonlinear theory for the quasi-steady-state propagation of an intense ion beam pulse in a background plasma

- 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 $\omega_{ce} > \beta\omega_{pe}$.

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

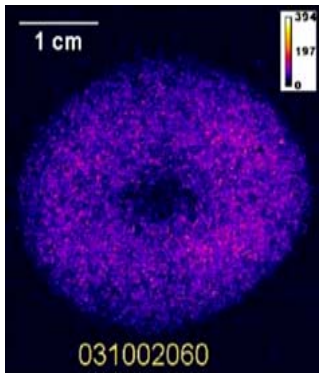


$$r_{spot} = \frac{\varepsilon}{r'} = v_{bT}\frac{L}{v_b}$$

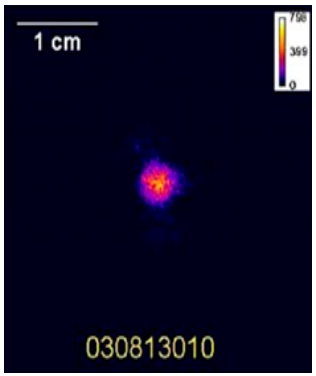
Beam envelope with and without taking into account beam space charge.

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

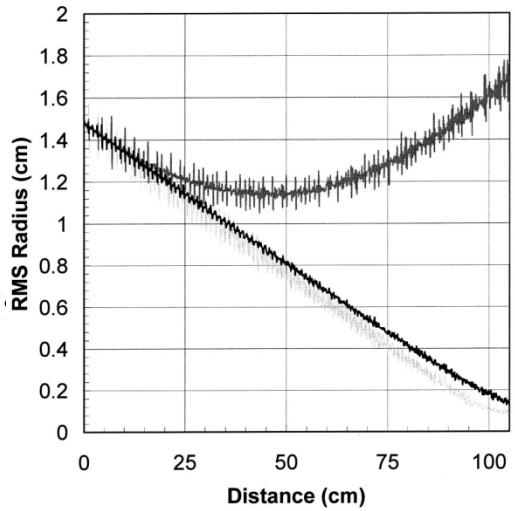
(a)



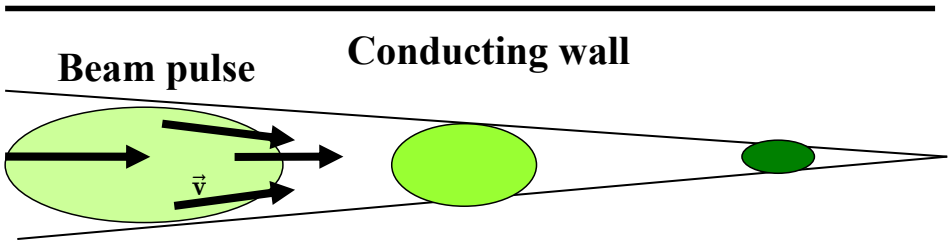
(b)



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



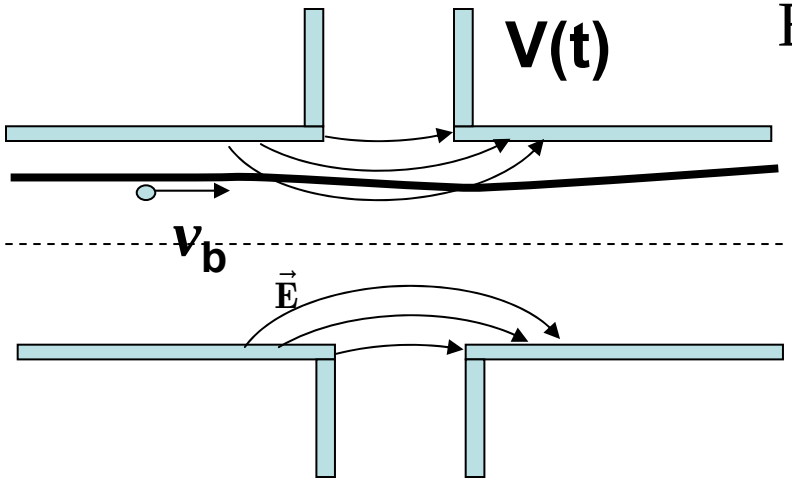
Outline



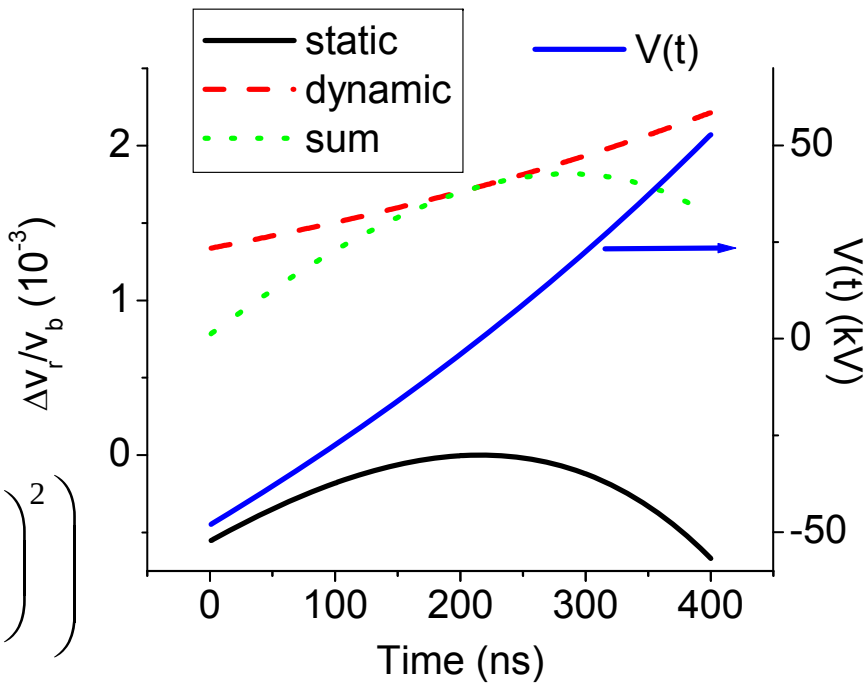
- Longitudinal compression
- Radial compression
- Simultaneous longitudinal and radial compression
- The physics of the neutralization process and requirements for plasma sources.

Aberration in the bunching module

acceleration gap of the induction bunching module.



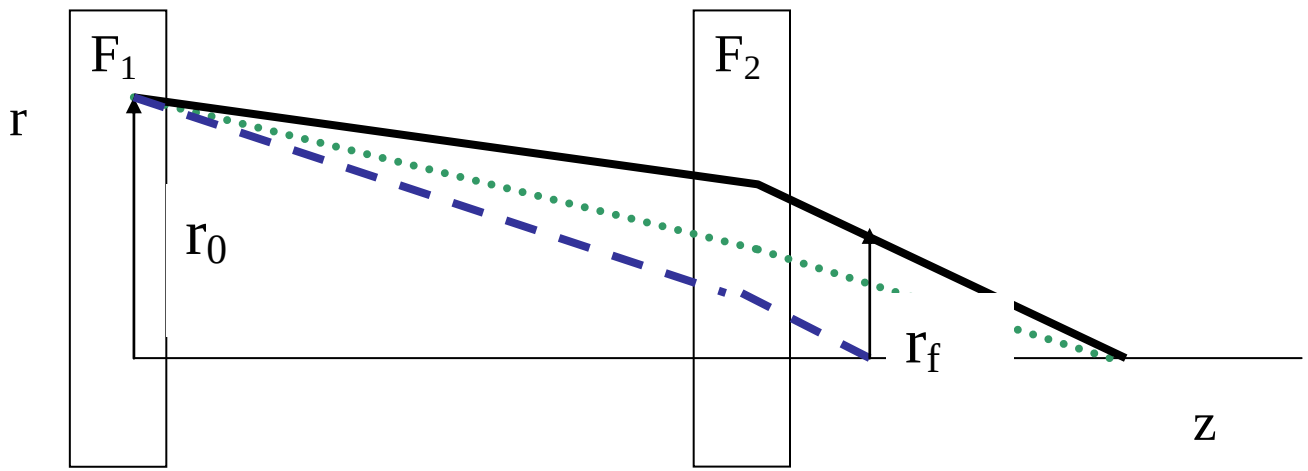
The static and dynamic aberrations for NDCX-I. Pulse t_p=400ns, E_b=300keV, r=1cm, R_w=3.8cm.



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

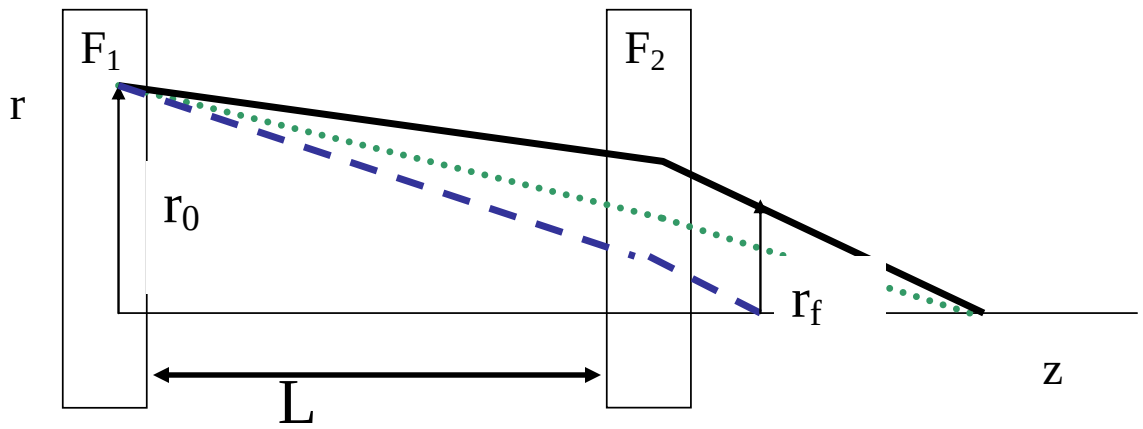
Strong final focusing element is utilized to reduce spot size at target.

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,

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

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

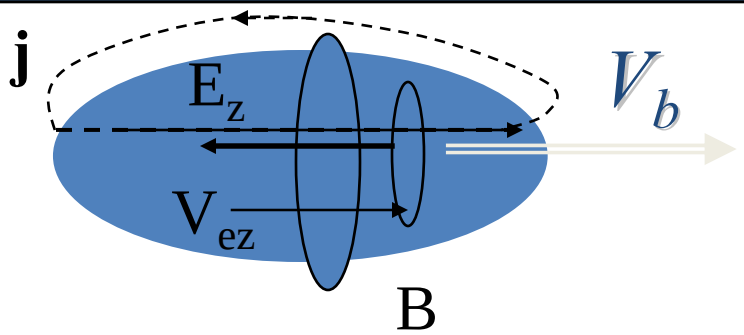
$$\frac{\partial \vec{p}_e}{\partial t} + (\vec{V}_e \bullet \nabla)\vec{p}_e = -\frac{e}{m}(\vec{E} + \frac{1}{c}\vec{V}_e \times \vec{B}), \quad \frac{\partial n_e}{\partial t} + \nabla \bullet \left(n_e \vec{V}_e\right) = 0,$$

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

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).

Current Neutralization



$$\frac{\partial \int Bds}{\partial t} \Rightarrow E_z \qquad mV_{ez} = \frac{e}{c} A_z$$

Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation*. For long beams canonical momentum is conserved**

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

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

* 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).

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

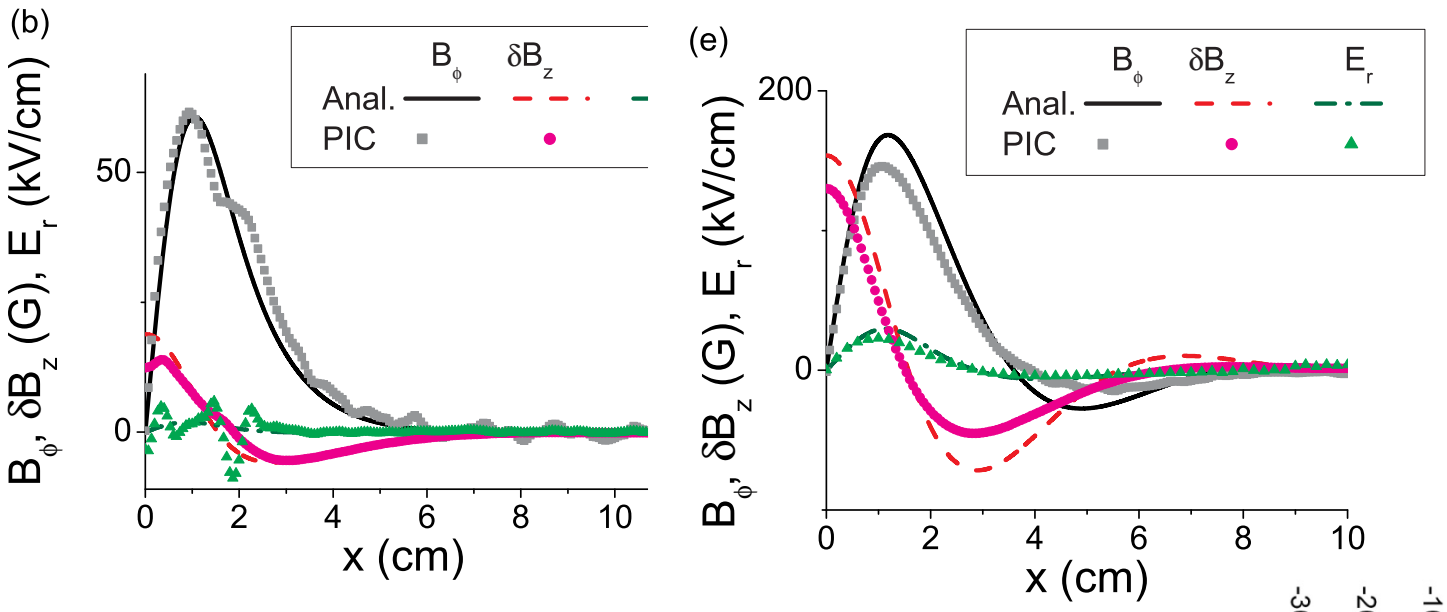
Electron rotation due to radial displacement

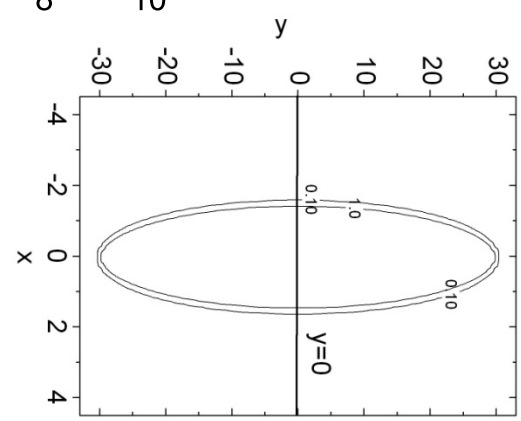
$$\omega_{ce} = \frac{eB_z}{mc}$$

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. (a) $n_{b0} = n_p/2 = 1.2 \times 10^{11} cm^{-3}$; $V_b = 0.33c$. applied solenoidal magnetic field, B_{z0} : (b) 300G; and (e) 900G corresponds to $c\omega_{ce}/V_b\,\omega_{pe}$= (b) 0.57 ; and (e) 1.7.