# Neutralized Compression and Focusing of Intense Ion Beam Pulses - Theory and Modeling*

Igor Kaganovich, *PPPL and HIFS-VNL*

*11th Meeting of the HIFS-VNL Program Advisory Committee*

*LLNL, December 8 and 9, 2010*

**Heavy Ion Fusion Science Virtual National Laboratory**

* This work was performed under the auspices of the U.S. Department of Energy under Contract DE-AC02-76CH03073.

# Outline

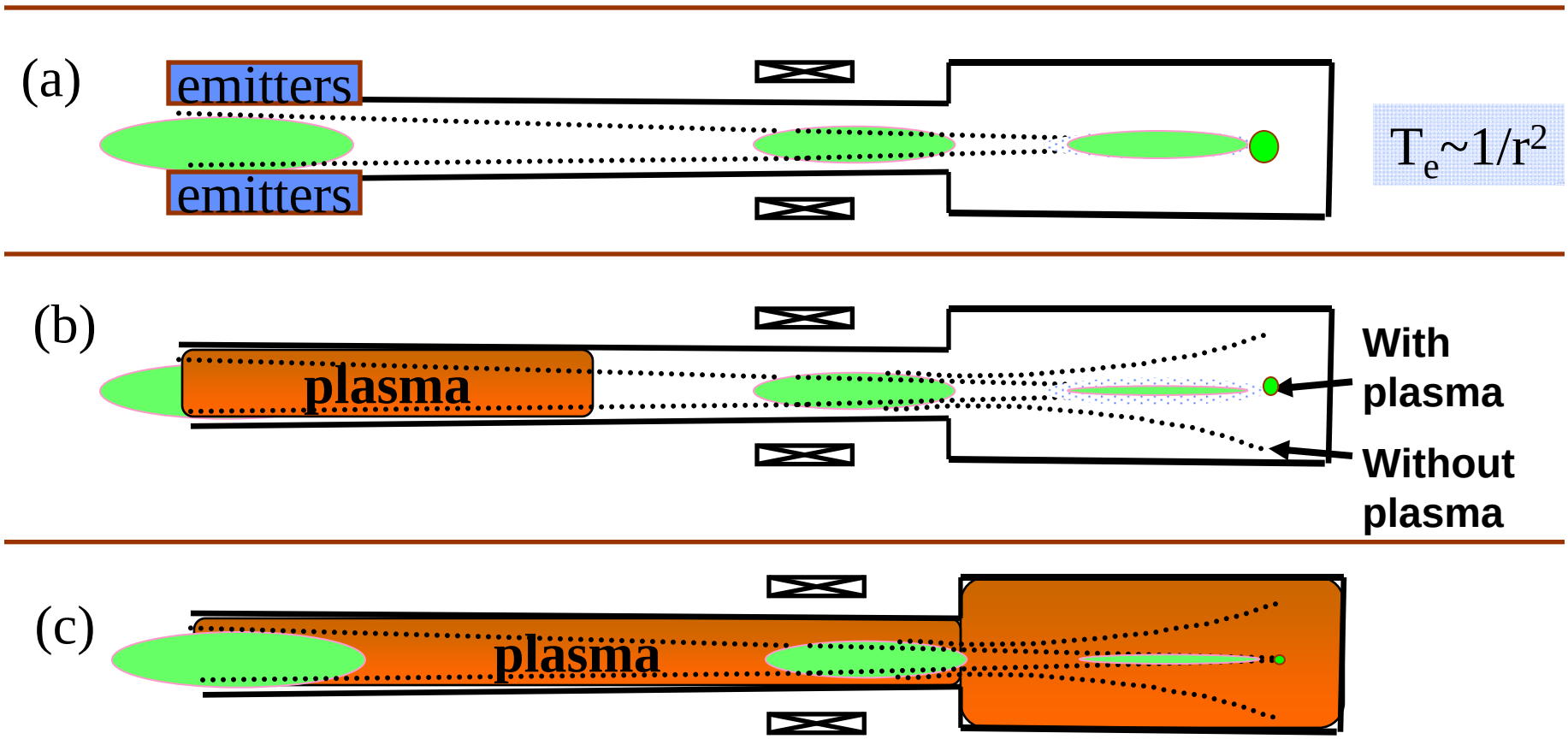
- Overview of established facts about neutralization

- Overview of needed to be established facts about neutralization

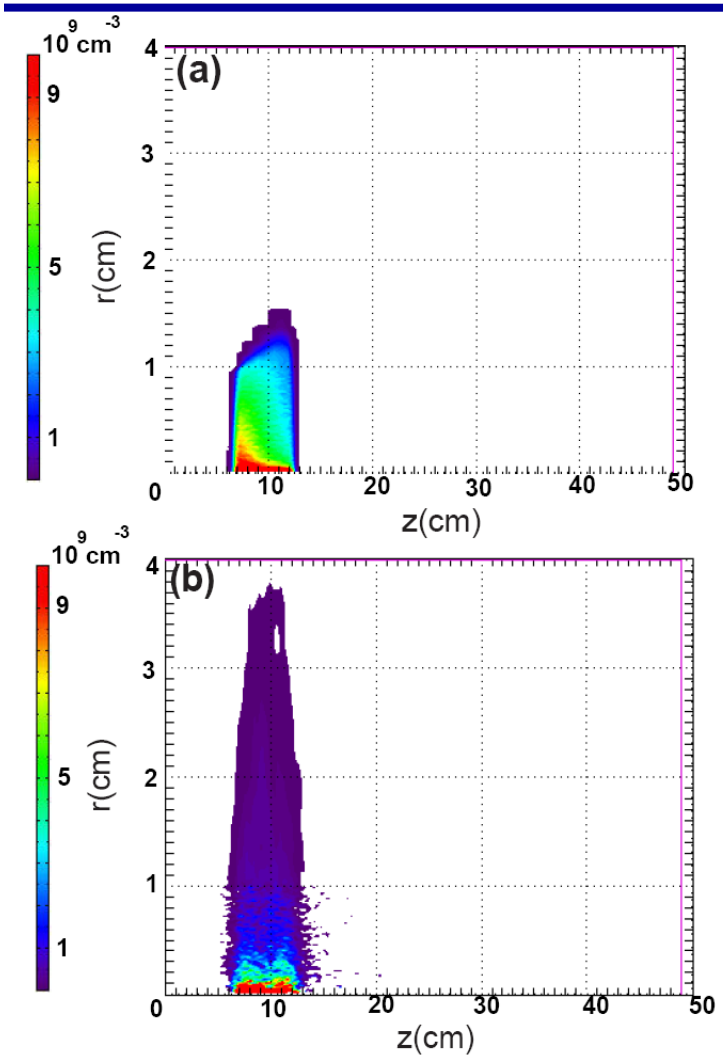
# Methods to neutralize intense ion beam

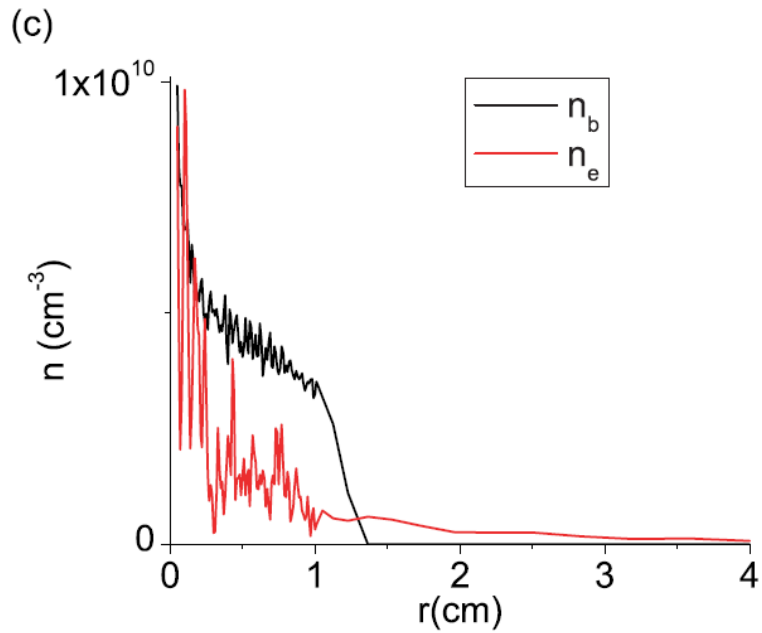
I. D. Kaganovich et al, Physics of neutralization of intense high-energy ion beam pulses by electrons, Phys. Plasmas **17**, 056703 (2010).

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



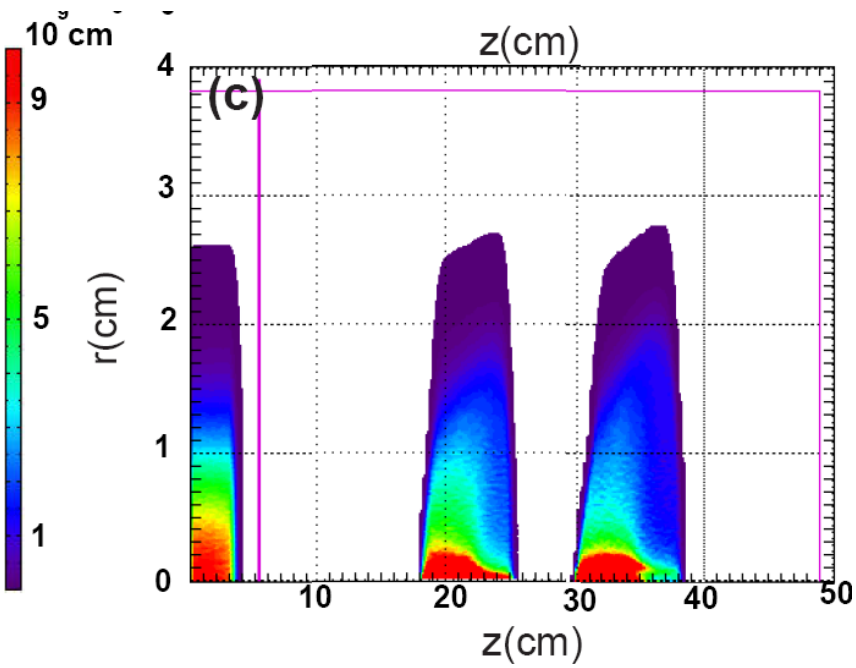
# Neutralization by emitting filaments positioned near the beam sides is no good!

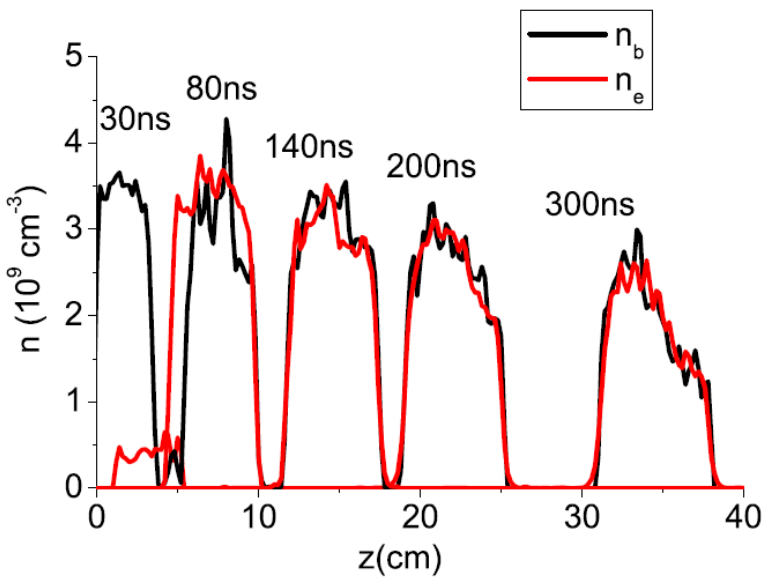



Color plots of (a) ion beam density, (b) electron density, and (c) 1D slice plot.
K+ 320keV; 44ns pulse. The beam radial profile is a gaussian with $r_b$ =1cm; and the maximum beam current density is 0.19A/cm$^2$.

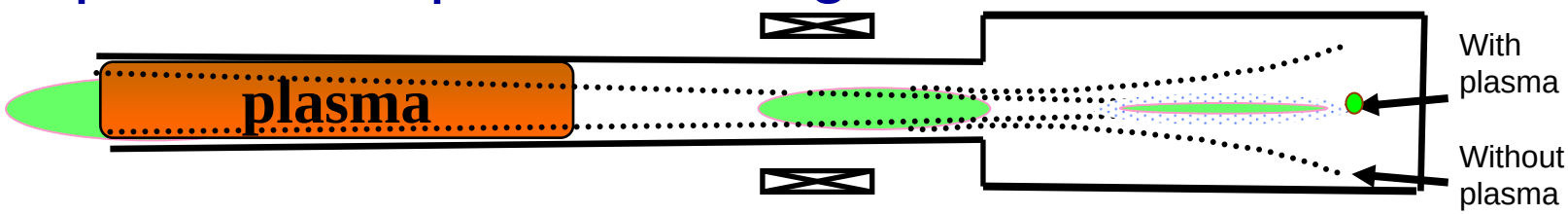
# Neutralization by emitting filaments immersed in the beam maybe good!



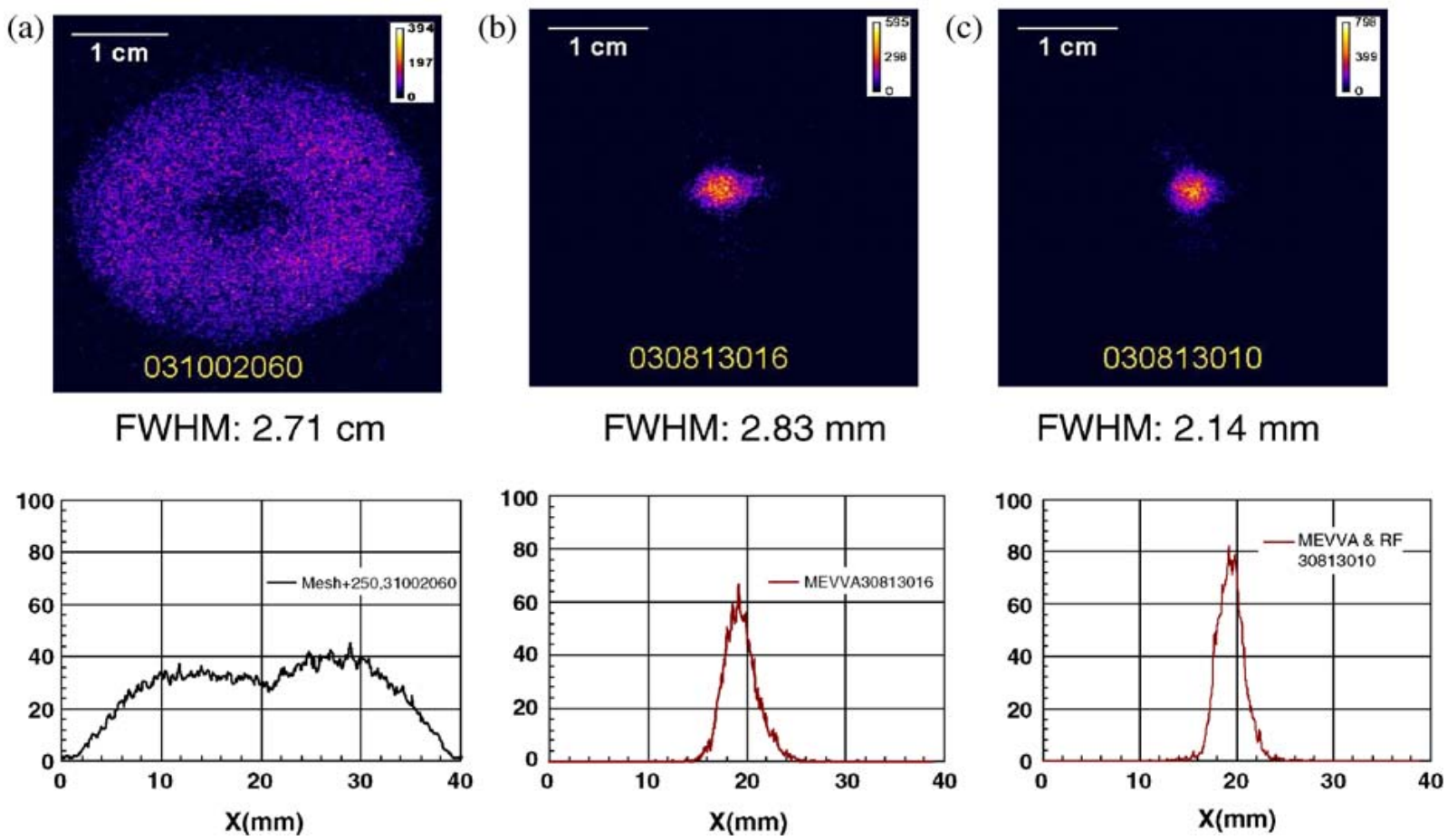




Color plots and one-dimensional plots of ion beam density at 30, 200, and 300 ns. Beam is neutralized with emission from a grid introduced into the beam path at *z=5 cm*.

# 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).

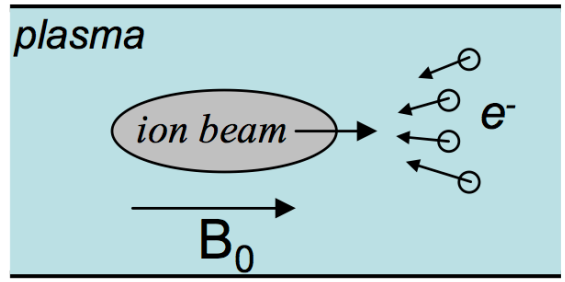



P.K. Roy et al, NIMPR. A **544,** 225 (2005).

# Radial force in plasma is always focusing with or without solenoidal magnetic field

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

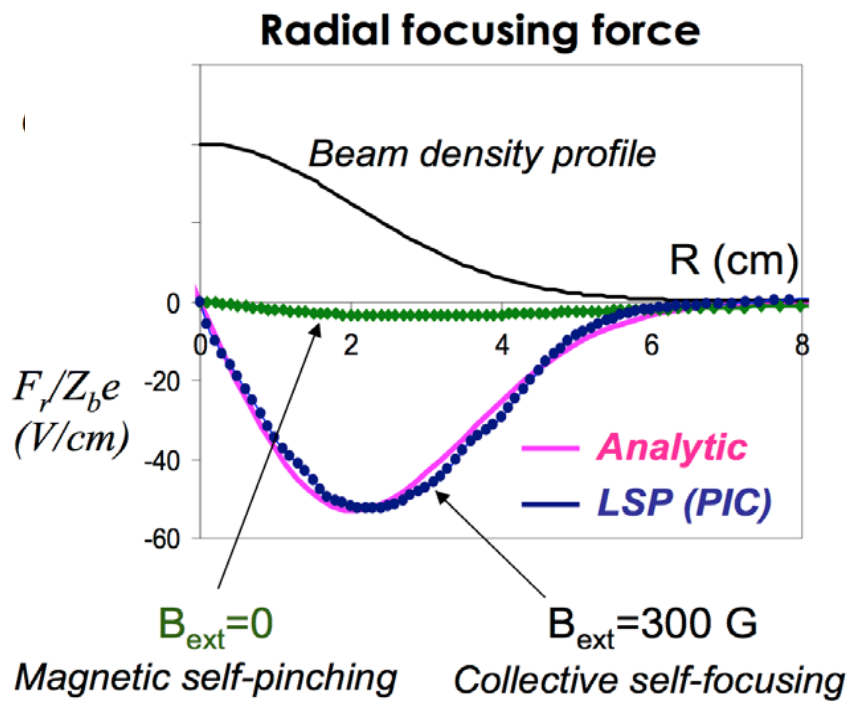
Provided the beam current is neutralized, *i.e.*, $Z_b n_b v_b = n_e v_{ez}$




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

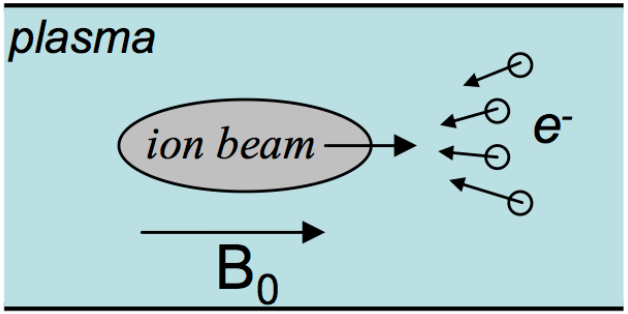
Force is determined by the kinetic energy of an electron moving with beam velocity!

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




M. Dorf, et al., PRL **103**, 075003 (2009).

# Degree of neutralization in NDCX-II beam




Beam potential 10s kV $\phi_b = \pi e^2 n_b r_b^2$

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

Neutralized beam potential 300V, $\phi_p = mV_b^2$

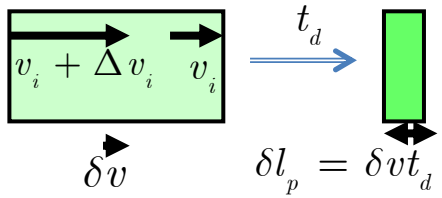
Degree of non-neutralization is <300V/30kV=1% .

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

Relative focusing strengths of self-force for $n_b = n_p$:
NDCX-I: $F_r L_{drift} / F_{sol} L_{sol} \sim 0.04$
NDCX-II: $F_r L_{drift} / F_{sol} L_{sol} \sim 0.5$

M. Dorf, et al., PRL **103**, 075003 (2009).

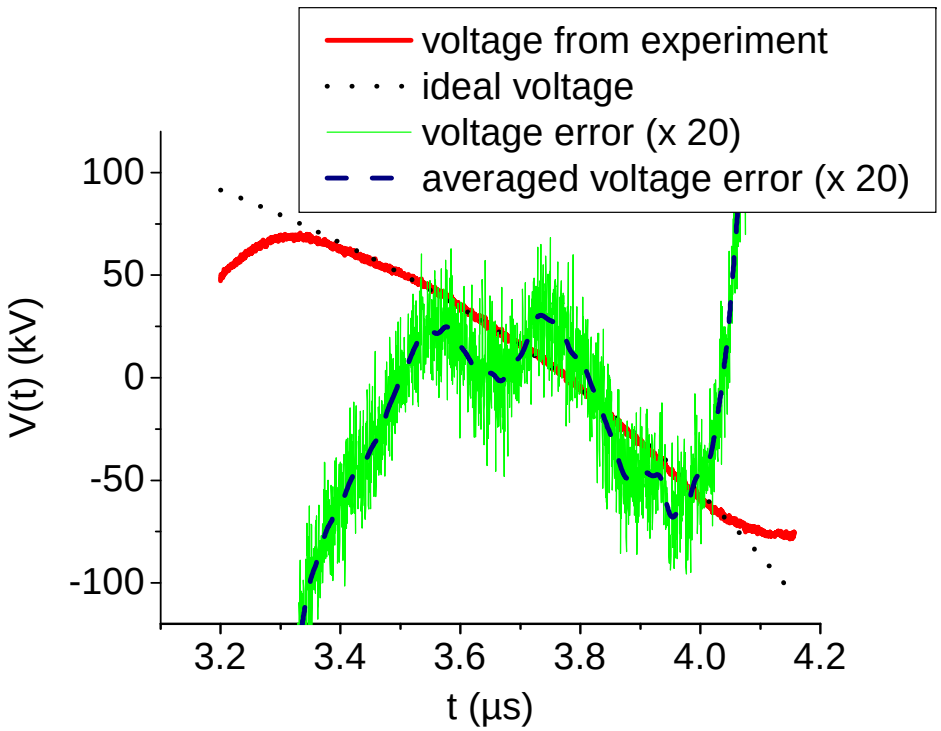
# The longitudinal compression is limited by voltage errors

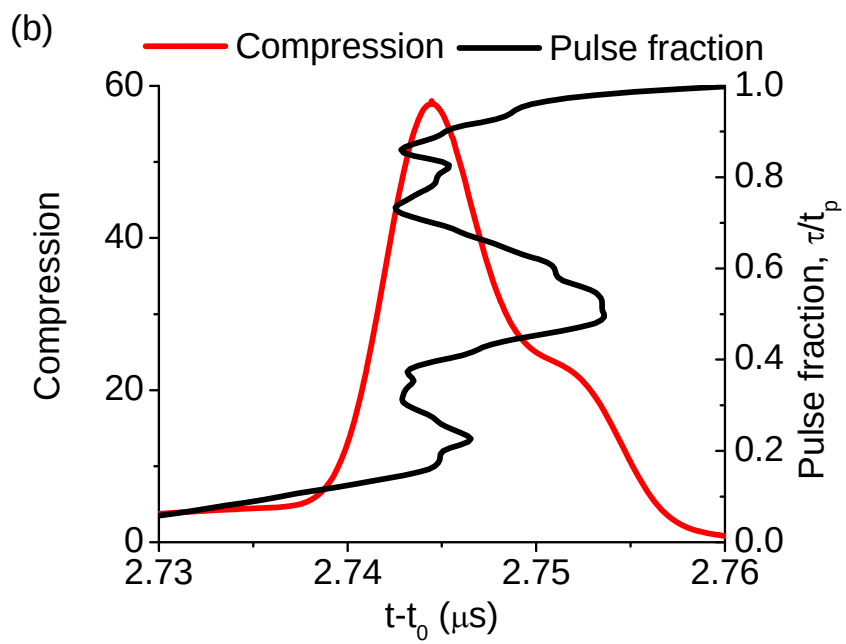



Experimental voltage waveform of the NDCX-I induction bunching module.
S.M. Lidia, et al, PAC 2009.

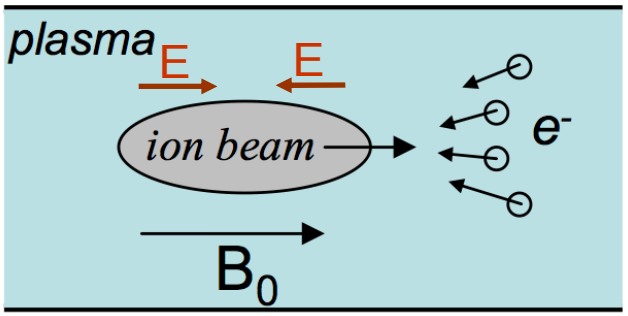
Calculated compressed pulse waveform at the target as a function of drift time.

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



# Effects of incomplete neutralization on longitudinal compression in NDCX-II beam




Neutralized beam potential 300V, $\phi_p = mV_b^2$

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

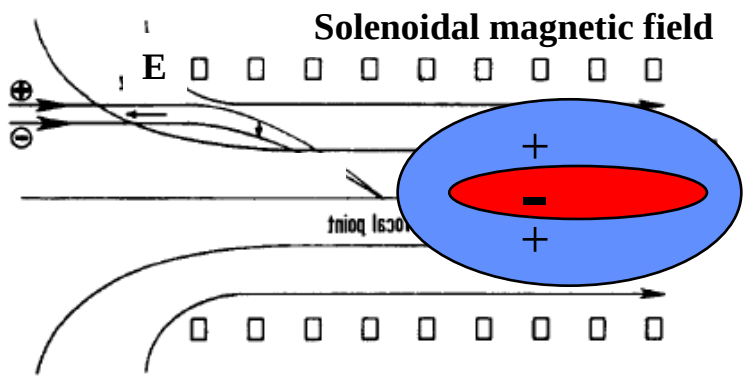
Unneutralized self-electric filed decelerates head and accelerates tail of the beam.

Change in the ion beam energy ~ $\phi_p = mV_b^2 \frac{l_{dr}}{l_p}\frac{n_b}{n_p}$, $l_p$ is initial pulse length

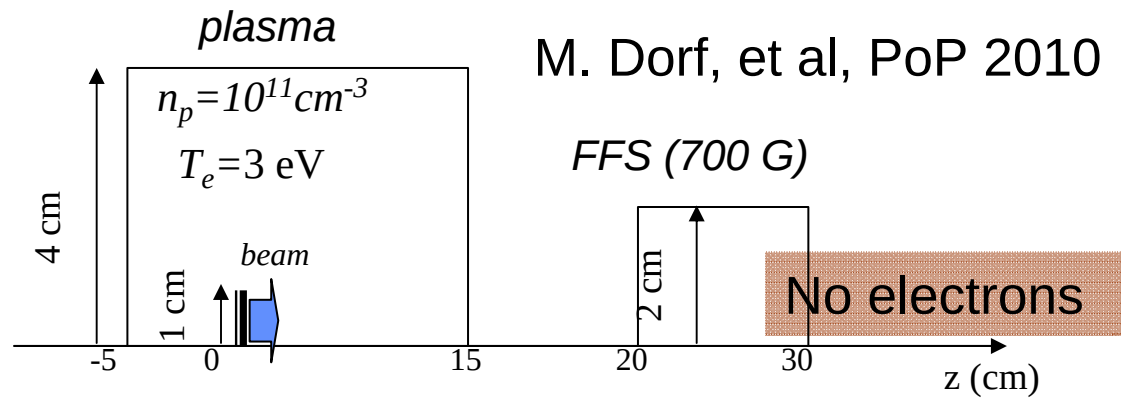
Longitudinal compression is determined by the voltage errors in the bunching module and compressed 2ns part requires voltage errors for part of the beam pulse ~100V.

Therefore, the plasma density requirement is $\frac{l_{dr}}{l_p}\frac{n_b}{n_p} < \frac{100V}{300V} < \frac{1}{3}$

# PIC simulations show collective focusing lens can be used for NDCX-II beam final focus instead of solenoidal lens.



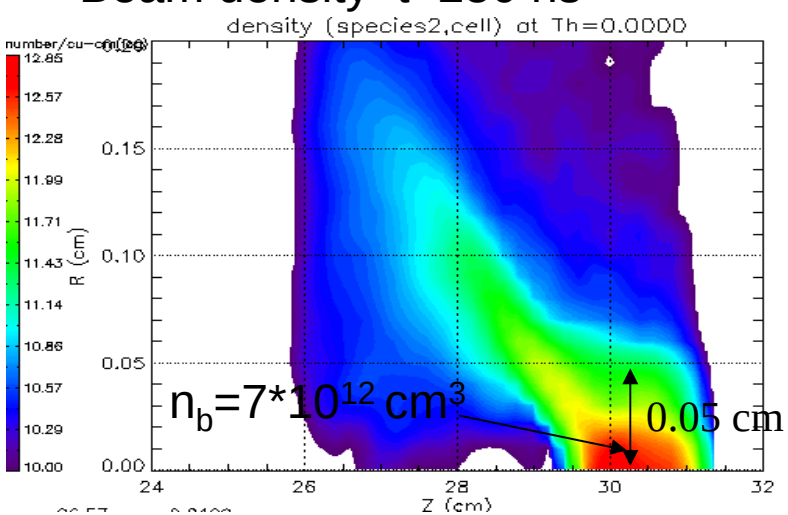

From R. Kraft, Phys. Fluids **30**, 245 (1987)




M. Dorf, et al, PoP 2010

Beam injection parameters $K^+$ @ 320keV, $n_b=10^{10}cm^3$, $r_b$=1 cm, beam pulse=40ns (5 cm)

Beam density t=250 ns




Scheme requires intense beam

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

and no plasma or electrons streaming from target (magnetic dipole)

# Outline

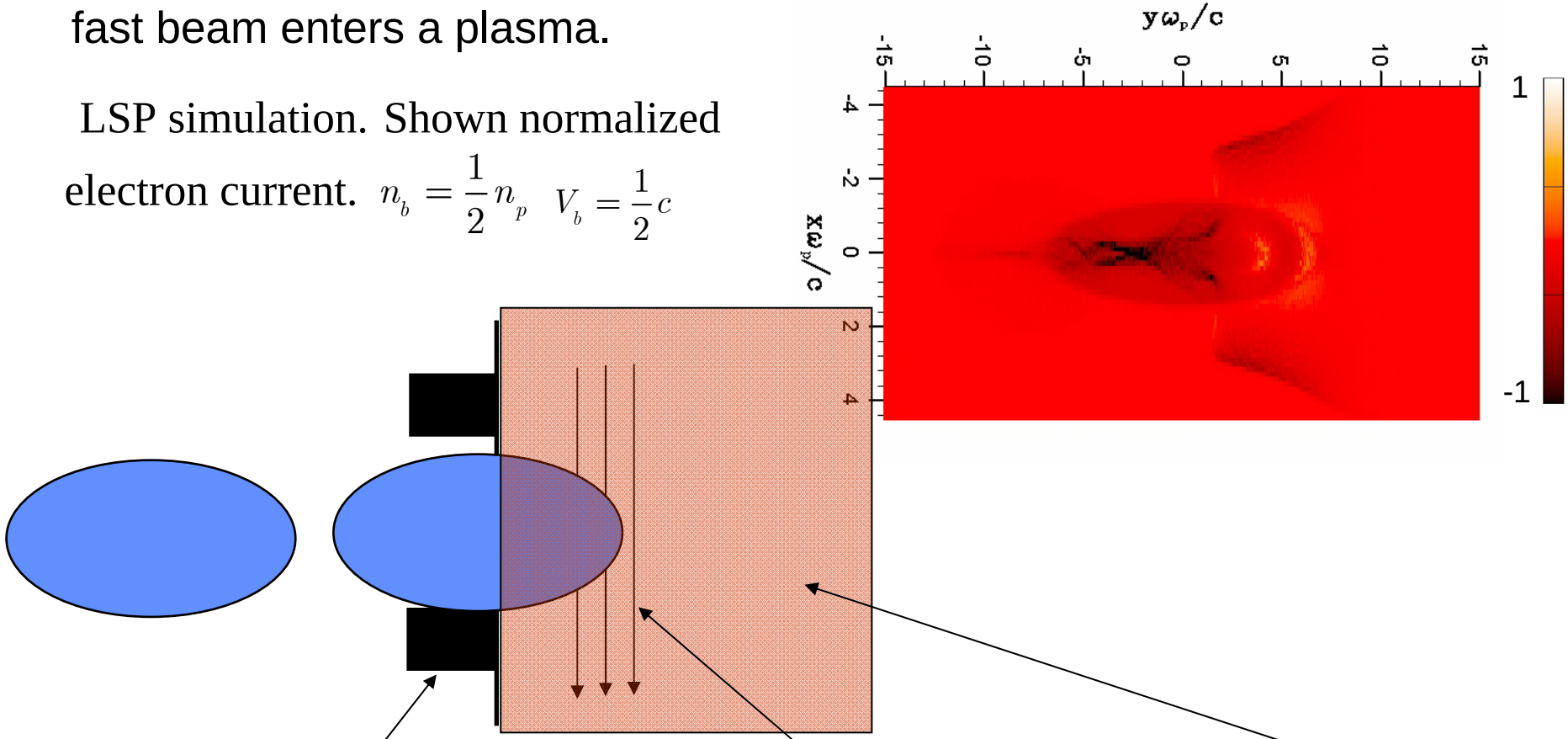
- Overview of established facts about neutralization

- Overview of needed to be established facts about neutralization

# Study of possible beam emittance growth during transition into a plasma

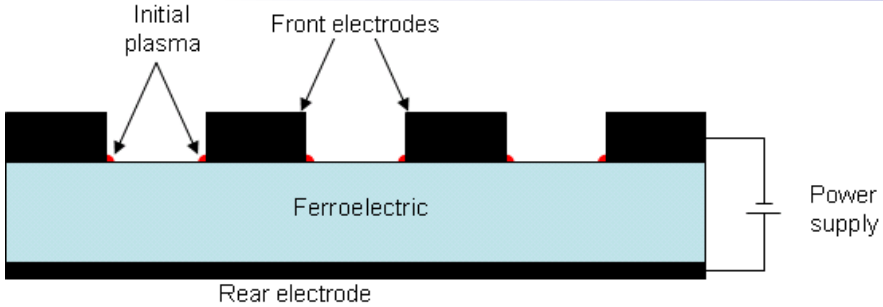
- Complex nonlinear electromagnetic fields are generated when intense fast beam enters a plasma.

LSP simulation. Shown normalized electron current. $n_b = \frac{1}{2} n_p \quad V_b = \frac{1}{2} c$

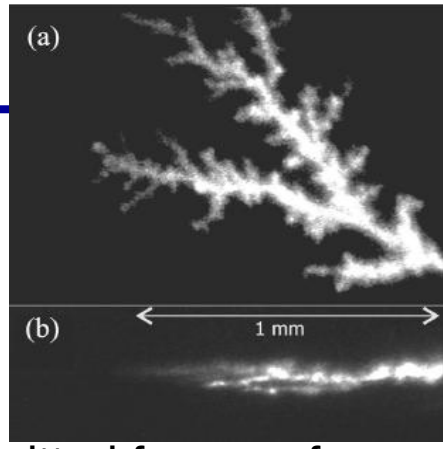



Negatively biased ring and magnetic dipole mitigate electron penetration into accelerator and reduce beam emittance growth.

# Study of mechanisms of plasma formation in ferroelectric plasma source




Photograph of plasma
top view (a)
side view (b)
Ya. E. Krasik

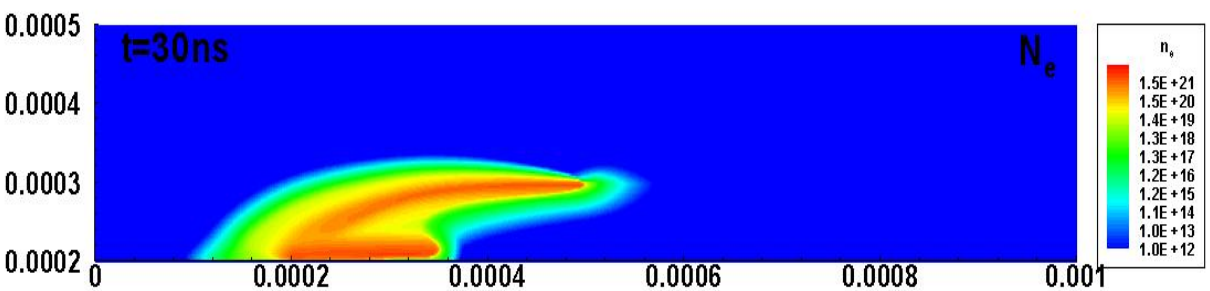


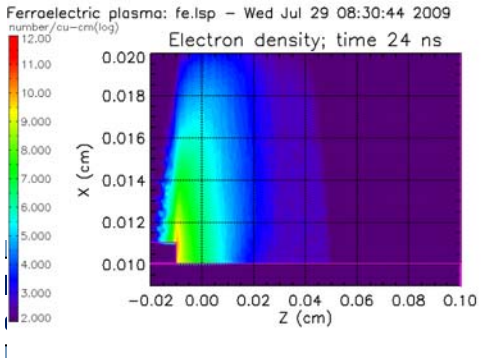

Plasma is produced from desorbed or sputtered gas and electrons emitted from surface in a very thin layer near the surface. Plasma density is increased for short nanosecond pulses or by applying a crowbar method.

**Need a model explaining why this method yields an increase in plasma density?**

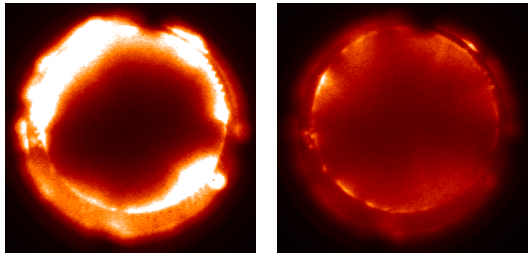
**Need a model for plasma expansion velocity into vacuum.**

Preliminary simulations with WARP, LSP and fluid code show complex nonlinear phenomena of plasma formation dependent strongly on gas desorption and electron emission.



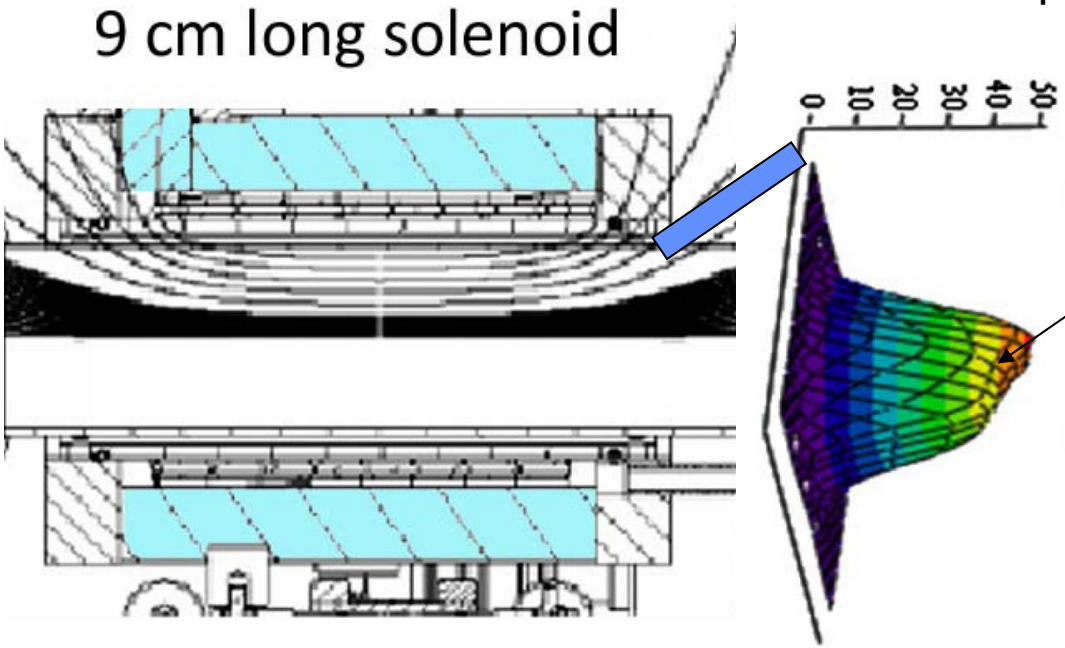



# Study of plasma filling the pipe in complex time-dependent magnetic field

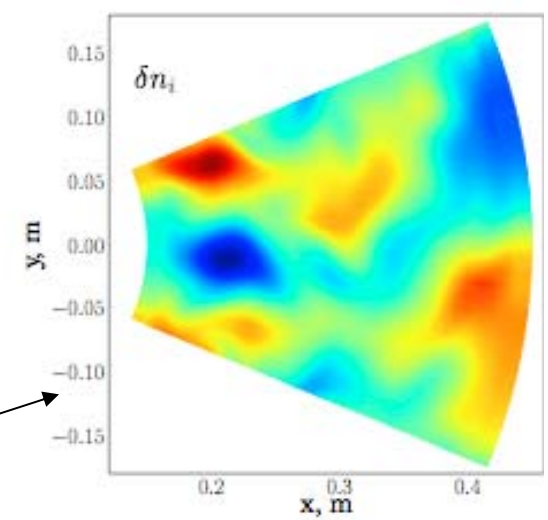



1. Plasma filling depends on how much plasma is generated near the surface and its velocity propagation into vacuum.

2. Plasma mostly flows along the magnetic field lines created by the CAPS filter coils, the 8 T solenoid, and the eddy currents. The tendency to follow magnetic field lines, plus the effect of magnetic mirroring limits the amount of plasma at the solenoid midplane.




Ion saturation current measured on a hexagonal array of copper collector disks. Prabir, *et al*.




3D instabilities, Umansky et al, resistive drift wave, rotational Interchange, Kelvin-Helmholtz

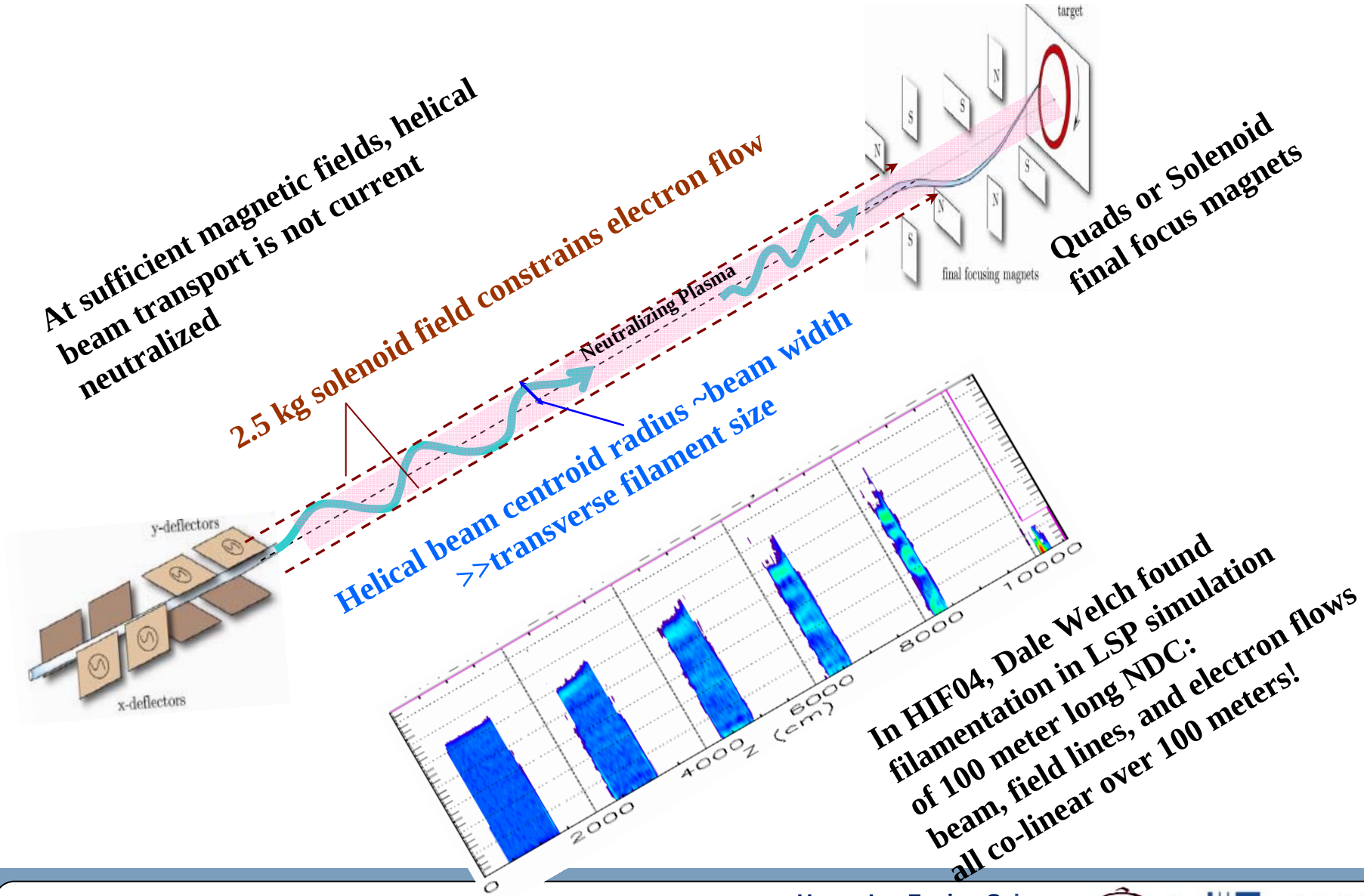
# Conclusions for simultaneous longitudinal and transverse neutralized compression

Analytical theory and simulation show that plasma can provide the necessary neutralization for compression, provided the plasma density exceeds the beam density everywhere along the beam path, i.e., $n_p > n_b$.

Further studies are needed:

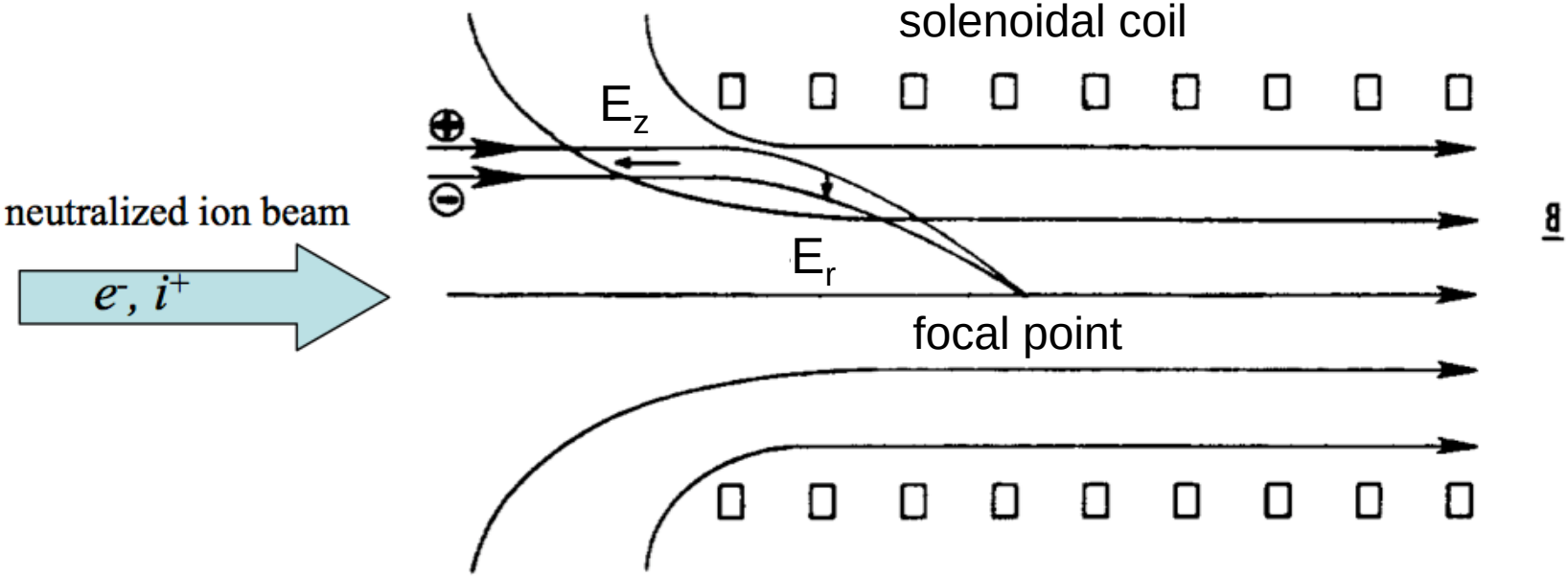
- beam emittance growth during transition into a plasma.
- mechanisms of plasma creation in ferroelectric source.
- plasma filling the pipe in complex time-dependent magnetic field.

# Beam filamentation (Weibel) instability should be investigated with *rotating helical beams* during NDC



# The "Robertson lens" is an example of a multi-species system that we need to simulate in full kinetic detail

- An ambipolar electrostatic field brings both species to a common focus
- For a given focal length, the required $B_0$ is smaller by a factor of $(m_e/m_i)^{1/2}$



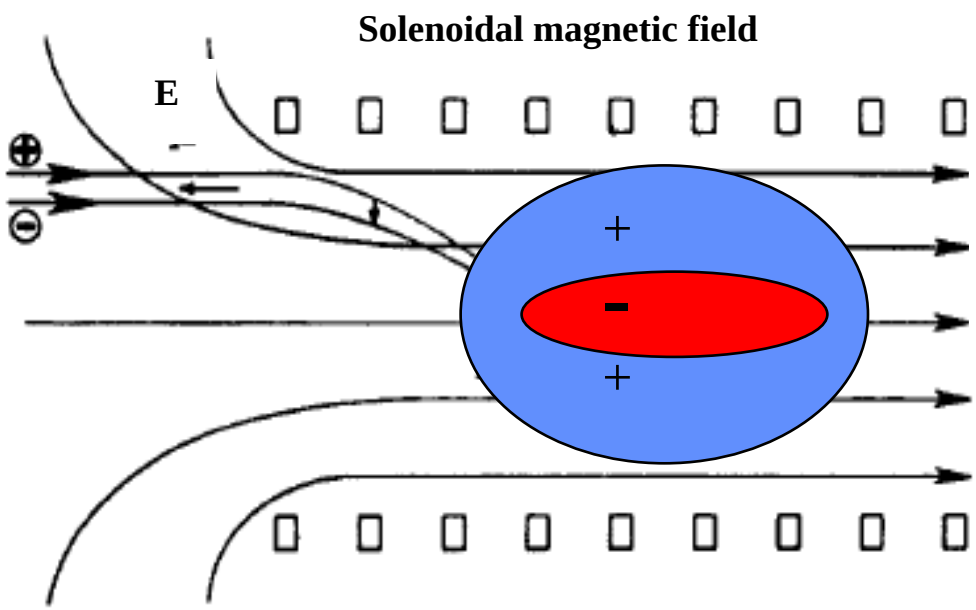

(from Kraft paper)

Focusing force on beam: $F_r = -\frac{r}{4} m_i \Omega_e \Omega_i \quad (\Omega_i = Z_b e B_0 / m_i c)$

References: S. Robertson, *Phys. Rev. Lett.* **48**, 149 (1982).
R. Kraft, B. Kusse, & J. Moschella, *Phys. Fluids* **30**, 245 (1987).

*requires:*
$r_b << c/\omega_{pe}$
$\omega_{pe} >> \omega_{ce}$

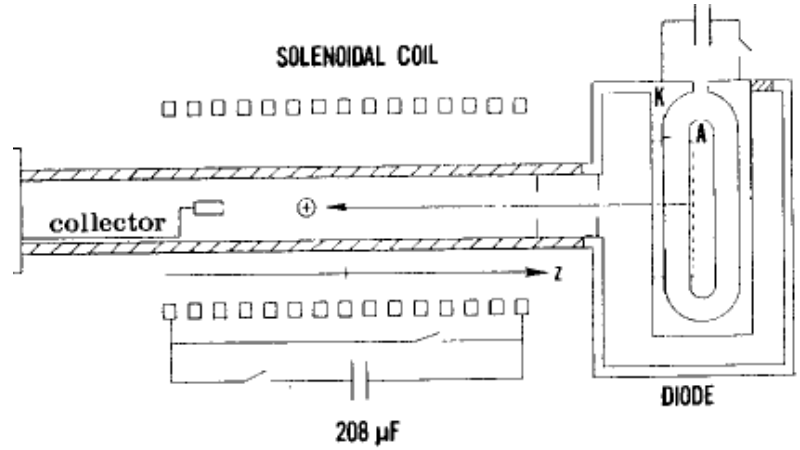
# Collective focusing schemes




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

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

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




. Experimental apparatus.

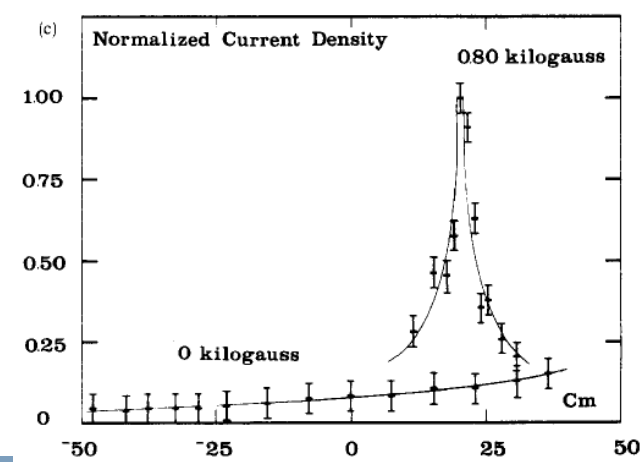
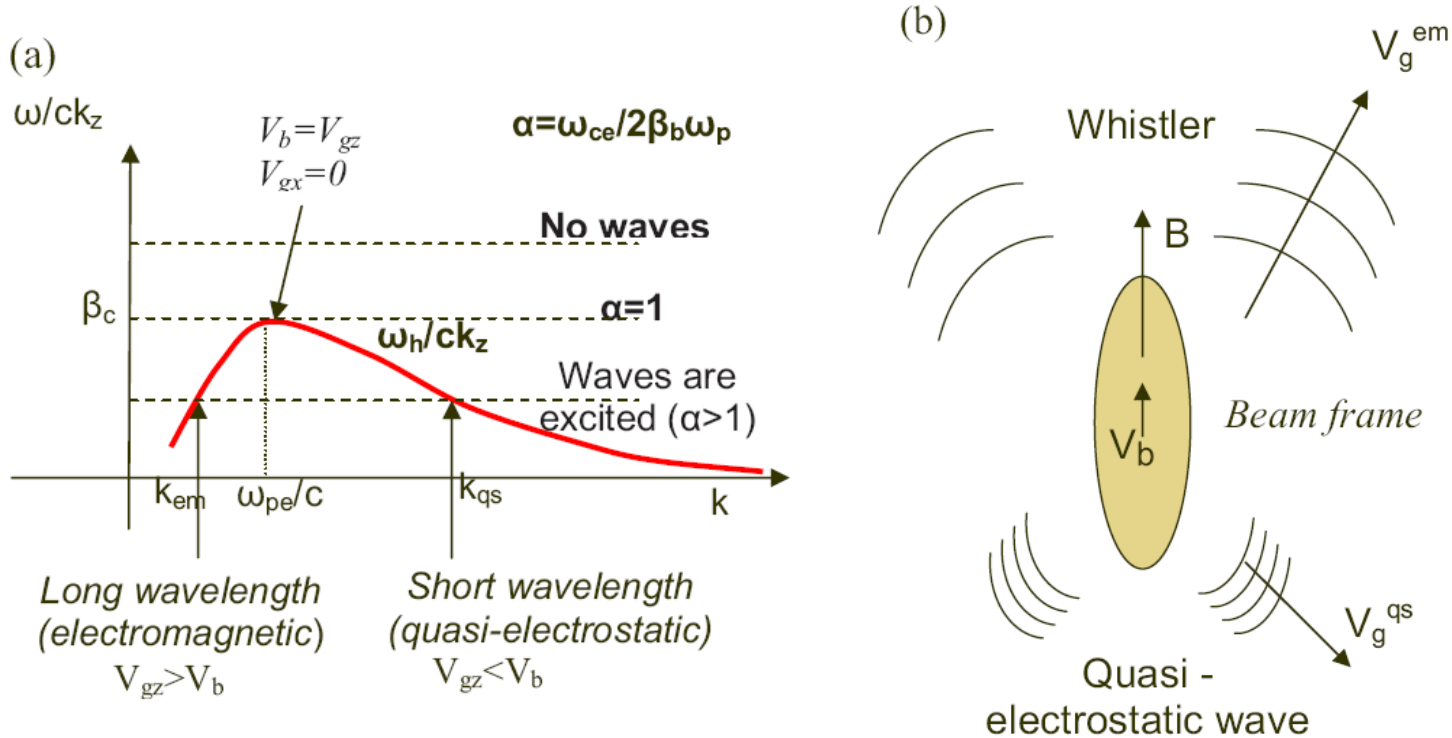



FIG. 8. Focused ion current. (a) Ion current density versus time ($B = 0$, 1.5 kG). (b) Peak ion current density versus axial position ($B = 0$, 1.5 kG). (c) Peak ion current density versus axial position ($B = 0$, 1.5 kG).

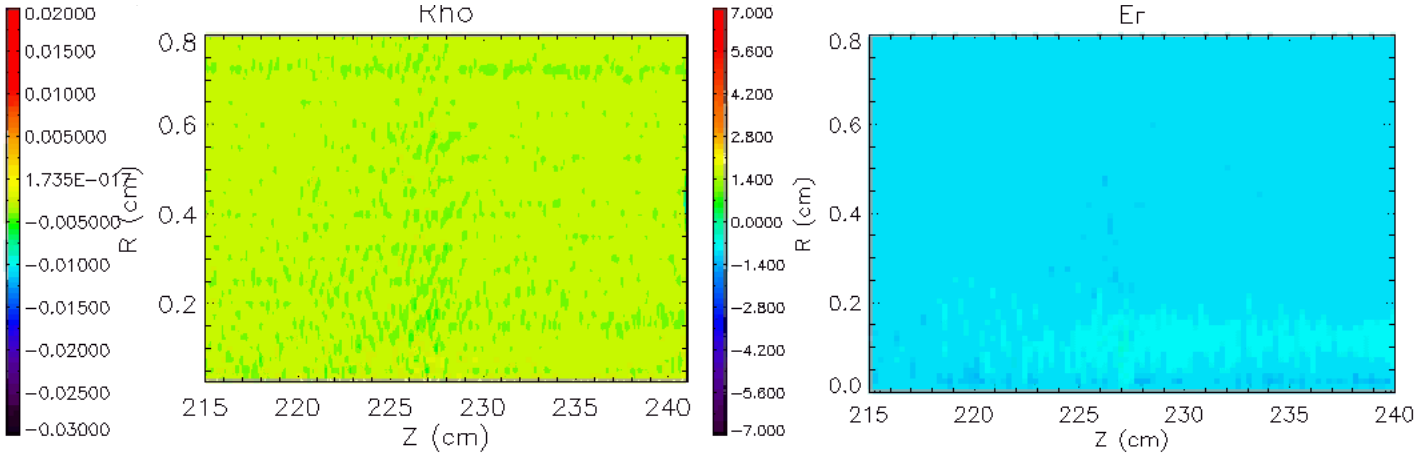
# The beam can excite whistler waves

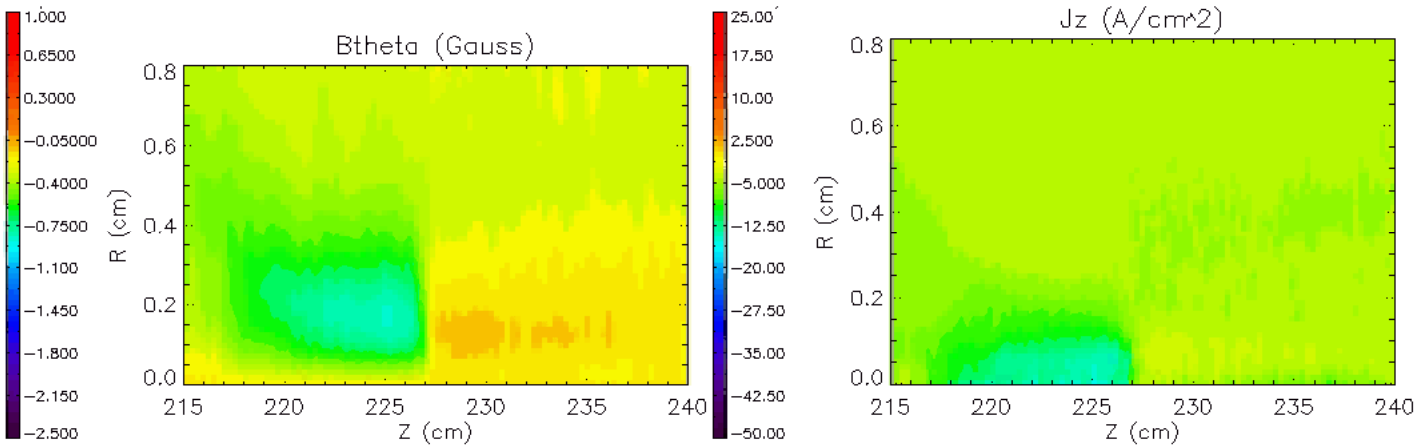


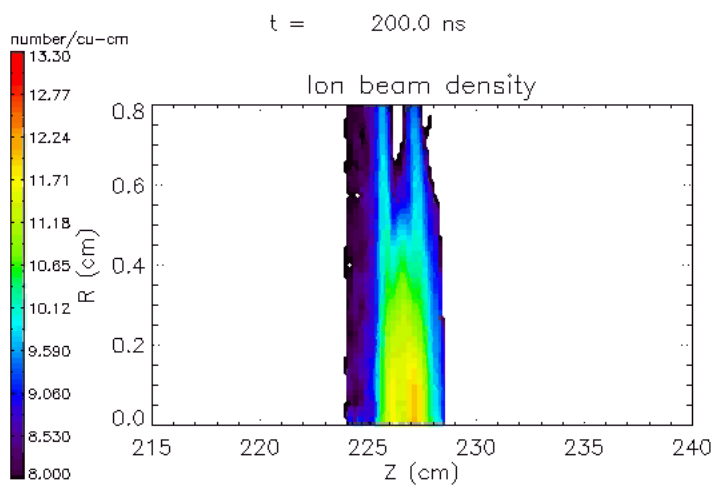

(a) The phase velocity of the whistler wave is plotted as a function of wave vector (solid curve) and is intersected by different values of the normalized beam velocity (dashed lines).

(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