Drift compression and Final Focus

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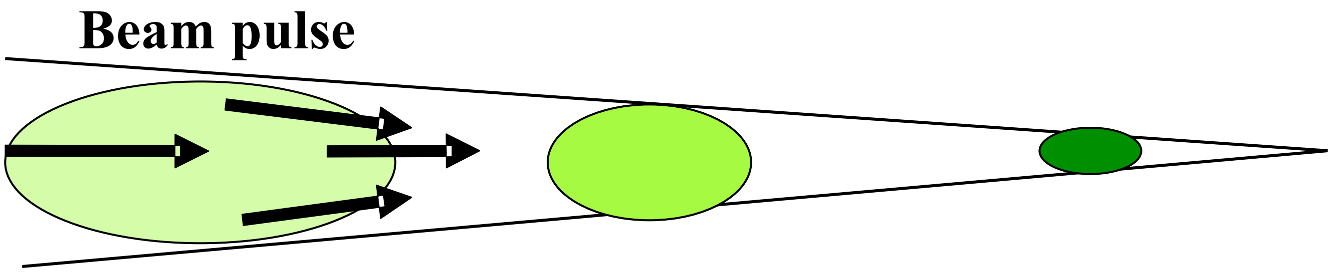
- Scott Massidda, Columbia University
- William Berdanier, Univ. Texas at Austin

Neutralized drift compression can potentially reach 300x900 ≈ 3 10^5 combined longitudinal and transverse compression of ion beam pulse.



If all ions of the beam pulse are ideally focused to one spot the final compression is limited by small temperature or emittance.

An example:

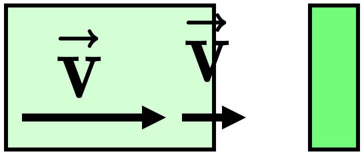
1 meter length pulse to 3 mm= 300 density compression

3 cm radius to 1 mm = 30^2=900 density compression.

Outline: **Drift compression and Final Focus**

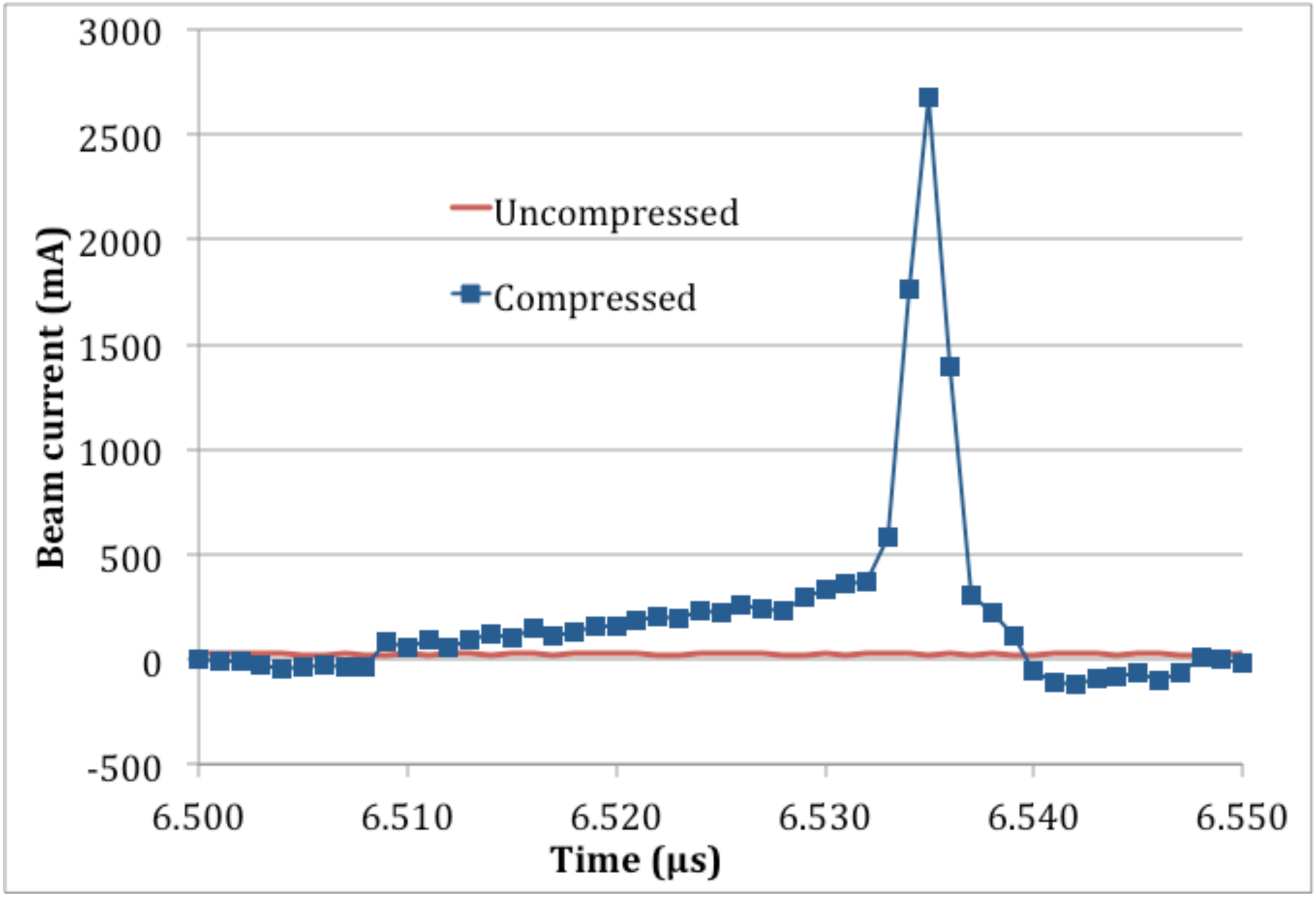
- Longitudinal Drift compression
    - Effects of voltage errors
- Simultaneous longitudinal and radial compression
    - Chromatic effects in final focus
- The physics of the neutralization process and requirements for plasma sources.

Longitudinal Compression

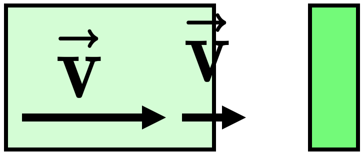


Experiments at NDCX I observed ~90 times compression: the peak current (2.7A) has increased from the uncompressed current (0.030A).

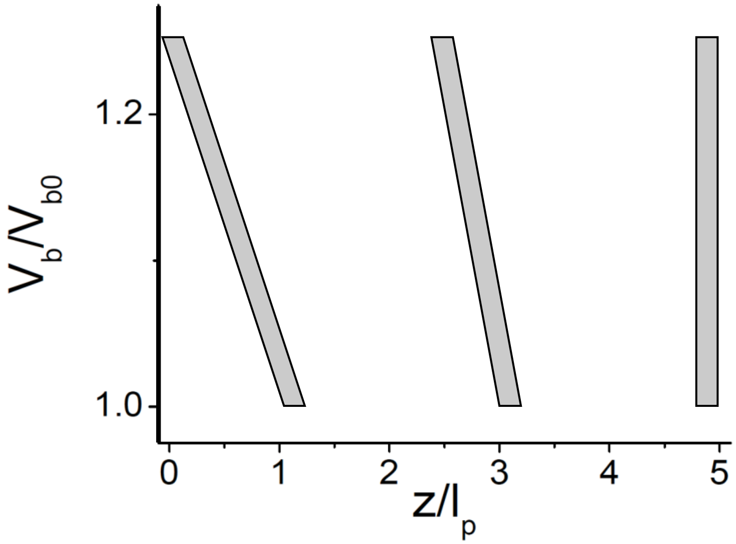
S. Lidia et al, 2011

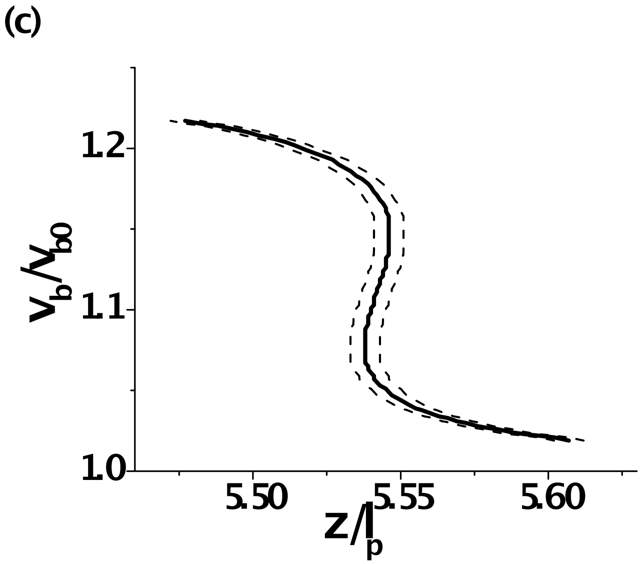


Longitudinal Compression is sensitive errors in velocity tilt



The phase-space during ideal compression with a linear velocity gradient.



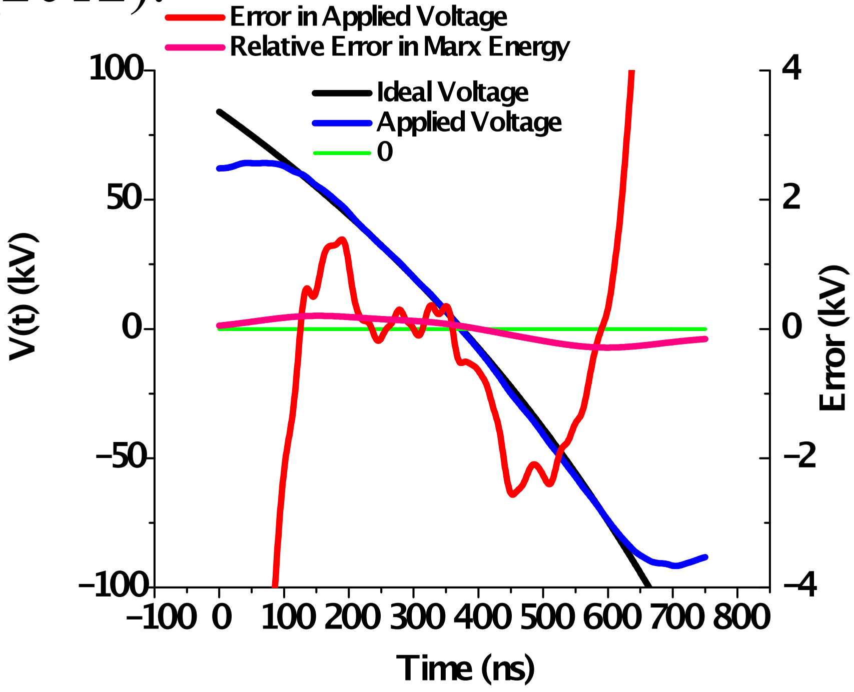


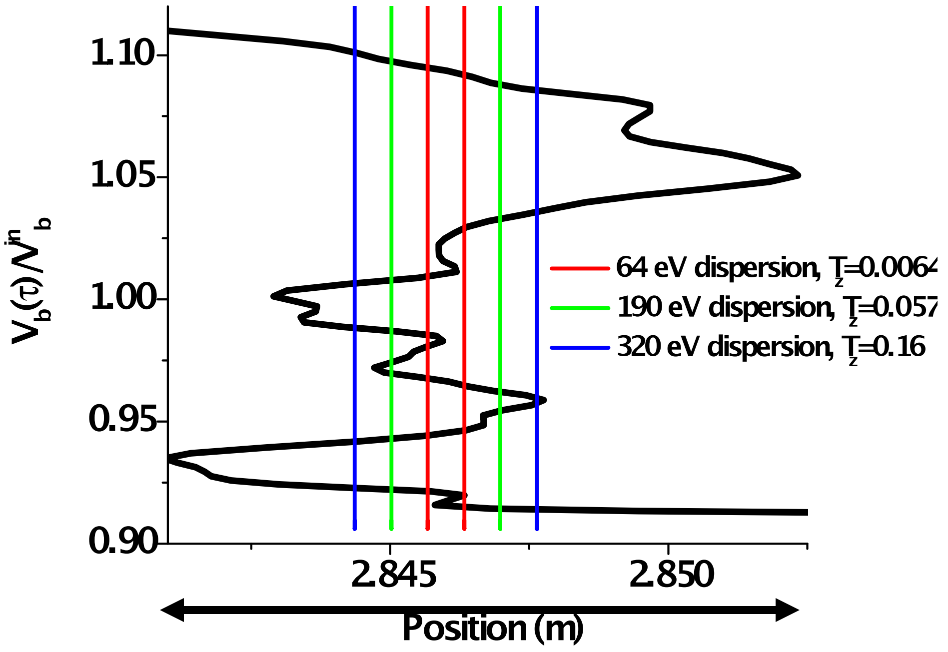
Compression time is given by $1/dv/dz$ is very sensitive to small scale wiggles, that results in different parts of the beam pulse being compressed at different location.

1-10% Voltage errors limit the longitudinal compression

Experimental voltage waveform of the NDCX-I induction bunching module from S. Massida, et al NIMA **678**, 39 (2012).

Phase space plot of the pulse with different mean intrinsic energy spreads, E_{b0} = 322keV and the target location is 2.846m.

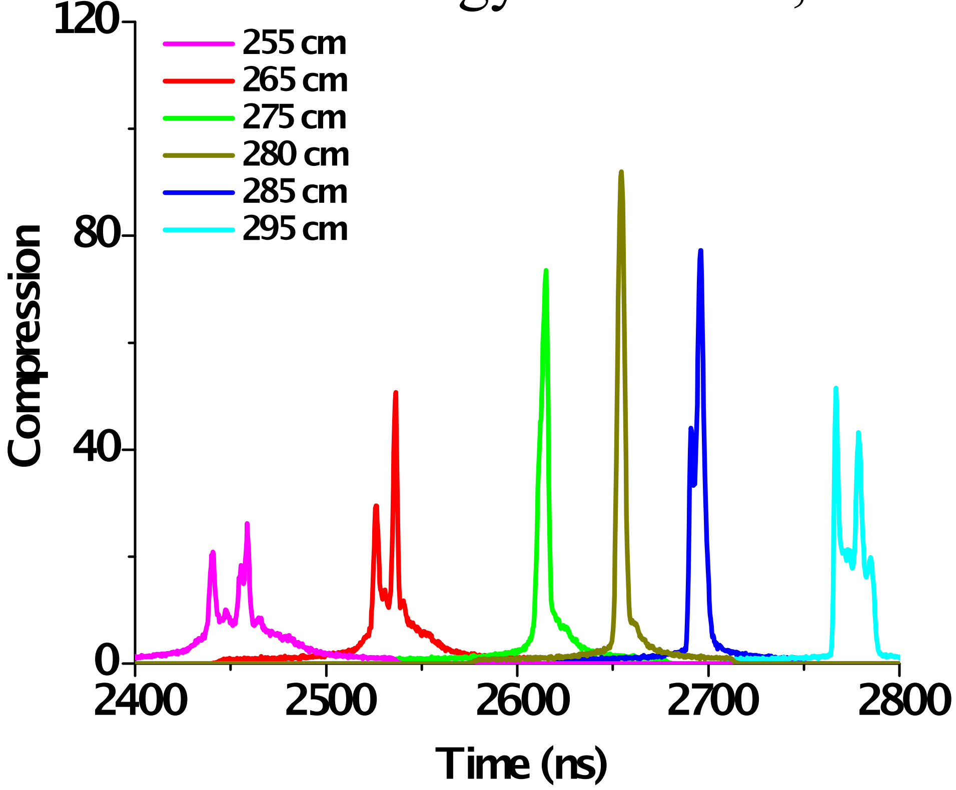




1 cm spread due to errors

Beam compresses for a wide range of locations near the target plane

The simulated compressed pulse waveform at six different target locations, from z= 255 cm to 295 cm as a function of drift time after the beam pulse passes through the induction bunching module for the NDCX-I voltage waveform. The beam energy is 317keV, and the energy spread is 252eV.

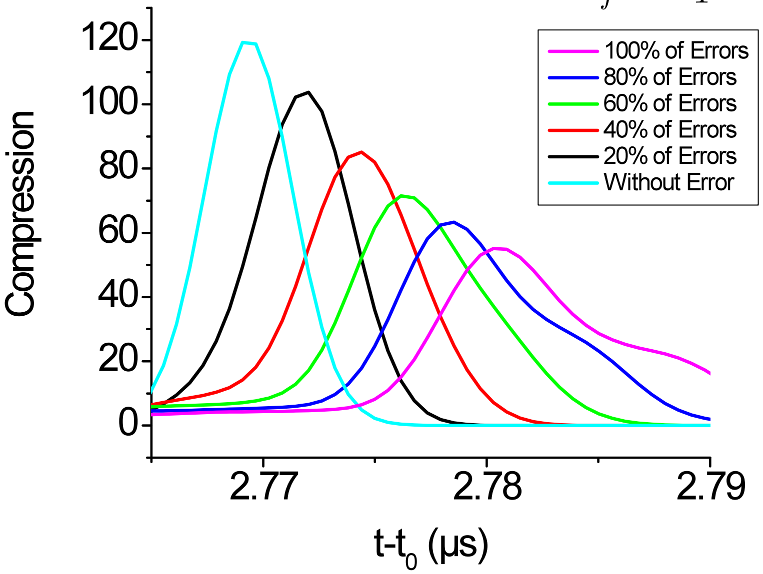


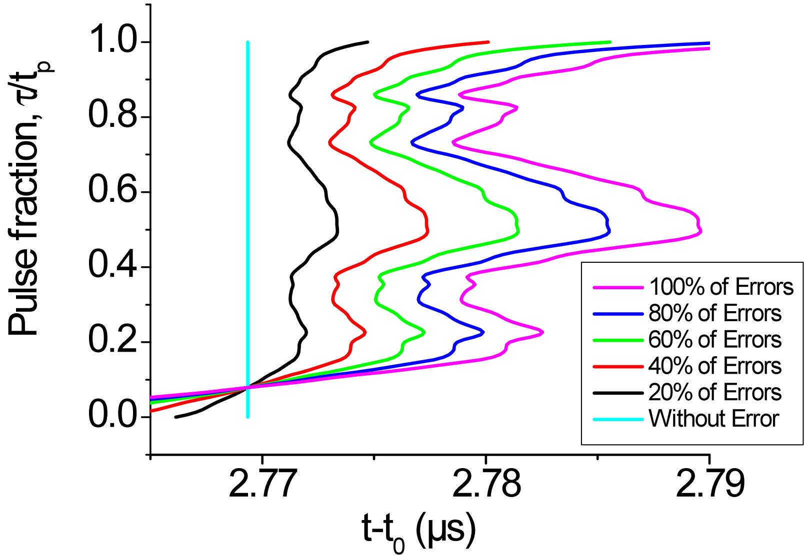
from S. Massidda, et al
NIMA **678**, 39 (2012).

Compression ratio is a weak function of errors, that is factor of two improvement will require a lot of work

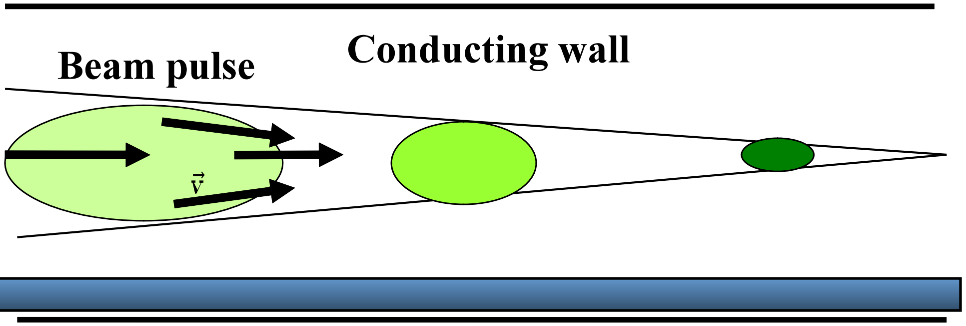
Simulated compressed pulse waveform and pulse location at the target location for reduced voltage errors as a function of time. The initial beam energy is 276keV, and the longitudinal temperature is T_z=0.27eV

$$C_{\max} \approx \frac{t_g}{t_f}\left(\frac{v_b E_b}{v_T dU}\right)^{1/2}$$





Outline

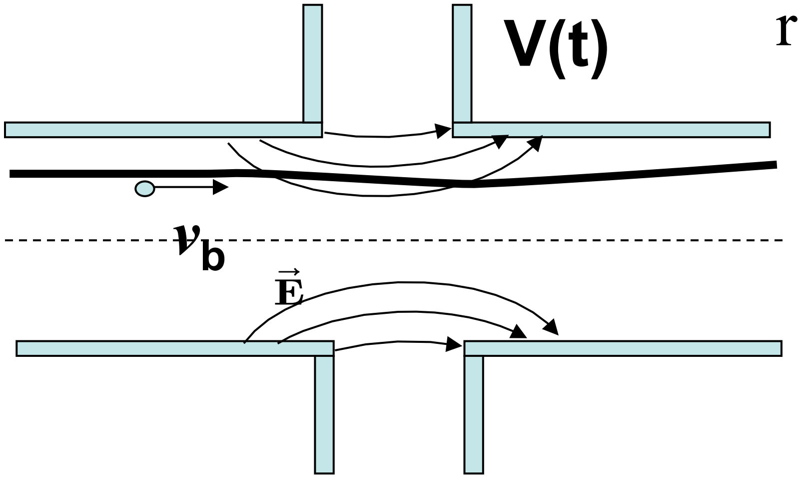


- Longitudinal Drift compression
  - Effects of voltage errors

- Simultaneous longitudinal and radial compression
  - Chromatic effects in final focus

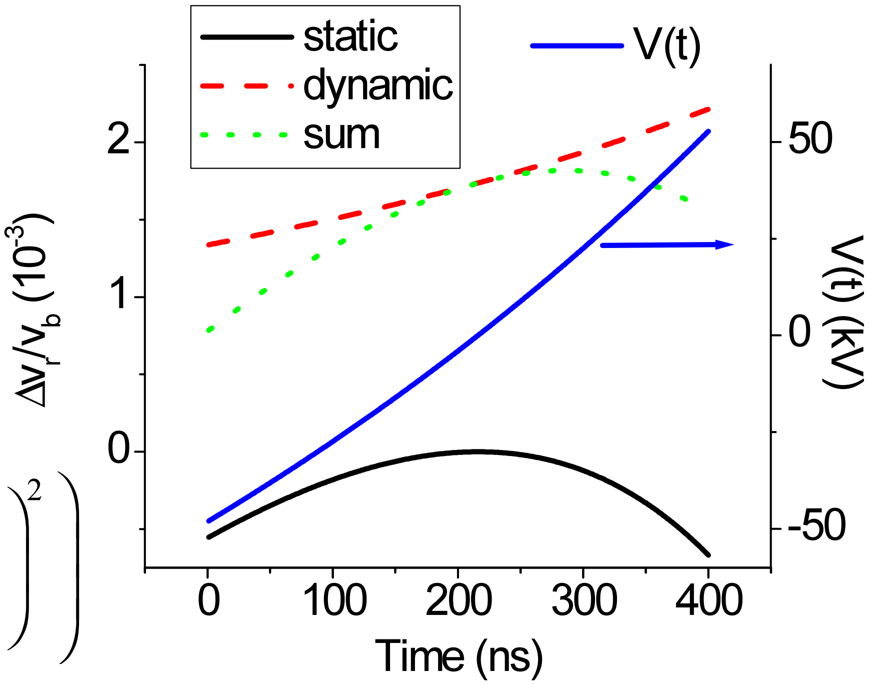
Aberrations in the bunching module results in beam defocusing

acceleration gap of the induction bunching module.



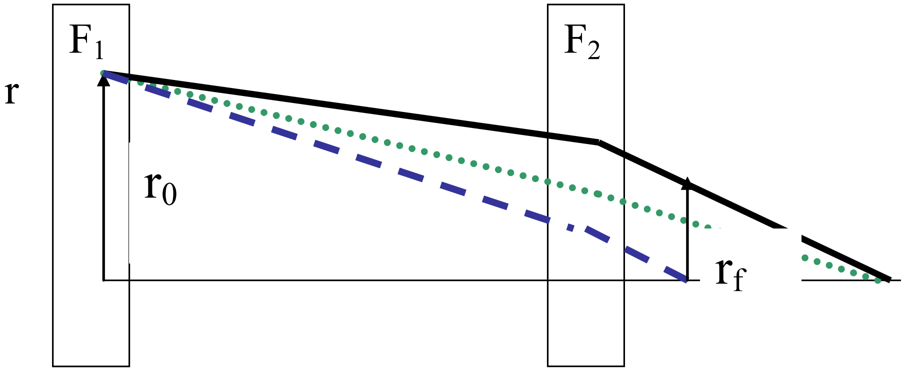
$$\frac{\Delta v_{br}}{v_{b0}} \cong \frac{r}{R_w}\left(-\frac{R_w}{4v_{b0}}\frac{e\dot{V}(t)}{E_b} - 0.082\left(\frac{eV(t)}{E_b}\right)^2\right)$$

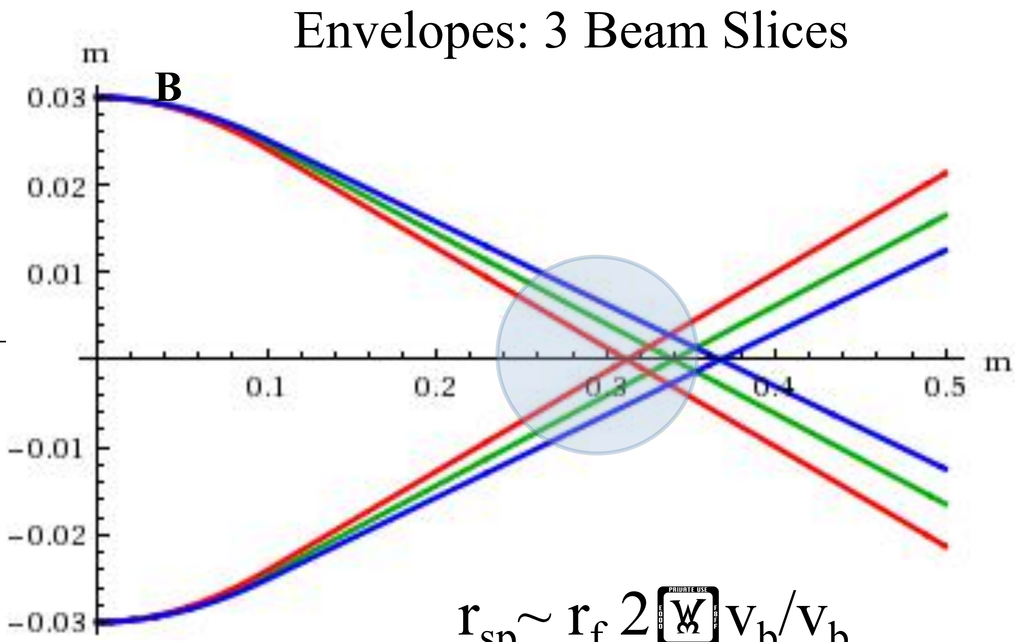
The static and dynamic aberrations for NDCX-I. Pulse t_p=400ns, E_b=300keV, r=1cm, R_w=3.8cm.



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

A strong focusing element mitigates defocusing errors in the bunching module, because beam from different radius is focused into the target, but introduces chromatic effects.




Envelopes: 3 Beam Slices

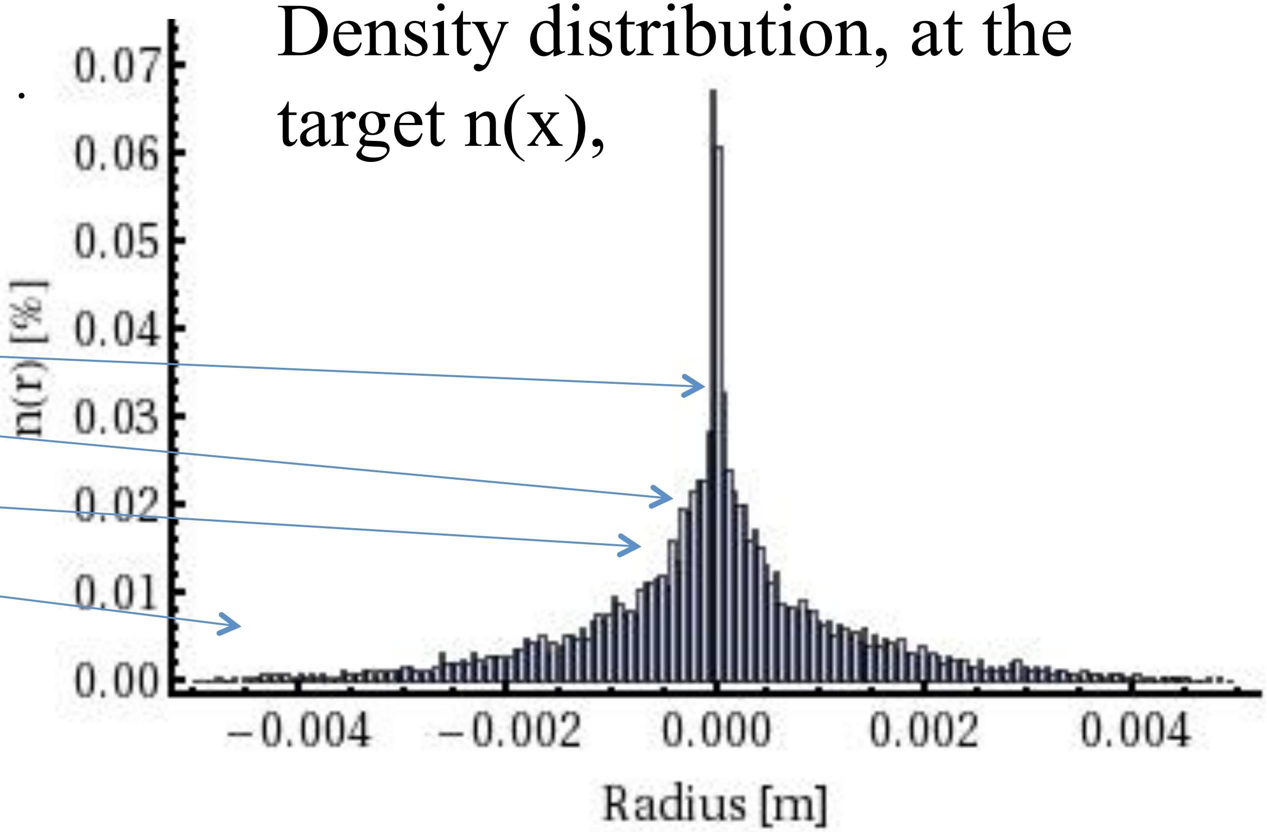
$r_{sp} \sim r_f\, 2$ [illegible] v_b/v_b

Chromatic effects in final solenoid yield a sharply peaked radial distribution with “long wings”

NCDX-II beam parameters, 8T solenoid 10% velocity tilt, initial beam radius, R_0, 30 mm, 3 MeV, Li^+ ions, ε=2.25 mm·mrad.

r_{50} – radius containing 50% of beam particles.
r_{90} – radius containing 90%.
r_{100} – radius containing 100% .

Density distribution, at the target n(x),

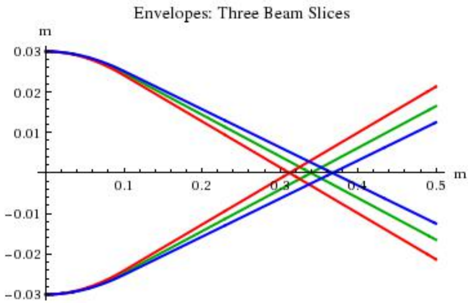


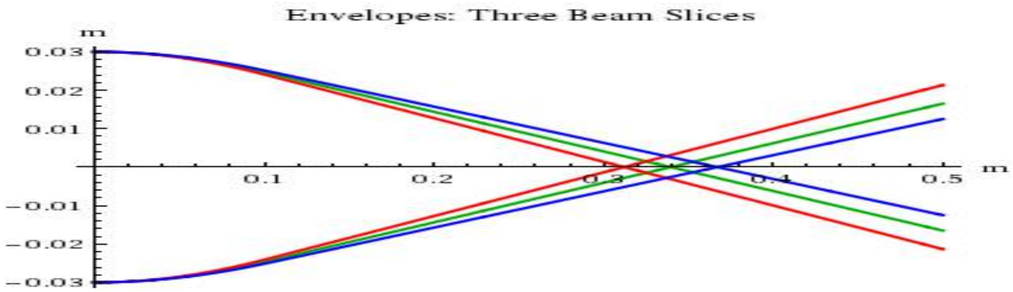
FWHM ≈150μm.
r_{50} = 540μm.
r_{90} = 1.57 mm.
r_{100} = 5.66 mm.

J. Mitrani, et al (2012)

Increasing strength of final solenoid does not reduce the spot size

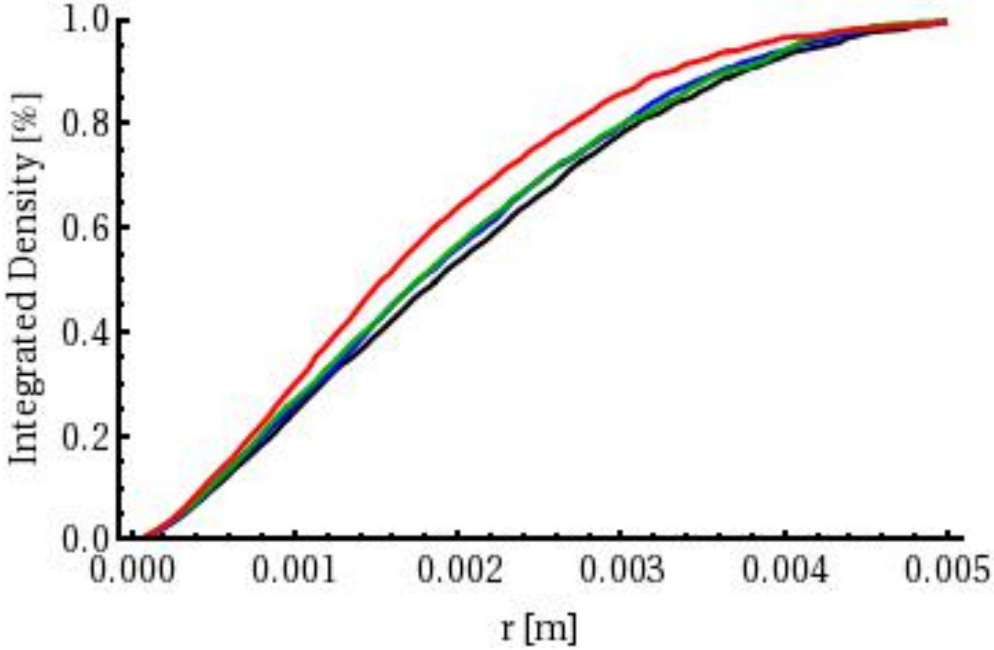
$r_{sp} \sim r_f\, 2\,\square\, v_b/v_b$





black/blue/green/red curves represent FFS field strengths of **3**, 8, 12, & 16T, respectively.

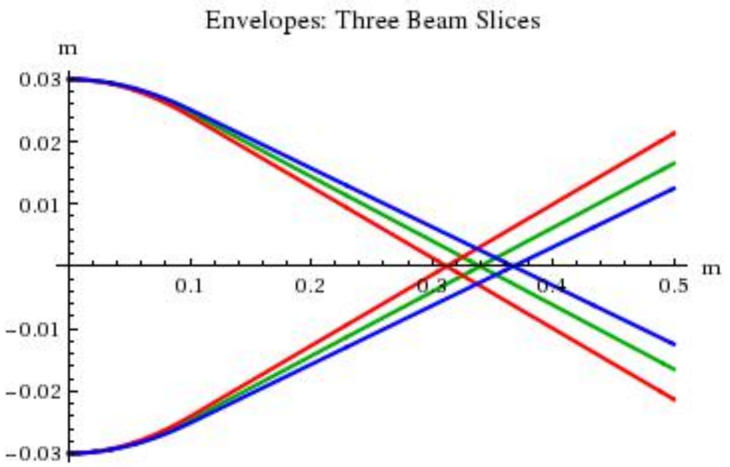
Density distribution, at the target n(x),

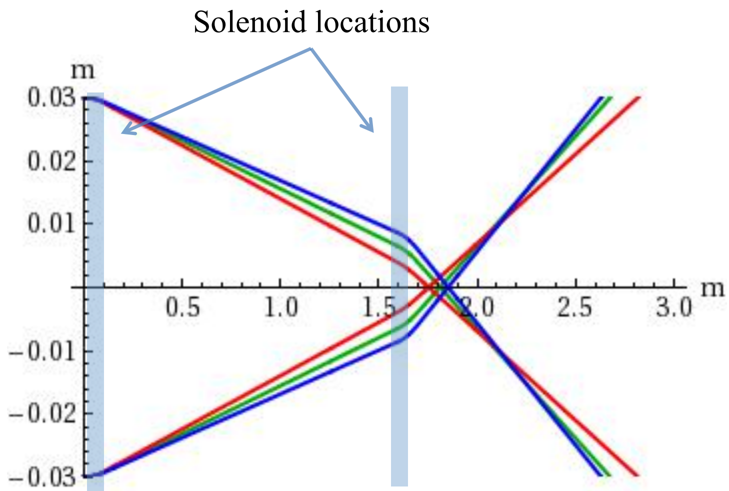


J. Mitrani, et al (2012)

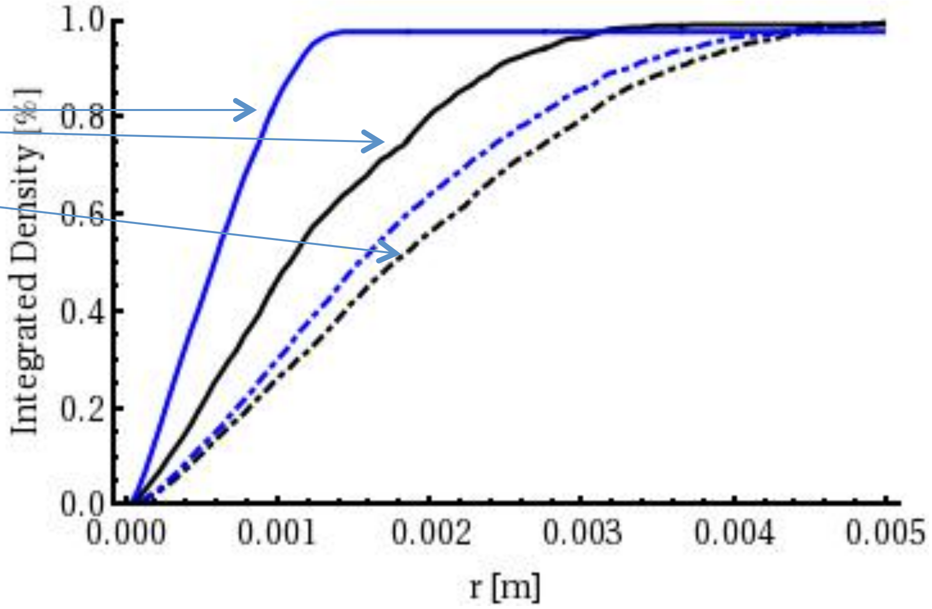
Using two solenoids yields about twice smaller spot size=100s micron!

$r_{sp} \sim r_f\, 2$ [illegible] v_b/v_b


Envelopes: Three Beam Slices


Solenoid locations

	One 8T FFS	One 16T FFS	2 Sol – 3T & 8T	2 Sol – 3T & 16T
Fwhm [µm]*	150	250	250	150
Fwhm [%]*	*15.2*	*23.1*	*31.6*	*15.6*
R_{50} [µm]	540	479	289	166
R_{90} [mm]	1.57	1.37	0.86	0.49
R_{100} [mm]	5.66	4.95	3.08	1.08



Outline

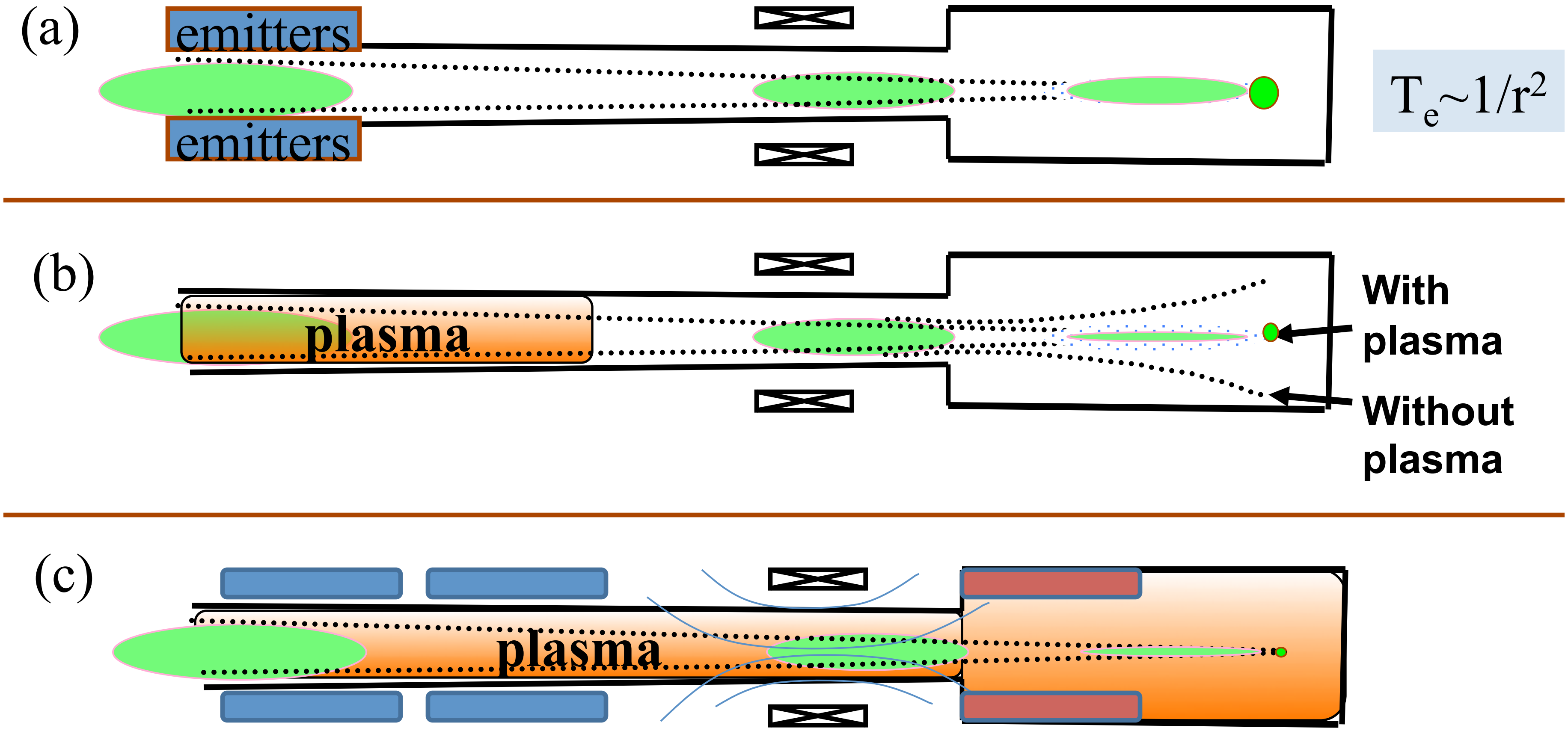
- Longitudinal Drift compression
  - Effects of voltage errors

- Simultaneous longitudinal and radial compression
  - Chromatic effects in final focus

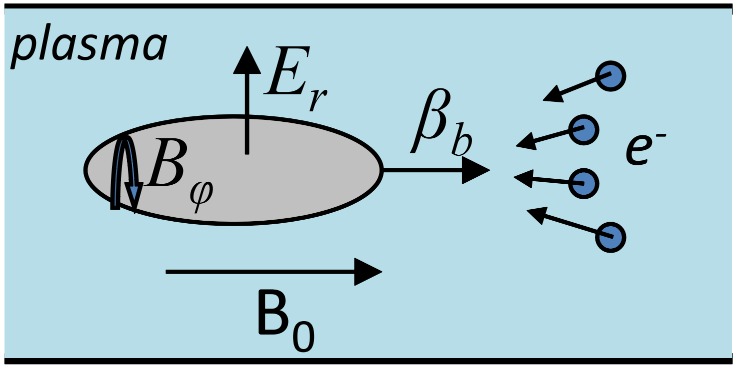
- The physics of the neutralization process and requirements for plasma sources.

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).



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

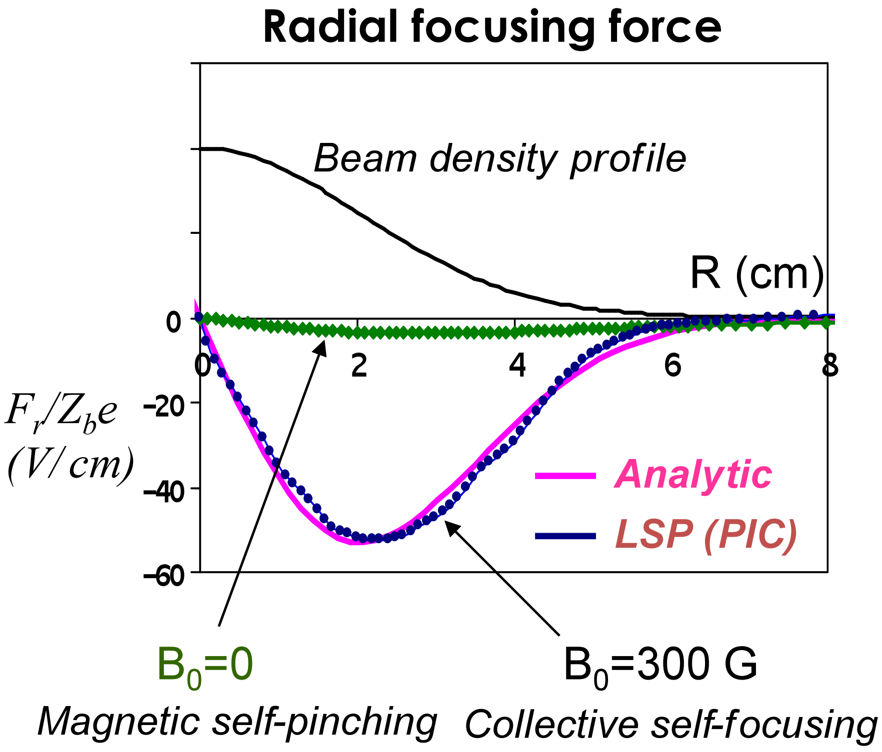


$$\mathbf{F_r = e(E_r - V_b B_{\varphi}/c),}$$

The focusing is provided by a strong radial self-electric field

Can be used for self-pinch ion beam transport (final transport section of a HIF-driver)

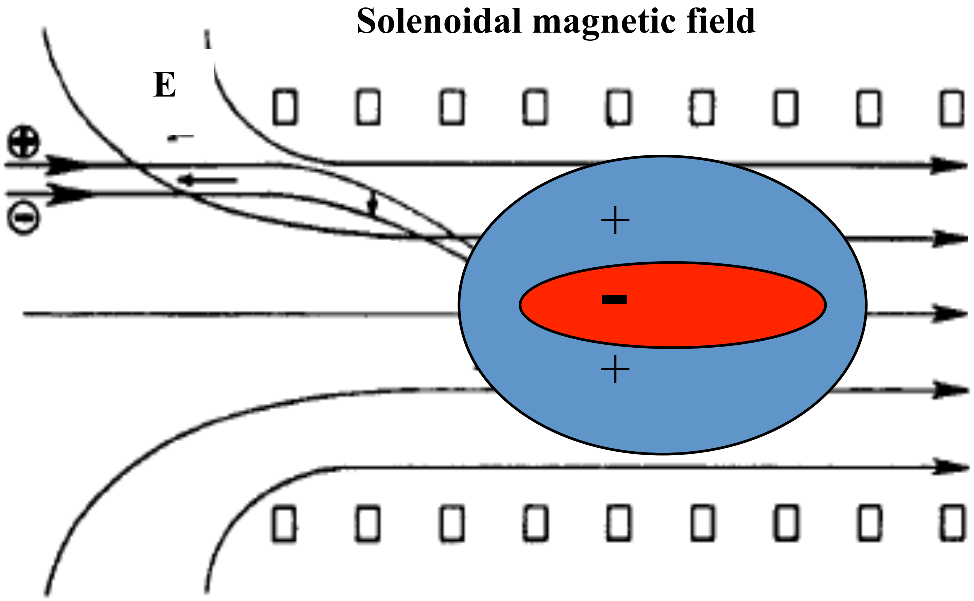
Fringe magnetic fields of a final focus solenoid do matter (NDCX-II)



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

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

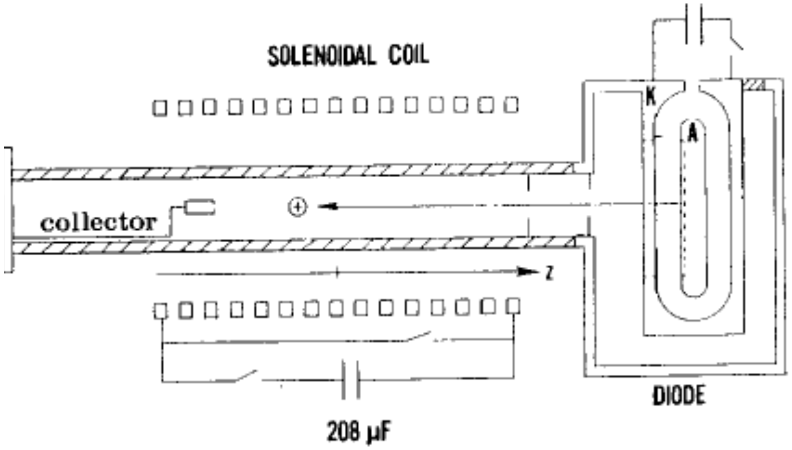
Collective focusing schemes



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~$1.5\cdot10^{11}$cm^{-3}



. Experimental apparatus.

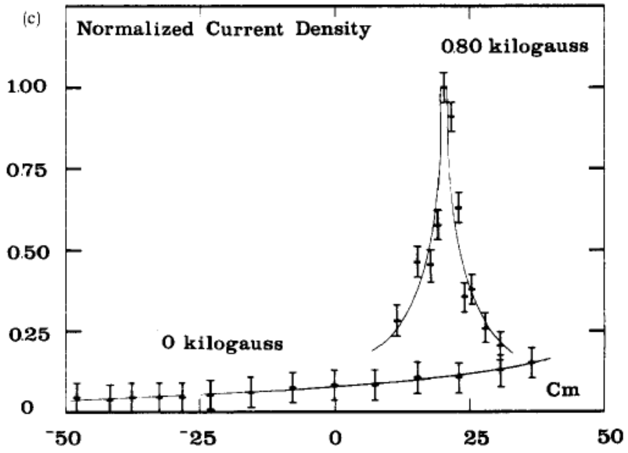
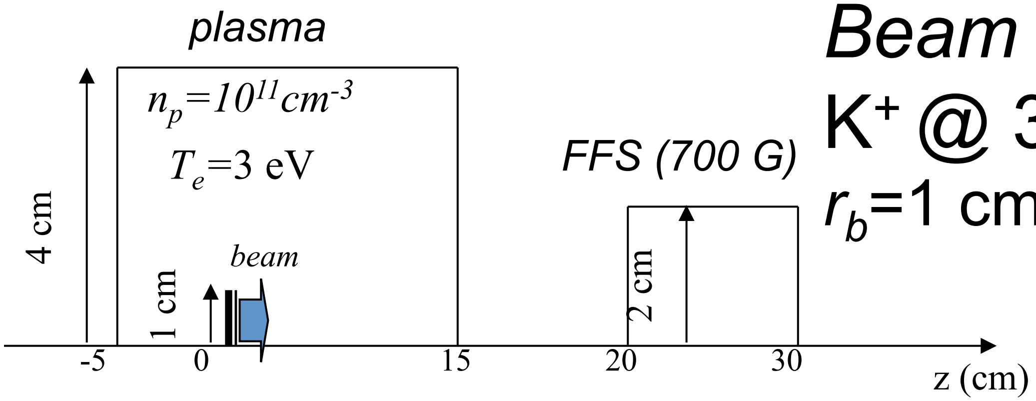


FIG. 8. Focused ion current. (a) Ion current density versus time ($B=0$, 1.5 kG). (b) Peak ion current density versus axial position ($B=0$, 1.5 kG). (c) Peak ion current density versus axial position ($B=0$, 1.5 kG).

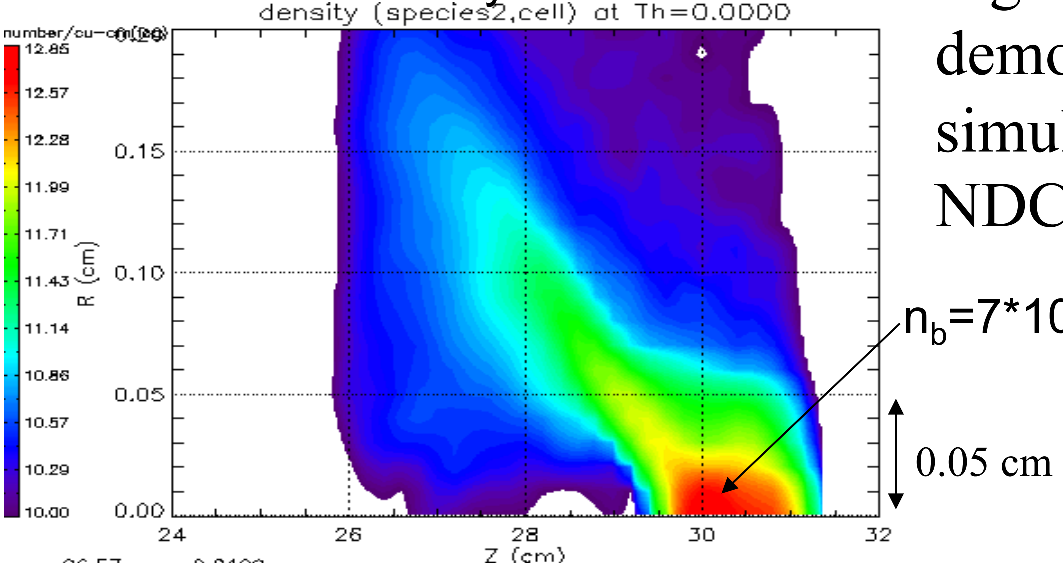
PIC Simulations show Collective Focusing Lens Can be Used for NDCX Beam Final Focus



Beam injection parameters

K^+ @ 320keV, $n_b=10^{10}cm^3$,
r_b=1 cm, compressed 700 times!

Beam density t=250 ns

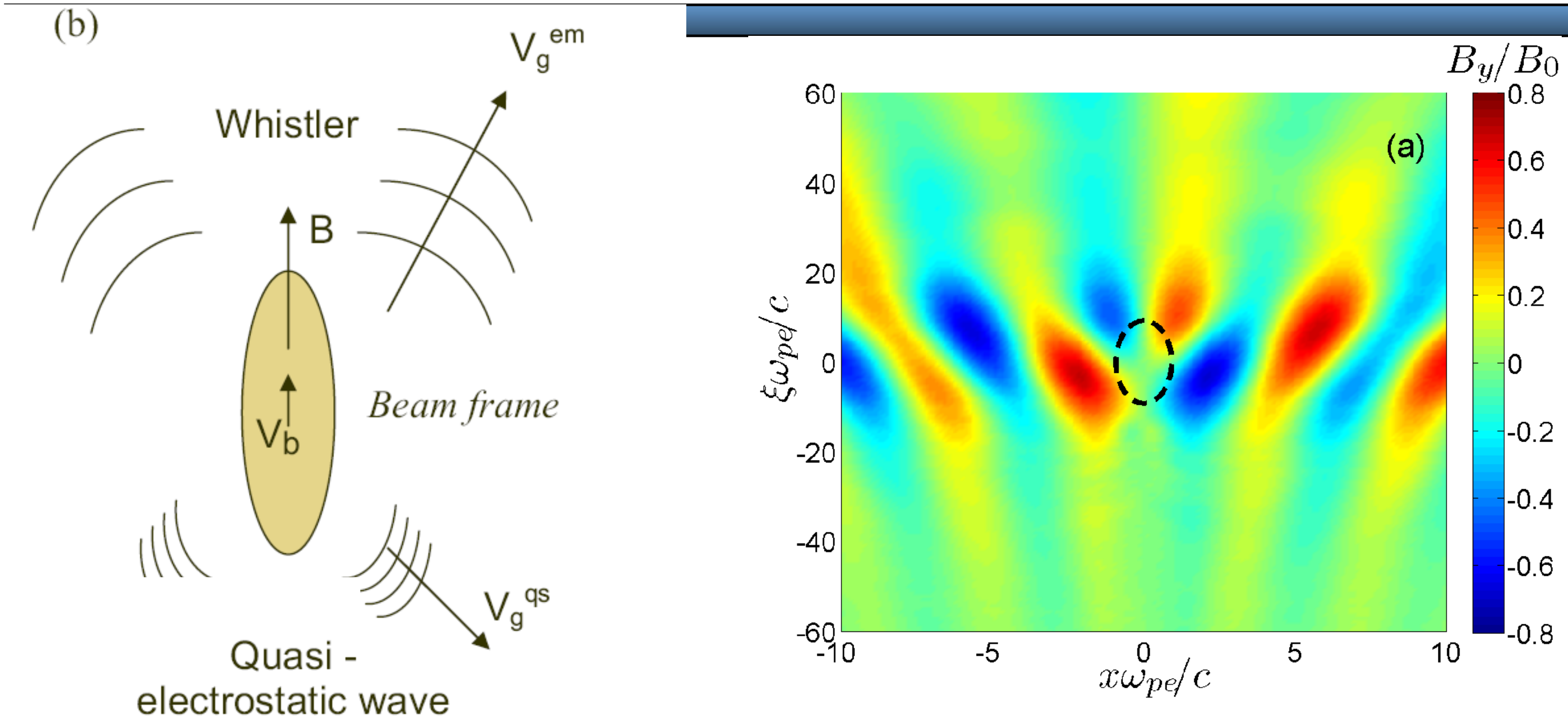


$n_b=7*10^{12}$ cm^3

Tight final focus r_f<1 mm was demonstrated in PIC (LSP) simulations for both NDCX-I and NDCX-II

M. Dorf , I. Kaganovich, E. Startsev, and R. Davidson, PoP **19**, 056704 (2012).

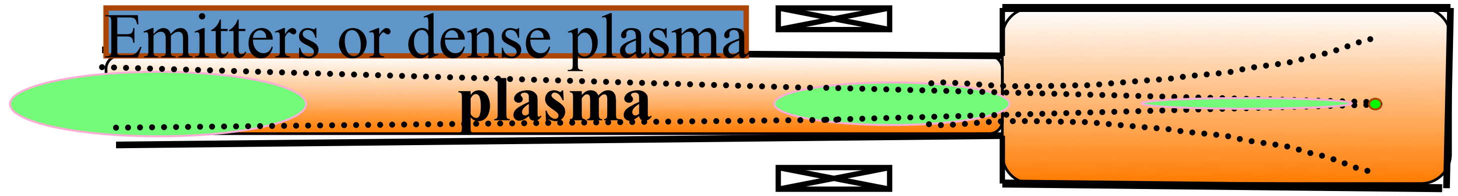
The beam can excite whistler waves



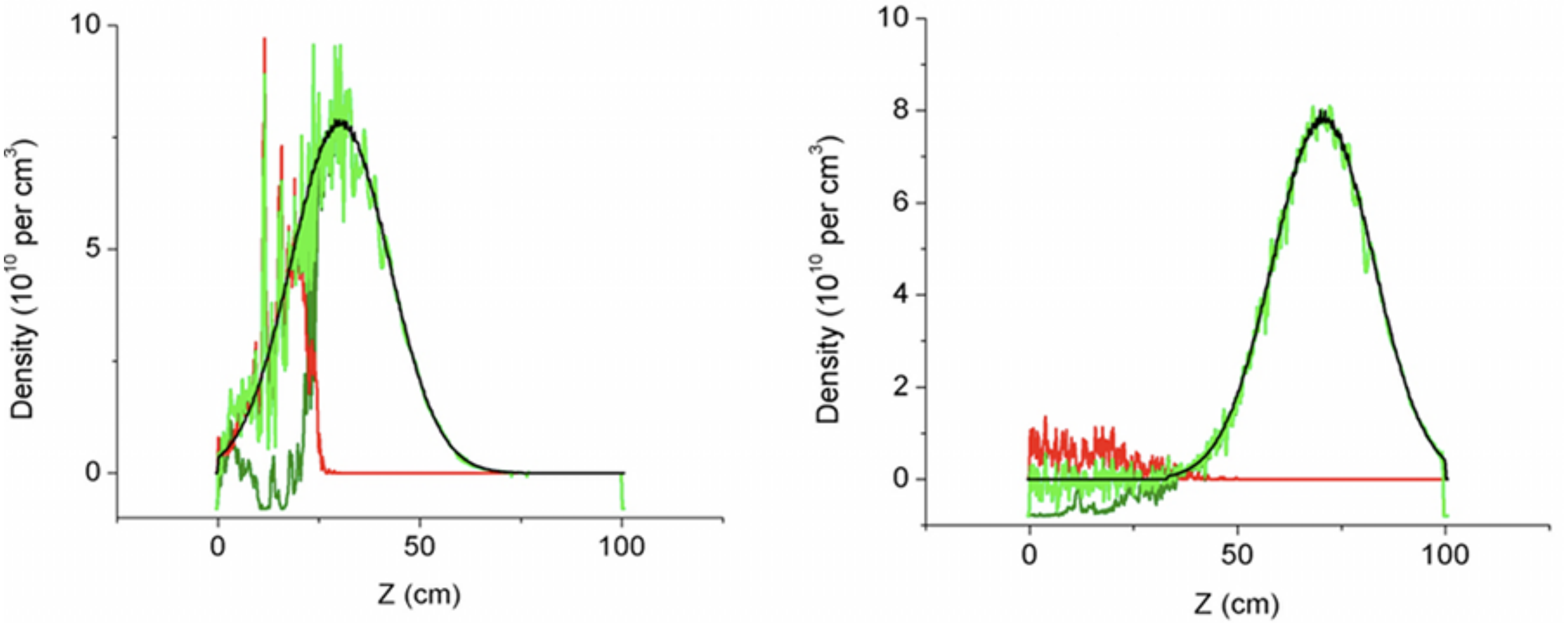
The whistler waves excited by the ion beam pulse.
M. Dorf, et al., Phys. Plasmas **17,** 023103 (2010).

Strong (resonant) wave excitation occurs at $\omega_{ce}/2\beta_b\omega_{pe} = 1$

Tenuous plasma from large volume can provide sufficient neutralization and avoid two stream instability



Density slices along r = 2 cm, Black is beam ion density, red is emitted electron density, dark green is plasma electron density , and bright green is the sum of the red and dark green curves.



William Berdanier, et al (2011)

Conclusions for Neutralized Drift Compression and Final Focus

Longitudinal compression is limited by errors in the applied velocity tilt and is not affected by plasma neutralization.

The radial compression is mostly limited by chromatic effects in the focusing system. Two solenoid scheme provide better focusing than one solenoid scheme. Inadequate neutralization and instabilities may affect focusing as well.

The applied magnetic field tend to increase self consistent radial electric field and can be actively used for beam focusing in various collective focusing schemes. However, it can be subject to instabilities and deleterious effects.