Use of plasmas for transport and focusing of intense particle beams in accelerators*

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Outline

- **Introduction to the PPPL beam dynamics group**
- **Concept of neutralized drift compression**
- **High Intensity Ion beam Facility NDCX-II**
- **Physics of ion beam neutralization by plasma**
- **Study of effects of two-stream instability on ion beam propagation in background plasma.**

PPPL Beam Dynamics Group (1/2)

PRINCETON PLASMA PHYSICS LABORATORY

Objectives

Develop advanced analytical and numerical models describing the nonlinear dynamics and collective processes in intense nonneutral beams in periodic focusing accelerators and transport systems, with emphasis on:

- Heavy ion fusion.
- High energy and nuclear physics applications.

- Experimental and theoretical studies of heavy ion beam propagation on and beam-plasma interactions in the target chamber.
- Basic experimental and theoretical investigations of nonneutral plasmas confined in a Malmberg-Penning trap and a Paul trap.

Personnel

PPPL Staff: R. C. Davidson, P. Efthimion, E. Gilson, L. Grisham, I. Kaganovich, R. Majeski, W. W. Lee, H. Qin, E. Startsev.

PPPL Beam Dynamics Group (2/2)

PRINCETON PLASMA PHYSICS LABORATORY

Technical focus of experimental activities:

Develop advanced beam and plasma diagnostics, and advanced plasma sources for intense charge bunch neutralization in neutralized drift compression experiments on NDCX-II.

Make use of Princeton 100kV Test Stand to develop and test advanced high density plasma sources for beam neutralization at very high beam intensities.

Technical focus of intense beam theory and modeling activities:

Advanced analytical and numerical modeling of intense beam propagation, nonlinear dynamics, beam-plasma interactions, and pulse compression.

Mitigation and control of collective interactions and instabilities; optimization of beam quality and brightness; identify techniques for halo particle production and control.

Beam pulse compression and focusing in neutralizing background plasma.

Atomic physics; develop improved charge-changing cross section models.

Concept of neutralized drift compression

For compression and focusing Intense ion beams, beams have to be propagated in plasma. =>

How to prepare, transport, control and focus high intensity ion beams beams (space charge > kV).

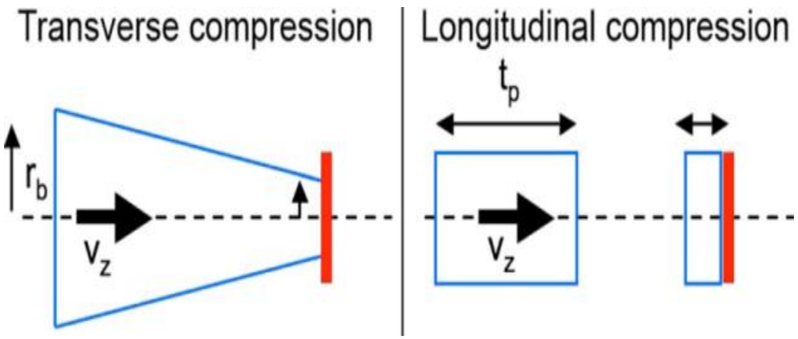
Recent Progress:

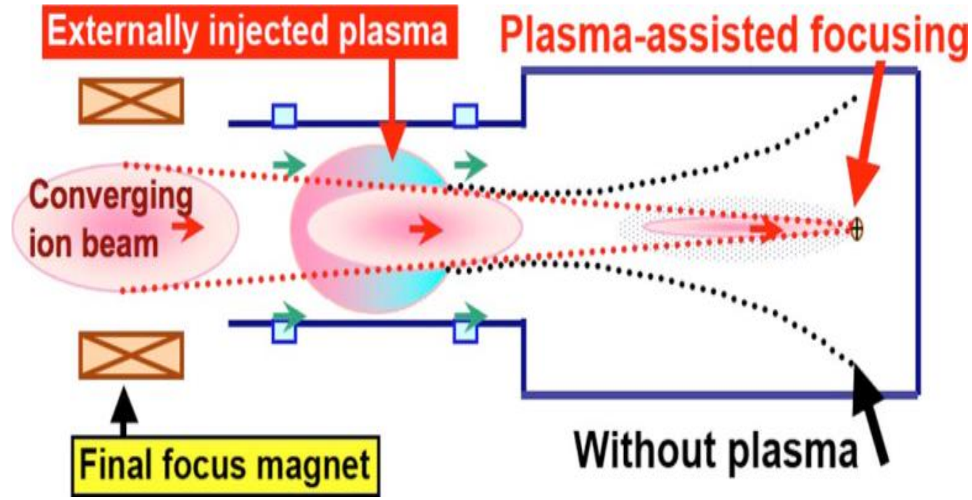
High Current Experiment (HCX) demonstrated controllable transport of high-space-charge ion beam [Phys. Rev. Lett. 97,054801; 98, 064801.]

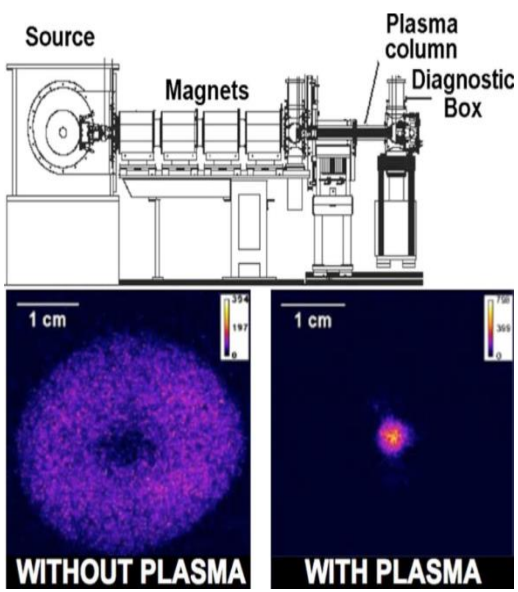
Neutralized Transport Experiment (NTX) demonstrated transverse focusing of intense ion beam by plasma charge neutralization.

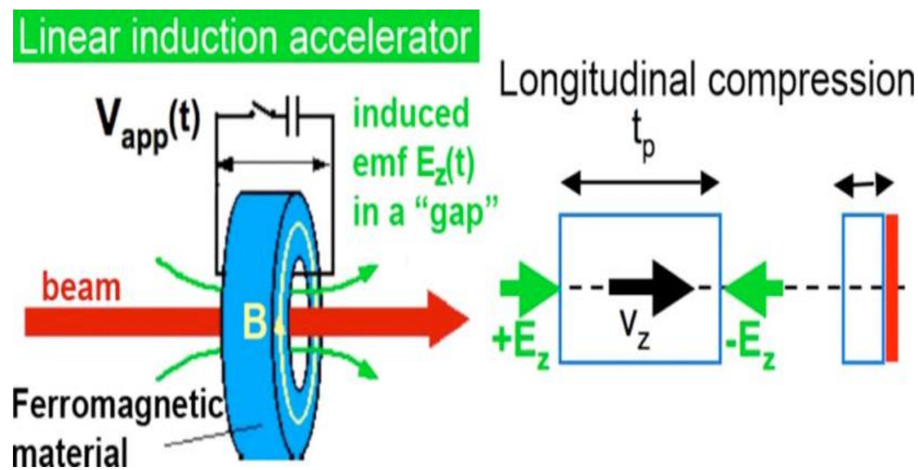
NDCX-I demonstrated unprecedented simultaneous longitudinal and transverse compression to achieve > 100 x 100 compression. [Phys. Rev. Lett. 95, 234801; 103, 075003; 103, 224802; 104, 254801; 110, 064803.]

Neutralized Drift Compression is Key Innovation



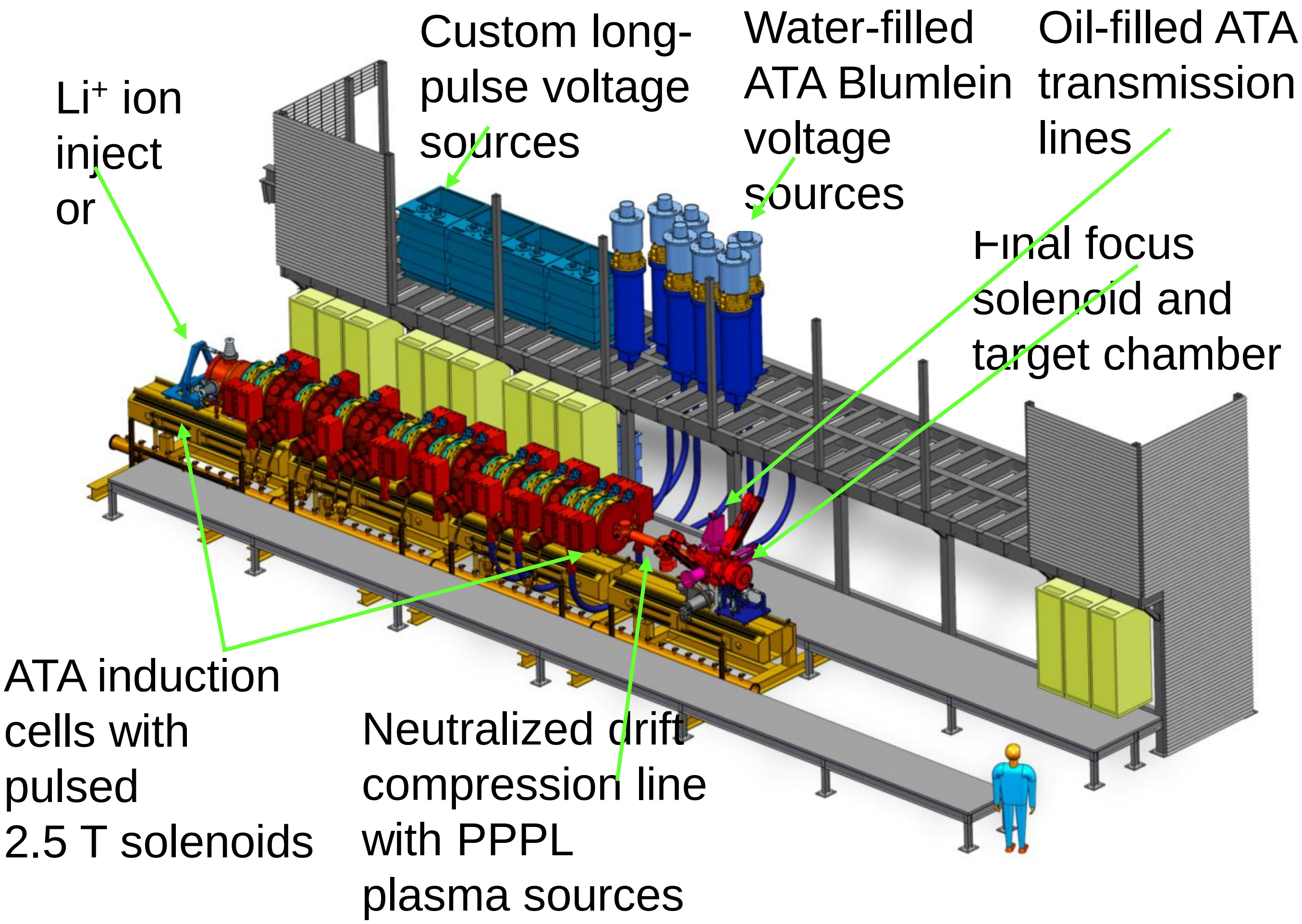






NDCX-II is a Versatile Accelerator that can Achieve Record-High Beam Brightness (1/3)

NDCX-II is an $11M ARRA-funded project.

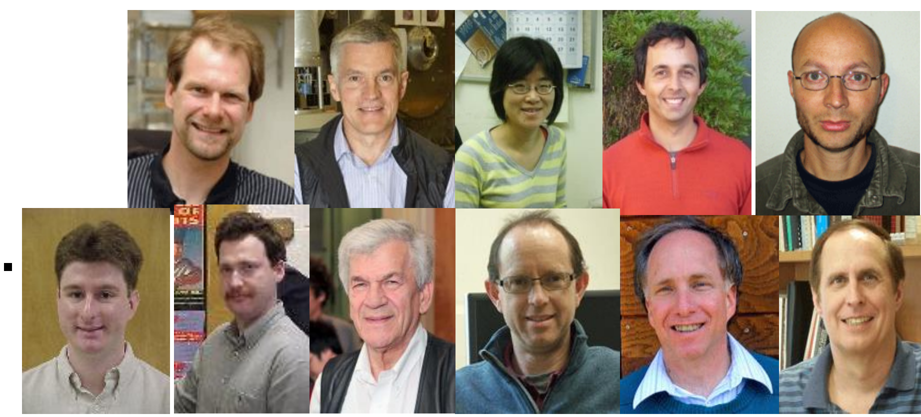


NDCX-II is a Versatile Accelerator can Achieve Record-High Beam Brightness (2/3)

- Since June 2014, LBNL, LLNL, and PPPL researchers have brought NDCX-II to full operation
- Pulse length: 2 ns, spot size 1.4 mm, 1.2 MeV, Li^+
- Now: He^+, Peak currents: ~0.6 A (~40 A/cm^2)
- We are now tuning to reach the design goals:
- 1 ns, 1 mm, >50 A, for volumetric heating up to 1 eV

Peter Seidl[1], A. Persaud[1], J.J. Barnard[2], R.C. Davidson[3], A. Friedman[2], E.P. Gilson[3], Grote[2], P. Hosemann, Q. Ji[1], I. Kaganovich[3], A. Minor[1,4], W.L. Waldron[1], T. Schenkel[1]

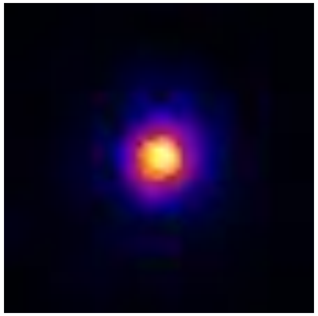
[1]LBNL, [2]LLNL, [3]PPPL, [4]UCB

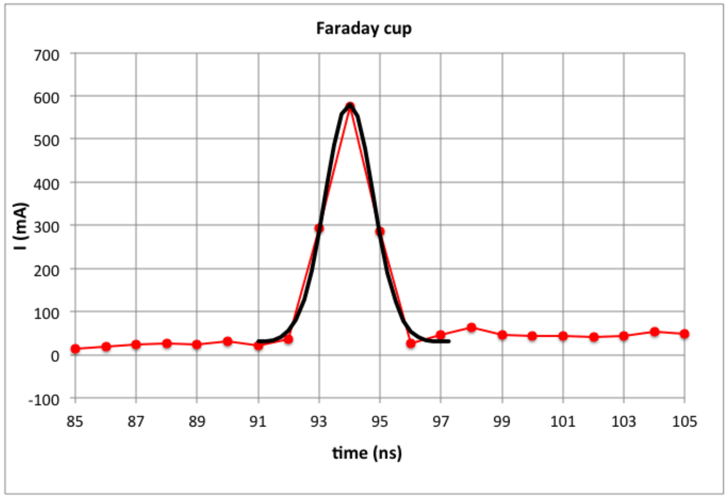


NDCX-II is a Versatile Accelerator that can Achieve Record-High Beam Brightness (3/3)

We have commenced experiments and have developed a compelling science case

- **Physics of intense ion beams**
- **Extreme chemistry and materials physics of defects**
- **Warm dense matter and equations of state studies up to 1 eV**





Carry out beam experiments of importance to heavy ion fusion:

- **Pulse shaping;**
- **Non-neutral drift compression;**
- **Neutralized drift compression.**

Jitter: $\sigma_{x,y}$ < 0.1 mm
Intensity σ_A/A < 7%

P.A. Seidl et al, NIM A 800, 98 (2015).

Cylindrical Barium Titanate Plasma Sources Create Plasma That Fills the Beamline – Fabricated and Tested at PPPL – Ready to be Installed on NDCX-II

Plasma source is made from barium titanate ceramic and is driven with thyratron-switched 150 nF capacitors with voltage and current pulse: 10 μs, 9 kV, 500 A.

The source produces plasma ~ 10^{10} cm^{-3} density, T_e ~ 3 eV. The plasma density is greater than the local beam density, and the temperature is low, as needed for effective charge neutralization.

Modular design allows plasma length and axial density profile to be changed, and for repairs to be made quickly.

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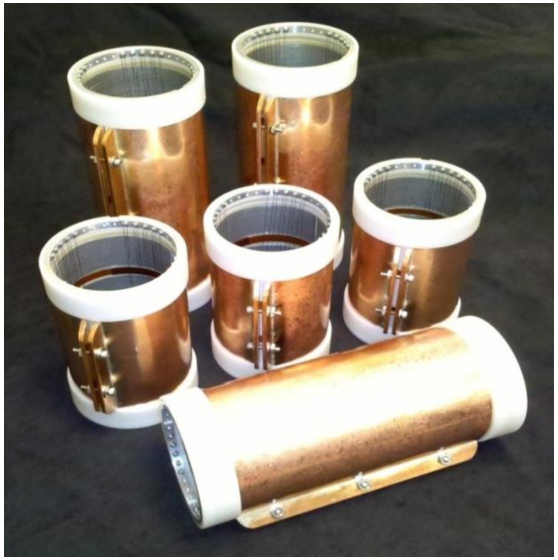

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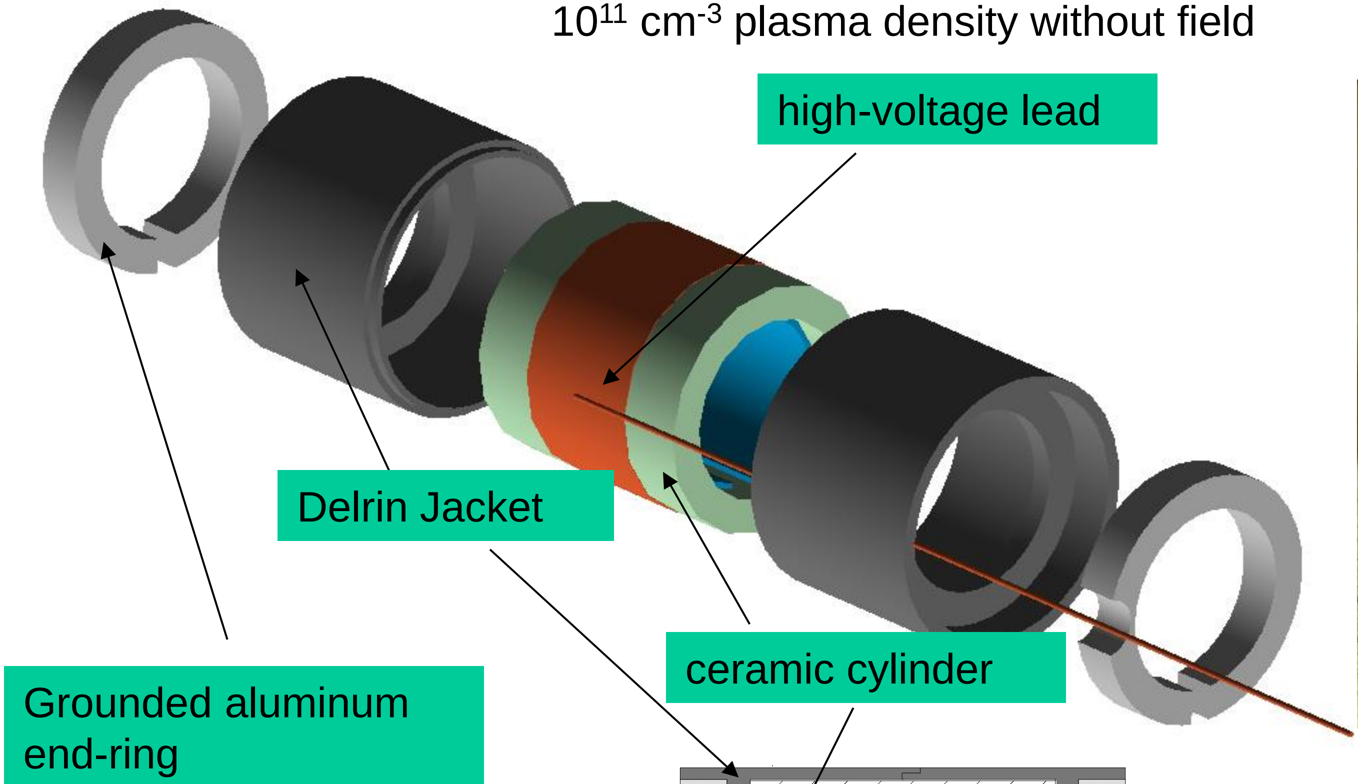
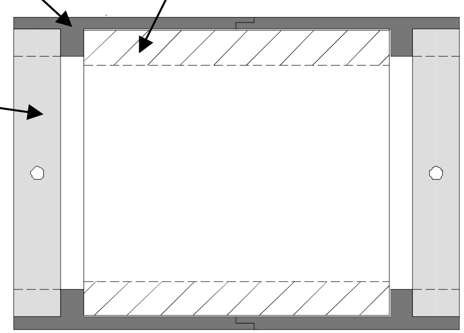
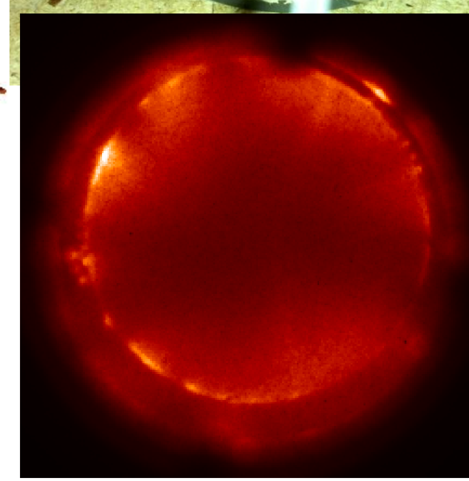
Compact ferroelectric plasma source was designed and tested by PPPL to create plasma inside 8T focusing solenoid

10^{11} cm^{-3} plasma density without field







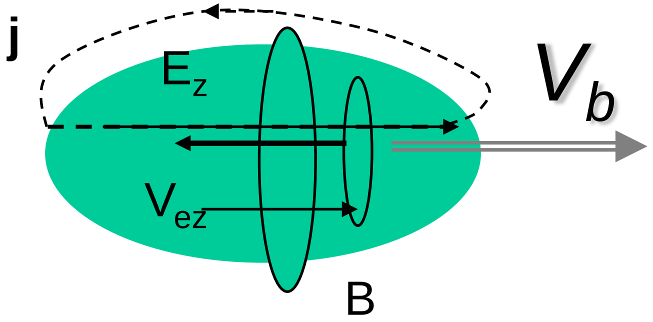
40 mm OD – fits inside solenoid
25 mm ID – accommodates beam
40 mm length

Conductors are slotted to prevent eddy current effects. Tests in field confirm good operation.

Theory of Neutralization by Dense Plasma

Practical consideration: what plasma sources are needed for 100000 times simultaneous neutralized drift compression?

Developed analytical theory of degree of charge and current neutralization for dense and tenuous plasma, including effects of magnetic field.



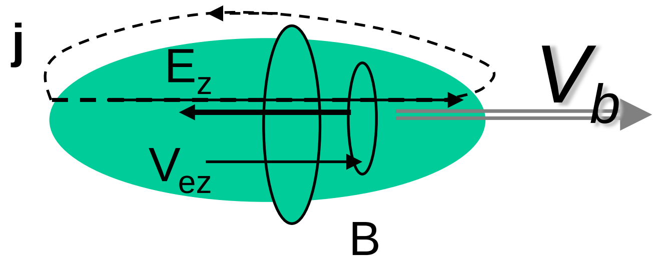
$$eE_r = \frac{1}{c} V_{ez} B_\theta = -mV_{ez} \frac{\partial V_{ez}}{\partial r}$$

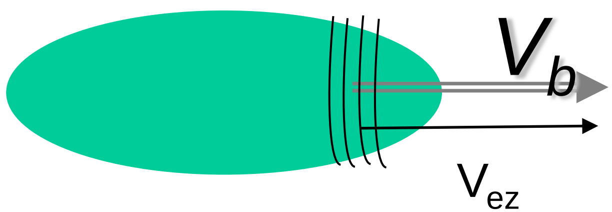
Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation direction.

$\phi = mV_{ez}^{\ 2} / 2e$ $\quad V_{ez} \sim V_b n_b / n_p$ $\quad \phi_{vp} = mV_b^{\ 2} \left(n_b / n_p \right)^2 / 2$ $\quad mV_{ez} = eA_z / c = e\int_0^r Bdr / c$

Two-stream instability may significantly affect beam propagation in background plasma

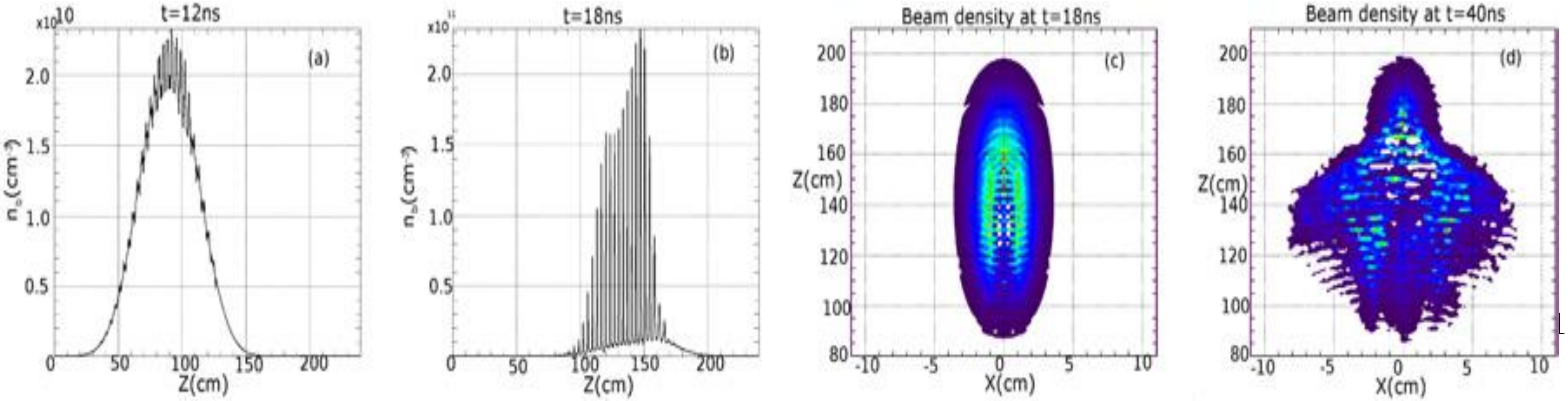
Left: No two-stream instability; Right: effect of two-stream instability



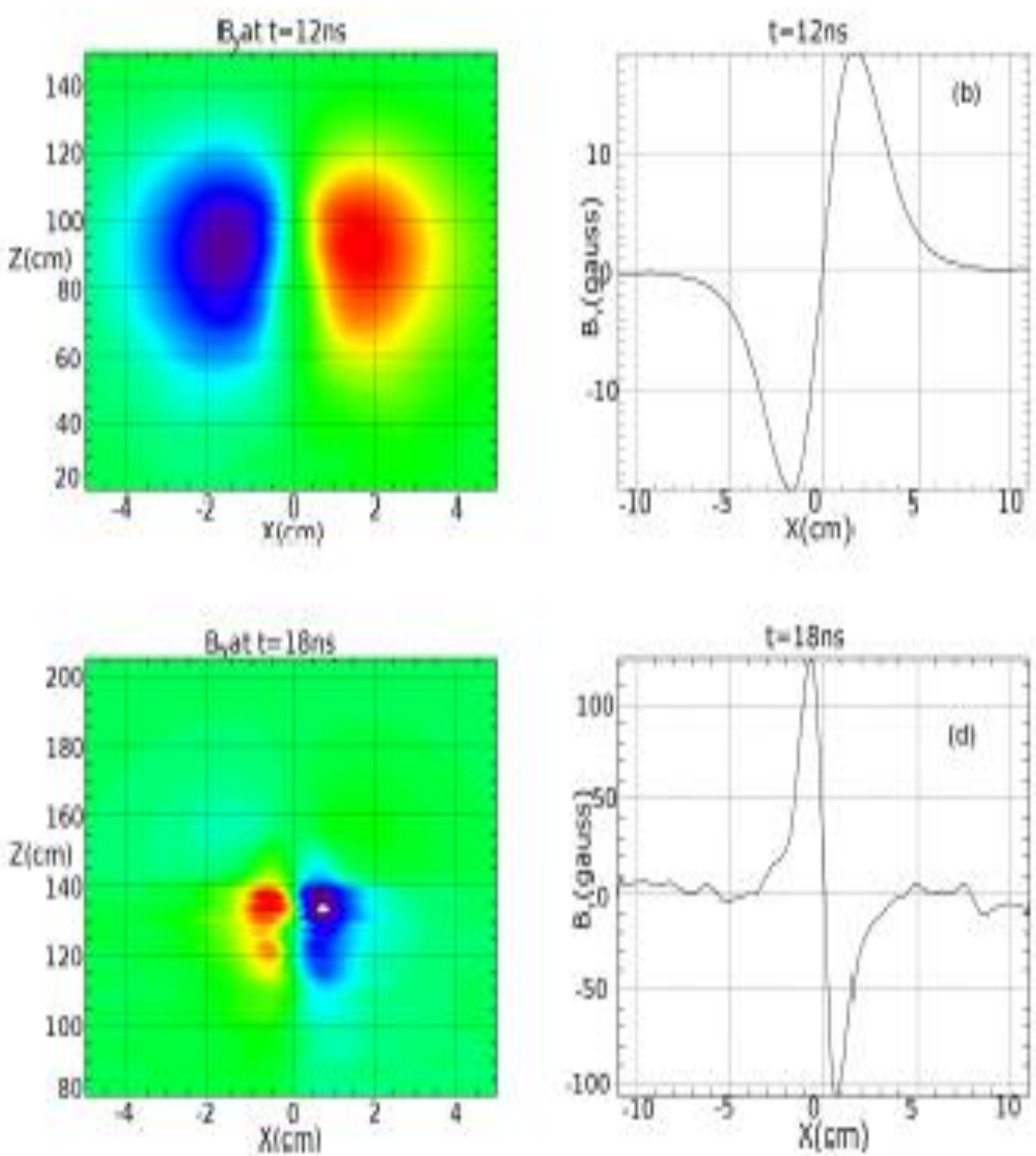


Plasma waves lead to bunching of the ion beam and accelerate plasma electrons to beam velocity

Longitudinal beam density profile at t = 12 ns (a) and t = 18 ns (b) and color plots of beam density at t = 18 ns (c) and t = 40 ns (d). E. Startsev et al, EPJ Web of Conferences 59, 09003 (2013)



Enhanced return current density reverses the azimuthal magnetic field



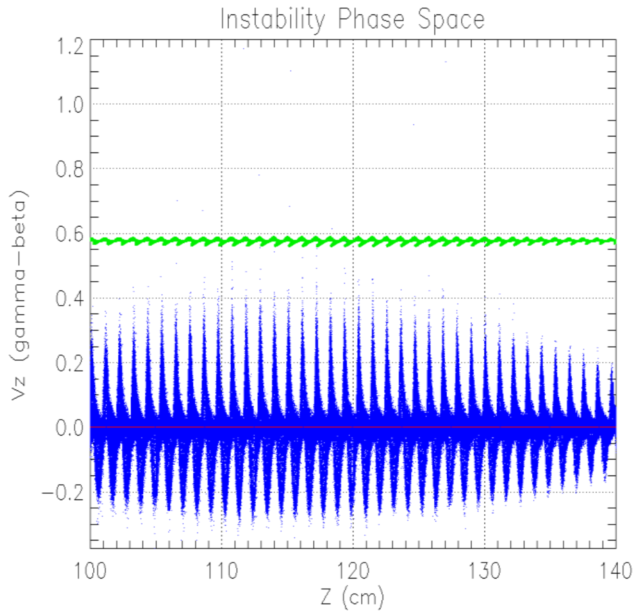
Self magnetic field of the ion beam propagating in plasma

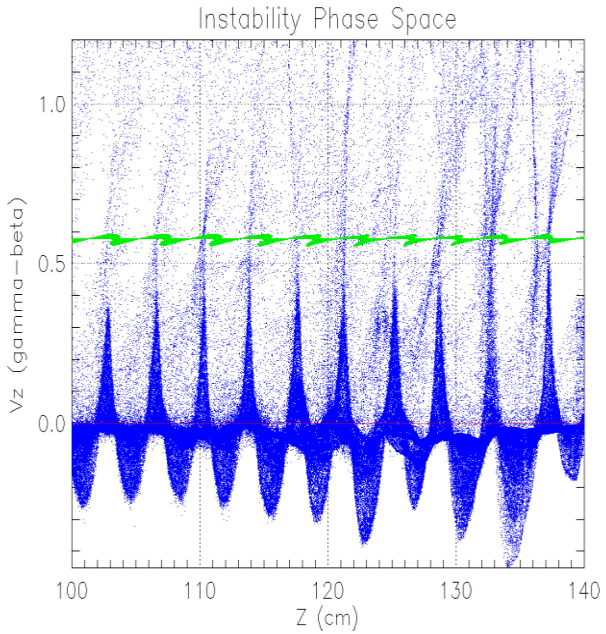
Top: without two-stream instability B~10G
Bottom with two-stream instability B~-100G

E. A. Startsev, et al, Nucl. Instrum. Methods A 773, 80 (2014)

Two Mechanisms of Instability Saturation

Instability saturates by wave-particle trapping of beam ions or plasma electrons depending on parameter $\left(\frac{n_b}{n_p}\right)^{\frac{2}{3}}\left(\frac{m_b}{m_e}\right)^{1/3}$ **E. Startsev et al, NIMA (2014)**





Phase-Space of beam ions and plasma electrons V_z **vs z. Proton beam** $n_b = 2 \times 10^{10}\ /cm^3$ **and** v_b **= c/2. Left:** $n_p = 2.4 \times 10^{12}/cm^3$ **- ion trapping regime, Right:** $n_p = 1.6 \times 10^{11}\ /cm^3$ **-electron trapping regime. E. Tokluoglu and I. Kaganovich, Phys. Plasmas 22, 040701 (2015)**

Two-Stream Instability Yields Beam Defocusing

- **In the presence of two-stream instability, the ponderomotive pressure from the axial E_z field of plasma waves creates an average transverse defocusing force**:

$$F_x = -eE_x = \frac{-e^2 \nabla_x |E_z|^2}{4m_e\, \omega_k} = -\frac{1}{4}\, m_e \nabla_x (v_m^e)^2$$

- **The averaged non-linear current $< \delta n_e\, \delta v_m^e$> originates from the plasma waves and overcompensate the beam current. The total current becomes reversed:**

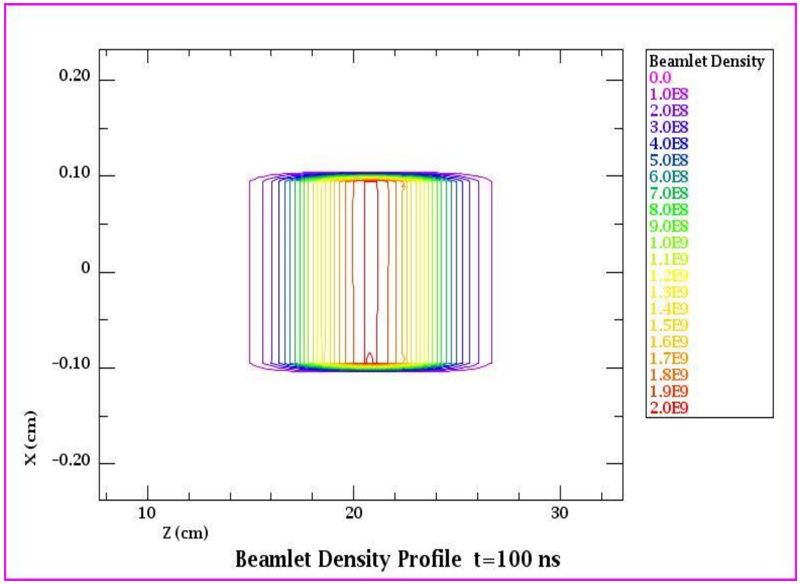
$$J_{tot} \sim J_z^b + J_z^e = \frac{J_z^b}{(1+r_b^2\omega_p^2/c^2)} \left(1 - \frac{1}{2}\ \frac{n_p}{n_b} \left(\frac{v_m^e}{v_b}\right)^2\right)$$

- **Consequently the self- magnetic B_y becomes reversed and magnetic force becomes defocusing:**

$$B_y = \frac{2\pi n_b r_b \beta_b}{(1+r_b^2\omega_p^2/c^2)} \left(1 - \frac{1}{2}\ \frac{n_p}{n_b} \left(\frac{v_m^e}{v_b}\right)^2\right)$$

E. A. Startsev, et al,
NIMA 773, 80 (2014)

Transverse Defocusing of the Beam due to Two-Stream Instability



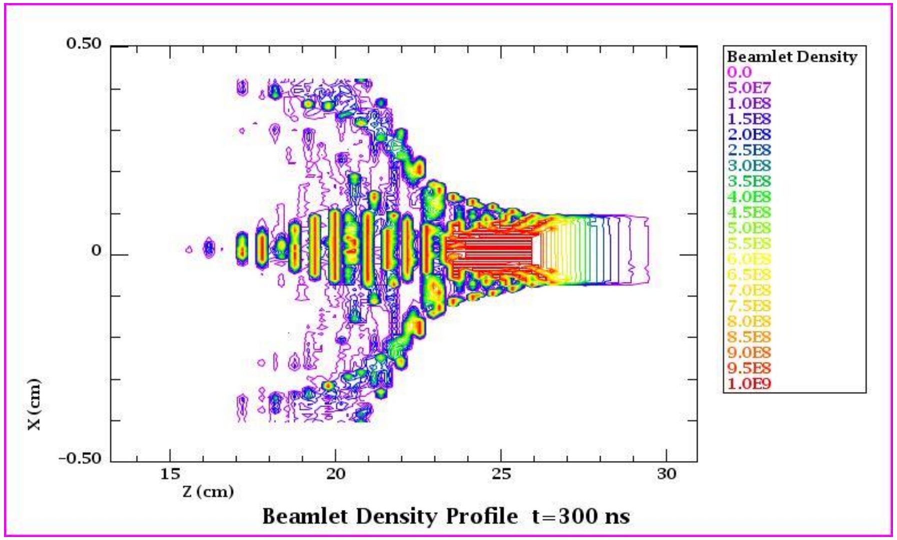
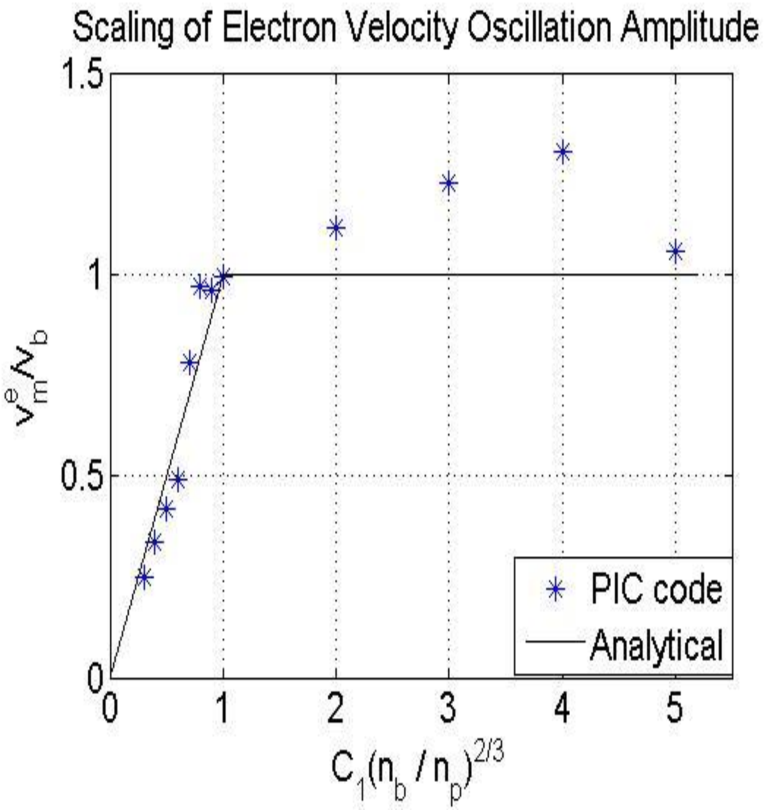


Fig. Beamlet Density Contour at t = 100 ns (1 m of propagation), Bottom: Beam Density Contour at t = 300 ns (3 m of propagation). NDCX-II beam parameters for apertured beam r_b=1 mm.

E. Tokluoglu and I. Kaganovich, Phys. Plasmas 22, 040701 (2015))

Verification of Analytical Estimates with PIC code



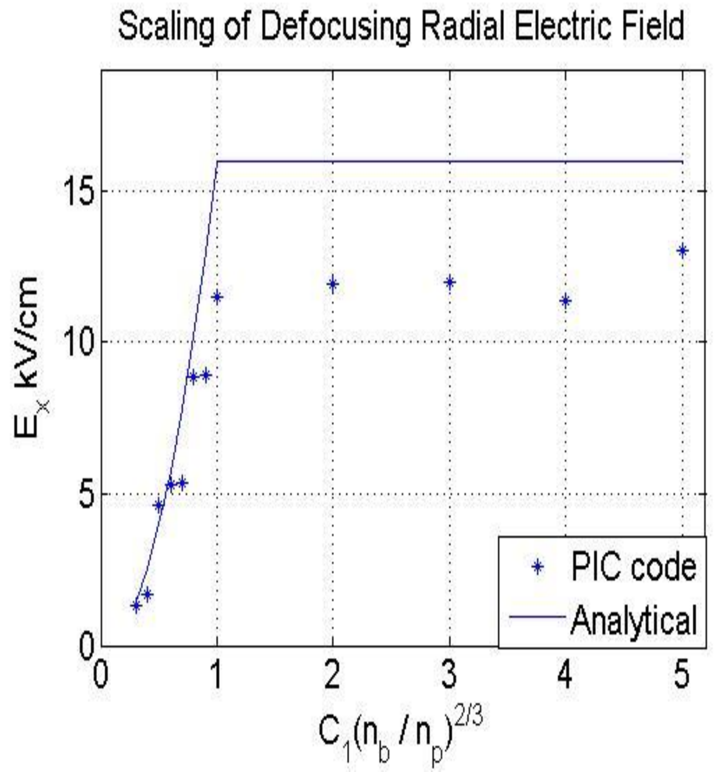


Fig. Left: Scaling of rms electron velocity oscillation amplitude measured on axis. Rig: Schaling of radial defocusing electric field from LSP simulation, measured at $r_b \sim 1\ cm$ which corresponds to the maximum field strength.

$\alpha = C_1(n_b/n_p)^{2/3}$, $C_1 = \left(\frac{m_b}{m_e}\right)^{1/3} \sim 12.24$ for H+ beam. E. Tokluoglu, et al (2015)

Verification of Analytical Estimates with PIC code

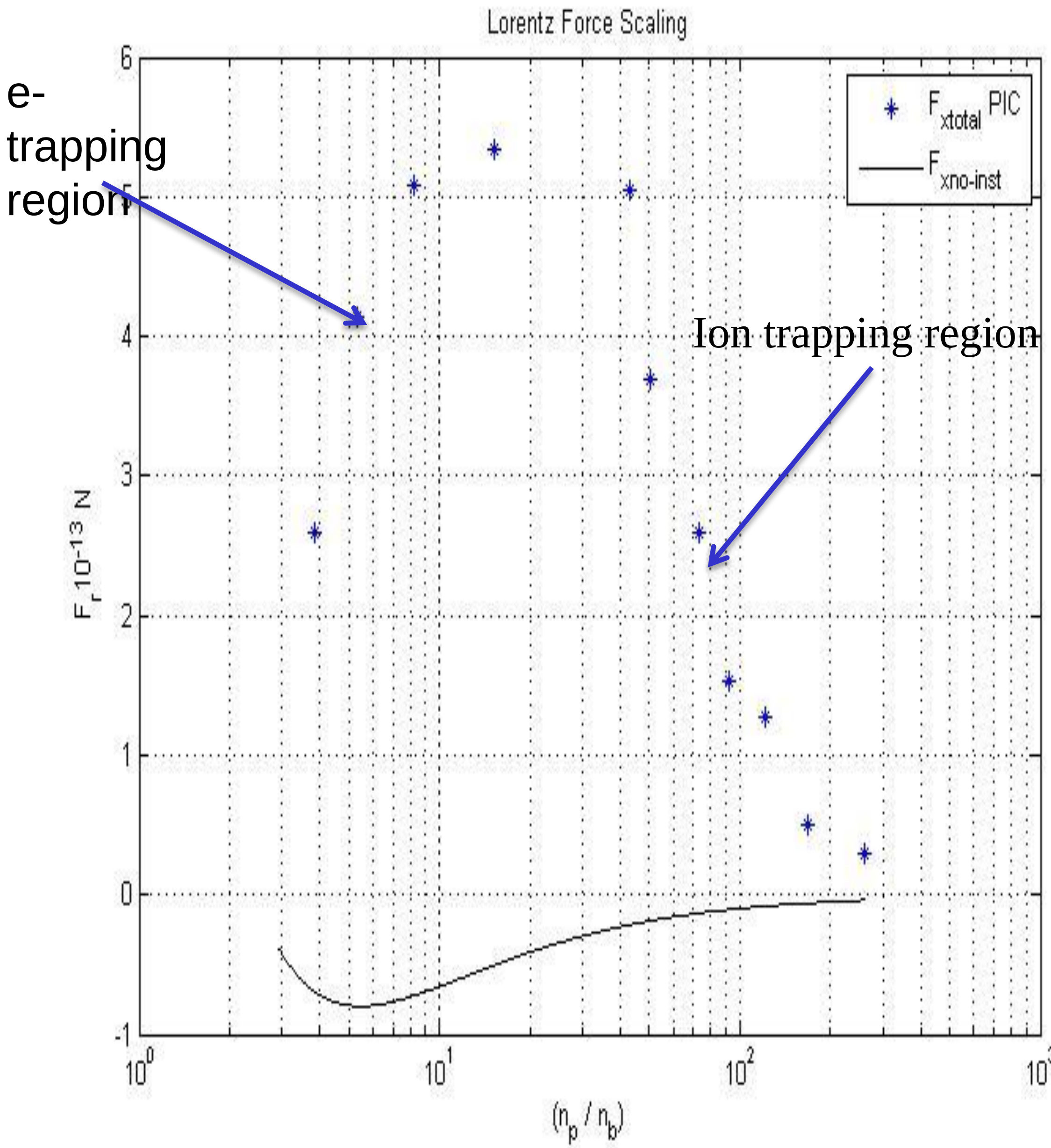
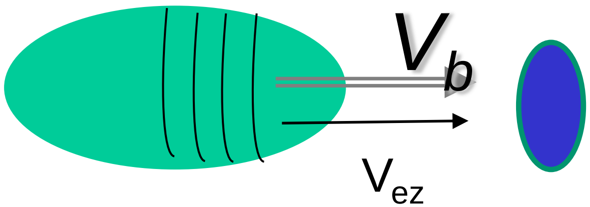


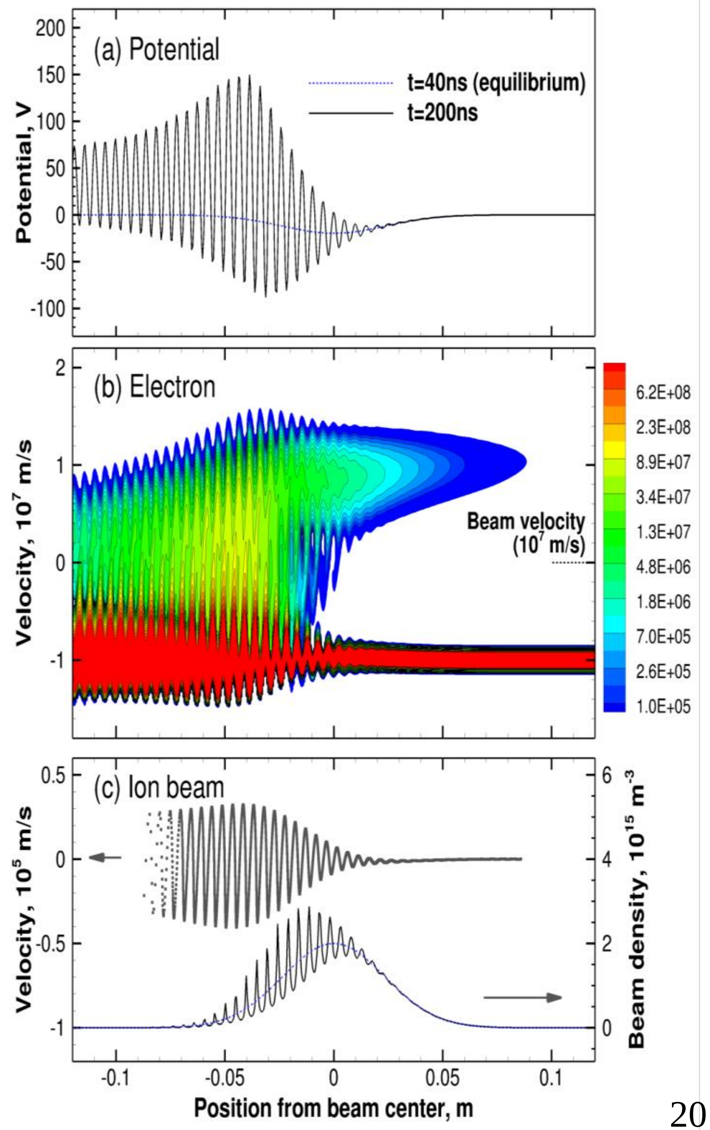
Fig. Lorentz Force (radial) F_x vs n_p / n_b log-scale. The points are LSP PIC code results where the instability is present, the continuous curve is the analytical estimate of the total defocusing force for the case of no instability.
E. Tokluoglu, et al (2015).

Electron Beam is Generated by Ion-Electron Two Stream Instability and Propagates Ahead of the Ion Beam



Ion beam => electron beam with twice of the ion beam velocity K. Hara, et al (2015)

Fig. Length of domain = 10 m & # of cells: 20000, time 200 ns,
Ion beam (PIC) : Li^+ = 7 amu; v_b=10^7 m/s; $n_{i,beam}$=$2x10^{15}$ m^{-3}.



Conclusions

- **The two-stream instability may cause a significant enhancement of the plasma return current and defocusing of the ion beam during propagation in plasma.**
- **The two-stream instability of an intense ion beam propagating in plasma may result in generation of a secondary electron beam accelerated ahead of ion beam pulse.**