Update on Beam-Plasma Interaction Research at Princeton Plasma Physics Laboratory*

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presented by

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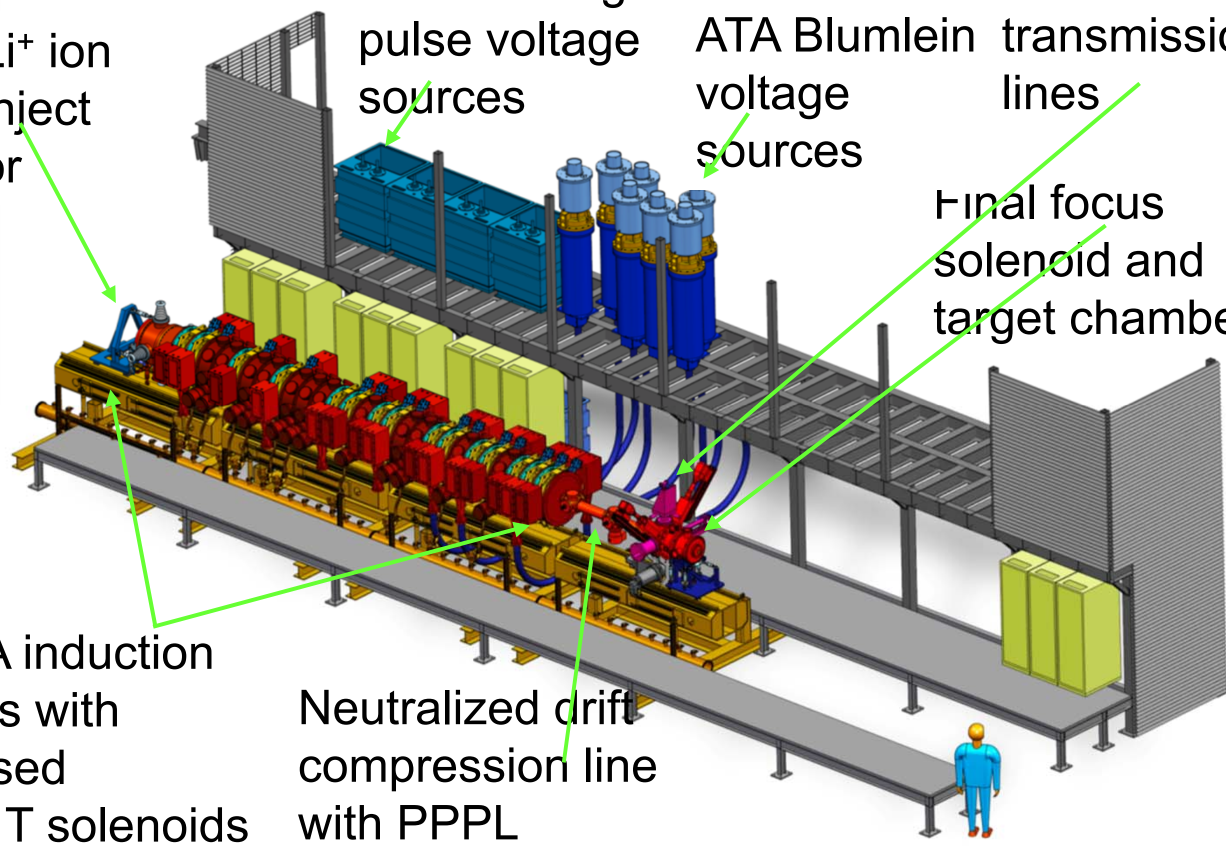
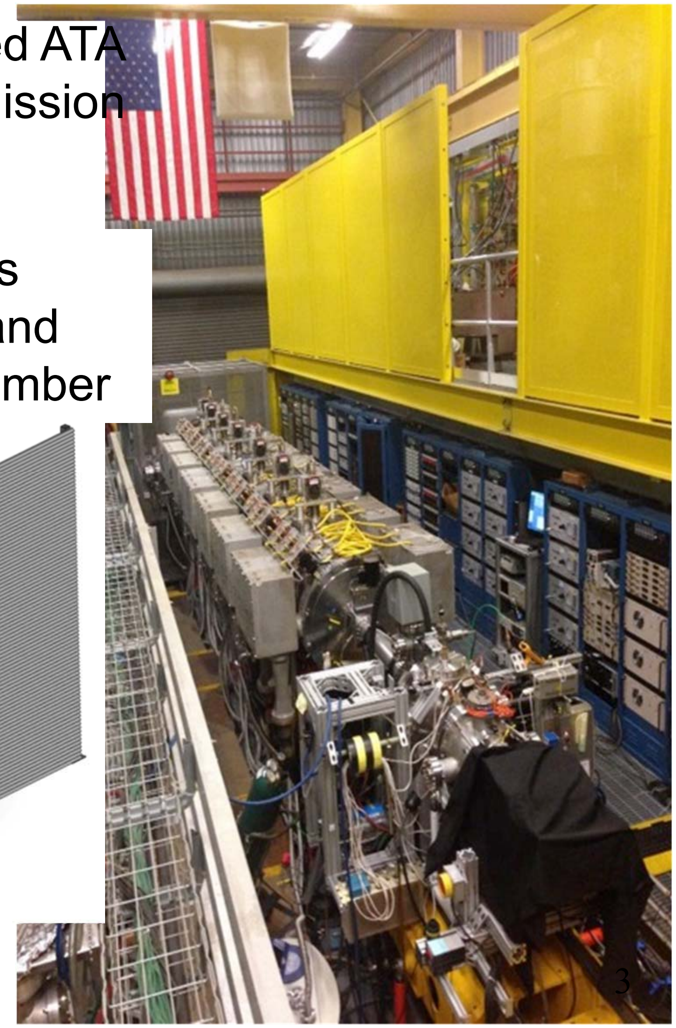
Outline

- **Study of effects of two-stream instability on ion beam propagation in background plasma.**
- **Electron beam generated by ion-electron two stream instability**
- **Dynamics of Space-Charge Neutralization of High-Perveance Ion Beams**

Much of this work is by: Ed Startsev, Erinc Tokluoglu, Ken Hara, Anton Stepanov

NDCX-II for Neutralized Drift Compression

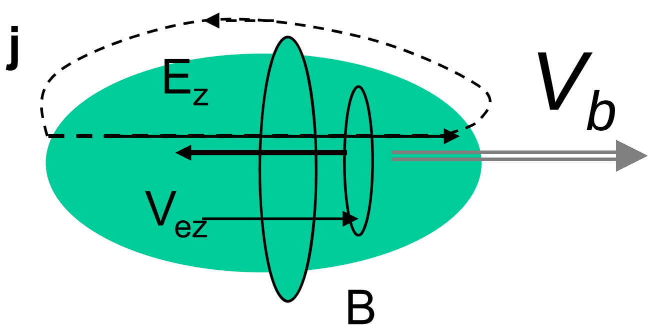




Theory of Neutralization by Dense Plasma

Practical consideration: what plasma sources are needed for 100,000 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.



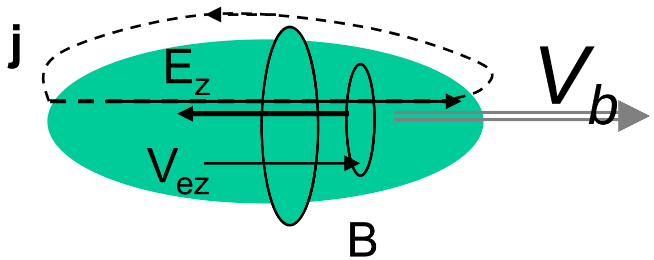
$$\frac{\partial \int Bds}{\partial t} \Rightarrow E_z \qquad eE_r = \frac{1}{c} V_{ez} B_\theta = -mV_{ez} \frac{\partial V_{ez}}{\partial r}$$

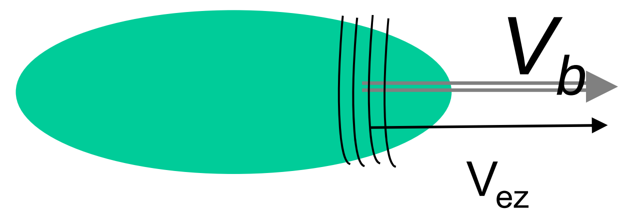
Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation direction.

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

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

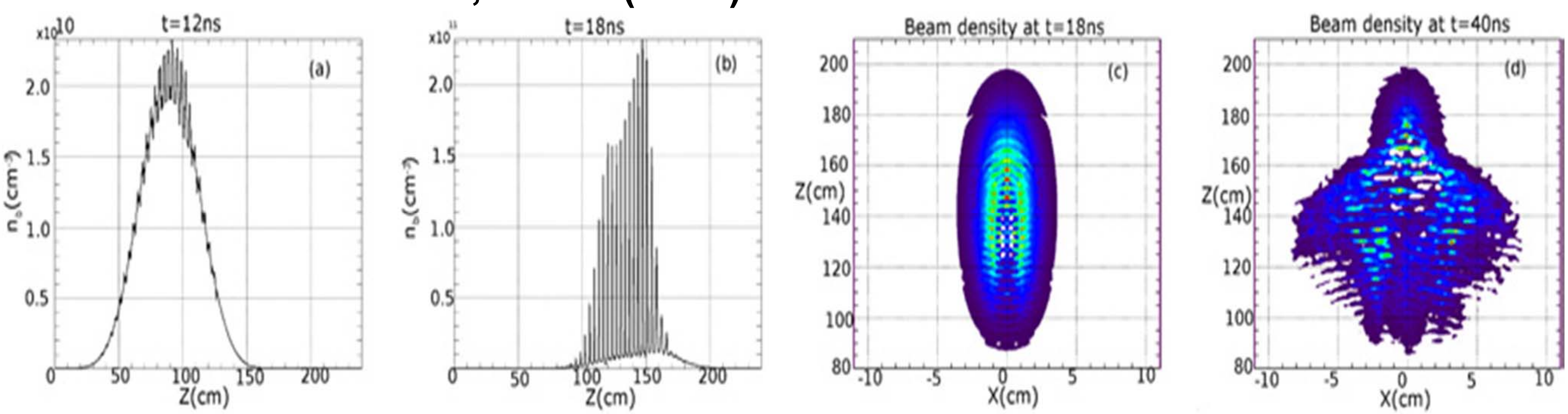
Left: No two-stream instability; Right: effect of two-stream instability



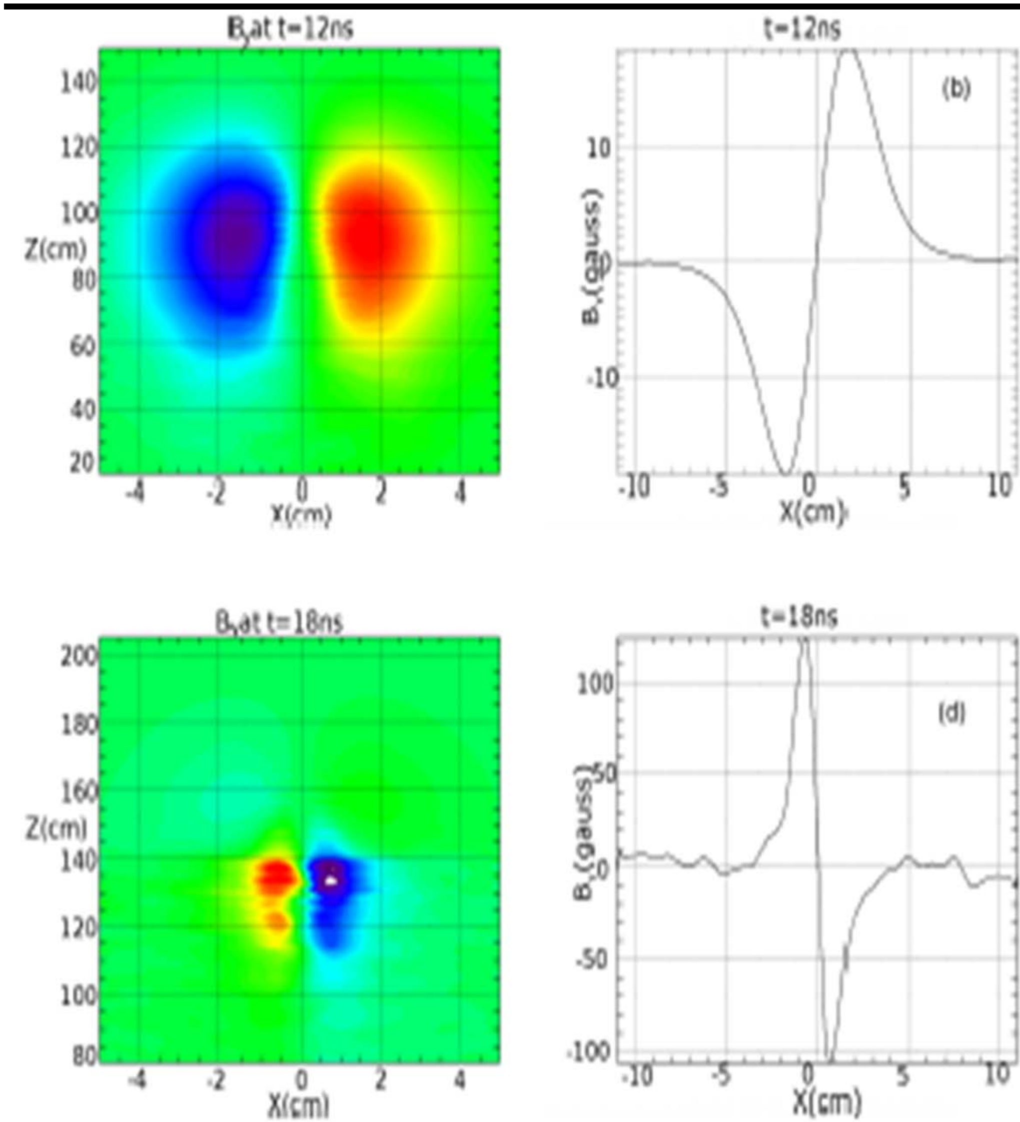


Plasma waves lead to bunching of the ion beam and accelerate plasma electrons to beam velocity

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

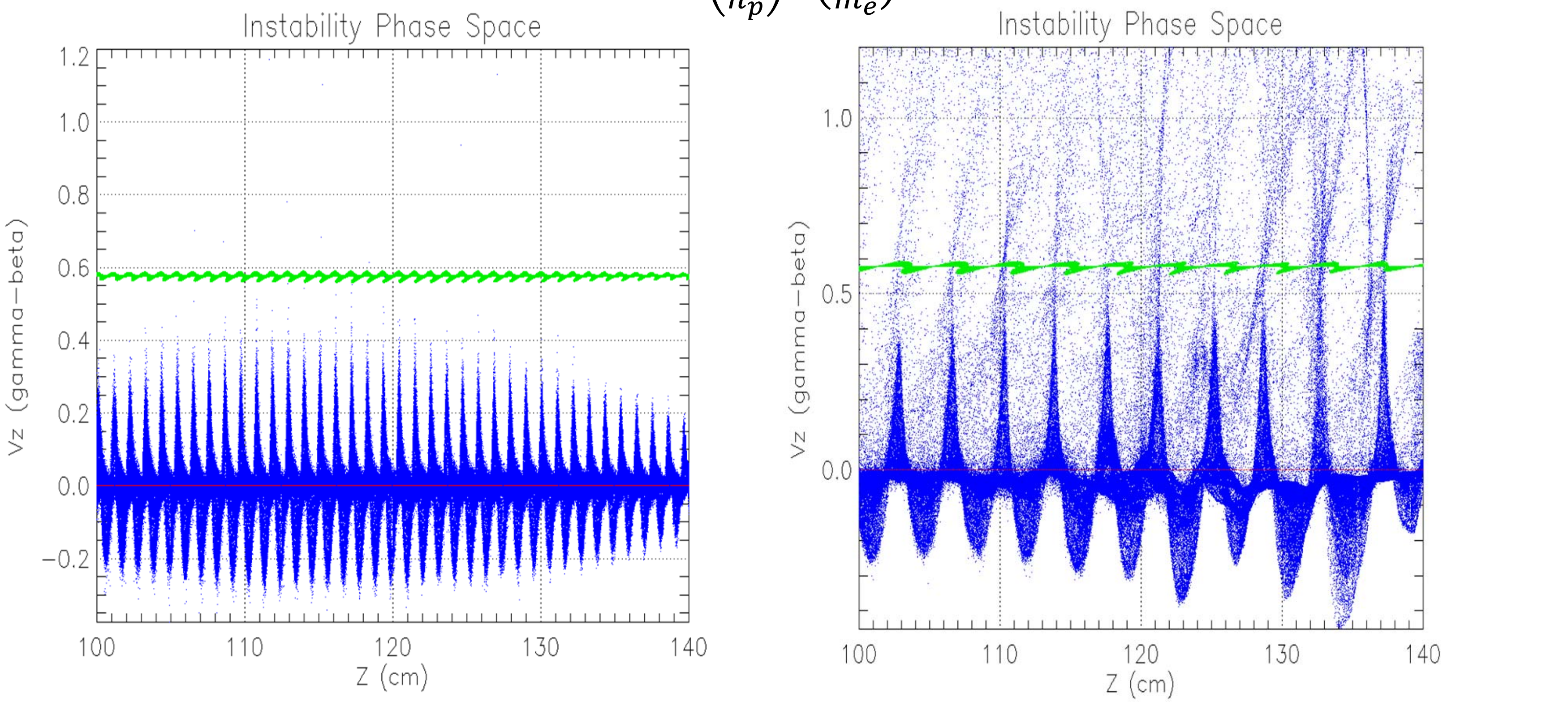
Top: without two-stream instability B~10G

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:**

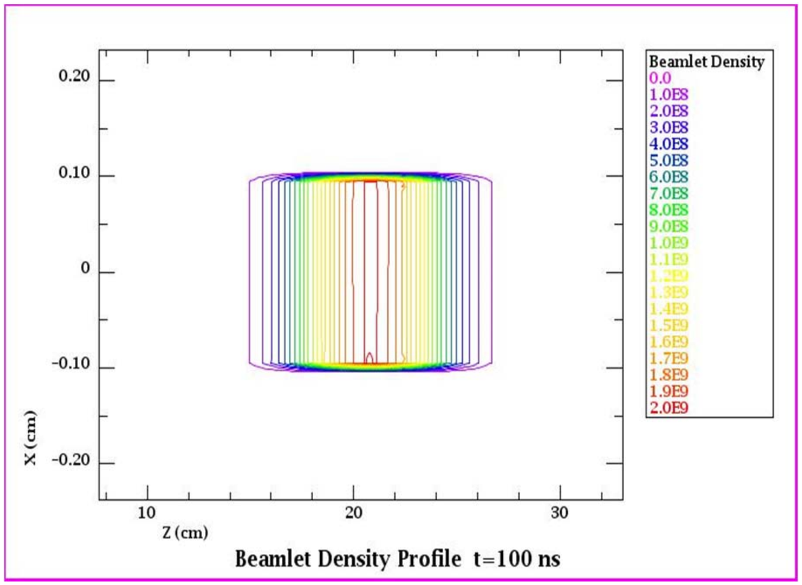
$$J_{tot} \sim J_z^b + J_z^e = \frac{J_z^b}{(1+r_b^2 \omega_p^2/c^2)} \left(1 - \frac{1}{2}\ \frac{n_p}{n_b} \left(\frac{v_m^e}{v_b}\right)^2\right)$$

- **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 733, 80 (2014)

Transverse Defocusing of the Beam due to Two-Stream Instability



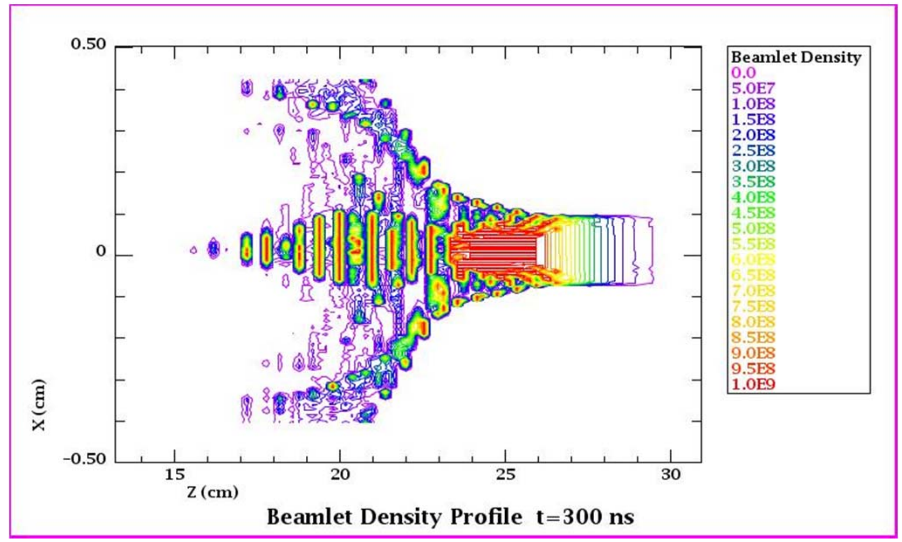


Fig. Beamlet Density Contour at t = 100 ns (1 m of propagation), Bottom: Beam Density Contour at t = 300 ns (3 m of propagation). NDCX-II beam parameters for apertured beam r_b=1 mm.

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

Electron Beam Generation Simulations

- **Stationary ions (Vlasov): Li^+, n_i=5.5x10^{16} m^{-3}; 0.3 eV.**
- **Stationary electrons (Vlasov): 0.4eV. Nonrelativistic.** $n_e = n_i + n_{i,beam}$
  - **Quasineutrality.** $n_e u_e = n_{i,beam} v_b$
  - **Current neutralization.**
- **Ion beam (PIC) : Li^+ = 7 amu; v_b=10^7 m/s (=*c*/30) where *c* = speed of light; $n_{i,beam}$=2x10^{15} m^{-3}; 0 eV.**

- **Electrostatic.**
  - **Potential = 0 V**
  - **Electric field = 0 V/m at far end in front of beam.**

Numerical Tools

- 1D1V Vlasov simulation:
  - Semi-Lagrangian technique = Strang time splitting,
  - Finite volume method with RK4-WENO5 (v).

- Length of domain = 10 m & # of cells: 20000.
- Velocity domain
  - v=[-4e7, 6e7] & # of velocity bins = 1000 for electrons,
  - v=[-5e4, 5e4] & # of velocity bins = 600 for ions,
  - 200,000 particles for ion beam.

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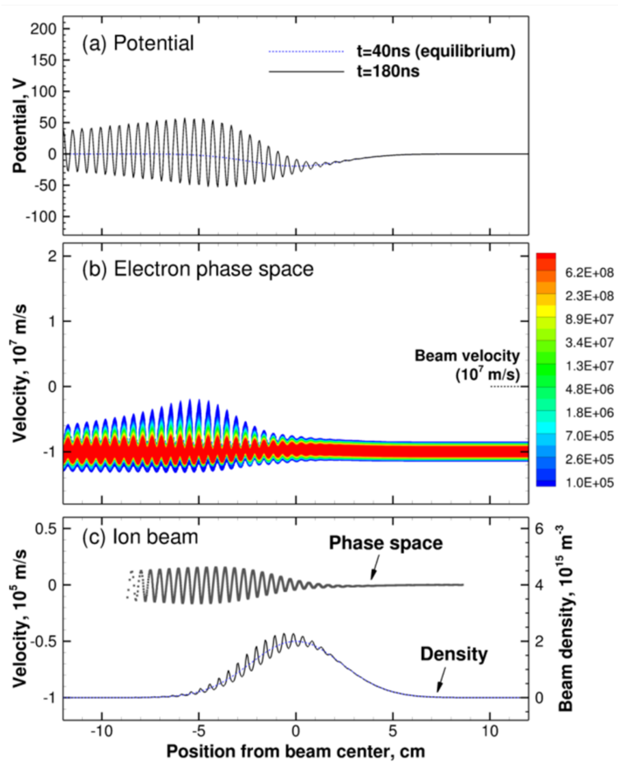
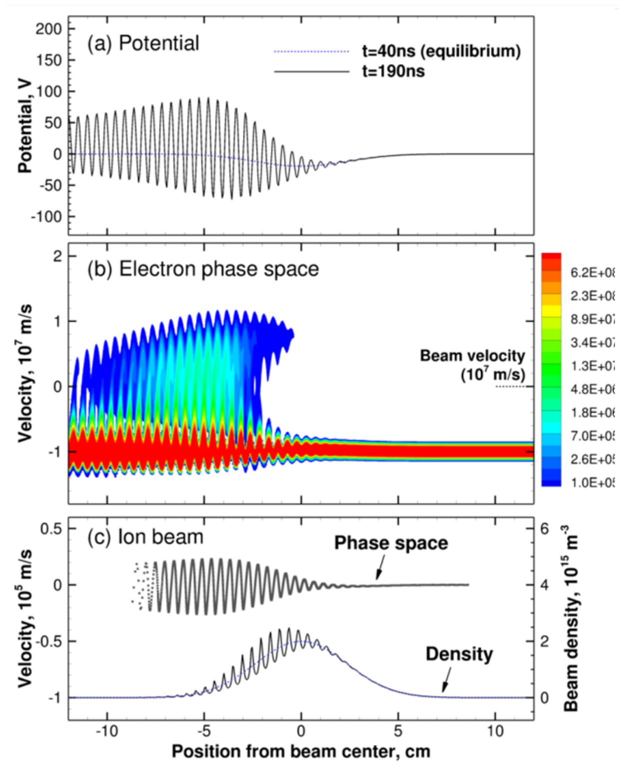
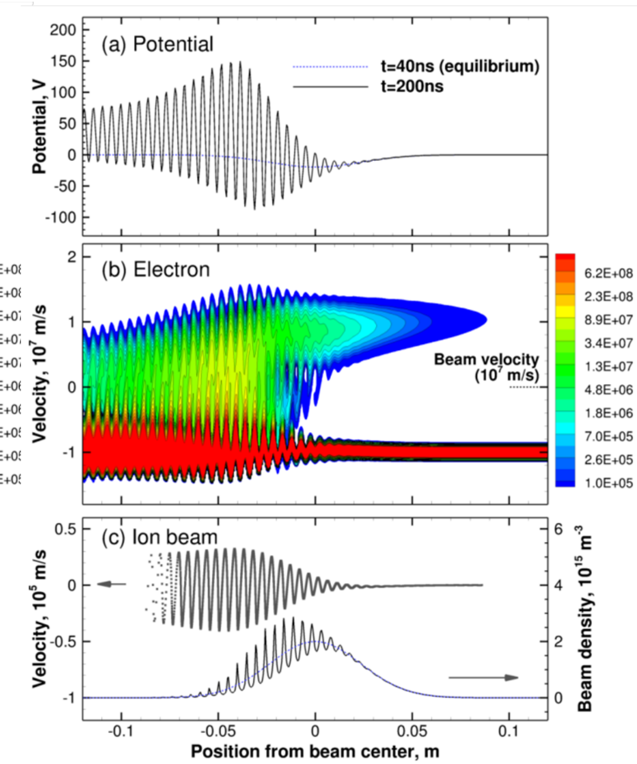
Ion Two-Stream Instability & Electron Acceleration



180 ns

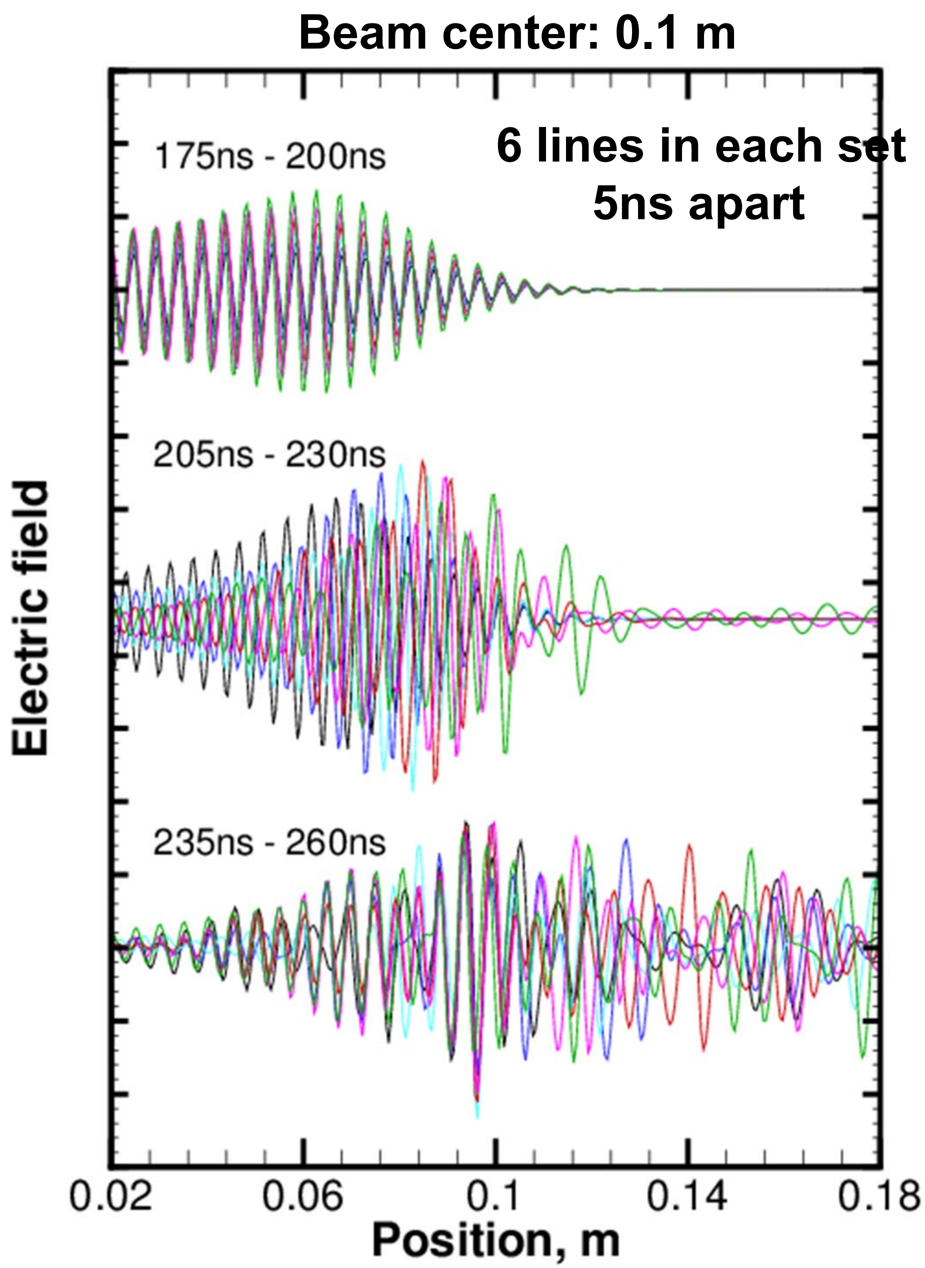


190 ns



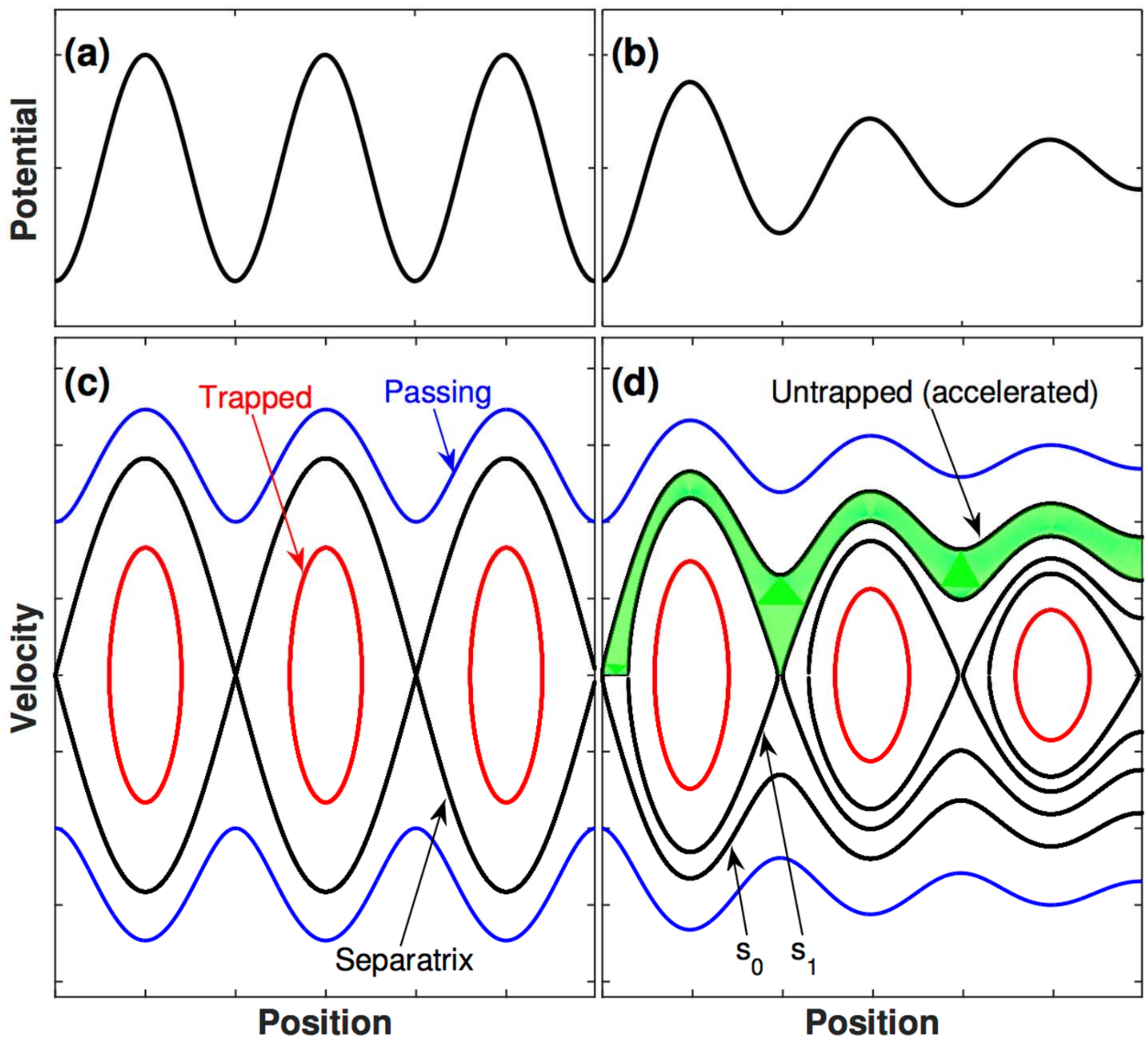
200 ns

Evolution



- **During linear growth (t<200ns)**
  - **Plasma wave slightly slower (about -10^5 m/s) than beam velocity**
  - **Predicted by theory**
- **Once electrons propagate (t>200ns), plasma wave propagates ahead of the ion beam.**
- **Can observe stationary plasma wave at beam center (t>240ns)**

Periodic vs. Non-periodic BGK



Barium Titanate Plasma Sources Create for 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.

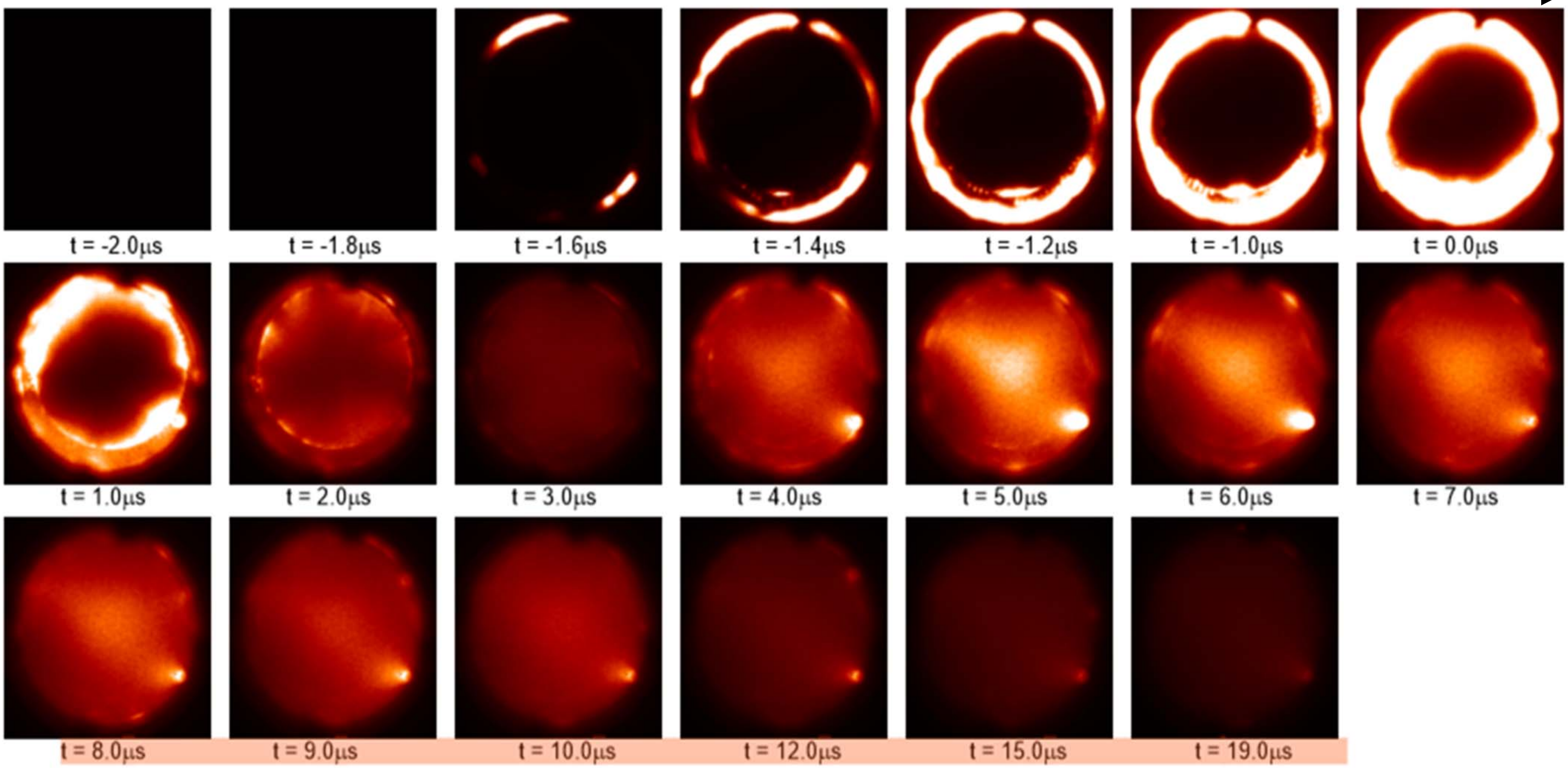
The source produces plasma ~ 10^{10} cm^{-3} density, T_e ~ 3 eV. The plasma density is greater than the local beam density, and the temperature is low, as needed for effective charge neutralization.

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

Fast photography of FEPS discharge

8 shot average
1 μs exposure

Surface plasma formation



Research Overview

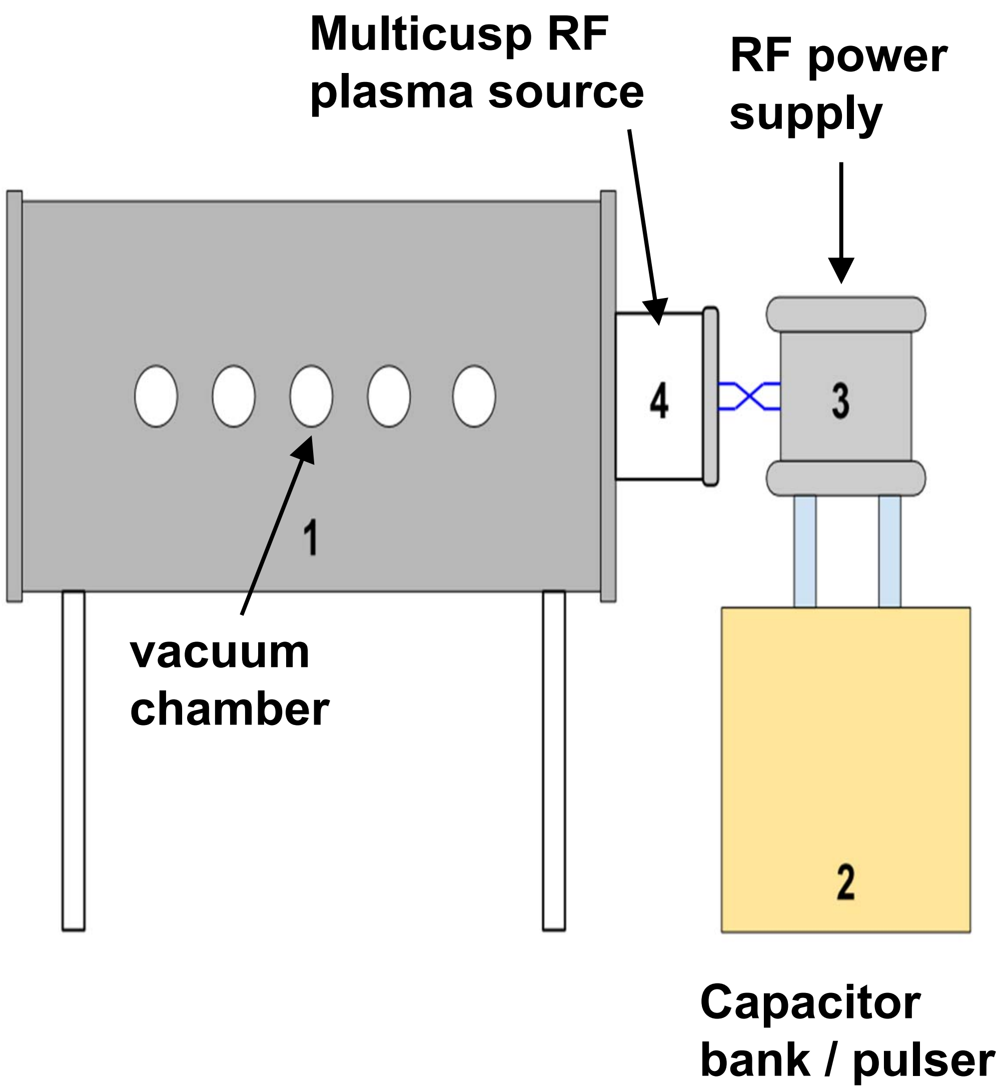
- Built an ion accelerator at PPPL to study space charge neutralization.
  - Based on STS-100 components from LBNL
  - 38 kV, 0.7 mA Ar^{+} beam

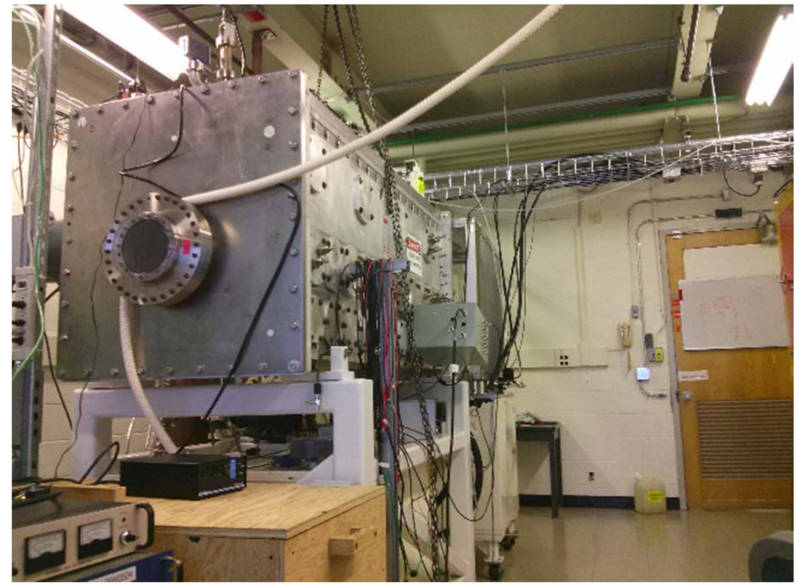
- 2 methods of neutralization were studied:
  - Autoneutralization at different background pressures
  - Neutralization by FEPS plasma

- Neutralization by FEPS plasma
  - Degree of attainable charge neutralization
  - Duration of neutralization
  - Presence of neutrals in the beamline

Princeton Advanced Test Stand

***formerly known as STS-**

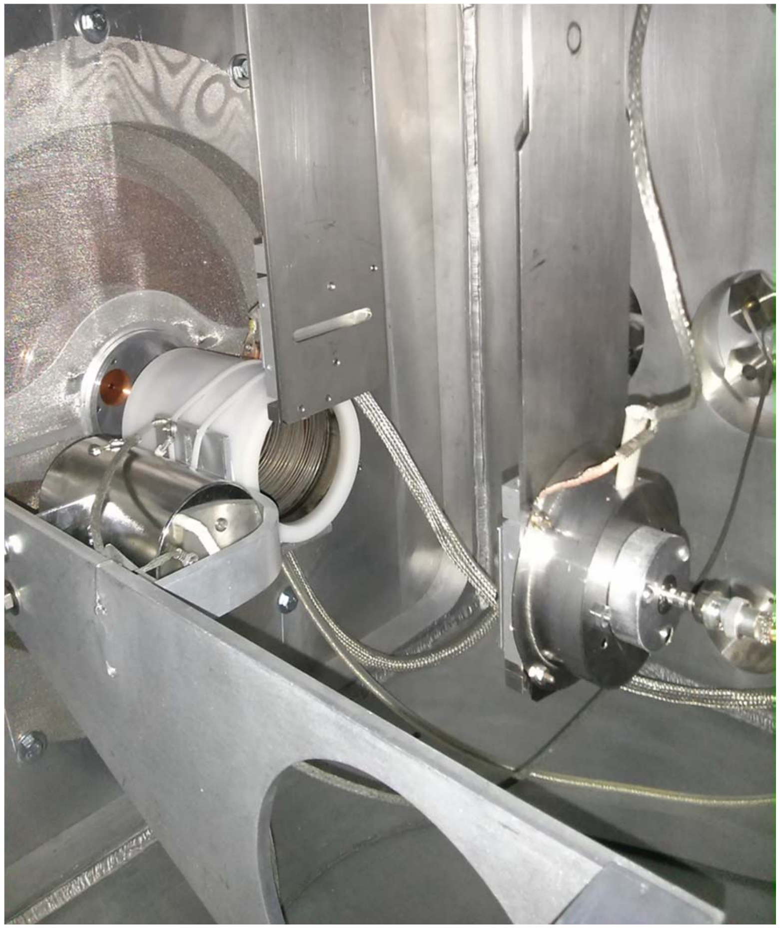




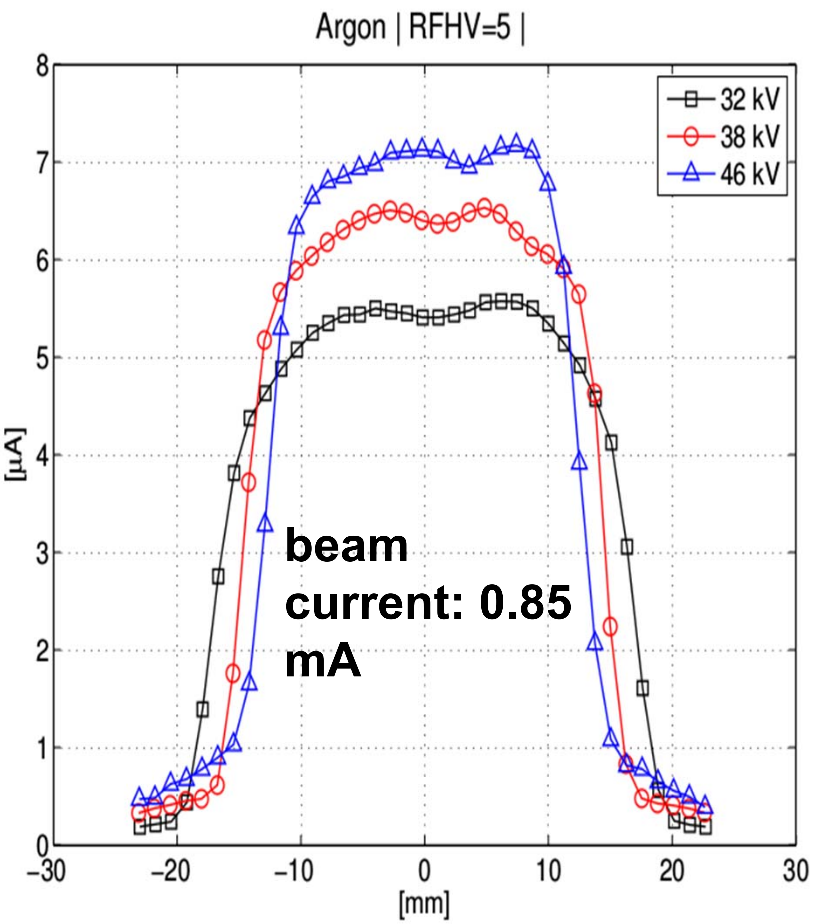
Accel. potential	38 kV
Beam current	0.7 mA
Perveance	3.9×10^{-4}
Transverse ES potential	15 V
Beam velocity	40 cm/μs

Overview of the Experiment

- Ion beam propagates from the source to a diagnostic
- Beam strikes a collimated Faraday cup 40 cm downstream from the source
- Time-evolution of transverse profiles can be measured



Flat-top profiles measured experimentally



Varying beam velocity at constant beam current.

flat-top current density profiles are consistent with space-charge expansion of an axisymmetric, uniform beam. Emittance is negligible.

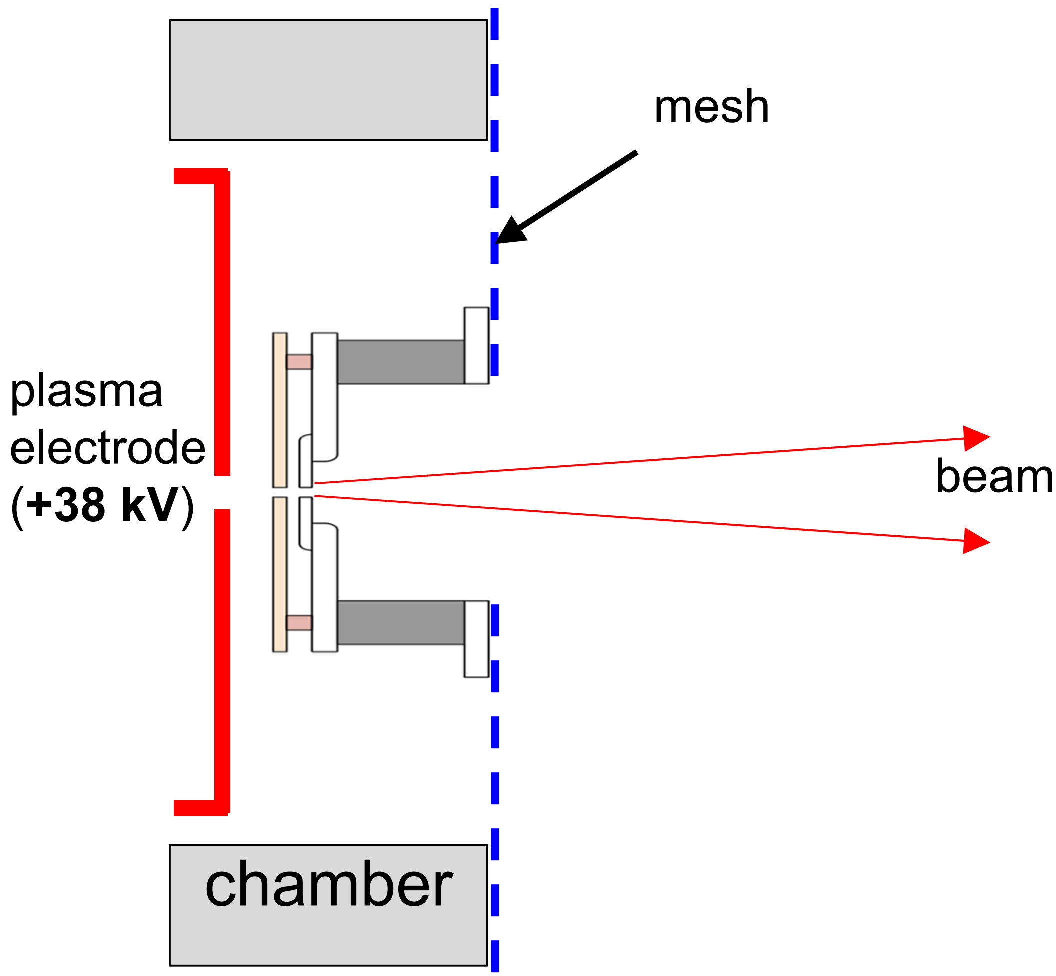
Experimental results: autoneutralization

- Expected to observe electron accumulation on the timescale of 10s of μs
  → Initially, no neutralization was observed at all, even at higher gas pressures

- The problem was not insufficient electron production, but **poor electron confinement**
  - **Electron loss** occurred due to fringe electric fields from the plasma electrode penetrating in the beam propagation region.

Electron removal also happened when the FEPS was installed in the path of the beam.

Electron loss

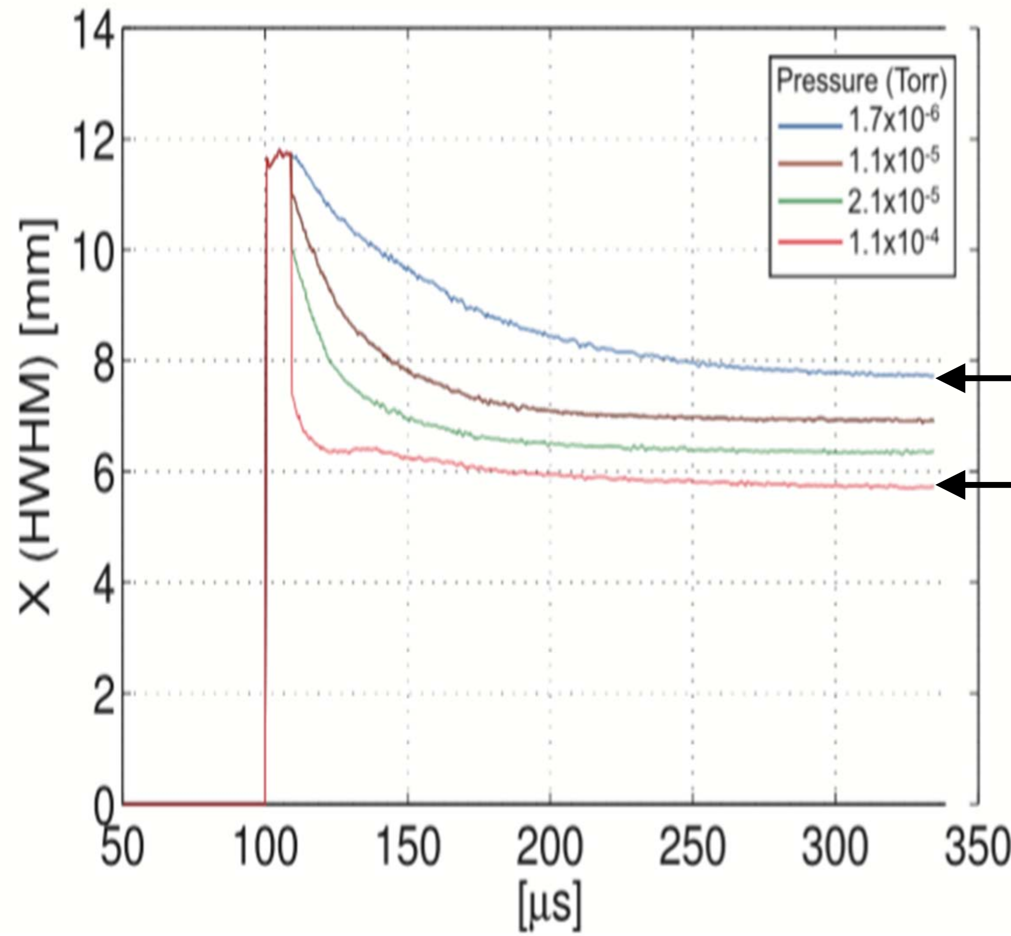


Stepanov *et al.*, Phys. Plasmas **23**, 043113 (2016)

Autoneutralization with shielding mesh

Beam radius vs. time

Rate of electron accumulation increases with pressure



$1.7\text{x}10^{-6}$ Torr

$1.1\text{x}10^{-4}$ Torr

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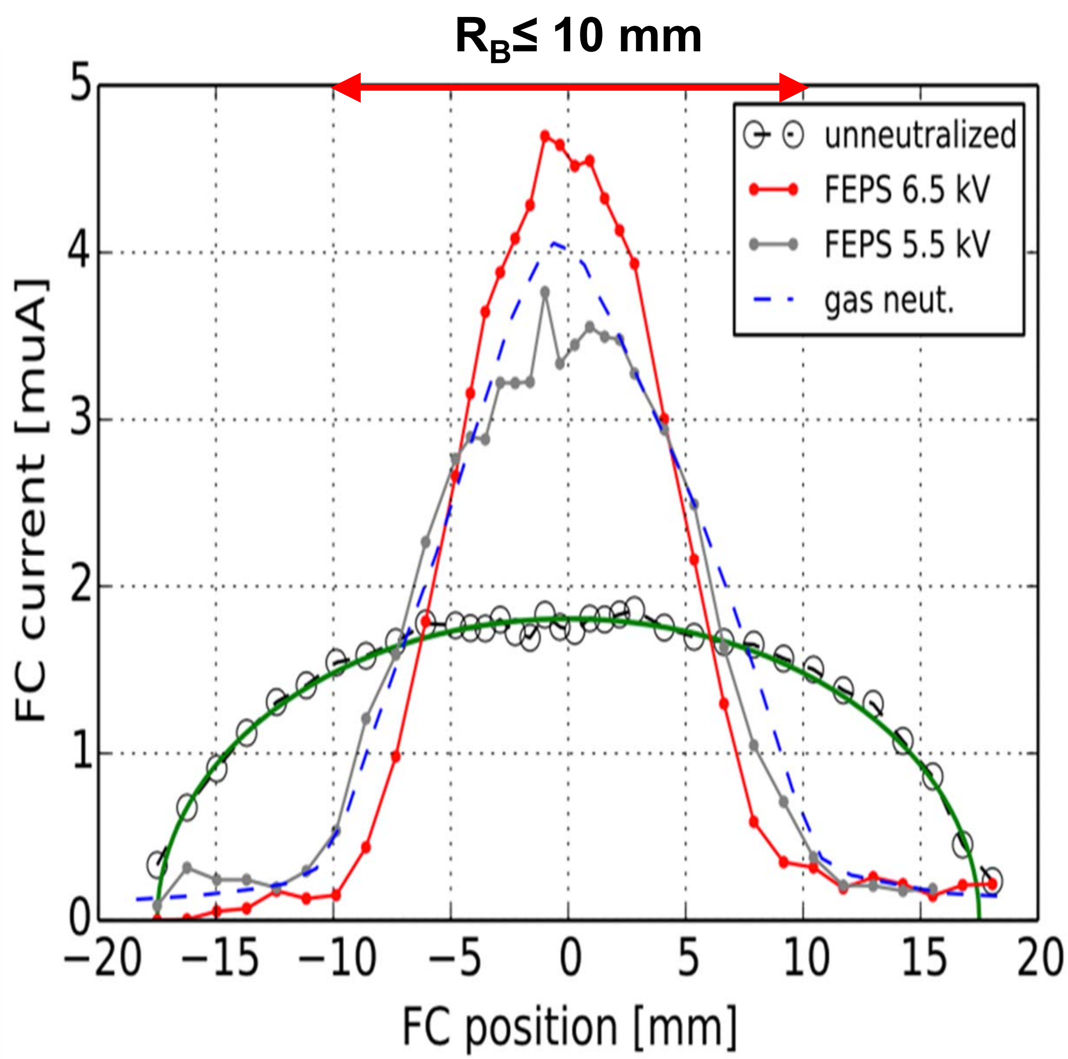
Transverse profiles before/after neutralization

1. unneutralized beam has a uniform current density profile: **j(r) = const**, R_B= 17.5 mm

$$I(x) = \int j(x,y)dy = \frac{2I_B}{\pi R_B}\sqrt{1 - x^2/R_B^2}$$

neutralization (6.5 kV)

1. Beam is narrower with FEPS than with gas neutralization



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The degree of charge neutralization is 98%

- Envelope equation can be used to estimate Q_{eff}
- requires R_0, $R`_0$, and the radius of the beam at the diagnostic (R_B)
- Initial divergence angle can be found from the unneutralized profile.
- Q_{eff} with FEPS neutralization can now be estimated
- Transverse ES potential is reduced from 15 V to 0.3 V → **electrons trapped in the beam have T_e < 0.3 eV**

$$\frac{d^2R}{dz^2} = \frac{f_e Q}{R} + \frac{\epsilon_\perp^2}{R^3}$$

$Q = 4\times10^{-4}$
$R_0 = 1.5$ mm
$R_B = 17.5$ mm

→ **$R`_0 = 1.2^0$**

$R'_0 = 1.2^0$
$R_0 = 1.5$ mm
$R_B = 10$ mm

→ $Q_{eff} = 0.02\ Q_0$

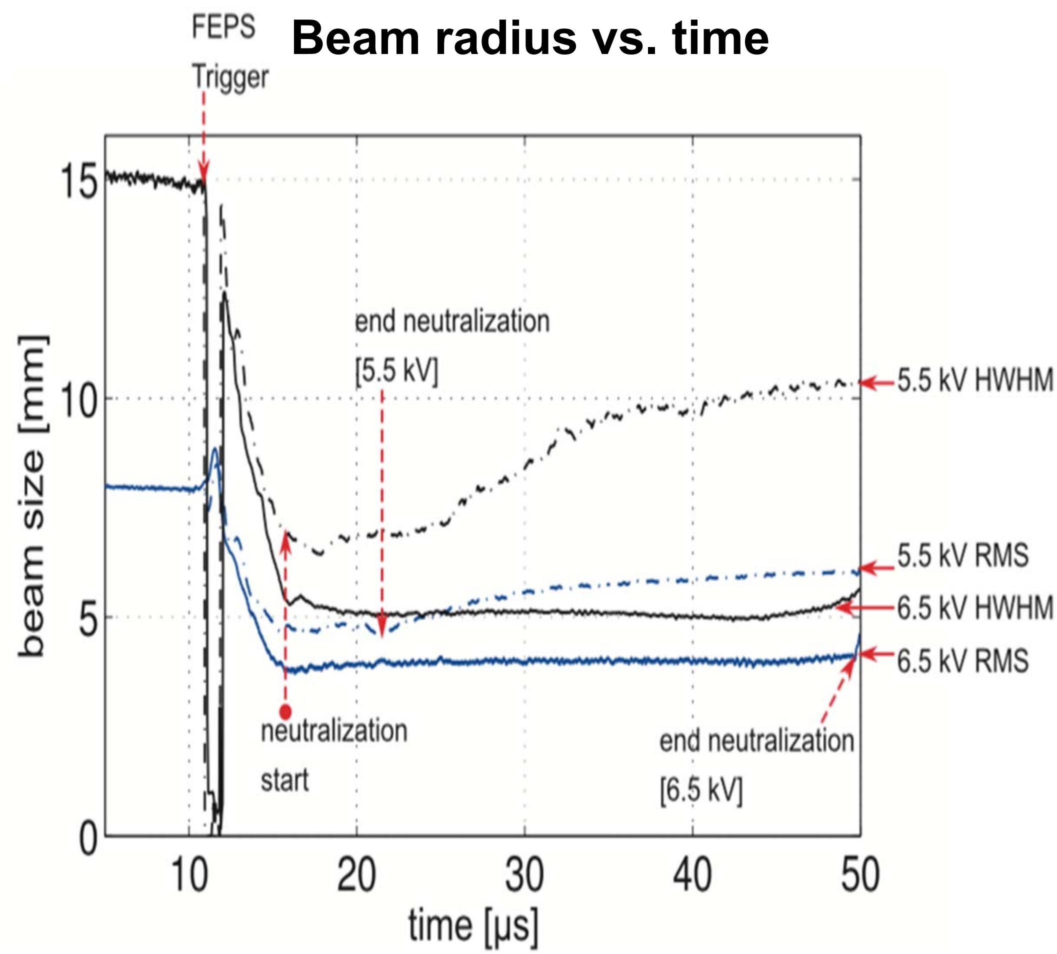
i.e. 98% charge neutralization

Beam radius vs time

FEPS driving voltage: 5.5 kV and 6.5 kV

Time to optimal neutralization	5 μs
Duration of neutralization	7 μs (5.5 kV) **35 μs (6.5 kV)**

Beam radius vs. time



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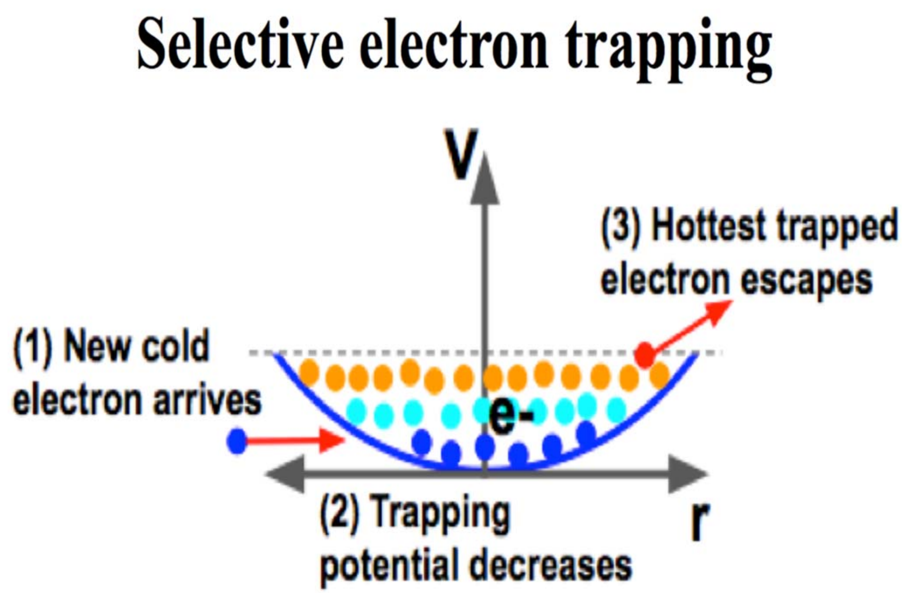
Cold electron accumulation mechanism

- Measured residual beam divergence is sufficiently low to conclude that **the beam is neutralized by "cold" electrons with E_{kin}< 0.3 eV.**

- FEPS plasma T_e is likely much higher (>1 eV). How can electrons in the beam be much colder than the source plasma? → **selective trapping of the coldest electrons from the plasma in the beam.**



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.
- Near-complete (98%) charge neutralization of a high-perveance, low energy ion beam by FEPS plasma has been demonstrated.
- Near-complete neutralization can last for >35 μs