EXPERIMENTAL AND THEORETICAL STUDY OF ION BEAM NEUTRALIZATION BY PLASMA

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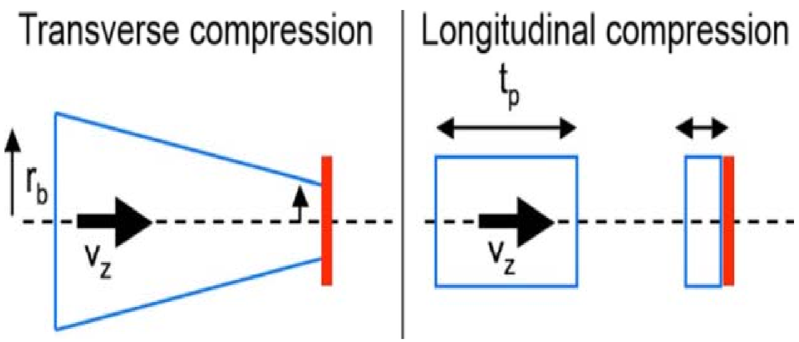
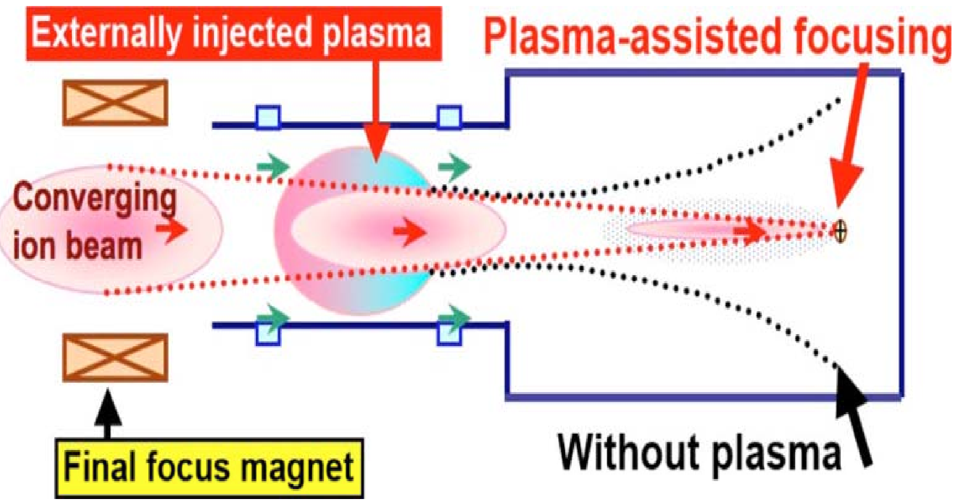
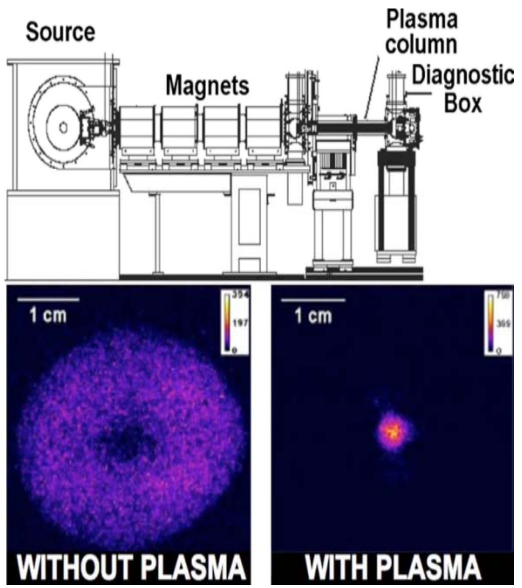
Outline

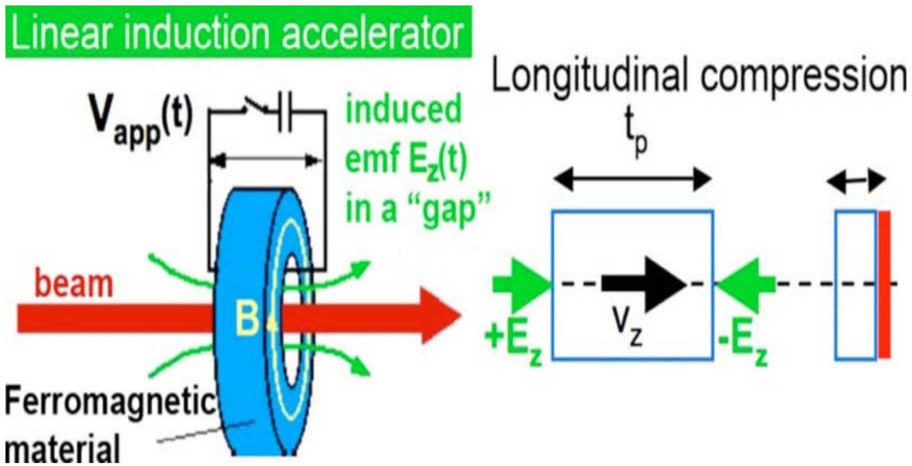
- **Physics of ion beam neutralization by plasma**
- **The two-stream instability causing a significant enhancement of the plasma return current and defocusing of the beam.**
- **The two-stream instability of an intense electron beam propagating in finite-length plasma with nonuniform density.**
- **Multi-dimensional kinetic simulations of instabilities and transport in ExB devices.**

Neutralized Drift Compression for Production of High Intensity Beam Pulses.



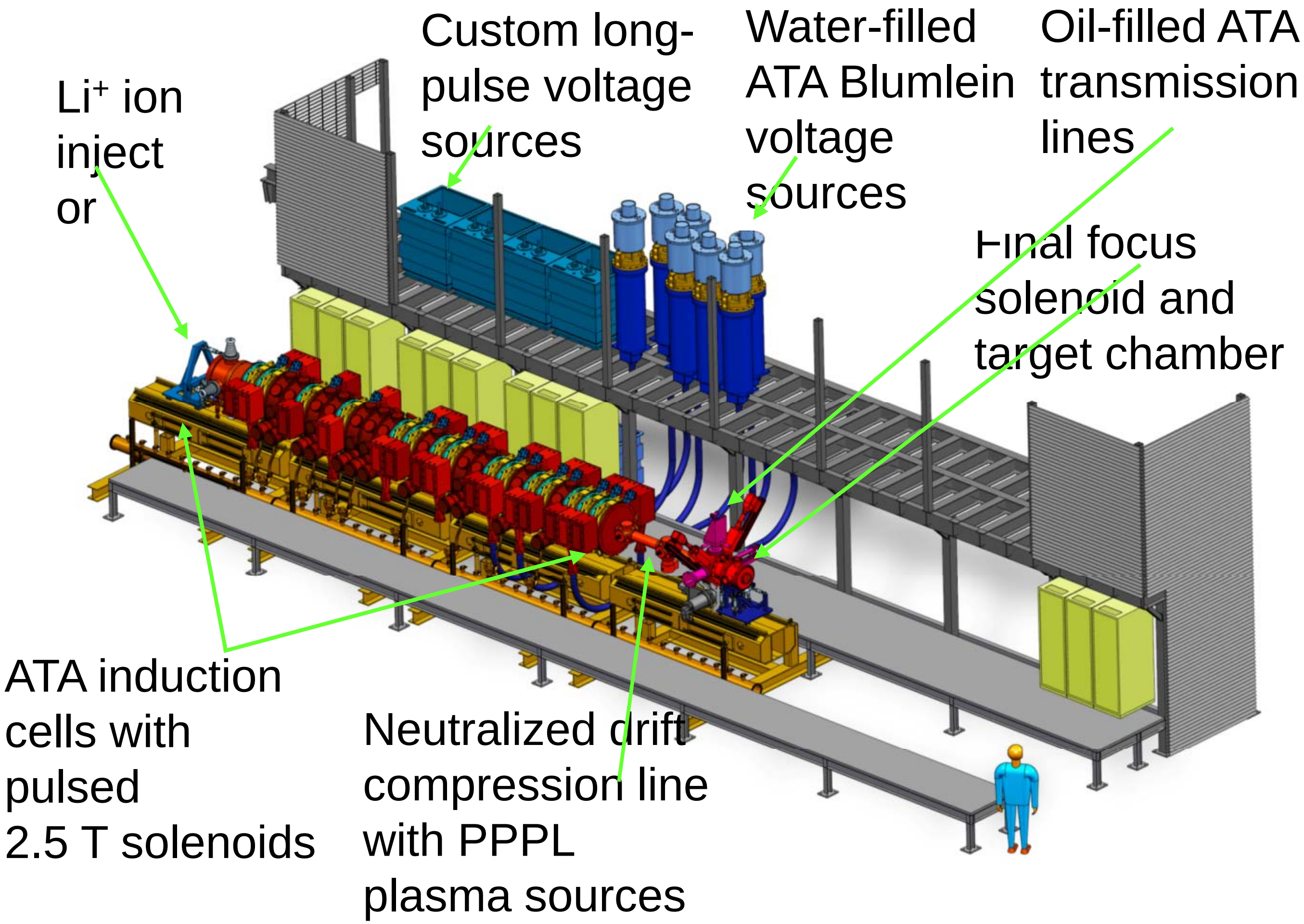






NDCX-II is a Versatile Accelerator that can Achieve Record-High Beam Brightness (1/3)

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

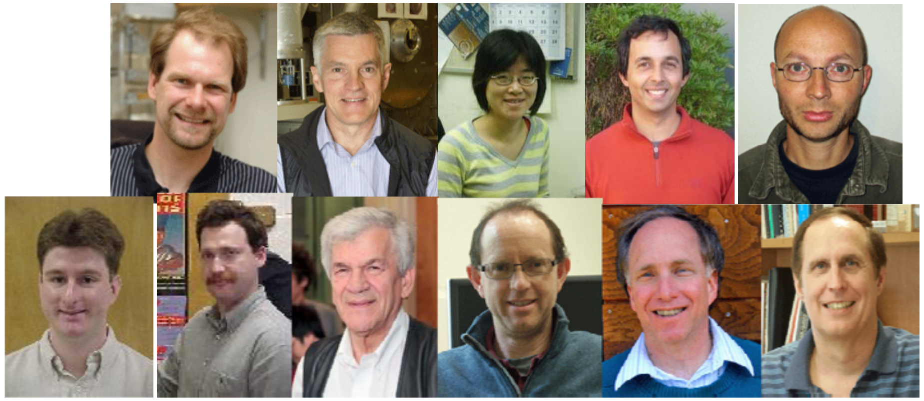


NDCX-II is a Versatile Accelerator can Achieve Record-High Beam Brightness (2/3)

- 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

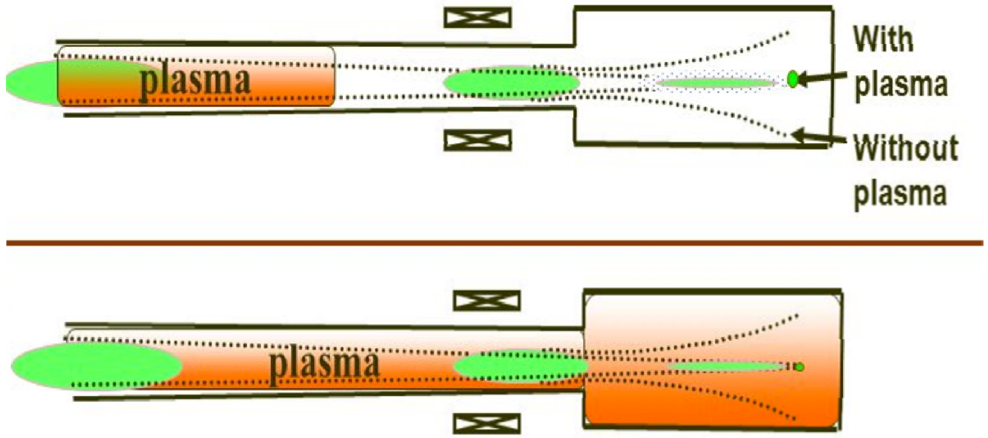
Peter Seidl[1], A. Persaud[1], J.J. Barnard[2], R.C. Davidson[3], A. Friedman[2], E.P. Gilson[3], Grote[2], P. Hosemann, Q. Ji[1], I. Kaganovich[3], A. Minor[1,4], W.L. Waldron[1], T. Schenkel[1]

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

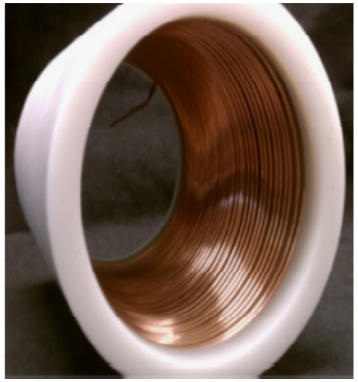


Ion Beam Charge Neutralization by Ferroelectric Plasma Sources

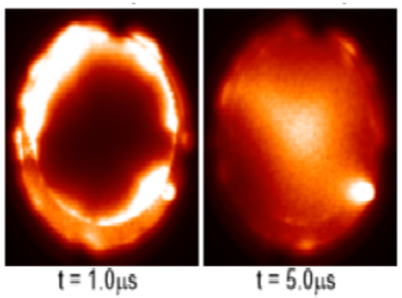
Charge neutralization has to be near-complete (>99%) to enable ballistic focusing.



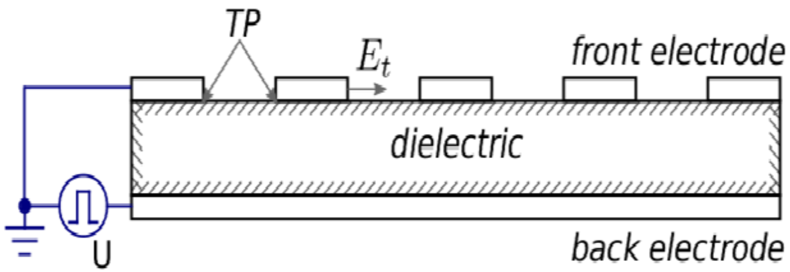
Ferroelectric Plasma Sources (FEPS) offer an attractive solution:



Ferroelectric Plasma Source

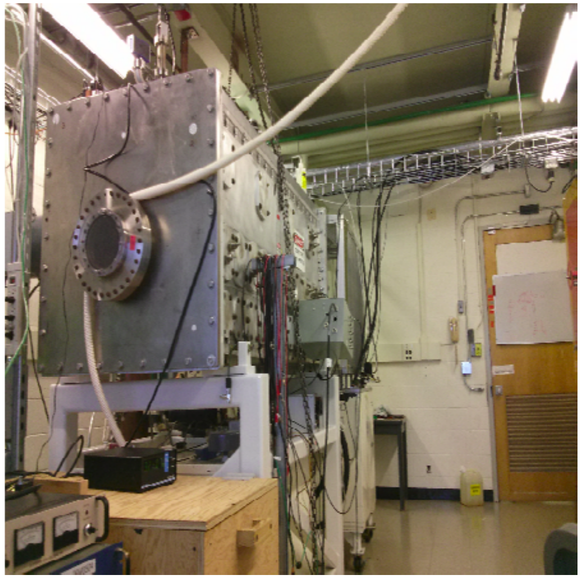


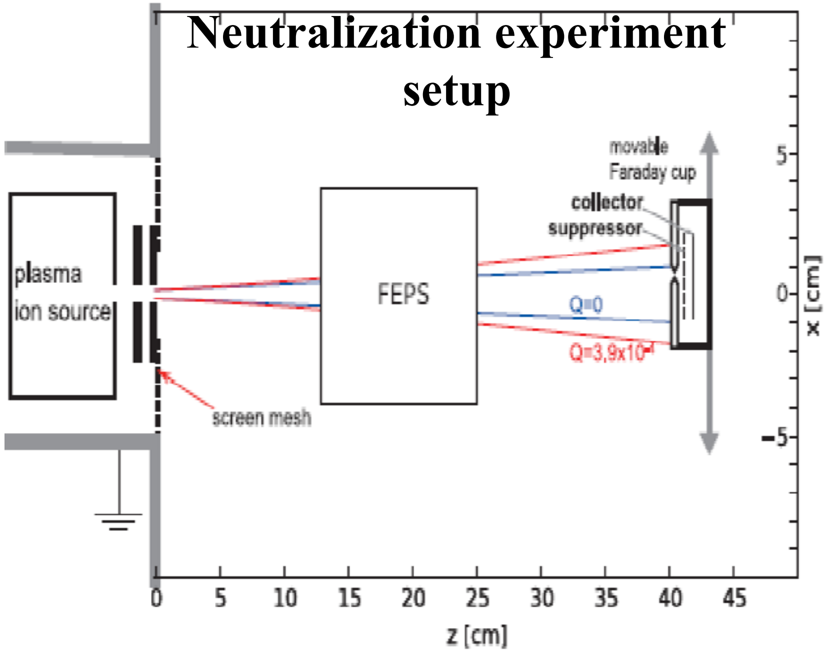
ICCD photographs of discharge



Plasma production based on the <u>surface discharge</u> mechanism. Plasma lifetimes of tens of **μ**s

Experiments on the Princeton Advanced Test Stand





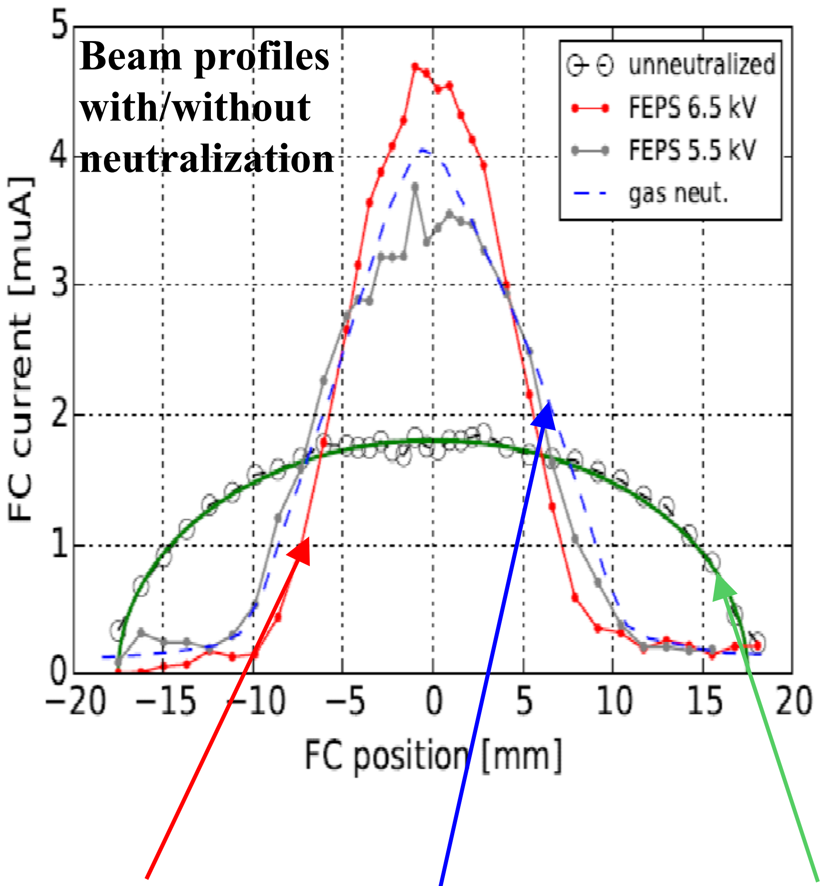
Accel. potential	38 kV
Beam current	0.7 mA
Perveance	$3.9\mathrm{x}10^{-4}$
ES potential	15 V

A high-perveance, 38 keV Ar+ ion beam was propagated through the FEPS plasma. The effects of charge neutralization were inferred from time-resolved measurements of the transverse beam profile.

Charge neutralization fraction of 98% was measured → transverse electrostatic potential of the ion beam reduced from 15 V to 0.3 V

ES confinement of electrons in the beam is required for neutralization → the beam was neutralized by “cold” electrons (E<0.3 eV).

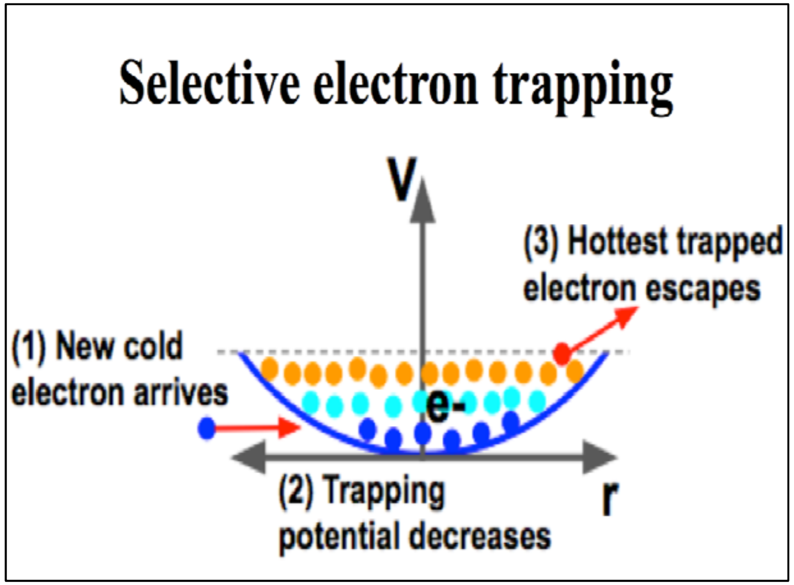
Observed neutralization efficiency requires presence of very cold electrons E_{kin}<0.3 eV



FEPS Plasma (>98%)

gas neutralization

unneutralized (flattop)



FEPS plasma T_e is likely a few eV, so how can electrons in the beam have E_{kin}<0.3 eV)?

→ **Selective trapping** of the coldest electrons from the plasma in the beam.

A. Stepanov et al, Phys. Plasmas (2016)

Comparison of neutralization methods

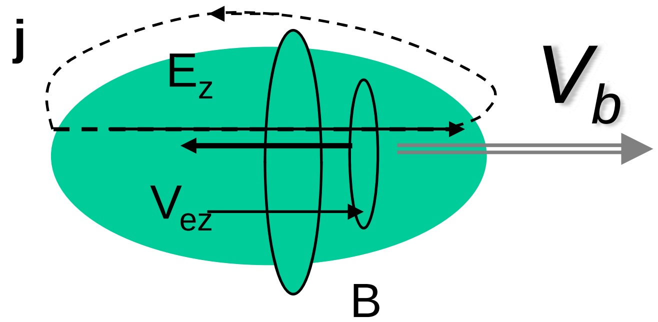
	Charge neutralization %
➢ **Hot filament** intercepting the beam *(Scaled Final Focus Experiment)**	**80%**
➢ **Gas neutralization:** e- produced by ion impact ionization of background neutrals *(Princeton Advanced Test Stand)*	**83%**
➢ **Plasma plug:** a localized region of plasma and short beam pulse *(Neutralized Transport Experiment)***	**96%**
➢ **Neutralization by volume plasma** *(Princeton Advanced Test Stand)*	**>98%**

* S.A. MacLaren et al, Physics of Plasmas **9**, 1712 (2002)
** E. Henestroza et al, PRSTAB **7**, 083501 (2004)
Review, I. Kaganovich et al Phys. Plasmas (2010),
W. Berdanier, et al. PoP (2015), A. Stepanov et al, Phys. Plasmas (2016)

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.



$$\frac{\partial \int B ds}{\partial t} \Rightarrow E_z$$

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

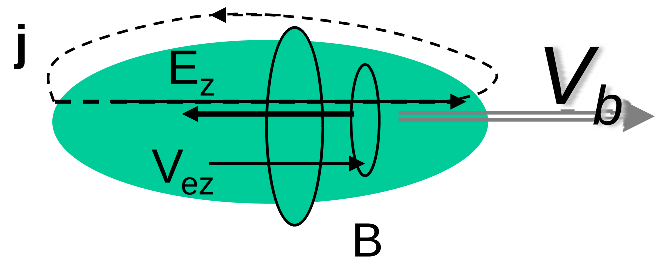
Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation direction.

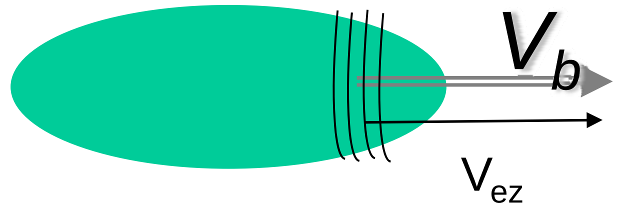
$$\phi = mV_{ez}^{\ 2} / 2e \qquad V_{ez} \sim V_b n_b / n_p \qquad \phi_{vp} = mV_b^{\ 2} \left(n_b / n_p \right)^2 / 2$$

, I. Kaganovich et al Phys. Plasmas (2001),

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

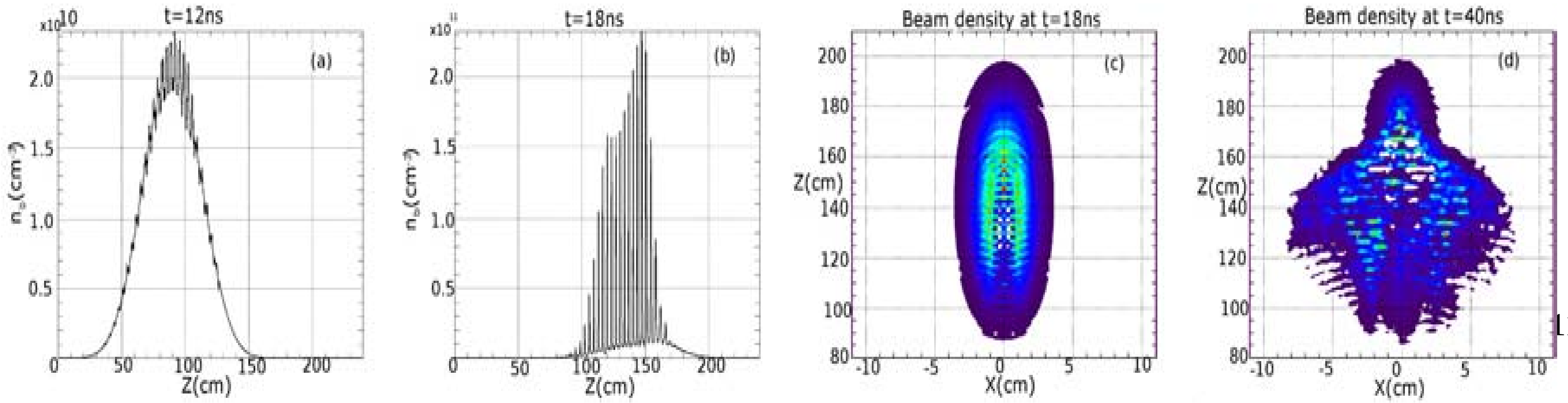
Left: No two-stream instability; Right: effect of two-stream instability



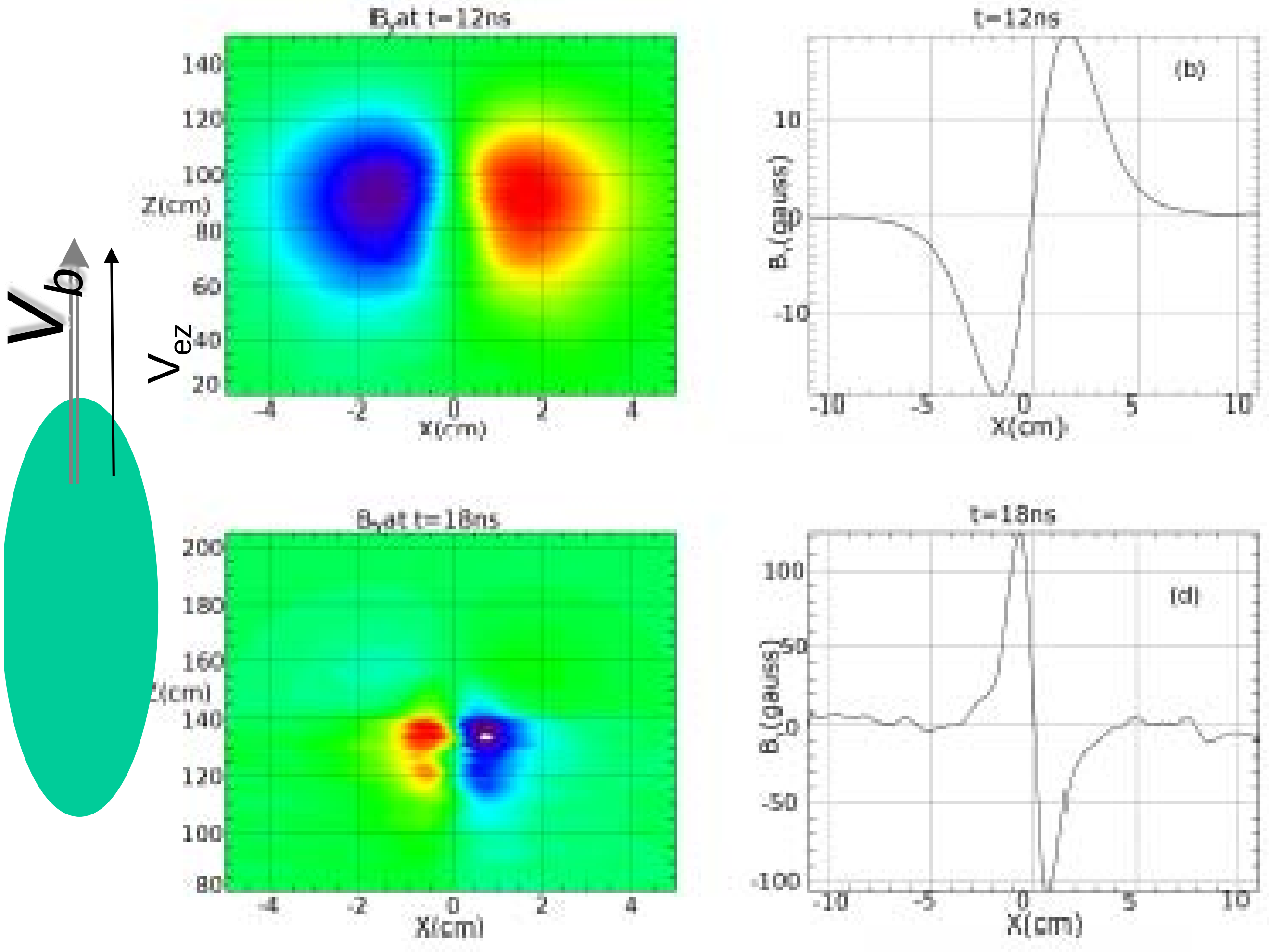


Plasma waves lead to bunching of the ion beam and accelerate plasma electrons to beam velocity

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), E. Tokluoglu (2015).



Enhanced return current density reverses the azimuthal magnetic field

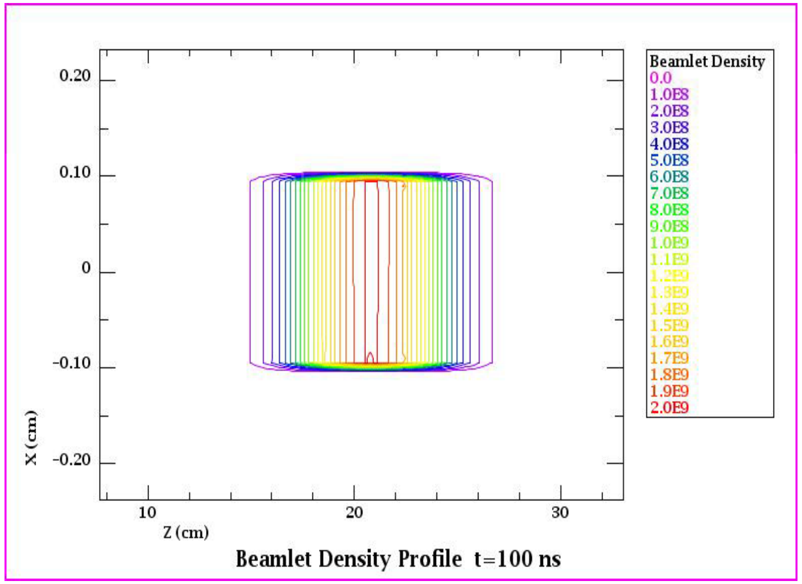


Self magnetic field of the ion beam propagating in plasma

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)

Transverse Defocusing of the Beam due to Two-Stream Instability



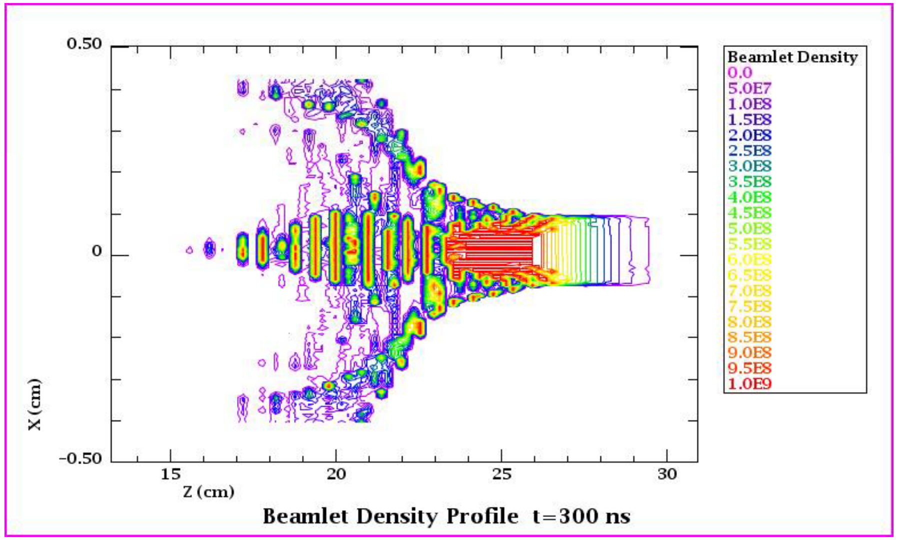
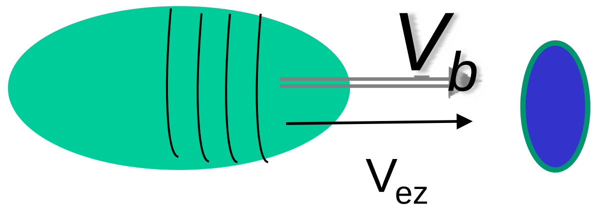


Fig. Beamlet Density Contour at t = 100 ns (1 m of propagation), Bottom: Beam Density Contour at t = 300 ns (3 m of propagation). NDCX-II beam parameters for apertured beam r_b=1 mm.

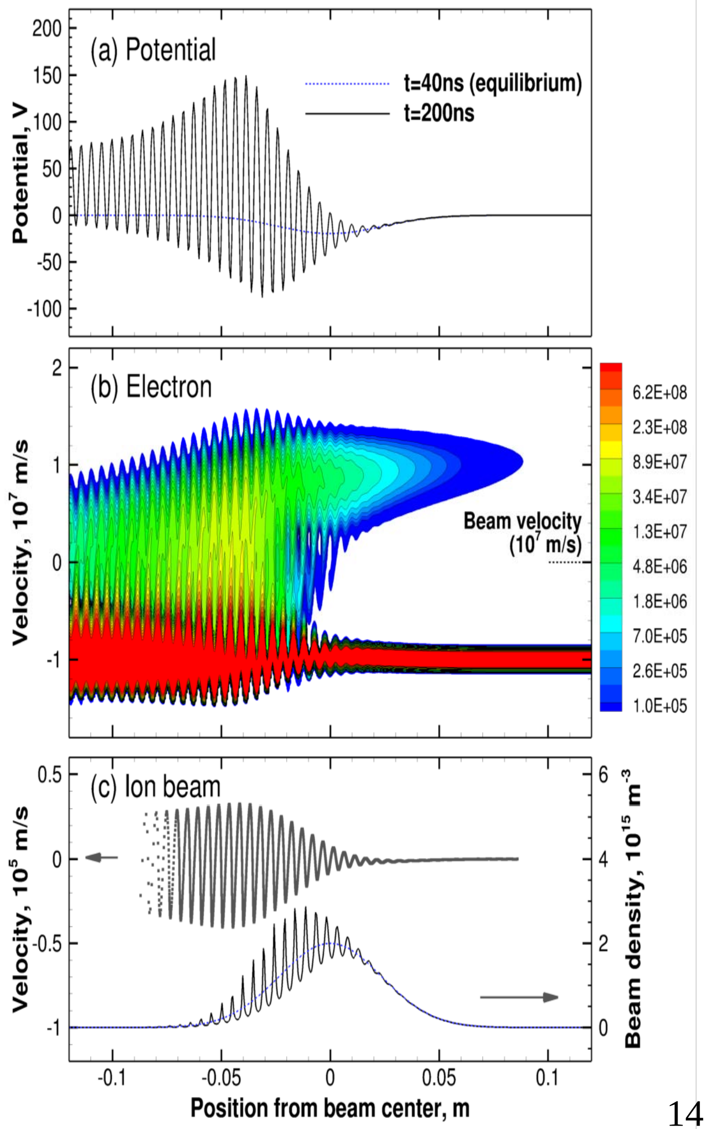
E. Tokluoglu and I. Kaganovich, Phys. Plasmas 22, 040701 (2015)

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

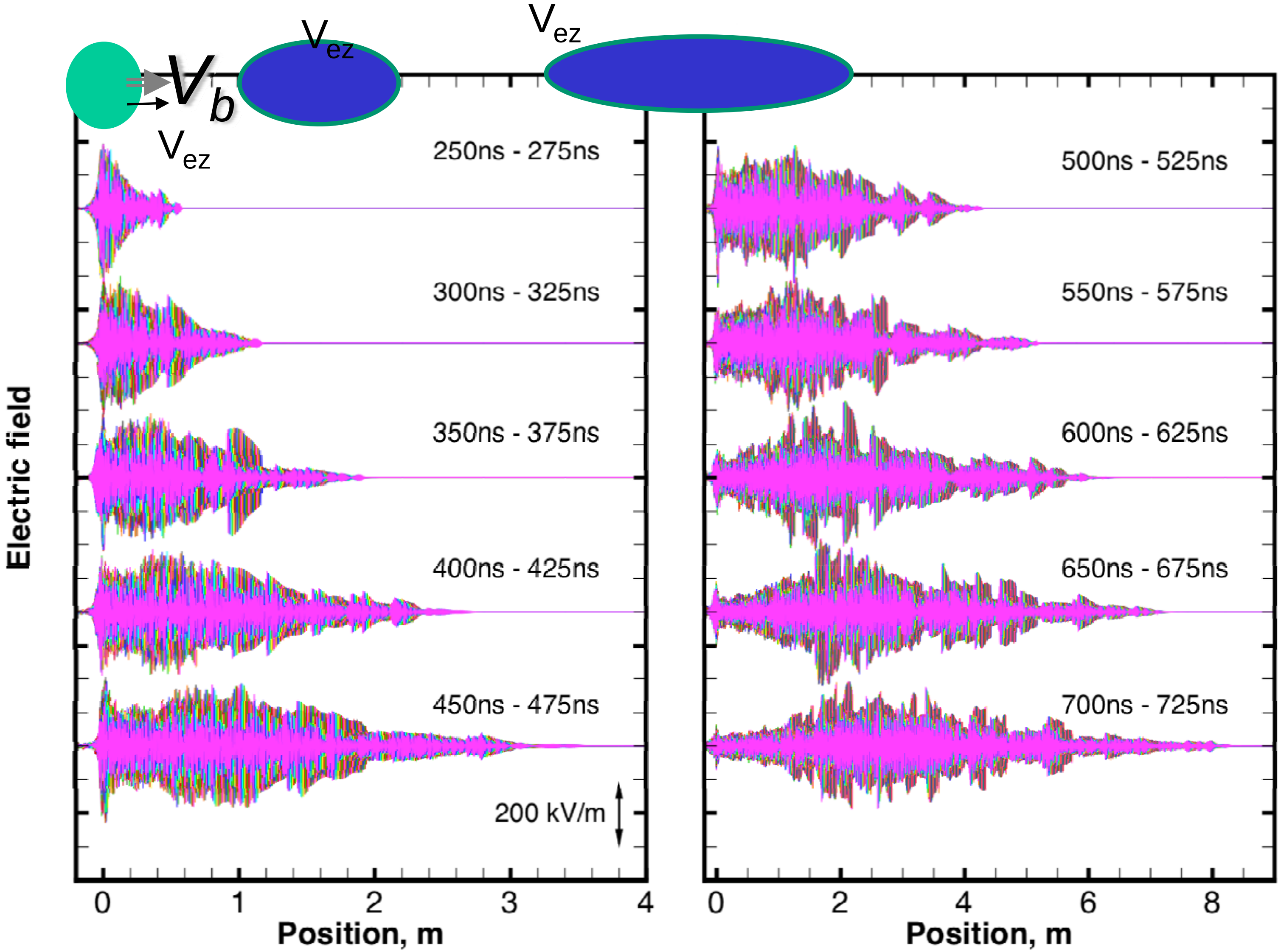


Ion beam => electron beam with twice of the ion beam velocity K. Hara, et al (2015)

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}.



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



Outline

- Motivation/Background
  - Neutralized drift compression
  - NDCX-II
  - Physics of ion beam neutralization by plasma
- Ion beam propagating in background plasma. The two-stream instability causing a significant enhancement of the plasma return current and defocusing of the beam.
- **The two-stream instability of an intense electron beam propagating in finite-length plasma with nonuniform density. Acceleration of bulk electrons due to two-stream instability.**

Results of the beam-plasma Interaction during the two-stream instability:

Simulations by D. Sydorenko

The HF electric field is the strongest here, note the bulk electrons accelerated rightward.

red = bulk

green = beam

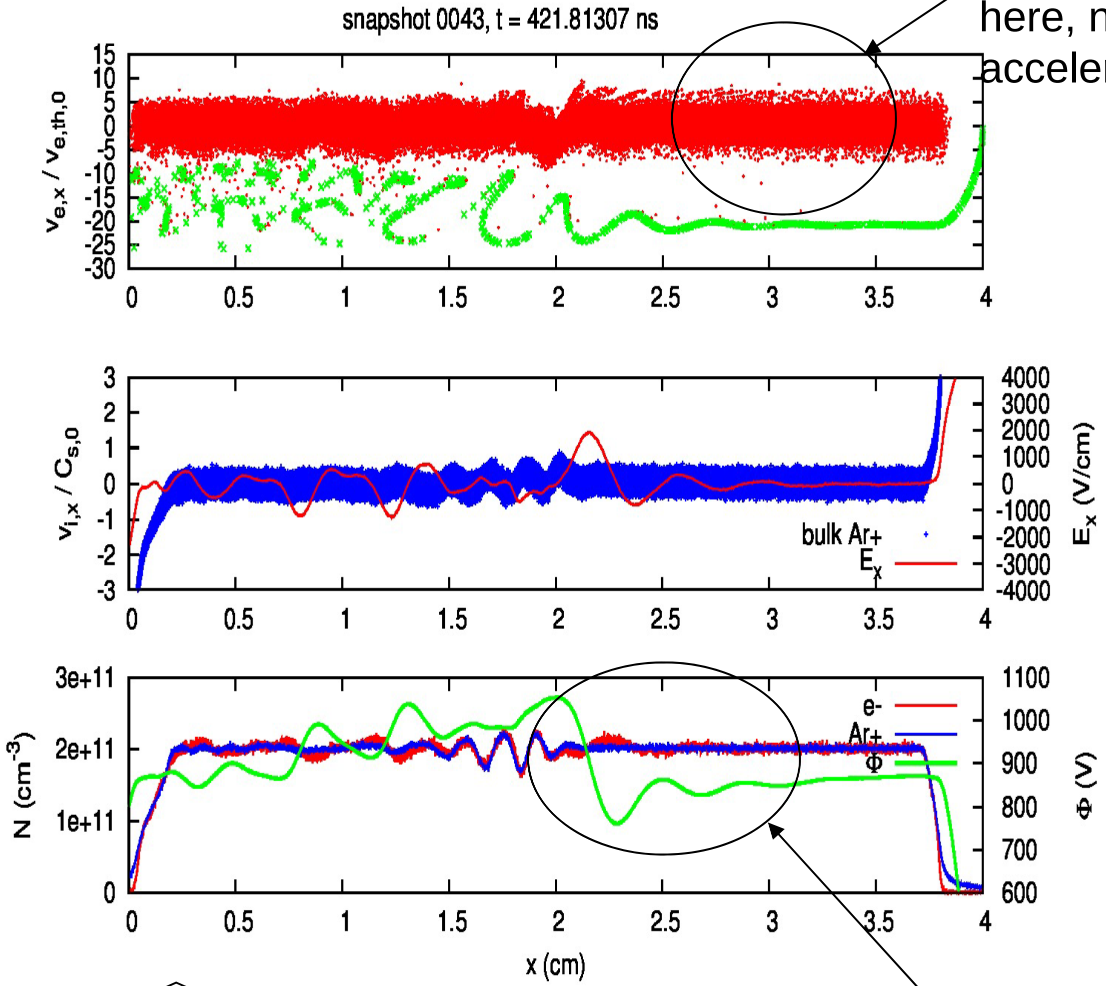
Electron velocity

Ion velocity

Density

Electric field

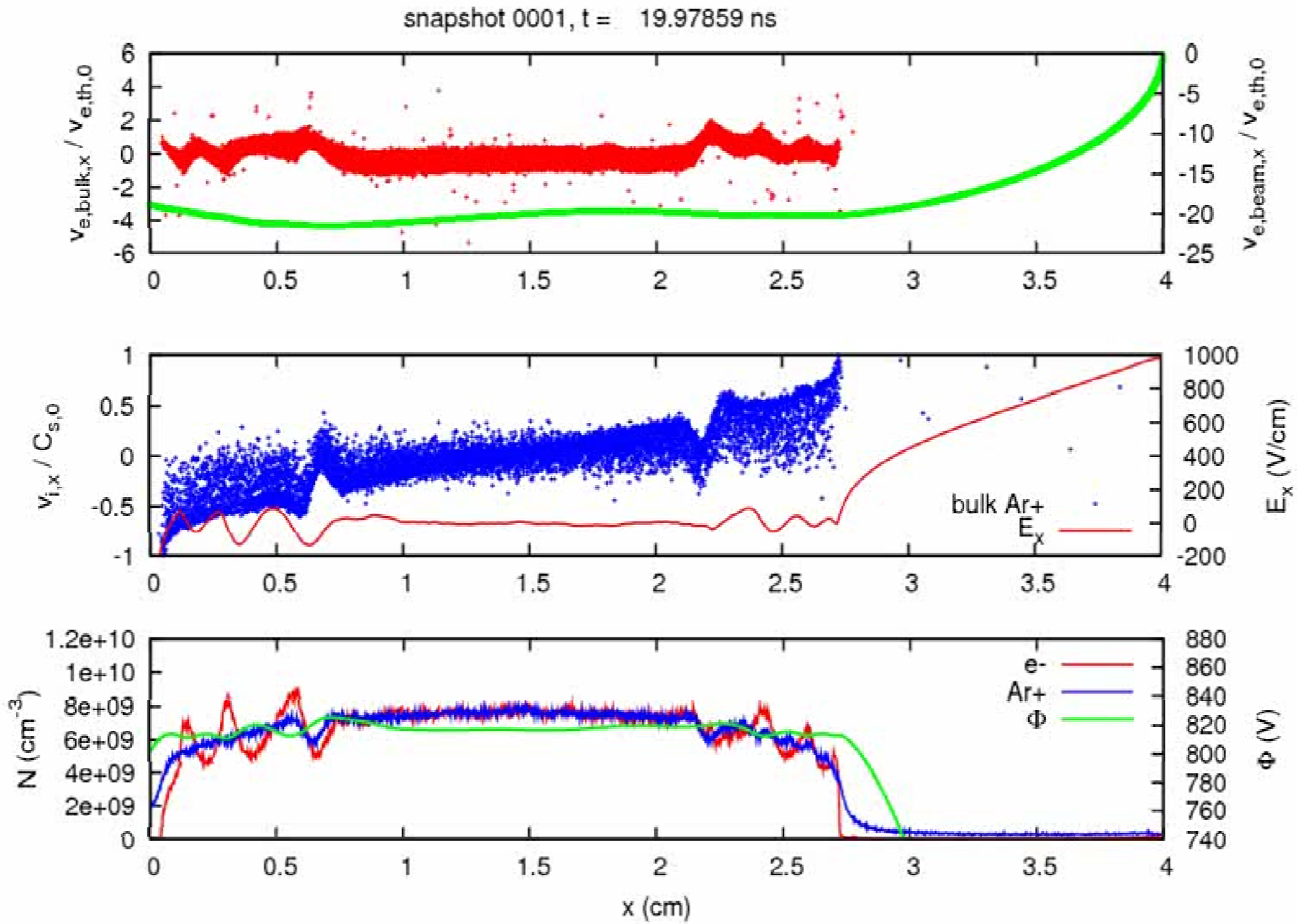
Electro-static potential



Note formation of ion perturbations

Anode

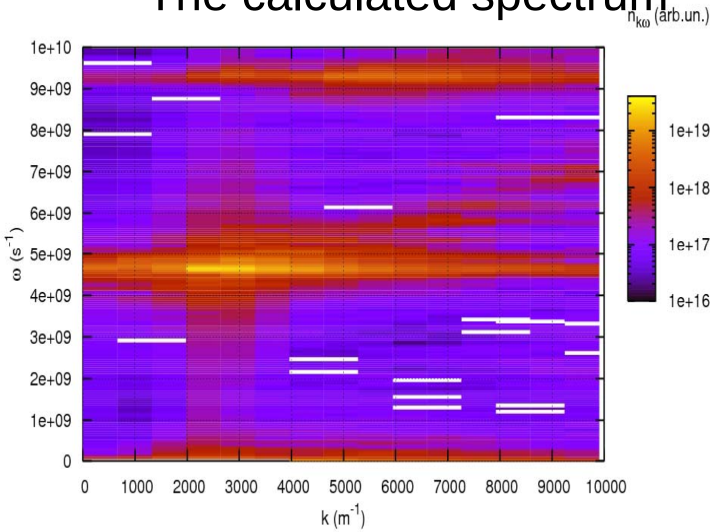
Cathode



snapshot 0001, t = 19.97859 ns
$v_{e,bulk,x} / v_{e,th,0}$
$v_{e,beam,x} / v_{e,th,0}$
$v_{i,x} / C_{s,0}$
E_x (V/cm)
bulk Ar+
E_x
N (cm^{-3})
Φ (V)
e-
Ar+
Φ
x (cm)

The global mode is excited with the same frequency

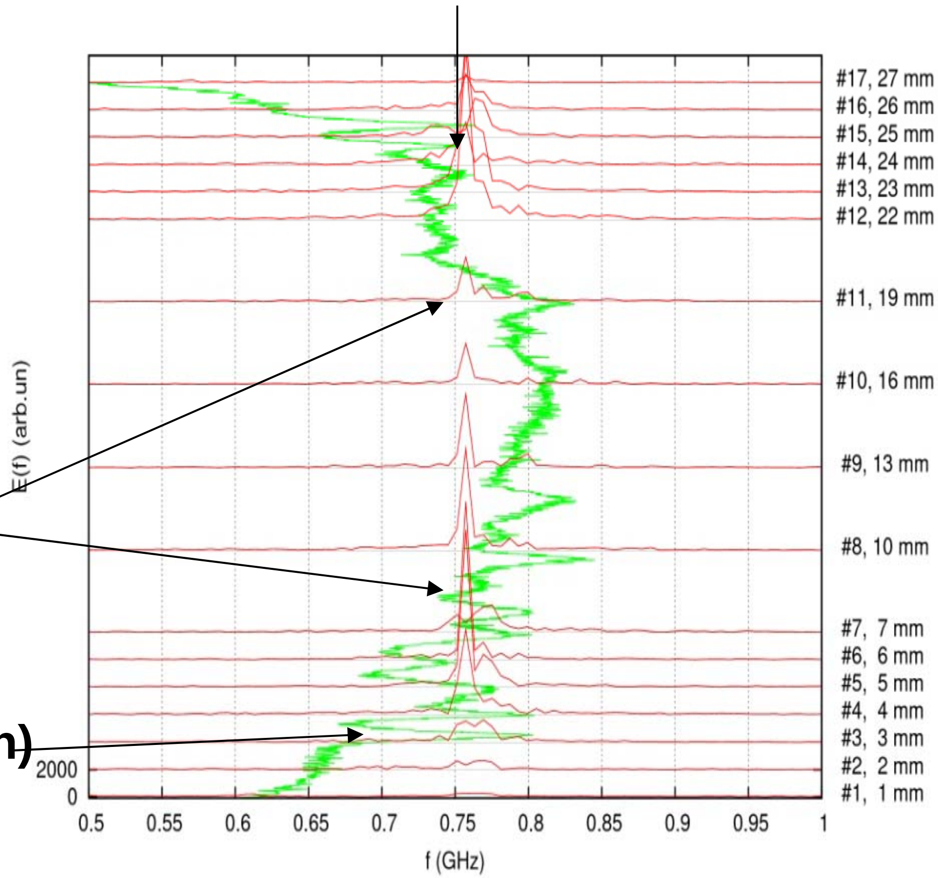
The calculated spectrum



Note that the frequency of the global mode excited by the beam is the same everywhere in the system.

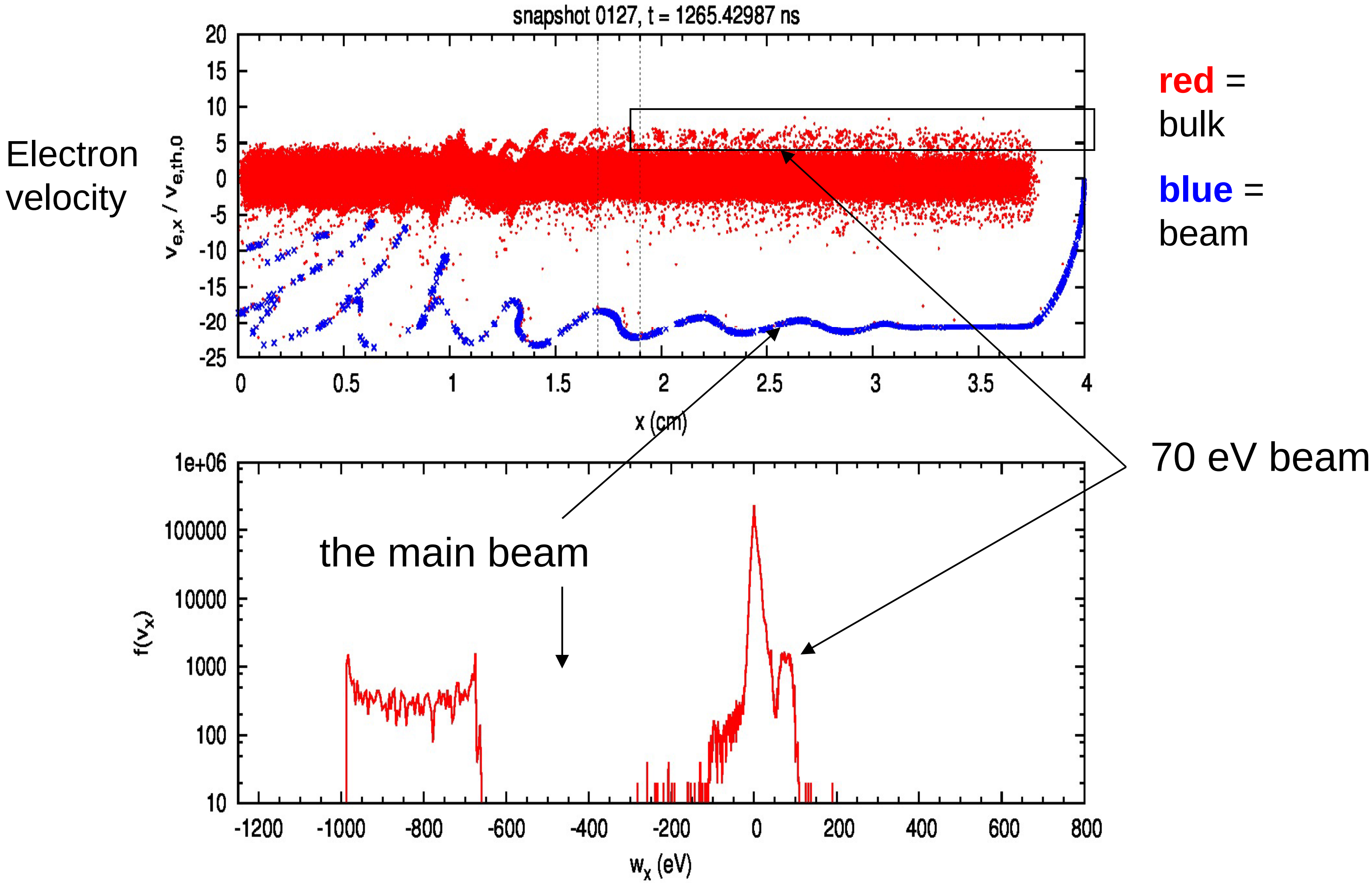
Spectra of E(t) at different locations during the intense two-stream instability event (red)

Local plasma frequency profile (green)



Intense localized HF electric fields may be a source of medium-energy electrons

Simulations by D. Sydorenko Phys Plasmas (2015), (2016).



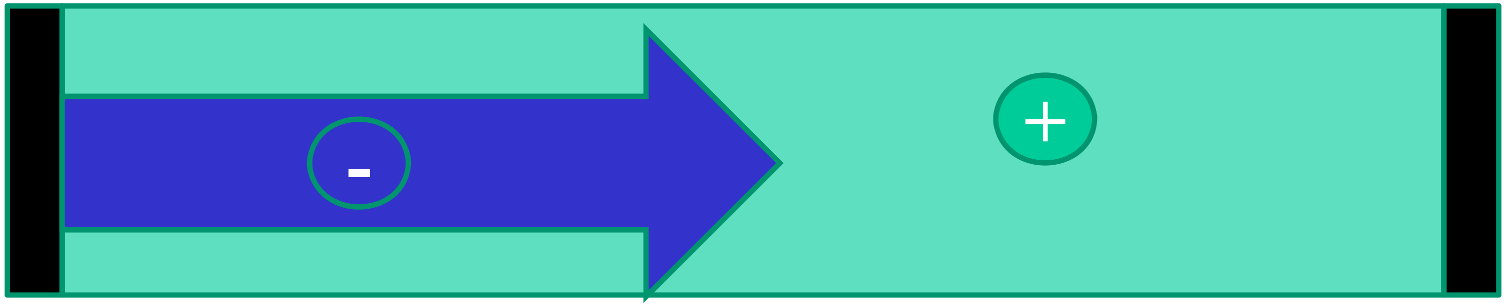
Revisiting Pierce Instability: Bandwidth Structure of Growth Rate of Two-Stream Instability of an Electron Beam Propagating in a Bounded Plasma

- **The two-stream instability of an intense electron beam propagating in finite-length plasma is revisited.**
- **It is shown that the growth rate in such a system is much smaller than that of infinite plasma or finite size plasma with periodic boundary conditions.**
- **Approximate formulas for growth rate and frequency are obtained.**

$$\gamma \approx \frac{1}{13}\omega_{pe}\left(n_b / n_p\right)\left(L\omega_{pe} / v_b\right)\ln\left(L\omega_{pe} / v_b\right)$$

, I. Kaganovich et al Phys. Plasmas (2016)

Pierce Model (1944)



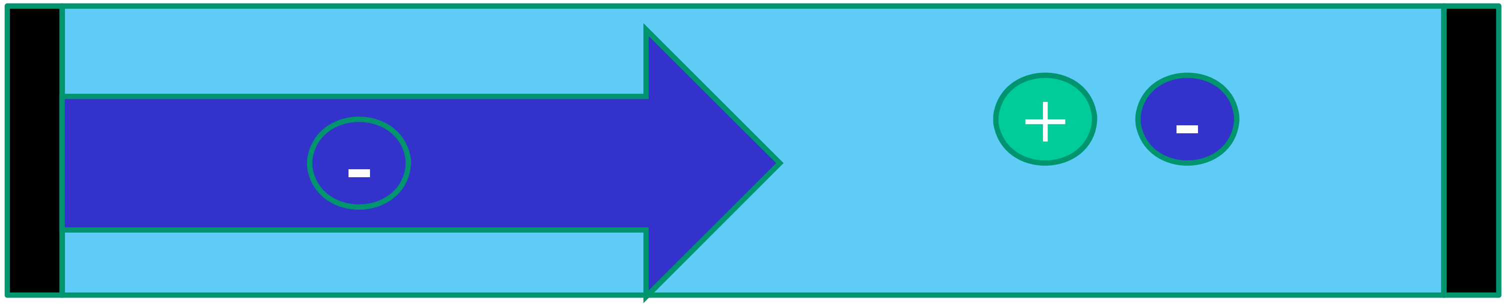
Electron beam is injected into ion background of equal density to the electron beam.

Electrodes with fixed potential set potential at boundaries.

Instability develops if $\omega_{pb} L / v_b > \pi$

This limits the current propagation through the gap.

I. Kaganovich, D. Sydorenko



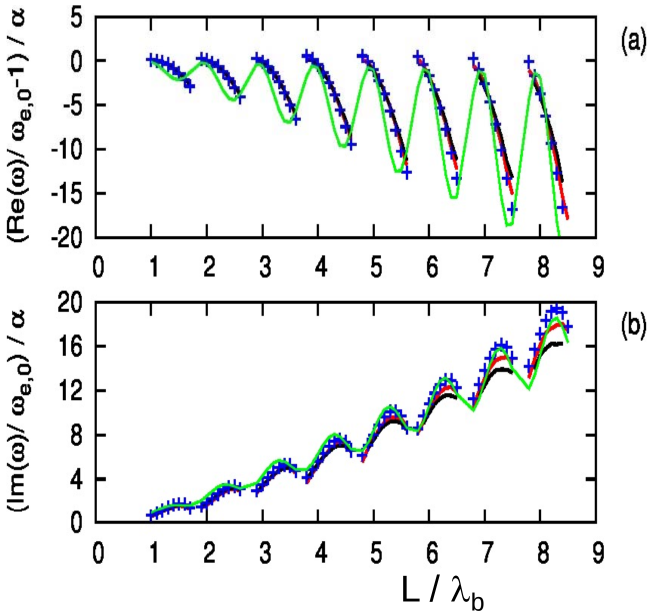
Electron beam is injected into electron and ion background of equal density.

Electrodes with fixed potential set potential at boundaries.

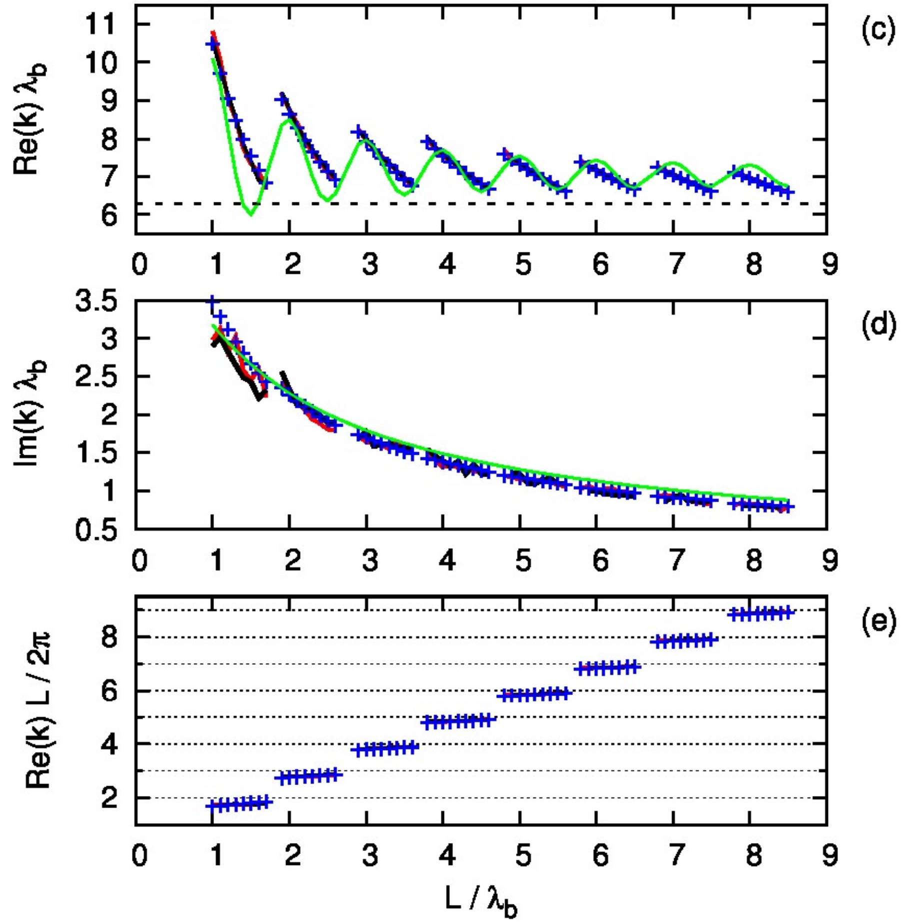
Instability is very different from textbook calculation for periodic b. c.

$$\omega_{e,0}\left(n_{b,0}/n_{e,0}\right)^{1/3}$$

Parameters of instability



Frequency (a), temporal growth rate (b), wavenumber (c), spatial growth rate (d), and the number of wave periods per system length (e) versus the length of the system.
The blue crosses mark values obtained by analytical solution.



Solid red and black curves represent values obtained in fluid simulations with α = 0.00015 (red) and 0.0006 (black). Solid green curves are values provided by fitting formulas. In (c), the black dashed line marks the resonant wavenumber.

Multi-Dimensional Kinetic Simulations of Instabilities and Transport in ExB Devices

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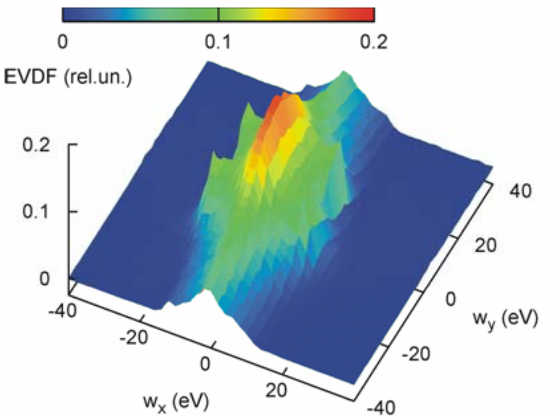
PARTICLE-IN-CELL CODES CAN RESOLVE COMPLEX MICRO PHYSICS AND COMPLEX GEOMETRY

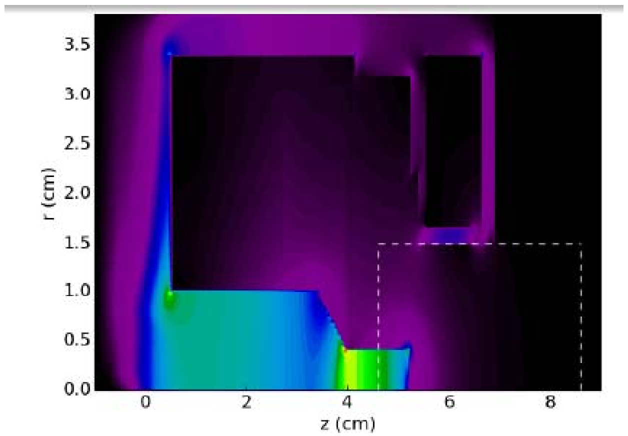
An electrostatic parallel, implicit, 1D PIC code EDIPIC.

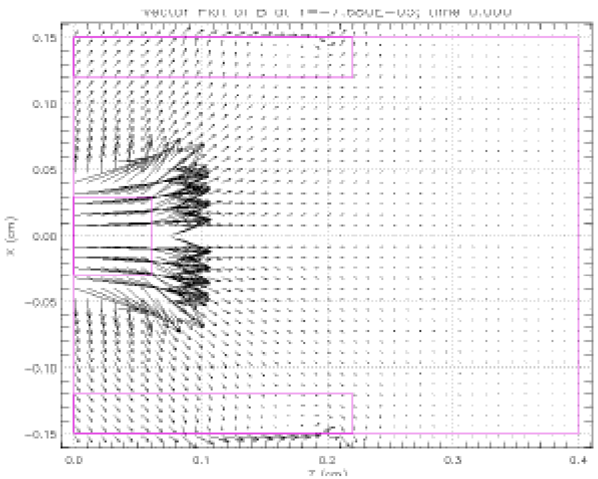
3D LSP code also includes electromagnetic and electrostatic modules.

We implemented anisotropic electron-atom scattering, ionization, and excitation as well as electron-ion and electron-electron collisions, electron induced emission, external circuit.

New Electrostatic PETSc Solvers (original solver did not converge).



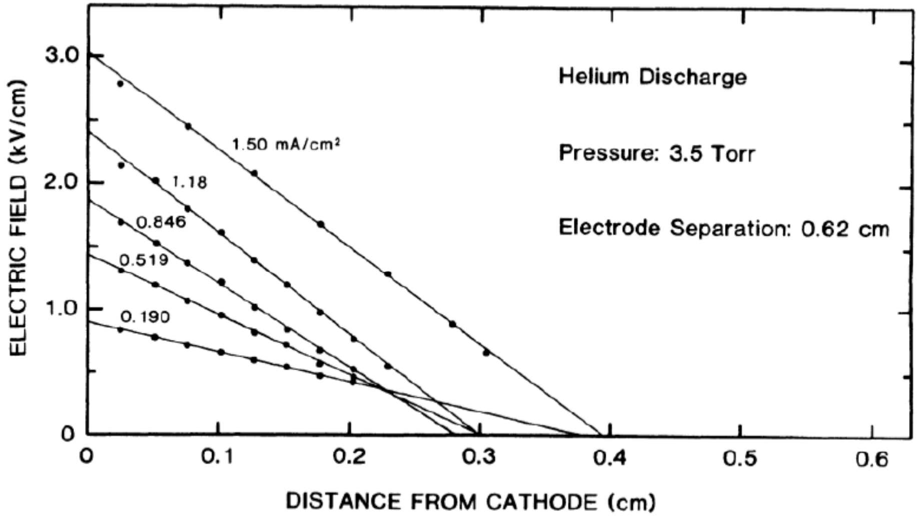




D. Sydorenko, *et al*, Phys Rev Lett. 103 145004 (2009).

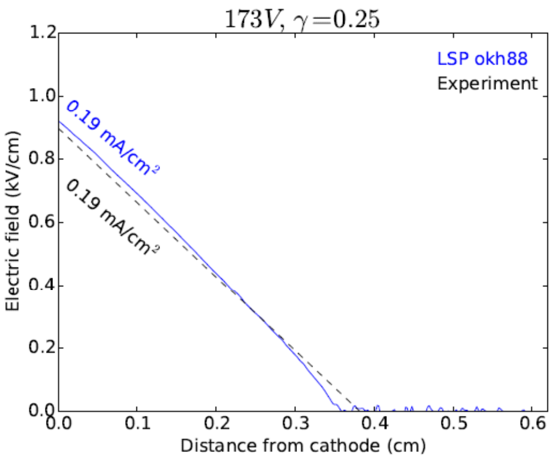
VERIFICATION AND VALIDATION OF CODES (1/3)

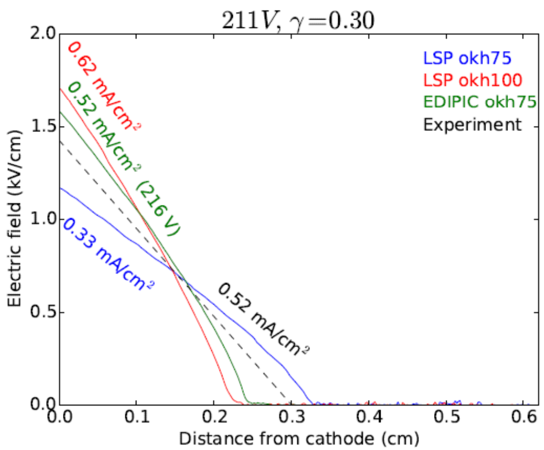
E. A. Den Hartog, D. A. Doughty, and J. E. Lawler, ”Laser optogalvanic and fluorescence studies of the cathode region of a glow discharge”, Phys. Rev. A 38, 2471 (1988).

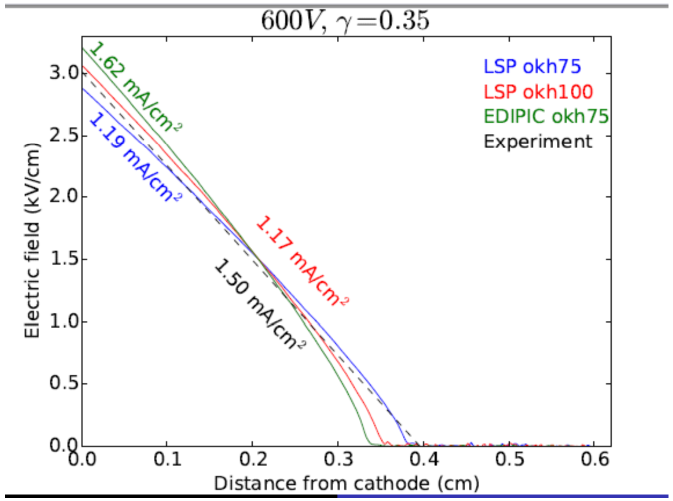


Accurate and complete measurements of the plasma quantities: E(x), γ, J, U.

J. Carlsson, et al PSST (2016)





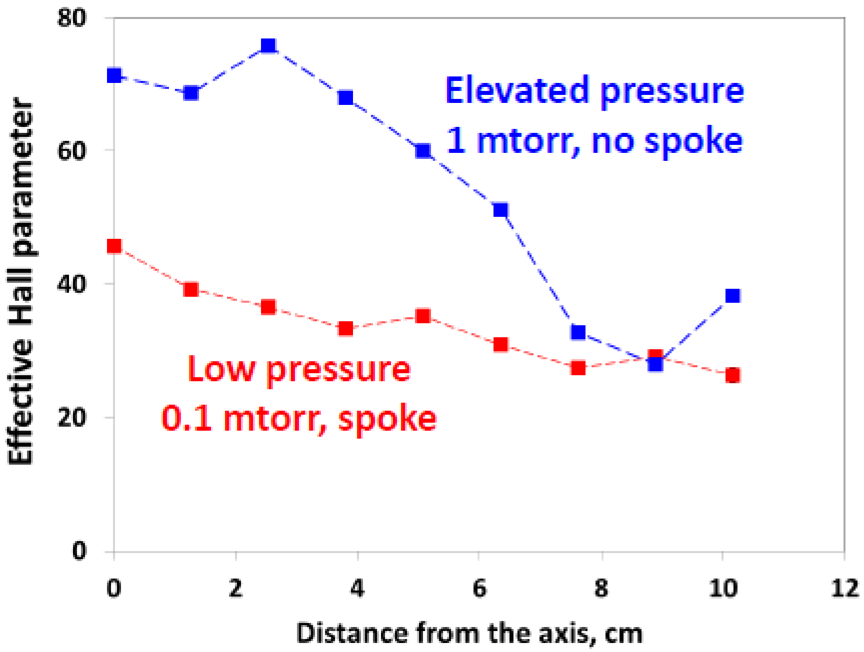


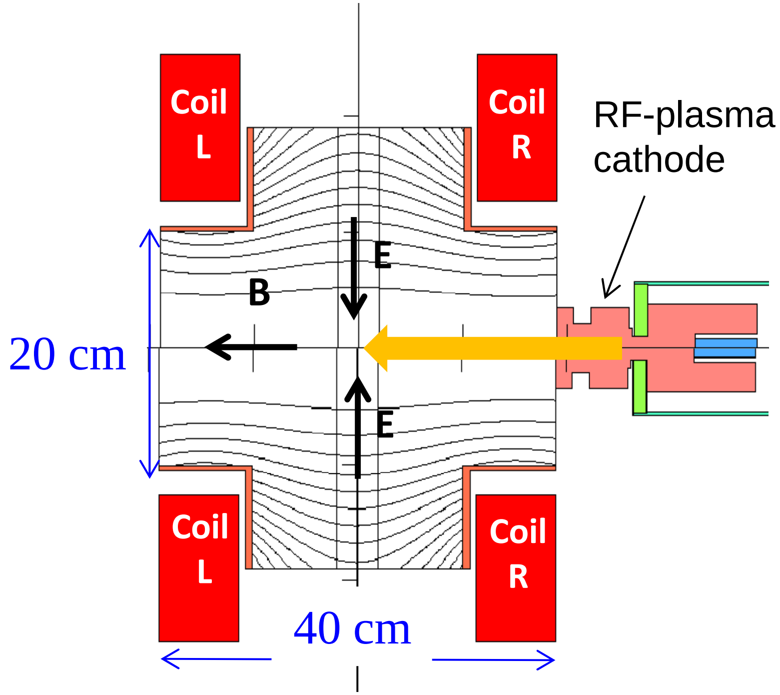
Anomalous transport in Penning-type E×B configuration
Y. Raitses PPPL IEPC 2015, 307

Device creates hot electrons in the center and cold on a periphery.

Anomalous transport determines the current. What is it?

What is spoke?

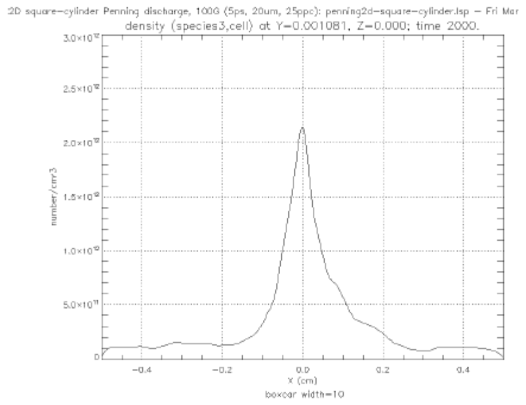


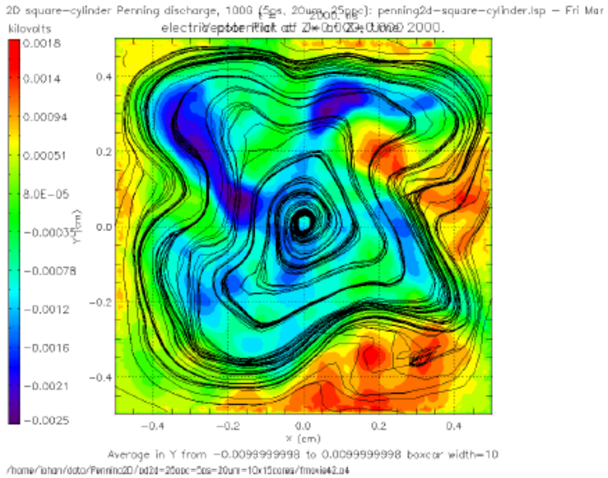


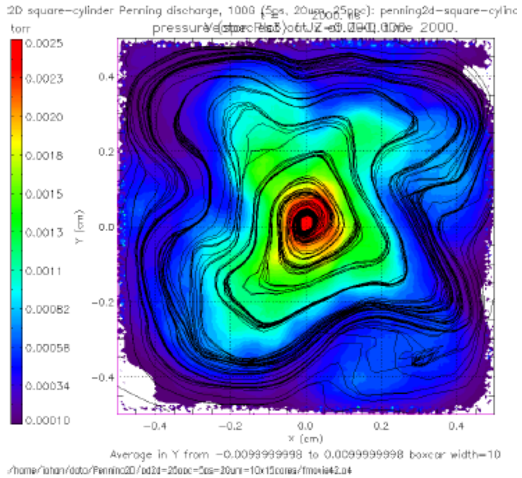
- Anomaly of electron cross-field transport, ν_{eff} / ν_m ~ 10-100

Anomalous transport in 2D is very robust and is much larger than collisional transports and in 1D.

Density profile (left) is peaked in the center, similarly to experimentally observed. Current streamlines on top of potential contours (middle) and electron-pressure contours (right) at 2 μs.





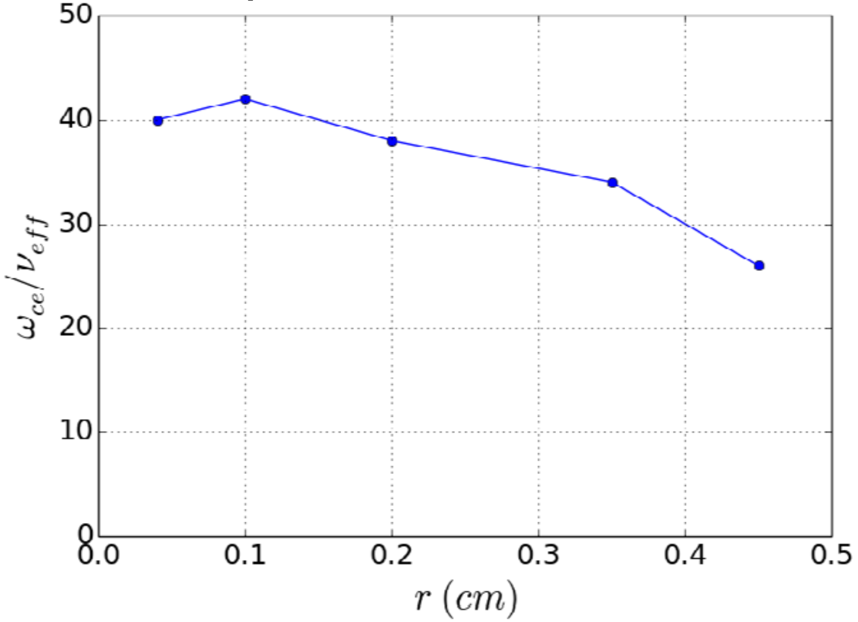


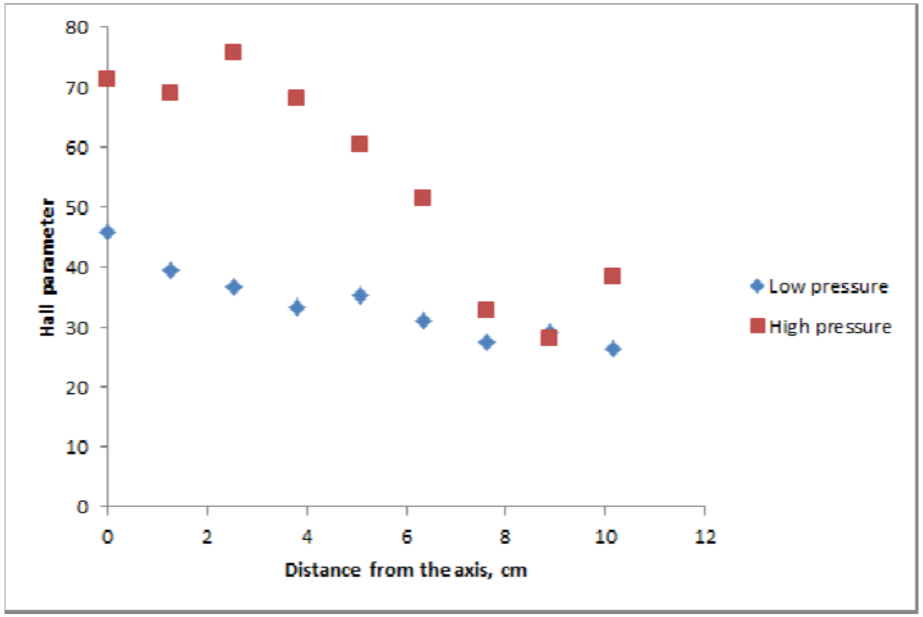
Spiral structure of current streamlines indicate that current is driven by slow, narrow but long perturbations similarly to ETG in tokamaks.

Current is driven by density gradient not electric field, similarly to experimentally observed!

Anomalous transport in 2D is very robust, Hall parameter is about 40 and is similar to experimental value.

Hall parameter in simulations (left) and experimental data (right). B=100G, P=0.2mTorr.

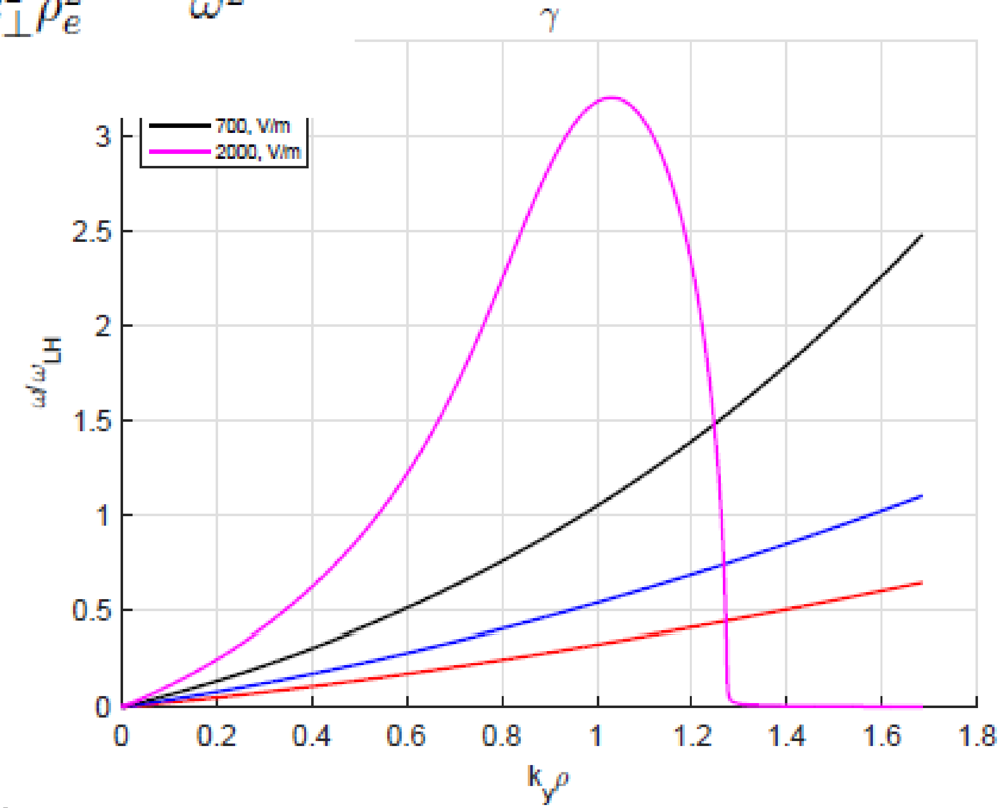




Variation of Hall parameter with parameters:
Magnetic field quadrupled to 400 Gauss: 46
Zero gas pressure: 20
Beam radius quintupled to 500 nm: 59
Number of particles quadrupled to 100 per cell per species: 34

Continuous mode excitation from Simon Hoh to low hybrid

$$\frac{\omega_* - \omega_D + (\omega - \omega_0 + i\nu_{en})k_\perp^2\rho_e^2}{\omega - \omega_0 - \omega_D + (\omega - \omega_0 + i\nu_{en})k_\perp^2\rho_e^2} = \frac{k_\perp^2 c_s^2}{\omega^2}$$



A. Smolyakov, et al PPCF (2016),
I. Ramadanov, et al Phys. Plasmas (2016)

CONCLUSIONS

- We have customized LSP, called PPPL-LSP, by adding state-of-the art collision models and implemented a direct electrostatic field solver (to avoid unphysical behavior due to large field residuals).
- PPPL-LSP had been successfully validated for a glow discharge and benchmarked against the EDIPIC code.
- PPPL-LSP is routinely ran on hundreds of processor cores.
- PIC simulations of Penning discharge show spoke formation and anomalous transport similar to experimental data.
- 3D simulations of Hall thruster are underway.

PPPL