Acceleration of plasma electrons by intense nonrelativistic ion or electron beams propagating in background plasma due to two-stream instability

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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.**
- **Electron beam-plasma interaction in a bounded plasma (two-stream instability):**
  - **Effects of finite size and boundaries**
  - **Effects of nonuniform plasma**
  - **Mechanism of electron acceleration in plasma wave**

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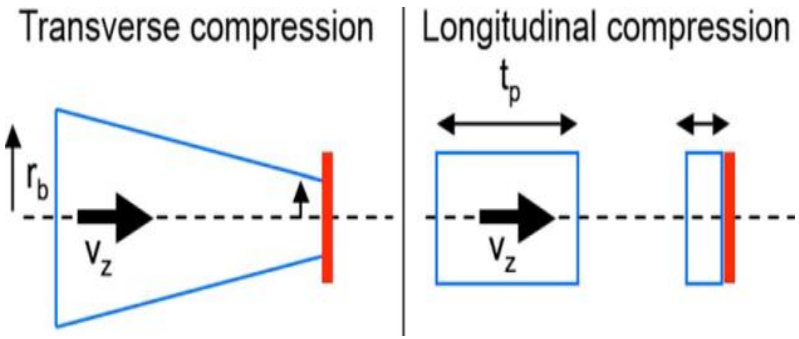
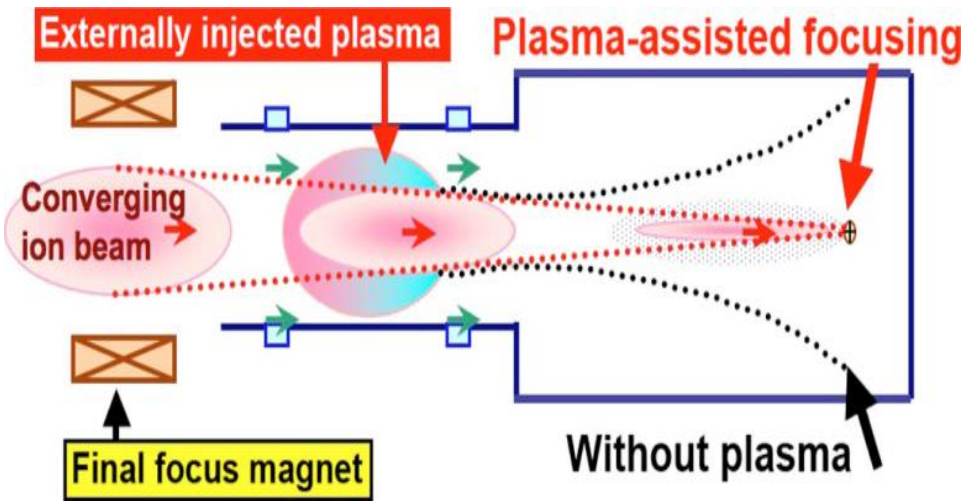
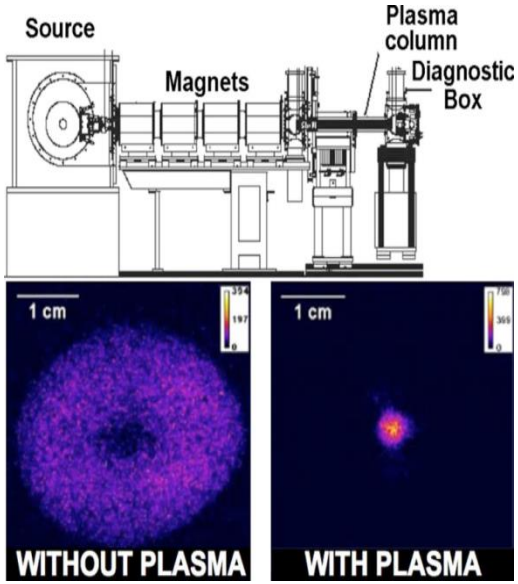
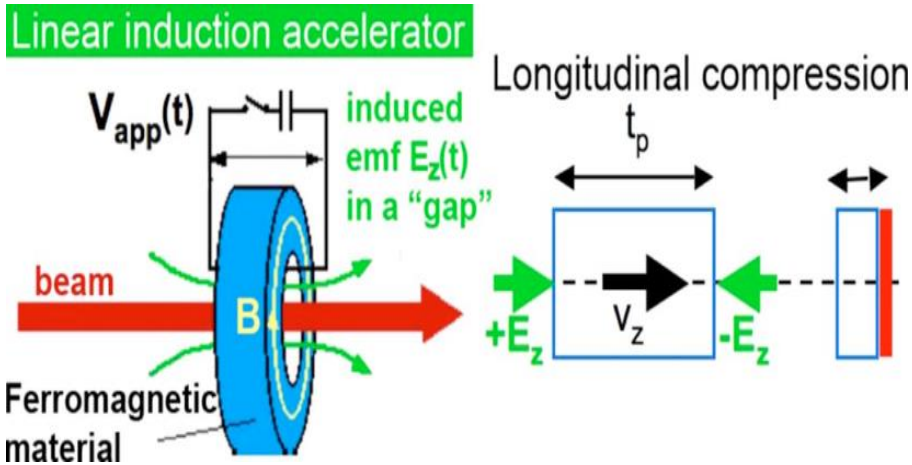
NEUTRALIZED DRIFT COMPRESSION IS KEY INNOVATION FOR ACHIEVING HIGH ION BEAM POWER ON TARGET





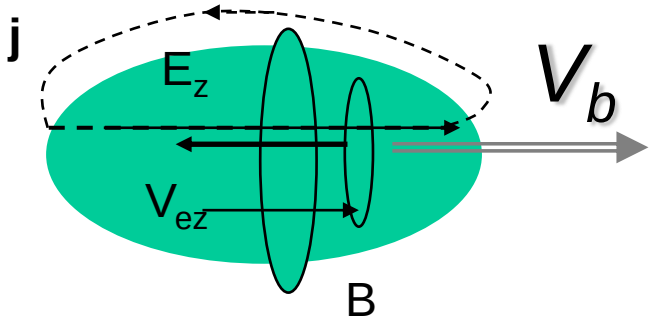




THEORY OF NEUTRALIZATION BY DENSE PLASMA

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.



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

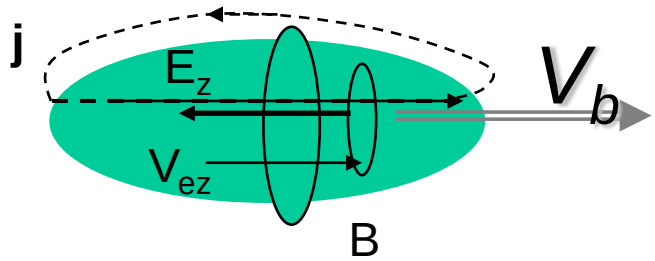
Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation direction.

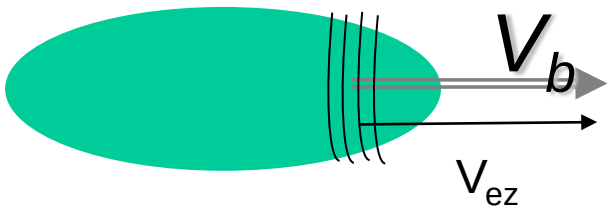
$$\phi = mV_{ez}^{\ 2} / 2e \qquad V_{ez} \sim V_b n_b / n_p \qquad \phi_{vp} = mV_b^{\ 2} \left(n_b / n_p \right)^2 / 2$$

$$mV_{ez} = eA_z / c = e\int_0^r B dr / c$$

TWO-STREAM INSTABILITY MAY SIGNIFICANTLY AFFECT BEAM PROPAGATION IN BACKGROUND PLASMA

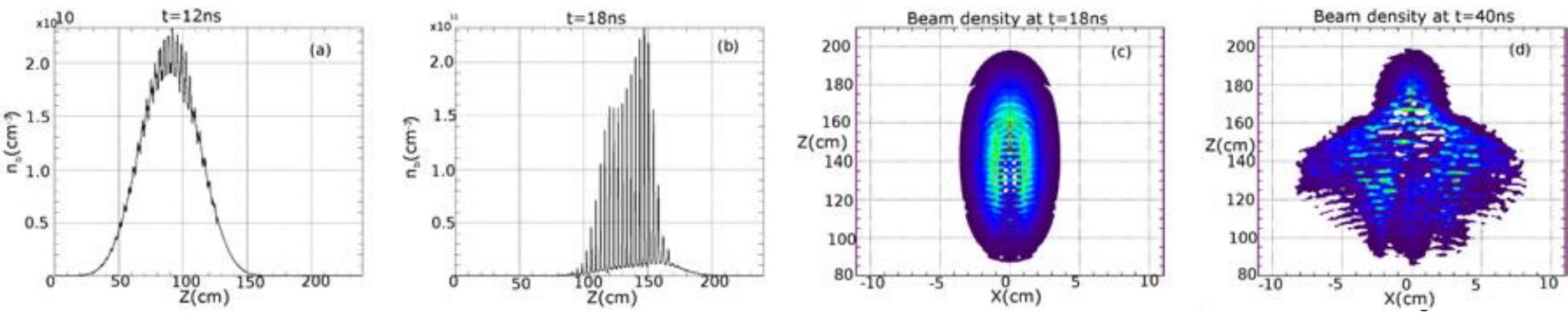
Left: No two-stream instability; Right: effect of two-stream instability



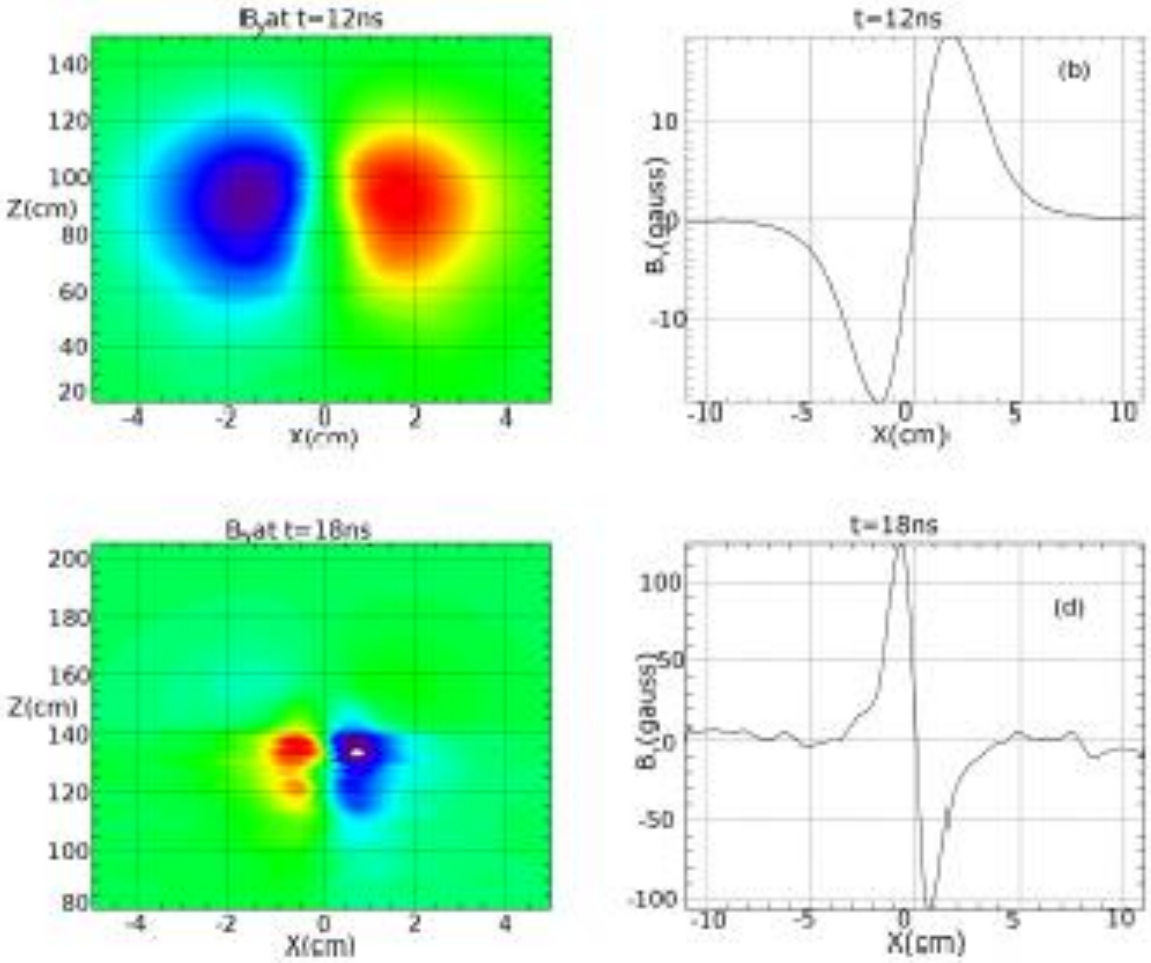


Plasma waves lead to bunching of the ion beam and accelerate plasma electrons to beam velocity

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-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:

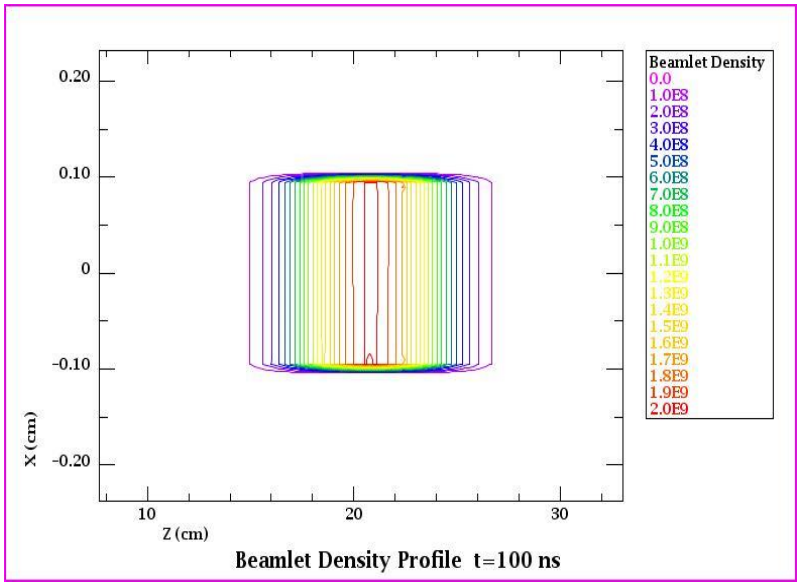
$$J_{tot} \sim J_z^b + J_z^e = \frac{J_z^b}{(1+r_b^2\omega_p^2/c^2)} \left(1 - \frac{1}{2}\ \frac{n_p}{n_b} \left(\frac{v_m^e}{v_b}\right)^2\right)$$

- 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



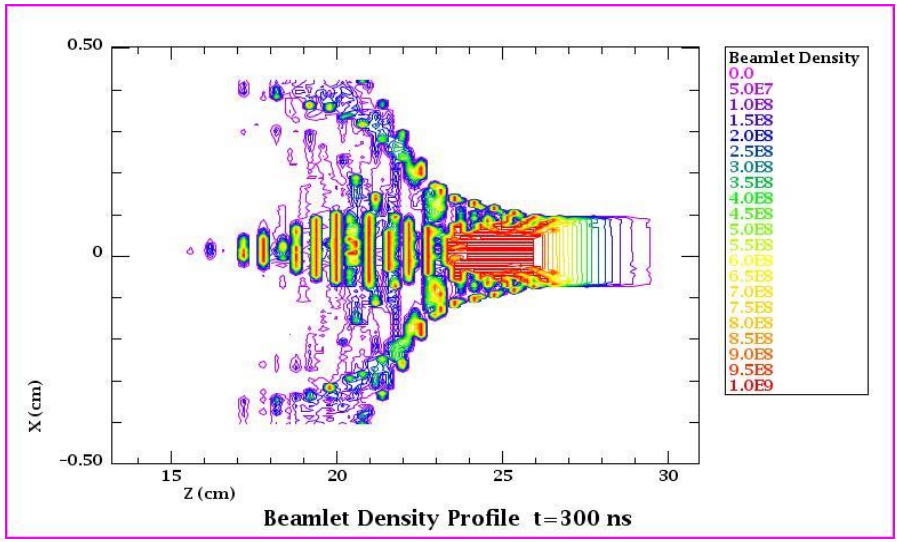
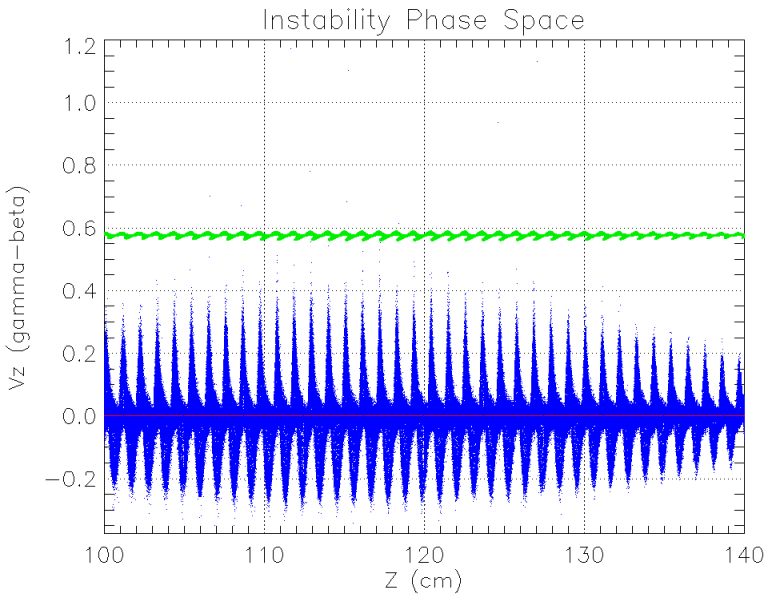


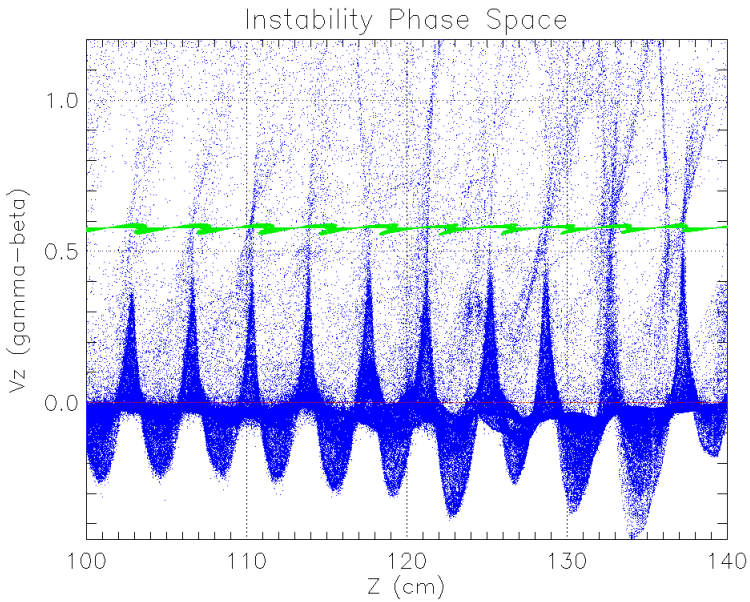
Fig. Beamlet Density Contour at t = 100 ns (1 m of propagation), Bottom: Beam Density Contour at t = 300 ns (3 m of propagation). NDCX-II beam parameters for apertured beam r_b=1 mm.

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

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)





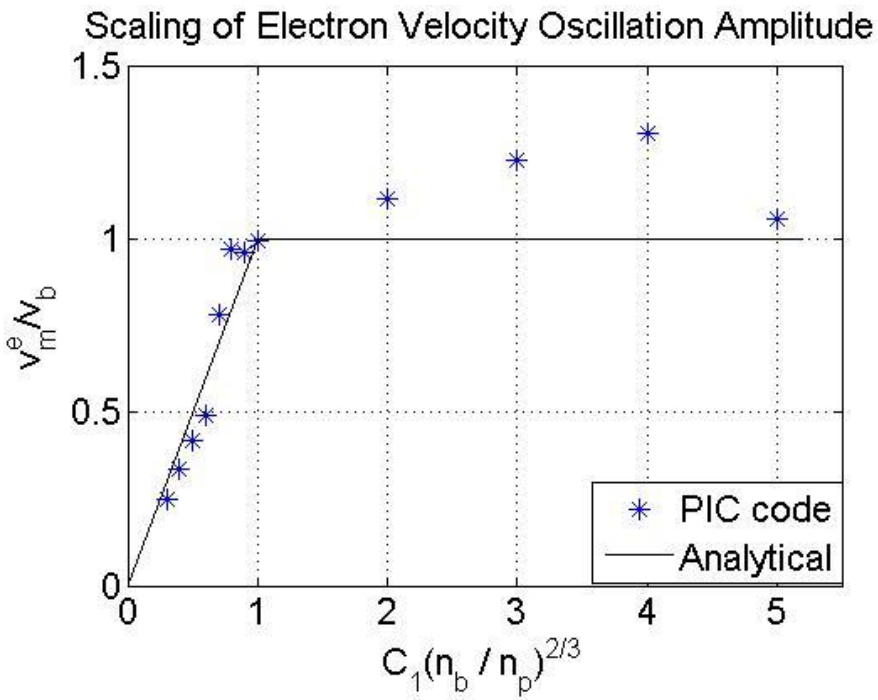
Phase-Space of beam ions and plasma electrons V_z vs z. Proton beam $n_b = 2 \times 10^{10}\ /cm^3$ and v_b = c/2.

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 et al., Phys. Plasmas (2017)

Verification of Analytical Estimates with PIC code



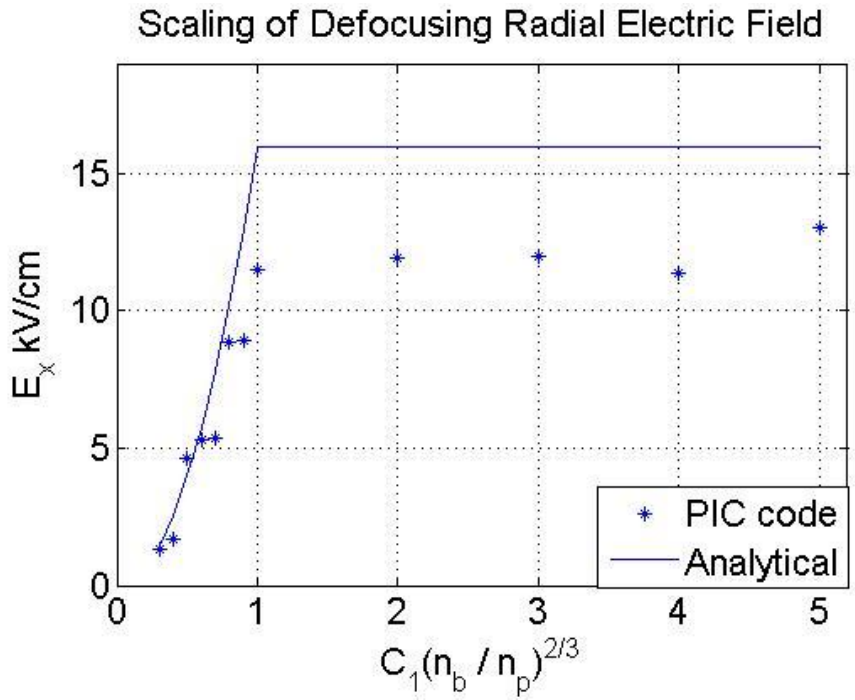
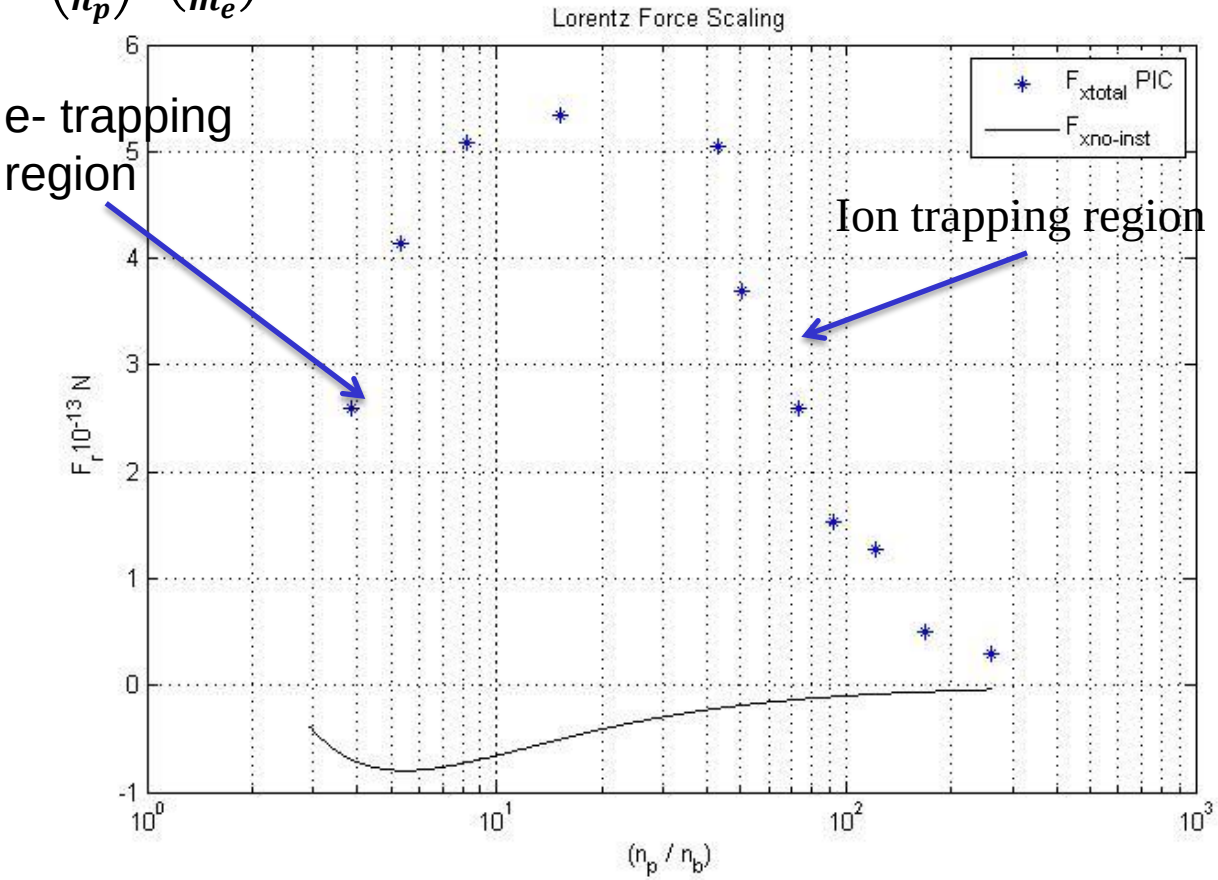


Fig. Left: Scaling of rms electron velocity oscillation amplitude measured on axis. Rig: Schaling of radial defocusing electric field from LSP simulation, measured at $r_b \sim 1\ cm$ which corresponds to the maximum field strength.

$\alpha = C_1 (n_b/n_p)^{2/3}$ **,** $C_1 = \left(\frac{m_b}{m_e}\right)^{1/3} \sim 12.24$ **for H+ beam. E. Tokluoglu, et al (2017)**

VERIFICATION OF ANALYTICAL ESTIMATES WITH LSP PIC CODE

Fig. Lorentz Force (radial) F_x vs $n_p/\,n_b$ log-scale as calculated by LSP PIC code - symbols, the continuous curve is the analytical estimate for no instability. E. Tokluoglu, et al (2015). 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)

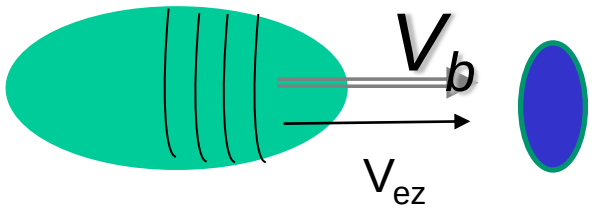


In the presence of two-stream instability, the ponderomotive pressure from the axial E_z field of plasma waves creates an average transverse defocusing force:

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

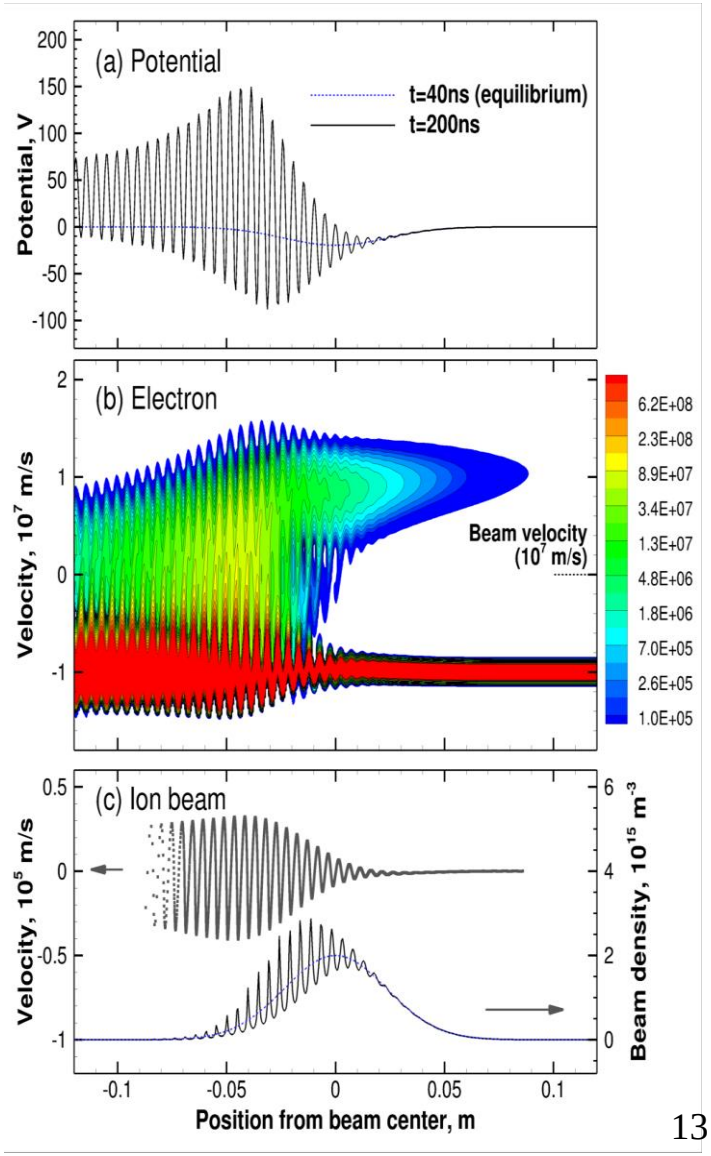
$$= -\frac{1}{4}\,m_e\nabla_x(v_m^e)^2$$

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, MO 2.6-6 17:30.

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}.



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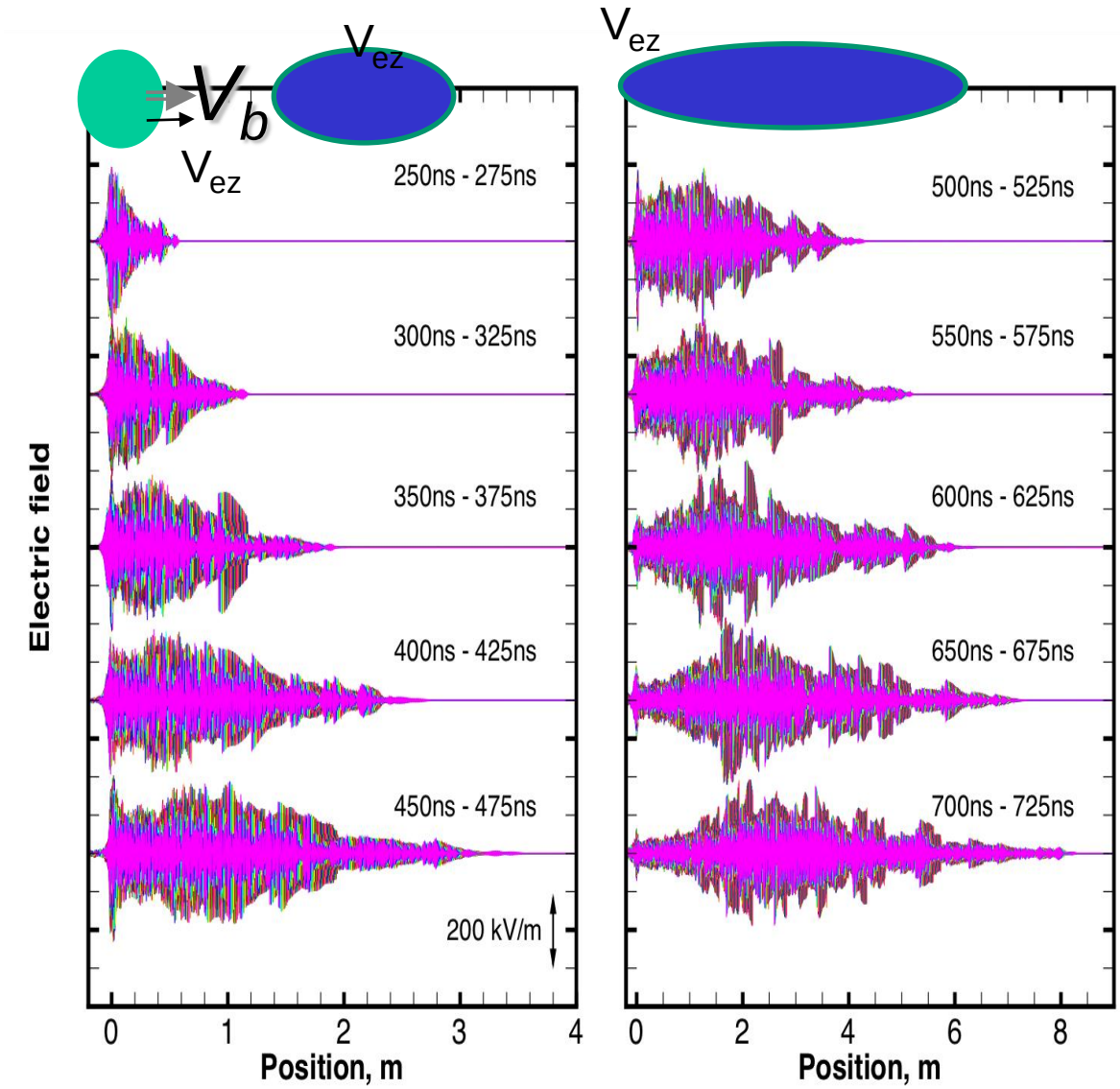

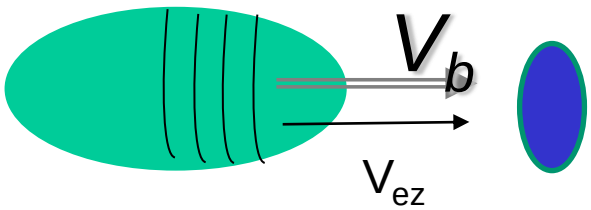

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K. Hara, MO 2.6-6

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- Motivation/Background
  - Description of Codes
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- **Electron beam-plasma interaction in a bounded plasma (two-stream instability): 16:30 MO 2.6-3**
  - Effects of finite size and boundaries
  - Effects of nonuniform plasma
  - Mechanism of electron acceleration in plasma wave

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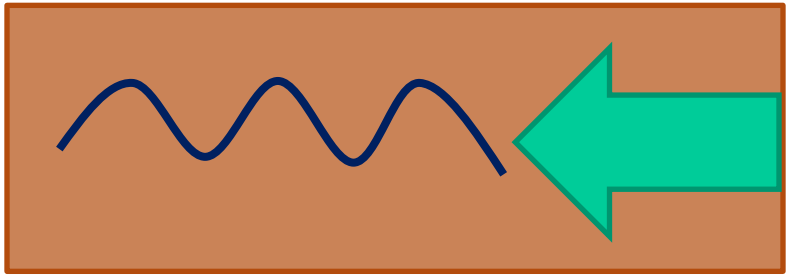
CONTROLLING PLASMA PROPERTIES BY INEJCTION OF ELECTRON BEAM INTO THE PLASMA

Electron beam is self generated in RF/DC system or by injection from the source.
Electron beam emitted from the walls can interact with plasma and effectively transfer energy to background electrons and ions.



Questions:

How effective is this process?
What are resulting electron and ion energy distribution functions?

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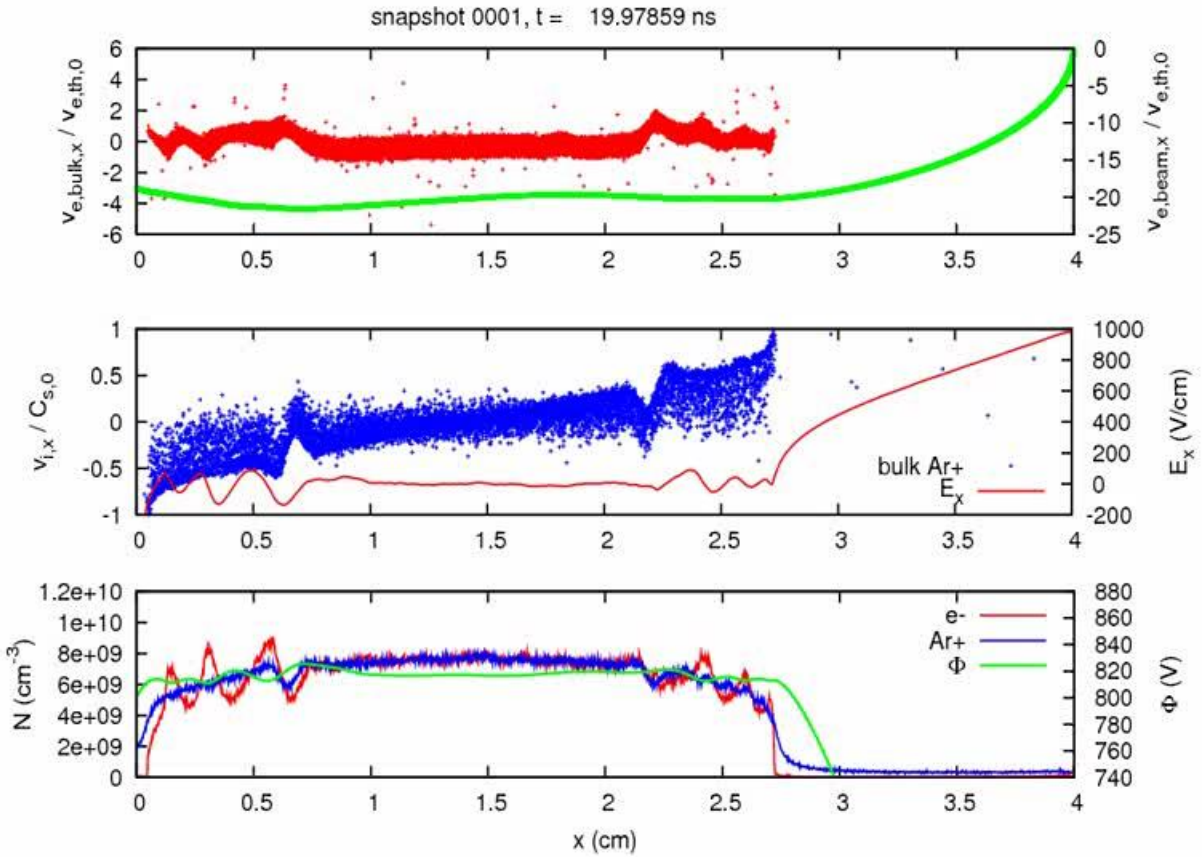
SIMULATION OF MULTI-PEAK ELECTRON VELOCITY DISTRIBUTION FUNCTION

Electron velocity

Ion velocity

Density



red = bulk

green = beam

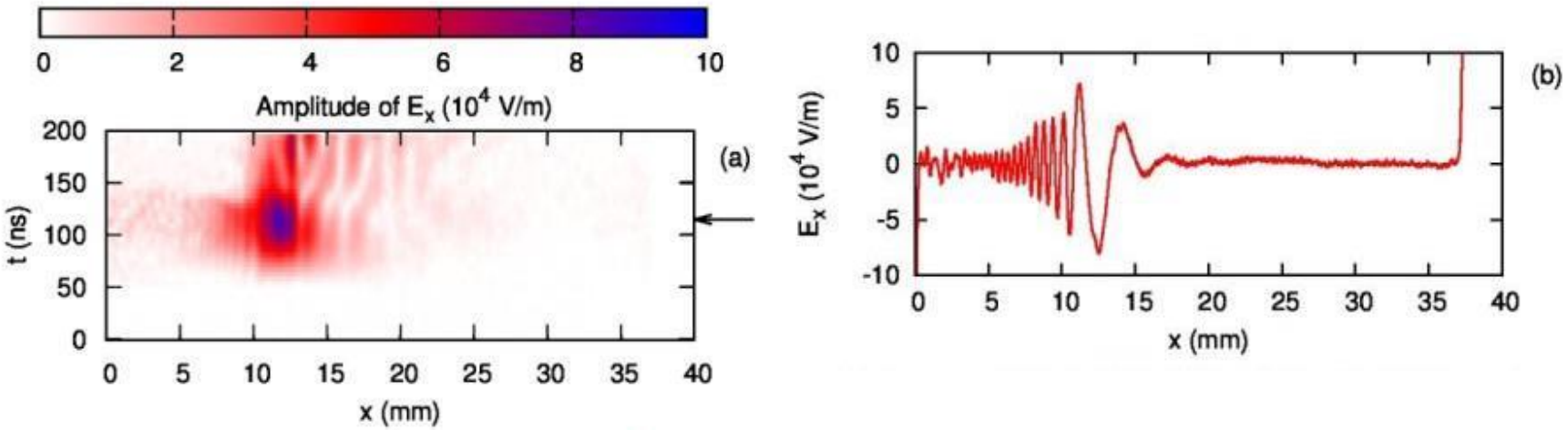
Electric field

Electro-static potential

Anode

Cathode

ELECTRIC FIELDS CAN REACH kV/cm WITH BEAM CURRENT OF 20 mA/cm^2



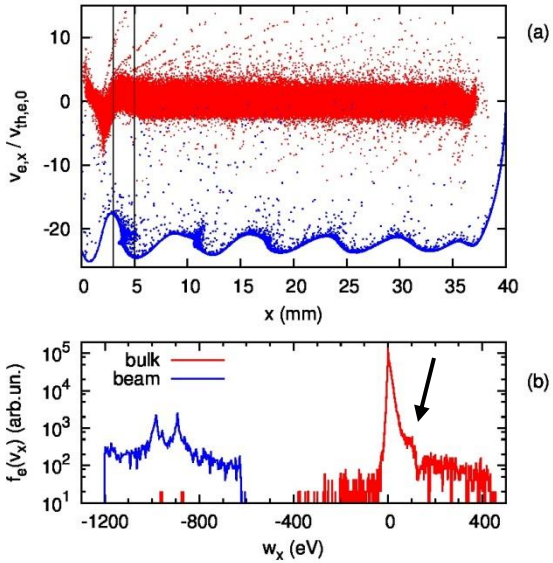
Now there is sufficient "kick" from the electric field to accelerate electrons out of the background.

SIGNIFICANT ACCELERATION OF BULK ELECTRONS

Snapshot 1, lowered frequency regime

Electron bulk (**red**) and beam (**blue**) phase plane

EVDF of bulk (**red**) and beam (**blue**) electrons



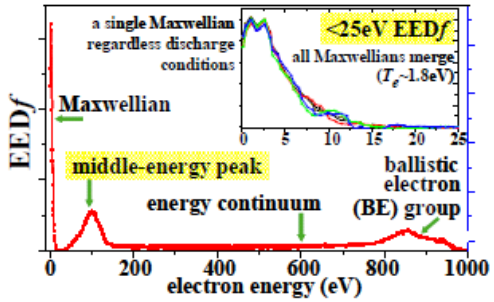


Fig. 1. Non-Maxwellian EED*f* of DC/RF plasma.

From [*Chen and Funk*, 2010].

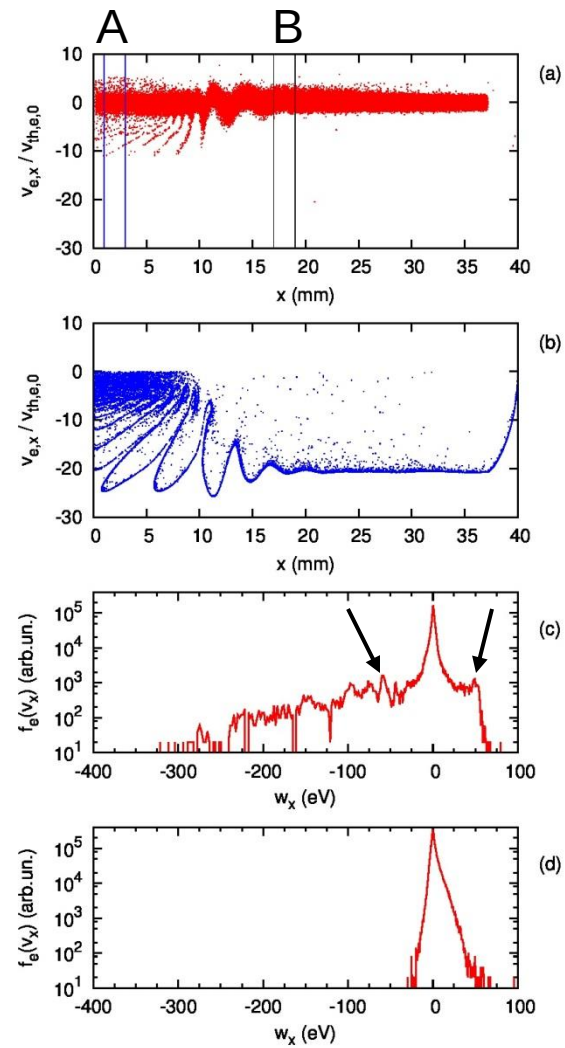
Snapshot 2, ordinary regime

Electron bulk phase plane

Emitted electrons phase plane

EVDF of bulk electrons in area A

EVDF of bulk electrons in area B



Arrows mark super-thermal electrons

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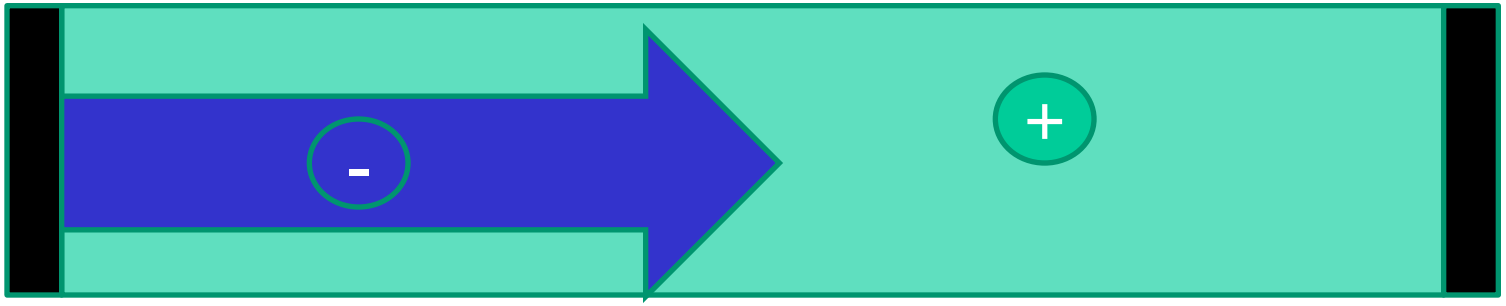
PIERCE MODEL (1944)



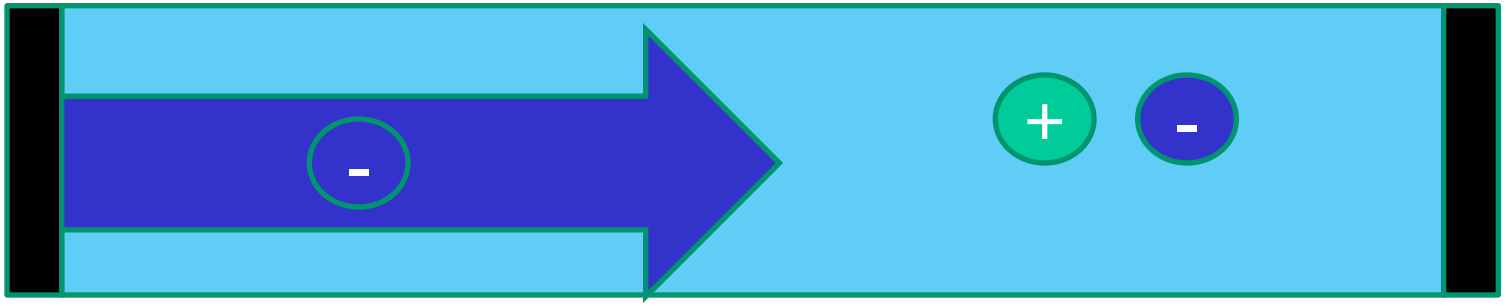
Electron beam is injected into ion background of equal density to the electron beam.

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.

OUR MODEL (2015?)



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

ANALYTIC SOLUTION

$$\frac{\partial n_{e,b}}{\partial t} + \frac{\partial v_{e,b} n_{e,b}}{\partial x} = 0$$

$$\frac{\partial v_{e,b}}{\partial t} + v_{e,b}\frac{\partial v_{e,b}}{\partial x} = -\frac{e}{m}E$$

$$\delta n_b(0) = \delta v_b(0) = \delta\phi(0) = \delta\phi(L) = 0$$

$$\delta\phi(t,x) = \left(Ax + Be^{ik_+x} + Ce^{ik_-x} + D\right)e^{-i\omega t},$$

the following additional relation between ω and k:

$$k_-^2\left(e^{ik_+L} - 1\right) - \frac{ik_-^2 k_+ \omega L}{\omega - k_+ v_{b,0}} = k_+^2\left(e^{ik_-L} - 1\right) - \frac{ik_+^2 k_- \omega L}{\omega - k_- v_{b,0}}.$$

$$k_\pm = (1 \mp \chi)\frac{\omega_{e,0}}{v_{b,0}}$$

(10)

$$-i\frac{2(1-\chi)}{(1+\chi)\chi}L_n + e^{i(1-\chi)L_n} - 1 - \frac{(1-\chi)^2}{(1+\chi)^2}\left[e^{i(1+\chi)L_n} - 1\right] = 0$$

SUMMARY OF ANALYTIC MODEL

We have studied the development of the two-stream instability in a finite size plasma bounded by electrodes both analytically and making use of fluid and particle-in-cell simulations.

We show that the instability reaches the asymptotic state when the wave structure has the same spatial profile and grows in time with a constant growth rate.

The spatial structure of the wave is close to a standing wave but has a spatial growth along the beam propagation.

We derived analytic expressions for the frequency, wave number and the spatial and temporal growth rates. Obtained analytic solution agrees well with the values given by fluid and particle-in-cell simulations.

- **Instability parameters are very different from the classical ones:**

growth rate $Im(\omega) \approx \frac{1}{13} L_n \ln(L_n) \left[1 - 0.18\cos\left(L_n + \frac{\pi}{2}\right)\right] \alpha\omega_{pe},$

where $L_n = L\omega_{pe}/v_b$, wavenumber $Re(k) \approx \frac{\omega_{pe}}{v_b}\left[1.1 + \frac{1+2.5\cos(L_n)}{1.1L_n}\right]$.

- **For comparison, the classical values:**

growth rate $Im(\omega) = 0.7\alpha^{1/3}\omega_{pe}$,

real resonance wavenumber $k = \omega_{pe}/v_b$.

BANDWIDTH STRUCTURE OF GROWTH RATE OF TWO-STREAM INSTABILITY OF AN ELECTRON BEAM PROPAGATING IN A BOUNDED PLASMA

- **An analytical model of two-stream instability development,**
- **I. Kaganovich and D. Sydorenko (2015)**

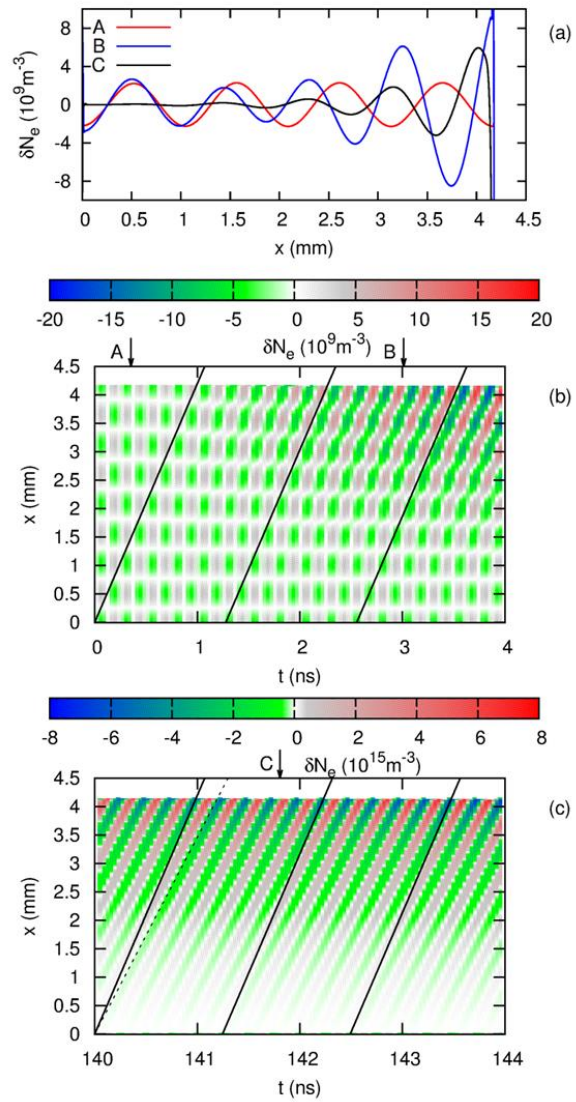
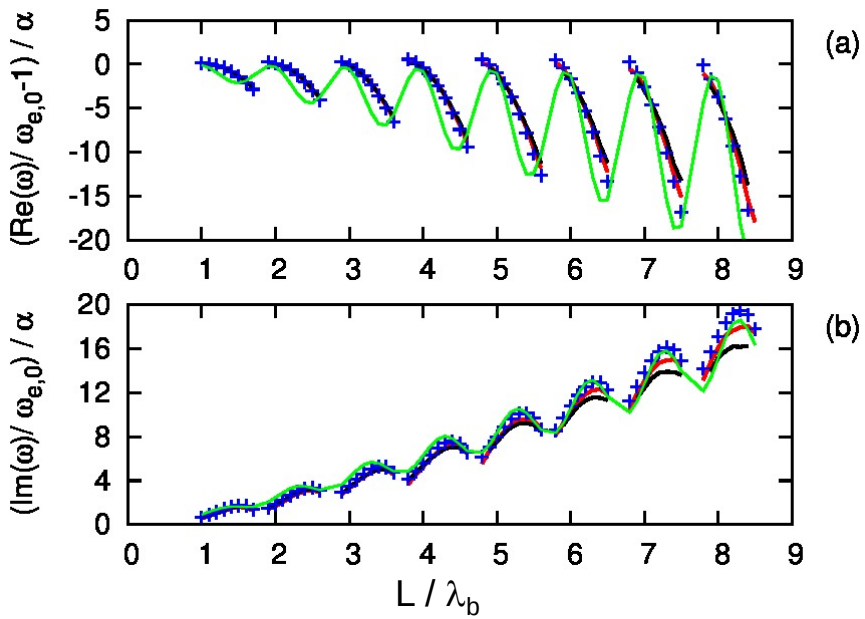


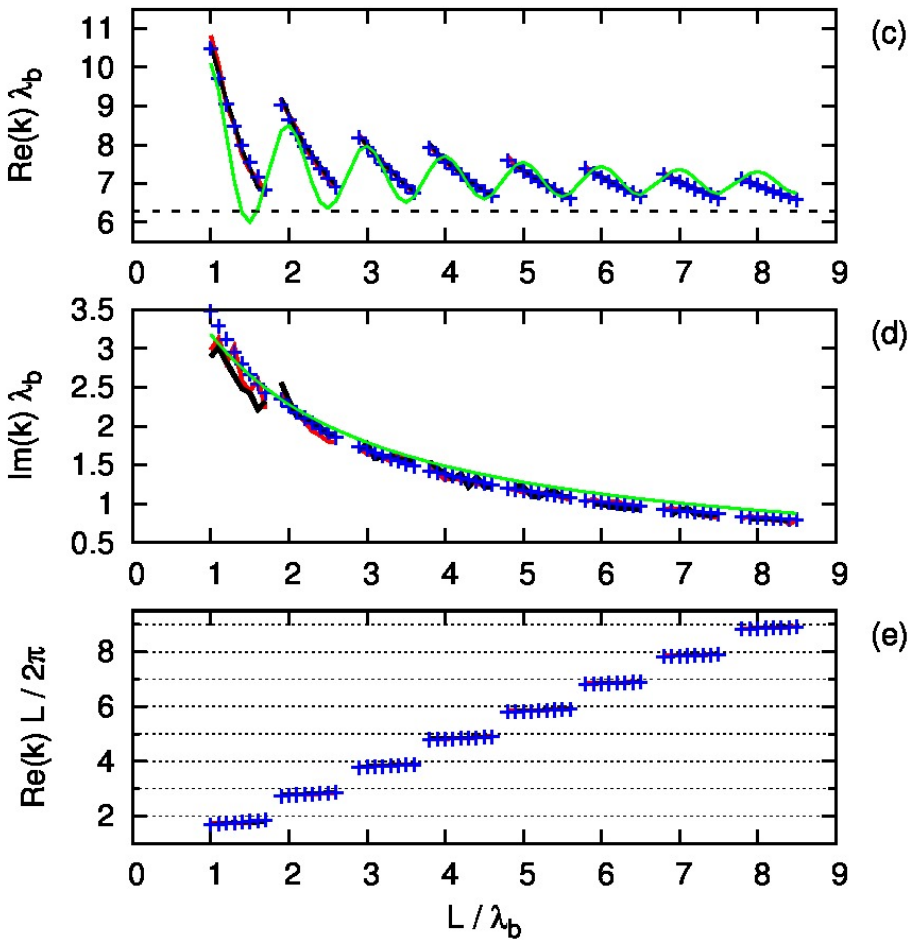
Fig. Dynamics of two-stream instability, the beam to plasma density ration, = 0.0006.

(a) Spatial profiles of bulk electron density perturbation obtained at t=0.35ns (curve A, red), t=3.01ns (curve B, blue), and t =141.8ns (curve C, black).

Panels (b) and (c) are color maps of evolution of density perturbations of bulk electron density in time intervals (b) 1-4ns, (c) 140-144ns. Here, solid black straight lines represent propagation with unperturbed beam velocity; dashed straight line represents phase velocity of the wave.

COMPARISON OF ANALYTIC THEORY AND PIC SIMULATIONS





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.

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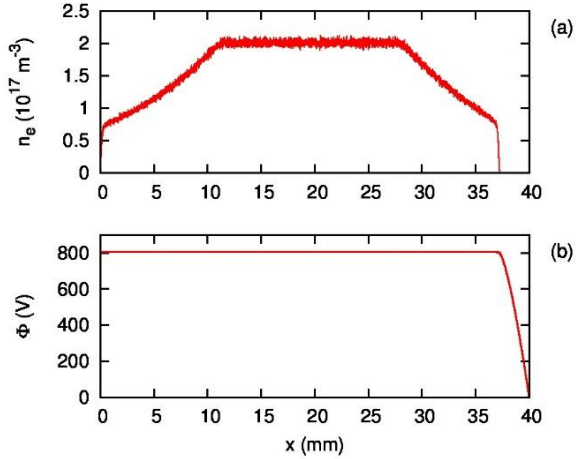
SHORT-WAVELENGTH PLASMA WAVES APPEAR IN THE DENSITY GRADIENT REGION

Initial profiles of electron density (top) and electrostatic potential (bottom).



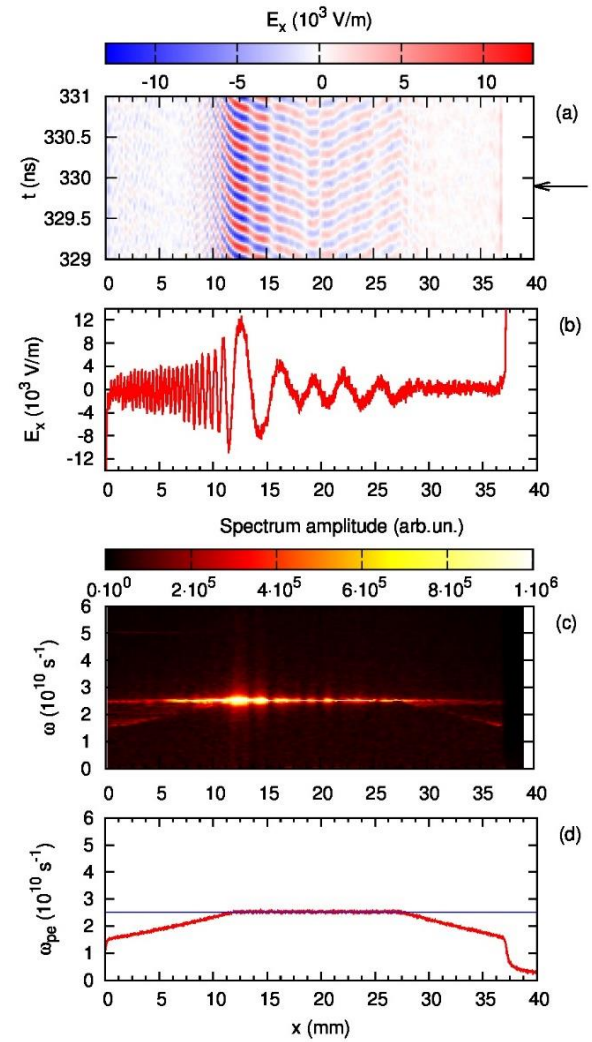
Cathode electron emission current 6.72 mA/cm2, relative beam density 0.000125.

Electric field vs coordinate (horizontal) and time (vertical).

Profile of the electric field at time marked by the arrow in the figure above. The anode is at x=0.

Amplitude of frequency spectrum of the electric field (color) vs the frequency (vertical axis) and coordinate (horizontal axis).

Electron plasma frequency (red) vs coordinate. The blue line marks the frequency excited by the beam.

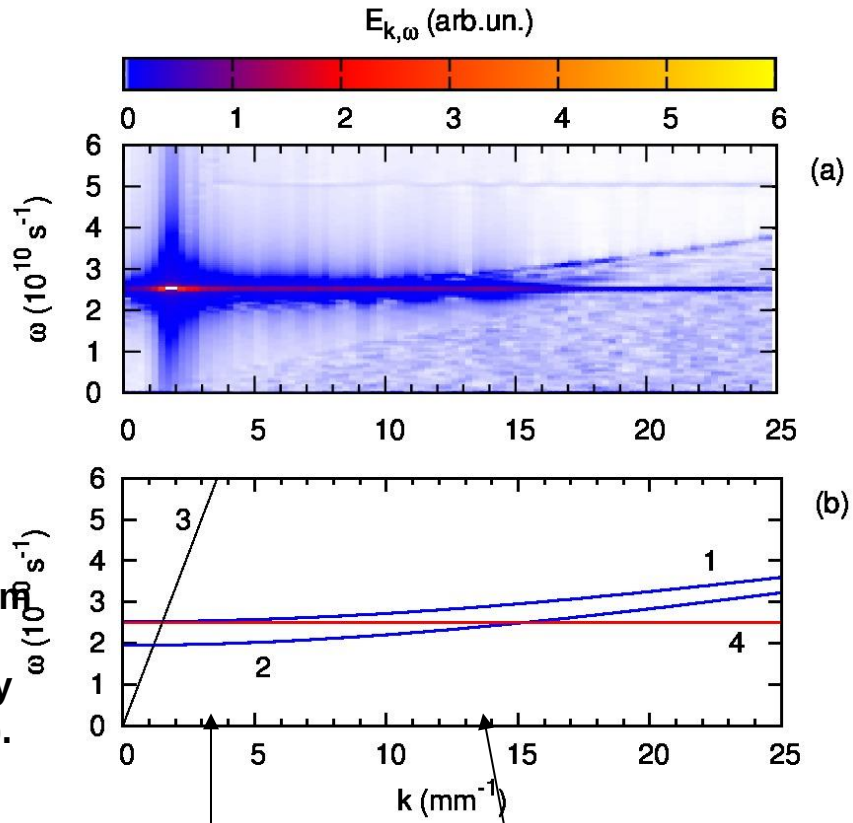


MECHANISM OF SHORT-WAVELENGTH ELECTRON PLASMA WAVE EXCITATION

Spectrum in k and w obtained for the electric field calculated in the simulation.

Theoretical dispersion: plasma wave in the density plateau (curve 1), plasma wave for density at x=5.9 mm (curve 2), the beam mode (curve 3), and the frequency excited by the beam (line 4).

$$\omega^2 = \omega_{pe}^2 + 3k^2 T_e/m_e$$



Wavenumber in the plateau area

Wavenumber in the density gradient area

The beam excites a strong plasma wave in the middle of the plasma.

The frequency of this wave defines the frequency of oscillations everywhere else.

In areas where the plasma density is lower, the wavenumber is larger, that is the wavelength is shorter.

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 electron beam propagating in finite-length plasma with nonuniform density may result in significant acceleration of bulk electrons.**
- **The temporal growth rate and the amplitude of saturation of the instability are different functions of the beam density compared to the classical values obtained for infinite plasmas.**
- **Plasma waves with short wavelength appear when a plasma wave excited by the beam enters a density gradient region with lower plasma density. The short-wavelength waves accelerate bulk electrons to suprathermal energies.**

SUMMARY

- **We considered numerically the two-stream instability in a dc discharge with constant electron emission from a cathode.**
- **Plasma waves with short wavelength appear when a plasma wave excited by the beam enters a density gradient region with lower plasma density.**
- **The short-wavelength waves accelerate bulk electrons to suprathermal energies (from few eV to few tens of eV). Such acceleration is a one-time process and occurs along the direction of the wave phase speed decrease. It is possible because the wave phase speed and amplitude are strongly nonuniform.**
- **Some of the accelerated electrons may be reflected by the anode sheath and reintroduced into the density gradient area where they will be accelerated one more time. The energy of an electron after the second acceleration can be an order of magnitude higher than its initial energy.**
- **These processes may be relevant to observations of suprathermal (~100eV) peaks on the EVDF in a DC/RF discharge [Chen and Funk, 2010].**
- **The temporal growth rate and the amplitude of saturation of the instability are different functions of the beam density compared to the classical values obtained for infinite plasmas.**

OUTLINE

- Motivation/Background
  - Description of Codes
- 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.
- **Electron beam-plasma interaction in a bounded plasma (two-stream instability):**
  - Effects of nonuniform plasma
  - **Mechanism of electron acceleration in plasma wave**

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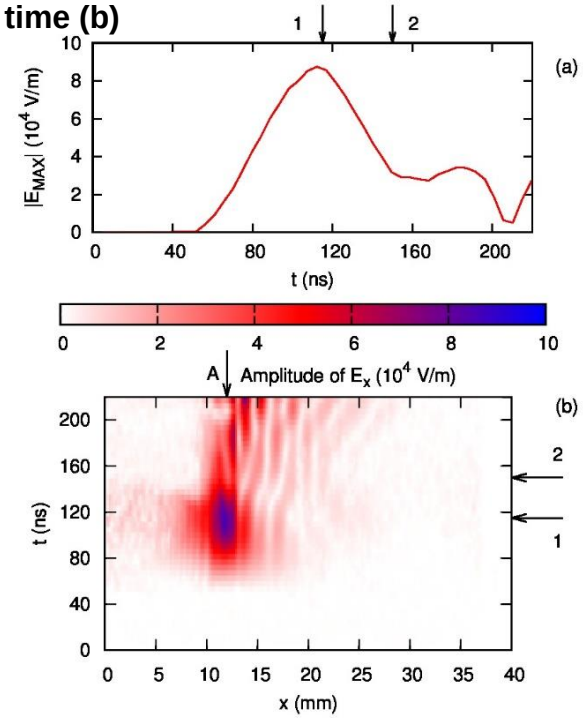
PLASMA PHYSICS
LABORATORY

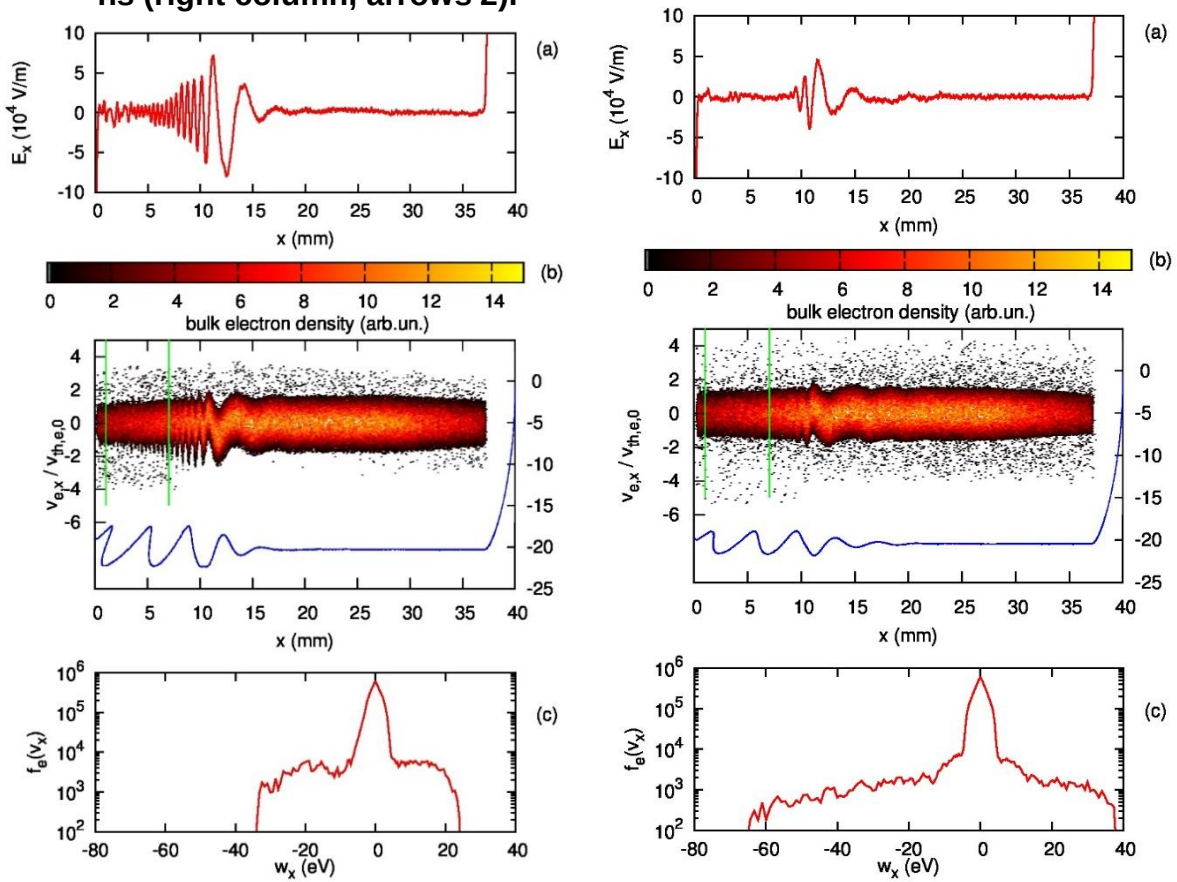
SUPRATHERMAL ELECTRONS APPEAR IN SIMULATION WITH HIGHER BEAM CURRENT

The electron emission current at the cathode is 20.13 mA/cm^2, relative beam density is 0.000377.

Electric field amplitude vs time at x=12 mm (a) and vs coordinate and time (b)



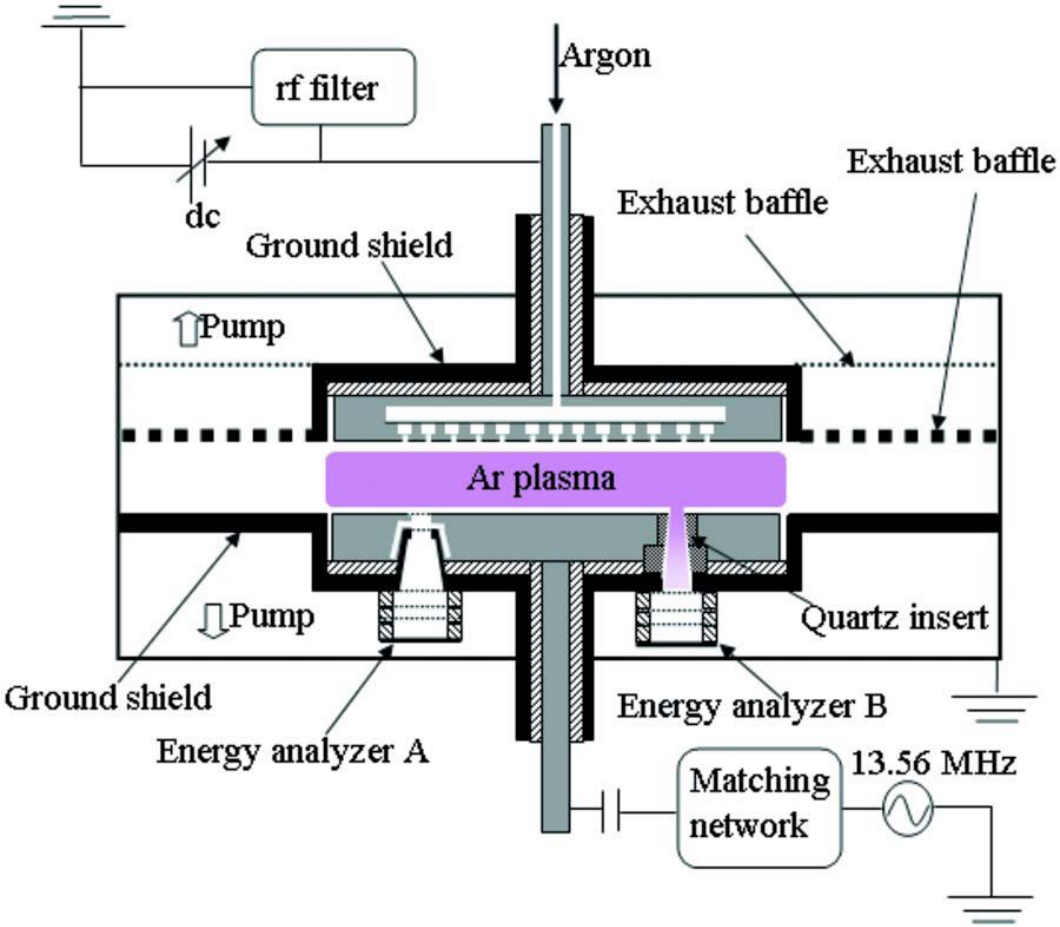
Electric field profile (a), phase plane v(x) (b), EVDF near anode (c). Time is 112 ns (left column, arrows 1) and 150 ns (right column, arrows 2).



The energy of suprathermal electrons is significantly higher at later stage of instability when the wave amplitude is lower. Why?

ETCHER WITH A CAPACITIVELY COUPLED PLASMA AND A RF-BIAS WAFER ELECTRODE AND DC BIASED ELECTRODE

DC biased electrode 800V



RF biased electrode (1-2kV) with wafer and electron energy analyzers

US Patent 7829469

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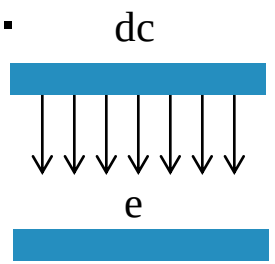
Simplicity and Reliability

- **Wide pressure window**
- **Independent control of the plasma generation and ion energy**
- **Rich in molecular radicals**

EXPERIMENTAL MEASUREMENTS SHOW FORMATION OF COMPLEX ELECTRON ENERGY DISTRIBUTION FUNCTION

A high energy beam with energy equal to the biased voltage, middle energy peak and low energy bulk electrons in the electron energy distribution function (EEDF) has been observed in a DC/RF discharge. L. Xu et al, Appl. Phys. Lett. 93, 261502 (2008).



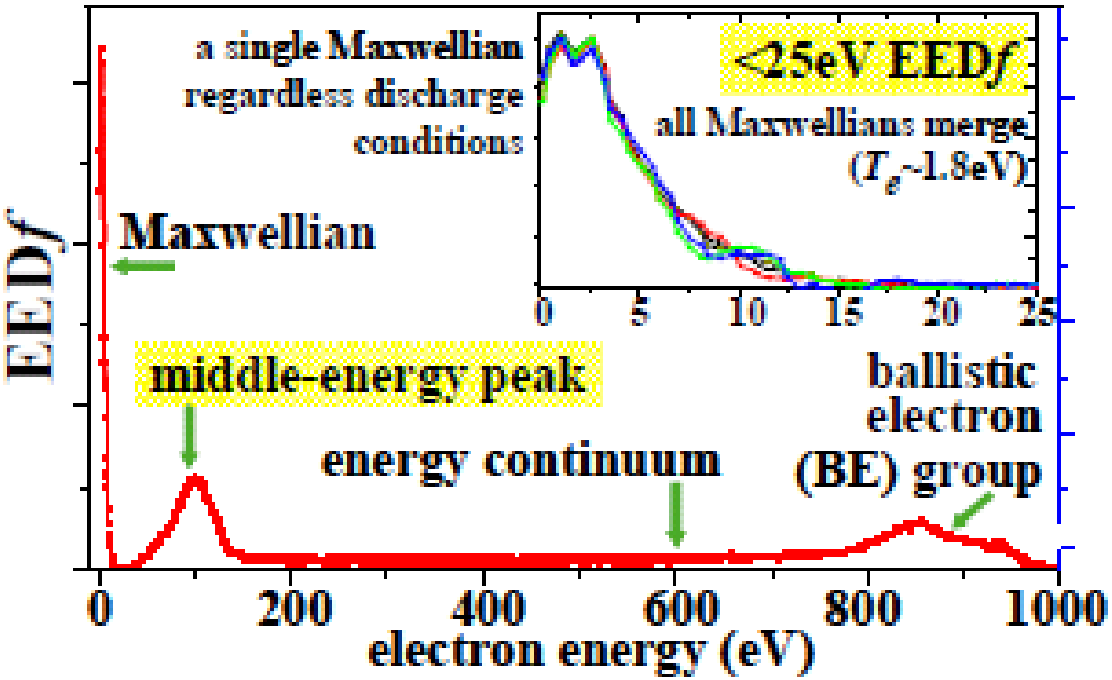
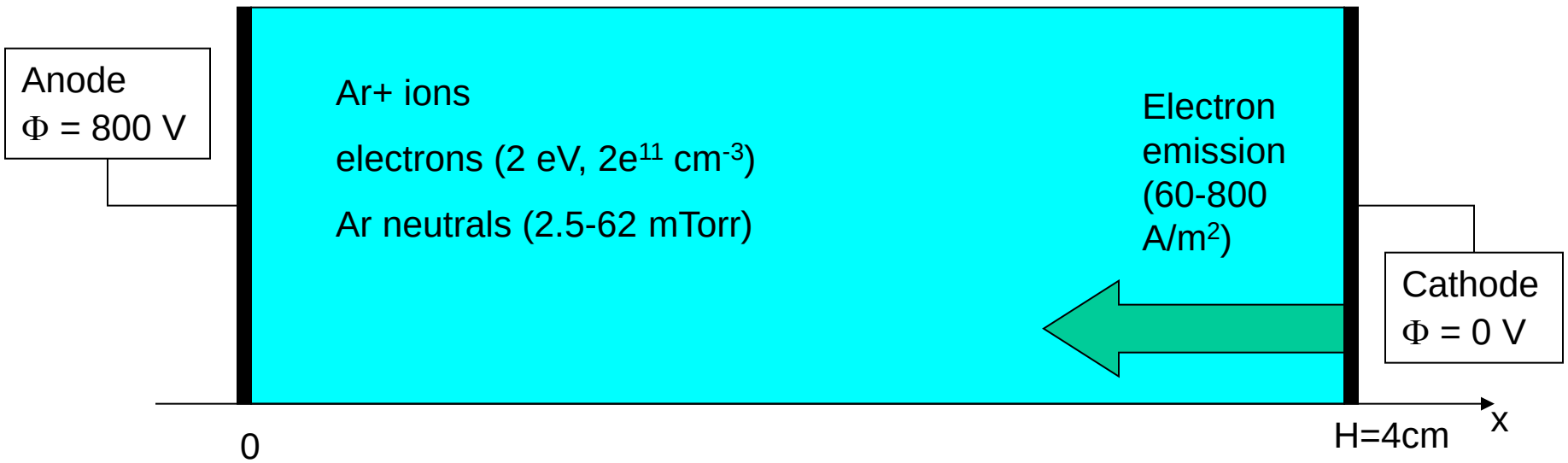


Fig. 1. Non-Maxwellian EEDf of DC/RF plasma.

DC SYSTEM SIMULATED WITH EDIPIC

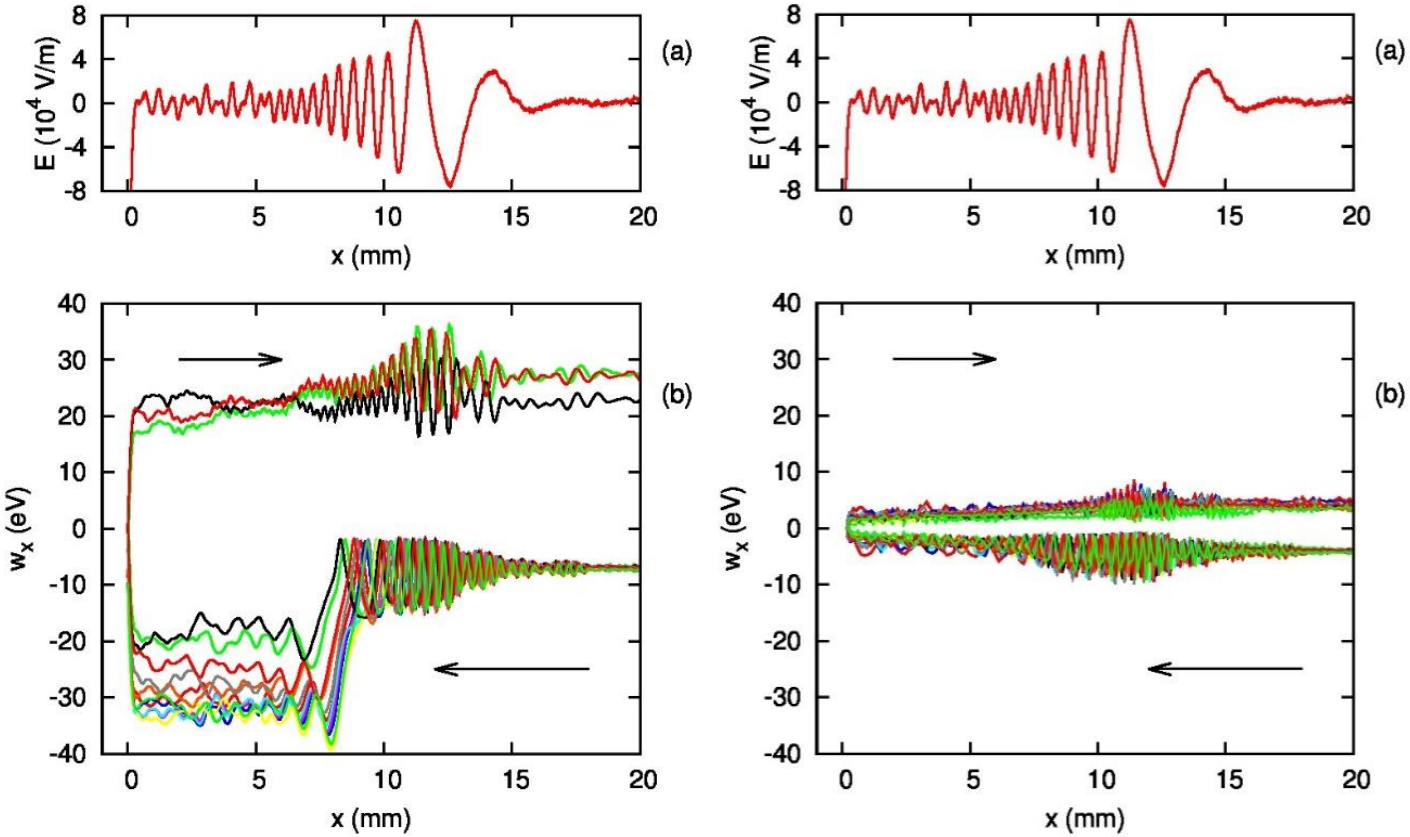


- **The EDIPIC (Electrostatic Direct Implicit Particle In Cell) code was developed by D. Sydorenko for simulation of Hall discharges, beam-plasma interaction, plasma sheath.**
- **EDIPIC code features:**
  - **Electrostatic, direct implicit algorithm**
  - **Electron-neutral and Coulomb collisions**
  - **Secondary electron emission**
  - **Abundant diagnostics output**
  - **MPI parallelization**

ACCELERATION WAS STUDIED WITH TEST PARTICLES

A representative profile of the electric field (top) and set of trajectories of test particles in the energy-coordinate phase space (bottom).

7 eV initial energy. Intense one-time acceleration.

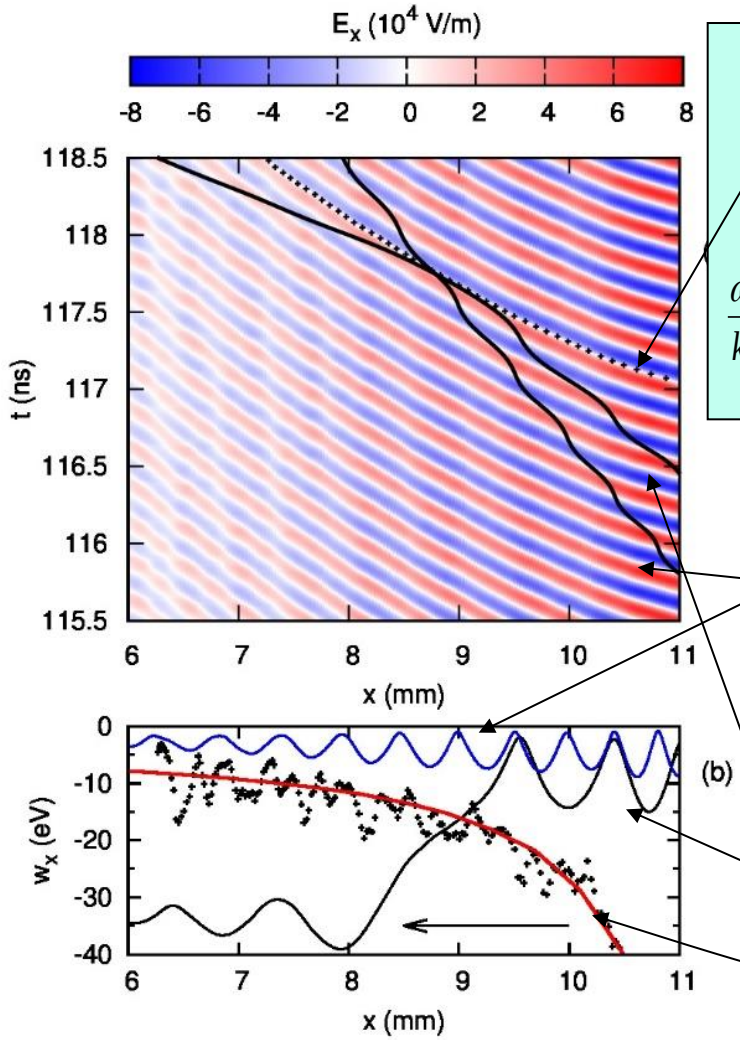


4 eV initial energy. No acceleration on average.

Acceleration is the combination of short resonance, strong field, and non-uniform wave phase velocity and amplitude

Color map of the electric field vs coordinate (horizontal axis) and time (vertical axis).

Phase space energy-coordinate.



Phase speed of plasma wave calculated by differentiation of level lines (black markers) and theoretically (red curve).

$$\frac{\omega}{k} = \frac{\sqrt{3T_e/m_e}}{\sqrt{1-n(x)/n_0}}, \quad n_0 - n(x) >> n_0 \frac{3T_e}{2w_b}$$

Particle with initial energy 4 eV. No acceleration.

Particle with initial energy 7 eV.

THE HIGHEST ENERGY IS ACQUIRED BY RECYCLED ELECTRONS

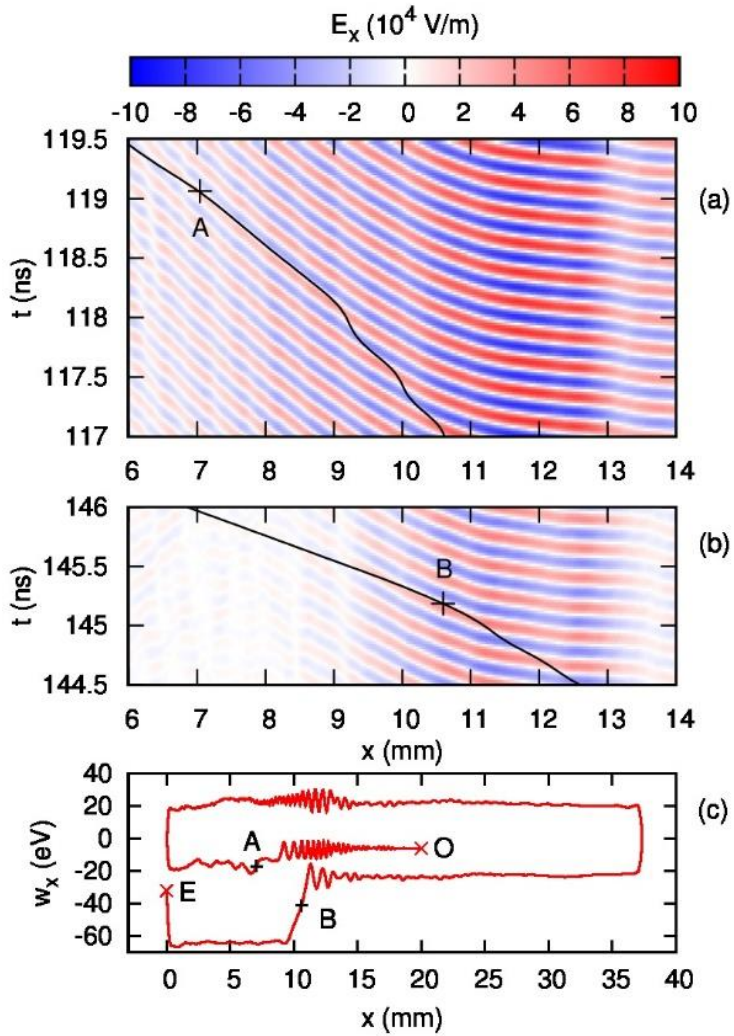
Color map of the electric field vs coordinate (horizontal axis) and time (vertical axis). Initial particle energy 6 eV.

First stage of acceleration.

Second stage of acceleration.

Phase space energy-coordinate.

O is the origin point, A is the first acceleration, B is the second acceleration, E – escape.



- **Some electrons do not escape after the first acceleration.**
- **Such electrons make a round trip through the plasma and density gradient area with higher initial energy.**
- **They interact with the short waves in areas where the wave phase speed is higher, closer to the instability area.**
- **The energy after the second acceleration (~65eV) is an order of magnitude higher then the initial energy (~6eV).**
- **Such a mechanism explains why the highest energy suprathermal electrons appear with a delay.**

THE AMPLITUDE OF INSTABILITY GROWS WITH THE BEAM CURRENT FASTER THEN EXPECTED

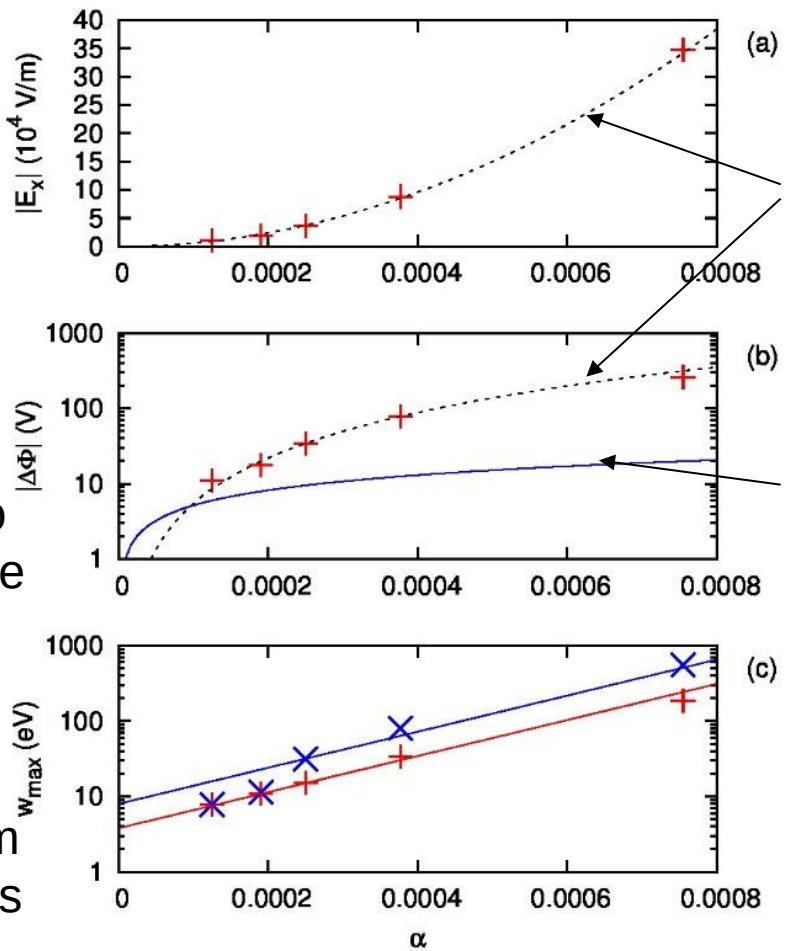
A set of simulations with beam current from 6.71 mA/cm² ($\alpha = 0.000125$) to 40.26 mA/cm² ($\alpha = 0.000755$) is performed.
The two-stage acceleration does not appear for $\alpha = 0.000125$ and $\alpha = 0.00019$.
With the two-stage acceleration, the maxmal energy of suprathermal electrons is much higher than that after the one-stage acceleration.

Markers are values from simulations.

Maximal electric field amplitude

Maximal potential perturbation amplitude

Maximal energy of suprathermal electrons



Relative density of the beam

Interpolation curves proportional to α^2

Saturation amplitude in an infinite plasma $e\Phi_{1,max} = 3w_b\alpha^{2/3}$

Red/blue crosses represent values before/after the two-stage acceleration.

SUMMARY

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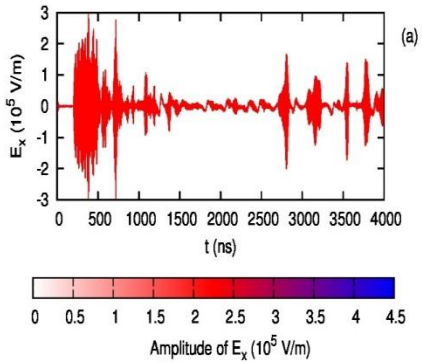
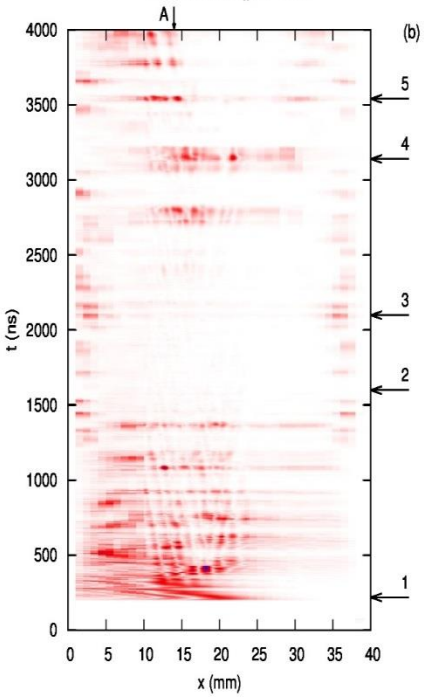
INTERMITTENCY, ION WAVES, OSCILLATIONS AT THE EDGES OF THE PLASMA

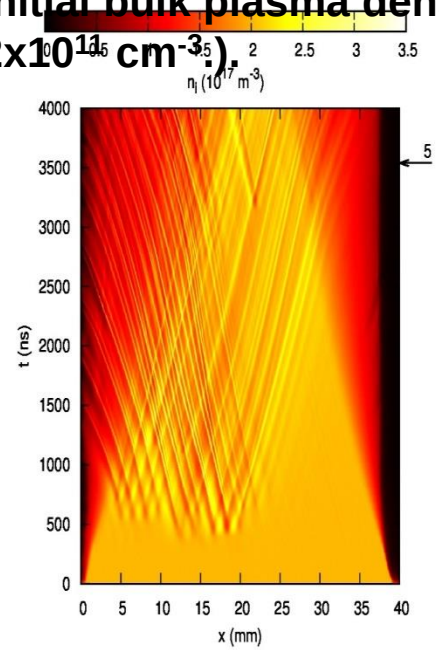
Electric field vs time in probe A



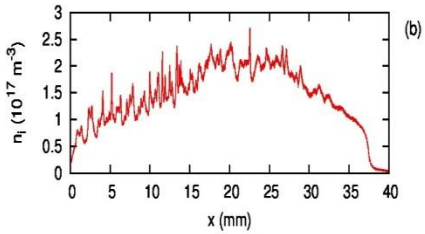
Amplitude of hf plasma oscillations vs coordinate (horizontal axis) and time (vertical axis)



Emission current 80.32 mA/cm², relative beam density 0.0016 (calculated with the initial bulk plasma density of 2×10^{11} cm^{-3}).



Ion density vs coordinate (horizontal axis) and time (vertical axis)



Ion density profile at time #5

Ion waves are produced by intense HF fields due to the modulation instability.