Effects of Beam-Plasma Instabilities on Neutralized Propagation of Intense Ion Beams in Background Plasma*

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Summary

- The streaming of an intense ion beam relative to background plasma can cause the development of fast electrostatic collective instabilities.

- The instabilities produce fluctuating electrostatic fields that can cause a significant drag on the background plasma electrons and can accelerate electrons up to velocities comparable ion beam velocity.

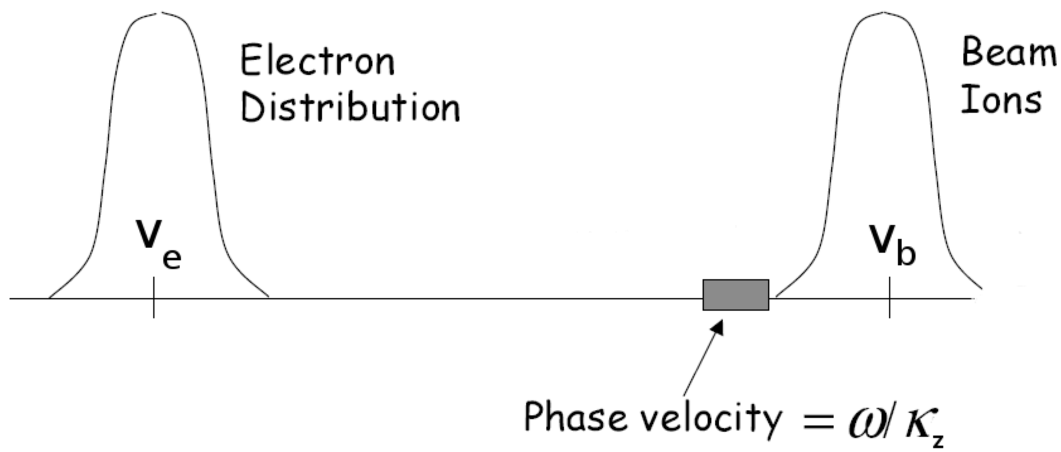
- Consequently, the (strong) electron return current can reverse the direction of the beam-induced self-magnetic field.

- As a result, the magnetic self-field force reverses sign and leads to a transverse defocusing of the beam instead of a pinching effect in the absence of instability.

- In addition, the ponderomotive force of the unstable wave pushes the background electrons transversely away from the unstable region inside the beam, which creates an ambipolar electric field, which also leads to a transverse defocusing of the beam ions.

- Because the instability is resonant it is strongly affected and thus can be effectively mitigated and controlled by the longitudinal focusing of the ion beam.

Schematic of Two-Stream Instability



- Two-stream collective interactions between the beam ions and plasma electrons excite unstable waves with phase velocity ω/k_z slightly below the ion beam velocity v_b.

Intense Beam Propagation in Neutralizing Plasma

- Beam parameters(protons, for purpose of illustration):

  (1) Gaussian beam density profile and pulse duration $T = 12ns$;

  (2) Beam velocity $v_b = c/2$ corresponding to $\gamma_b = 1.15$, where c is the speed of light in vacuo;

  (3) Beam density is $n_b = 2 \times 10^{10} cm^{-3}$;

  (4) Beam radius is $r_b = 2cm$ and $r_b \sim \lambda_p = c/\omega_{pe}$, where $\omega_{pe} = (4\pi e^2 n_p/m_e)^{1/2}$;

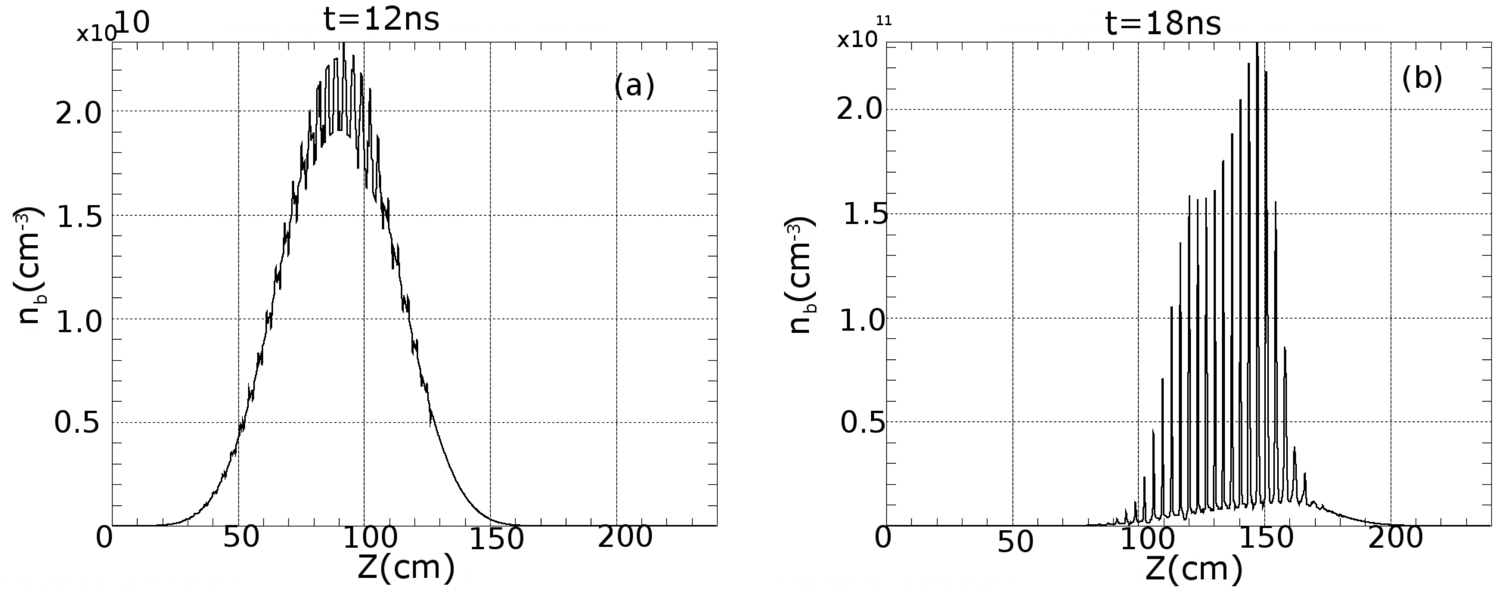
- Beam propagates through a stationary, singly-ionized carbon plasma with plasma density $n_p = 2 \times 10^{11} cm^{-3}$.

- Characteristic linear exponentiation time of two-stream instability is $\Gamma^{-1} = (Im\omega)^{-1} = 0.8ns$.

- The reason for simulating proton beam propagation is to study collective effects on a short time scale, due to the lower beam ion mass.

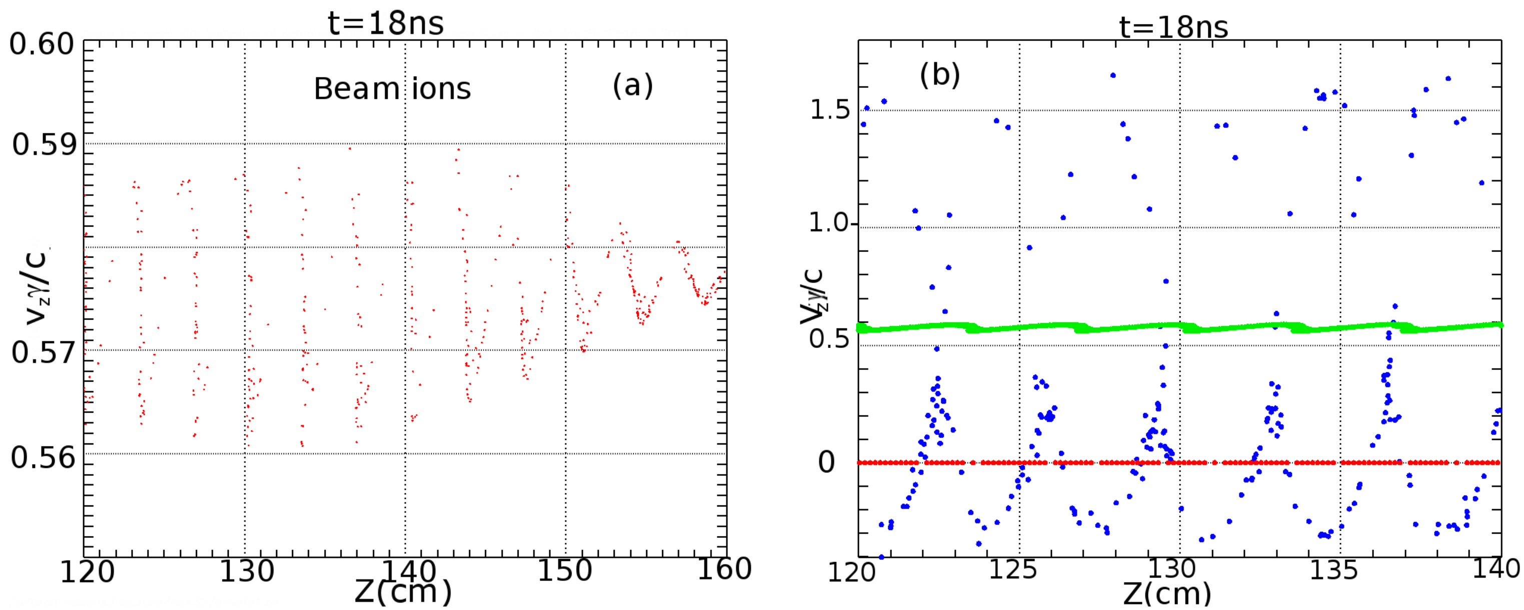
- Simulations are carried out in slab geometry $(\partial/\partial z \neq 0, \partial/\partial x \neq 0, \partial/\partial y = 0)$ using the LSP code.

Instability can lead to beam break-up



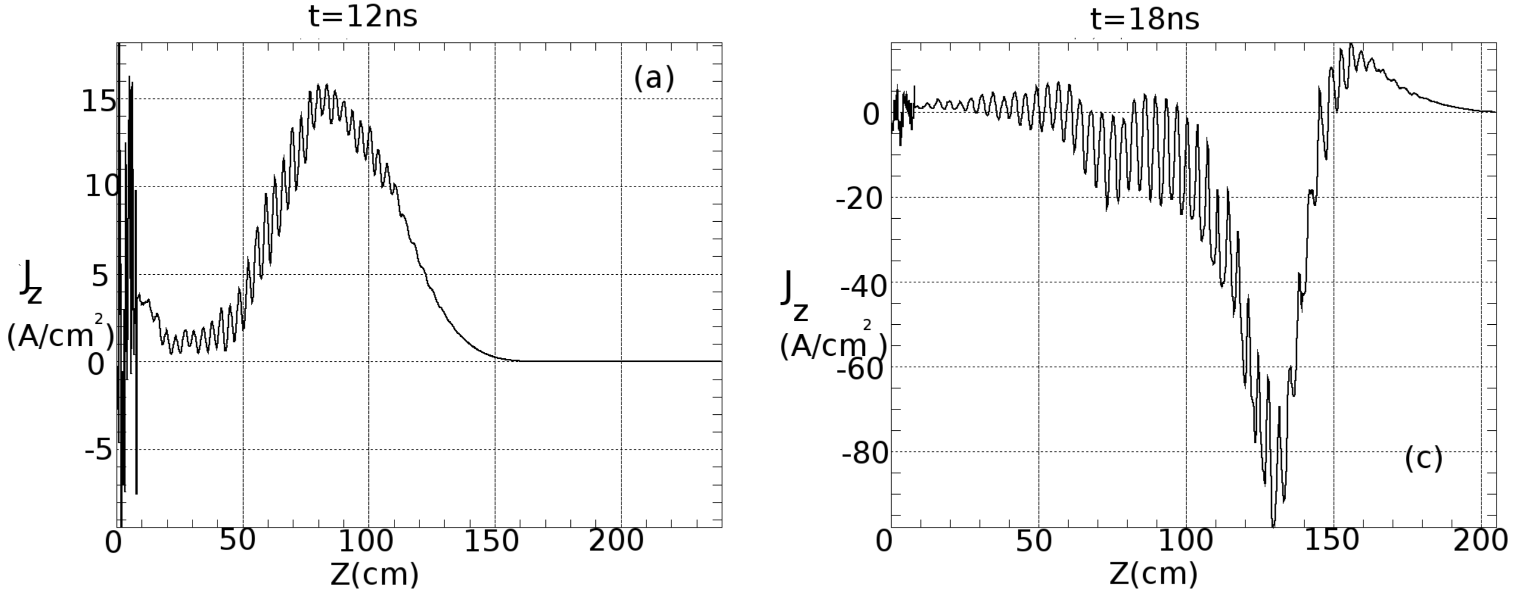
- Longitudinal beam density variations can be of order 100% of the original beam density.

Particle Phase-Space



- Instability saturates nonlinearly by particle trapping.
- Background electrons oscillate with velocity amplitude $v_m^e \sim v_b$.

Average plasma electron return current density can exceed the beam current density



- Plots of total current density j_z at $r = 0$.

Estimate of average current density

- Electron current density

$$\langle J_z^e \rangle = J_z^{ind} + \langle J_z^{non} \rangle = J_z^{ind} - e\langle \delta n^e \delta v_z^e \rangle = -en_p \langle v_z^e \rangle - e\frac{n_p}{v_b}\langle (\delta v_z^e)^2 \rangle$$
$$= -en_p \langle v_z^e \rangle - \frac{1}{2}\frac{n_p}{n_b}\left(\frac{v_m^e}{v_b}\right)^2 J_z^b$$

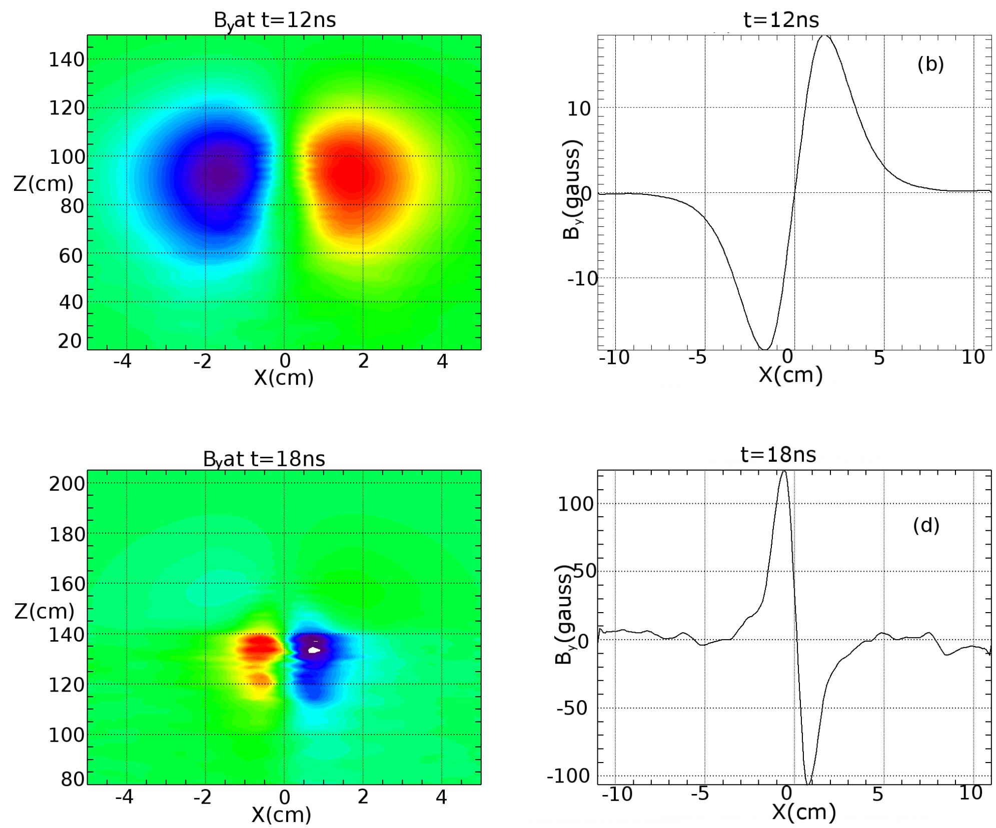
where v_m^e is the velocity oscillation amplitude of the plasma electrons in the wave, and we used $\delta n^e = n_p(k_z/\omega)\delta v_z^e$ and $\omega/k_z \approx v_b$.

- $J_z^{ind} = -en_p\langle v_z^e \rangle$ is the average longitudinal electron current produced by the longitudinal inductive electric field which acts to reduce the current density $\langle J_z^{non} \rangle + J_z^b$ by the factor $(1 + r_b^2\omega_{pe}^2/c^2)^{-1}$.

- The total current density is then given by

$$\langle J_z \rangle = J_z^b + \langle J_z^e \rangle = \frac{J_z^b}{(1 + r_b^2\omega_{pe}^2/c^2)}\left[1 - \frac{1}{2}\frac{n_p}{n_b}\left(\frac{v_m^e}{v_b}\right)^2\right].$$

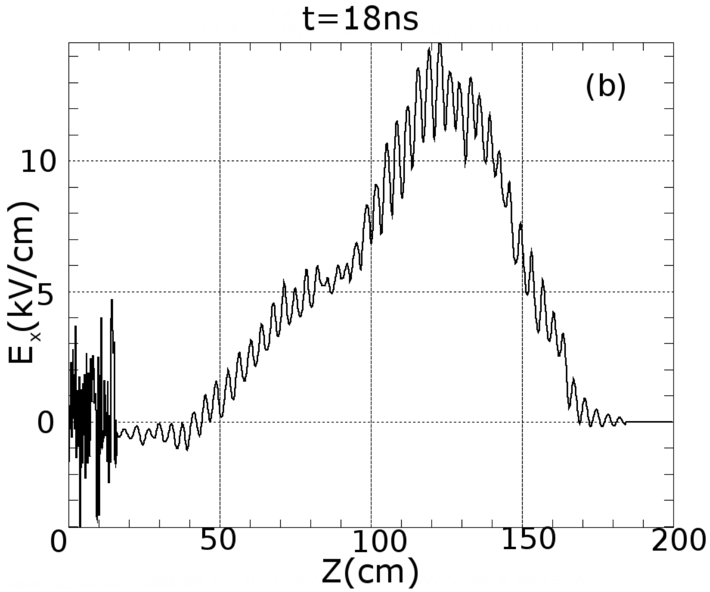
Enhanced return current density reverses the azimuthal magnetic field

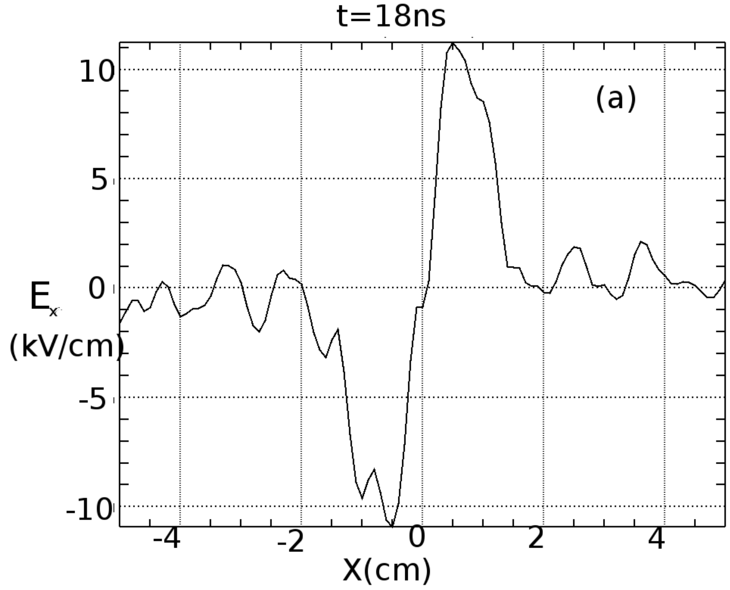


$$\langle B_y \rangle = \frac{4\pi}{c}\langle J_z \rangle r_b \sim \frac{2\pi e n_b r_b \beta_b}{(1 + r_b^2\omega_{pe}^2/c^2)}\left[1 - \frac{1}{2}\frac{n_p}{n_b}\left(\frac{v_m^e}{v_b}\right)^2\right],$$

- if $v_m^e/v_b > (2n_b/n_p)^{1/2}$ the azimuthal magnetic field $\langle B_y \rangle$ is reversed.

The average transverse electric field also becomes enhanced by the instability

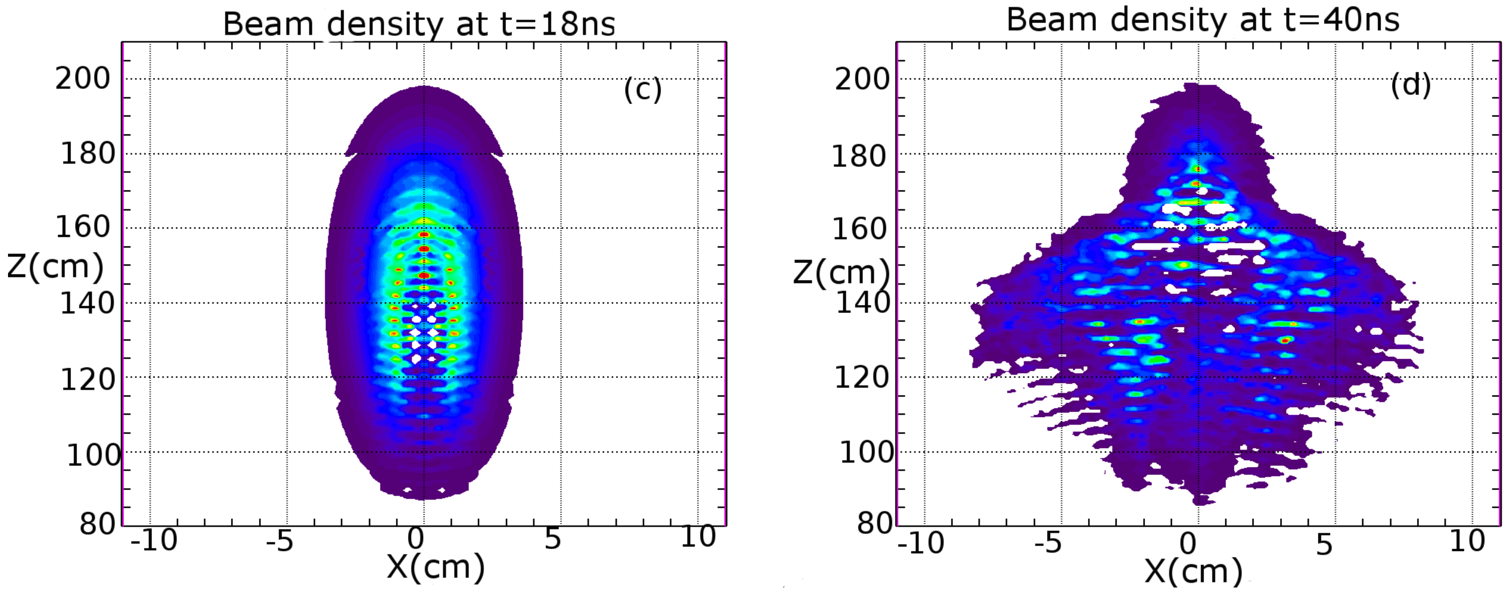




- The ponderomotive pressure of the unstable wave pushes electrons away from the unstable region inside the beam which sets up an ambipolar transverse electric field

$$e\langle E_x \rangle \sim m_e \frac{(v_m^e)^2}{4r_b}.$$

Nonlinearly generated fields can lead to beam defocusing



- For beams with $r_b > c/\omega_p$ both forces are of similar magnitude and are defocusing for the beam ions, i.e.,

$$e\langle E_x \rangle \sim e\frac{v_b}{c}\langle B_y \rangle.$$

- For beams with $r_b < c/\omega_p$, we find $e\langle E_x \rangle > e\frac{v_b}{c}\langle B_y \rangle$.

Neutralized Drift Compression Experiment-II

- Lithium Ion Beam parameters:

  (1) Gaussian beam density profile and pulse duration $T = 20ns$;

  (2) Beam velocity $v_b = c/30$ and $\gamma_b = 1.0006$, where c is the speed of light in vacuo;

  (3) Beam density is $n_b = 2 \times 10^9 cm^{-3}$;

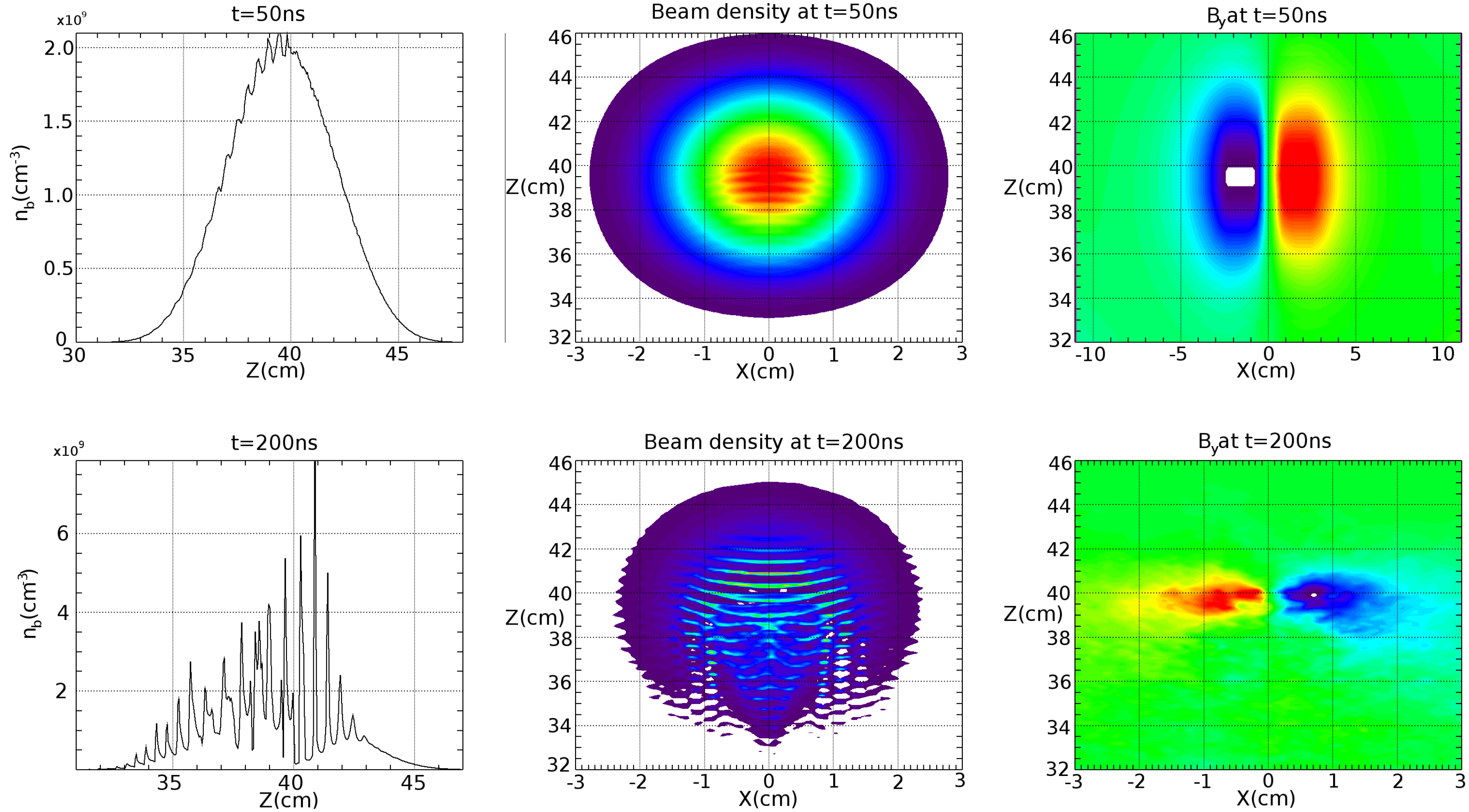
  (4) Beam radius is $r_b = 1.41cm$ and $r_b \sim \lambda_p = c/\omega_{pe}$.

- Beam propagates through a stationary, singly-ionized carbon plasma with plasma density $n_p = 0.55 \times 10^{11} cm^{-3}$.

- Characteristic linear exponentiation time of two-stream instability is $\Gamma^{-1} = (Im\omega)^{-1} = 4.1ns$.

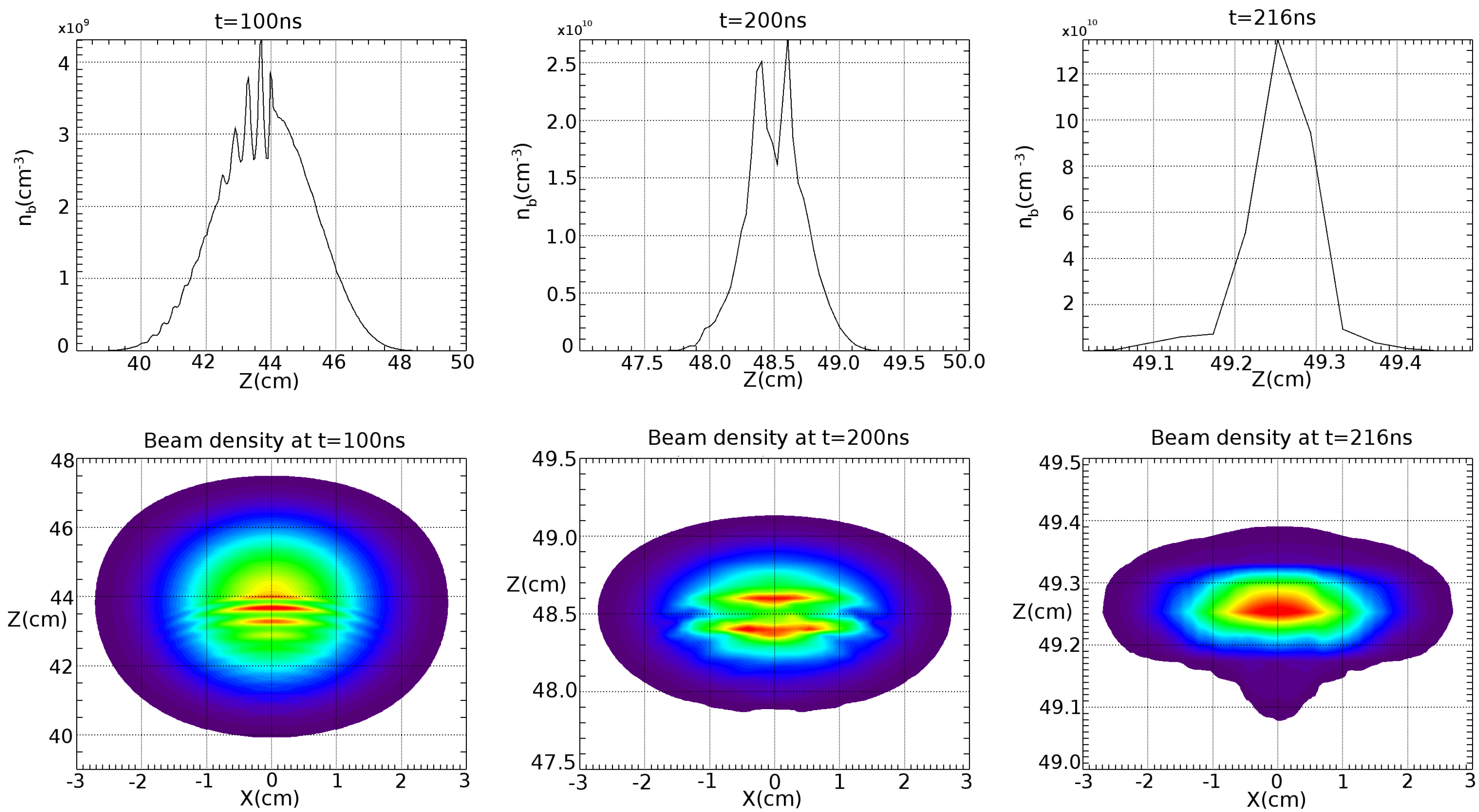
- In compression experiments the beam enters plasma with a velocity tilt $\Delta v_b/v_b = 0.1$, which should produce longitudinal beam compression after $T = 220ns$.

With no velocity tilt, two-stream instability leads to beam break-up at 200ns but no transverse defocusing



- Longitudinal beam density variations of order 90% of the original beam density.

With velocity tilt $\Delta v_b/v_b = 0.1$ the instability does not develop enough to break-up the beam



- A maximum longitudinal compression factor of $C = 67$ is achieved at 216ns.

Defocusing Force and Distance Estimates

- The unstable waves grow until the plasma electrons start to oscillate with velocity amplitude of order the beam velocity

$$v_m^e \sim \omega/k_z \approx v_b$$

- Or the beam ions begin to oscillate with velocity amplitude

$$v_m^b = v_b - \omega/k_z \sim \Gamma/k_z \approx (\Gamma/\omega_p)v_b$$

  Here $\Gamma \sim \omega_{pe}(\omega_{pb}/\omega_{pe})^{2/3}$ is the linear instability growth rate, and the velocity amplitudes of the ions and electrons are related by $v_m^e = (m_b/m_e)v_m^b$.

- Therefore, the amplitude of background electrons velocity oscilations at saturation can be estimated as

$$\left(\frac{v_m^e}{v_b}\right) \sim min\left[\left(\frac{n_b}{n_p}\right)^{2/3}\left(\frac{m_b}{m_e}\right)^{1/3}; 1\right].$$

- Estimates for the defocusing time T when $\Delta r_b/r_b = 1$ and the defocusing propagation distance $L = v_b T$ (with developed instability) are

$$m_b\frac{r_b}{T^2} \sim m_e\frac{(v_m^e)^2}{r_b}, \quad T \sim \left(\frac{r_b}{v_b}\right)\frac{(m_b/m_e)^{1/2}}{v_m^e/v_b}, \quad L \sim r_b\frac{(m_b/m_e)^{1/2}}{v_m^e/v_b}$$

Ion Beam with Velocity Tilt

- The two-stream instability gain for an ion beam with the velocity tilt which produces ion beam focusing in background plasma after time T_f is given by[1-3]

$$G = 0.8\omega_{pb}T_f$$

where $\omega_{pb} \approx (4\pi e^2 n_b/m_b)^{1/2}$ is the ion beam plasma frequency.

- For NDCX-II, $G \approx 4$ with $\exp(G) = 55$ and the initial density perturbation does not grow significantly due to the instability.

- The instability gain during the same time T_f for the NDCX-II beam with no velocity tilt is $G \approx 10$ with $\exp(G) = 2\times 10^4$ and the instability develops to the nonlinear saturation level.

[1] E. A. Startsev, R. C. Davidson and M. Dorf, Nuclear Instruments and Methods in Physics Research **A606**, 42 (2009).

[2] E. A. Startsev, R. C. Davidson, Nuclear Instruments and Methods in Physics Research **A577**, 79 (2007)

[3] E. A. Startsev, R. C. Davidson, Phys. Plasmas **13**, 062108 (2006);

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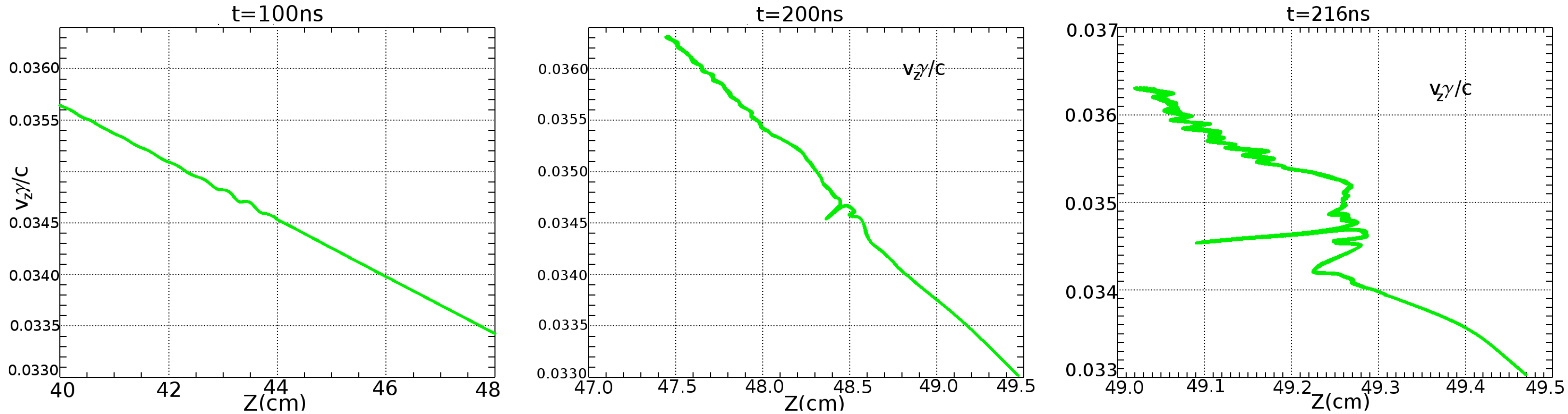
BACK-UP SLIDES

Beam Phase-Space (with $\Delta v_b/v_b = 0.1$)



- Compression is limited by the instability spoiling the beam longitudinal phase space.