Numerical model with continuous injection of an electron beam into a plasma for simulation of electromagnetic emission processes

Vladimir Annenkov, Evgeniia Volchok, Igor Timofeev

Budker Institute of Nuclear Physics, SB RAS
Novosibirsk State University
Novosibirsk, Russia

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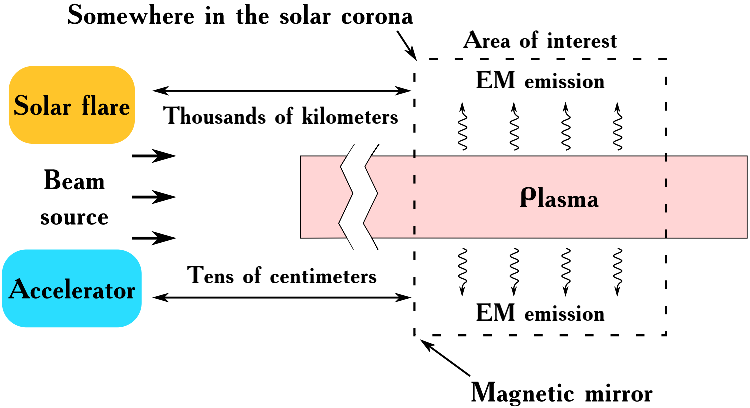
BINP SB RAS

Contact: v.v.annenkov@inp.nsk.su

Electron beams in plasma

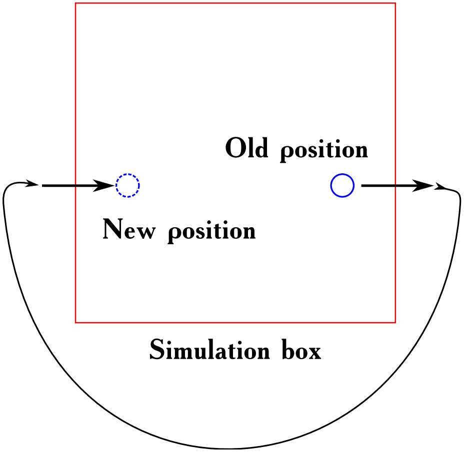
- Electron fluxes are generated in various processes on the Sun;
- Passing through the plasma, they cause electromagnetic emission;
- In laboratory facilities:
  - fusion plasma heating and confinement tasks;
  - promising generators of powerful narrowband radiation.



Infinite model

- The "infinity" of the plasma is realized by imposing periodic boundary conditions;
- The model is excellent for testing theories developed under the assumption of infinite plasma.
- There is a limited amount of energy in the system;
- Because of the periodic conditions in the system, only a limited number of oscillations determined by the geometric size of the simulation area is possible.

Periodic boundary conditions

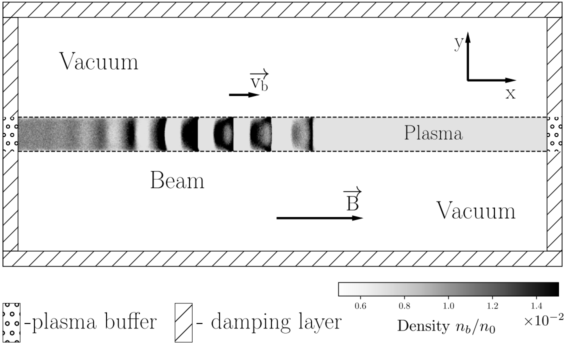


Model with continuous injection

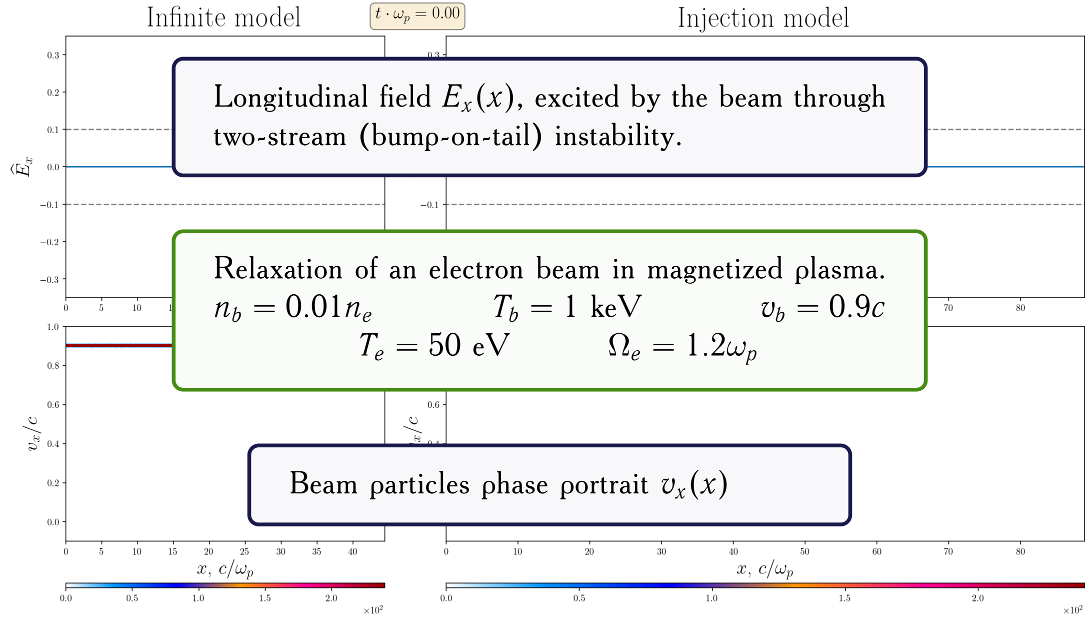
- Continuous injection of "fresh" particles into the system;
- Special open boundary conditions to ensure the departure of particles from the system and the arrival of new ones to create the correct compensation curren.

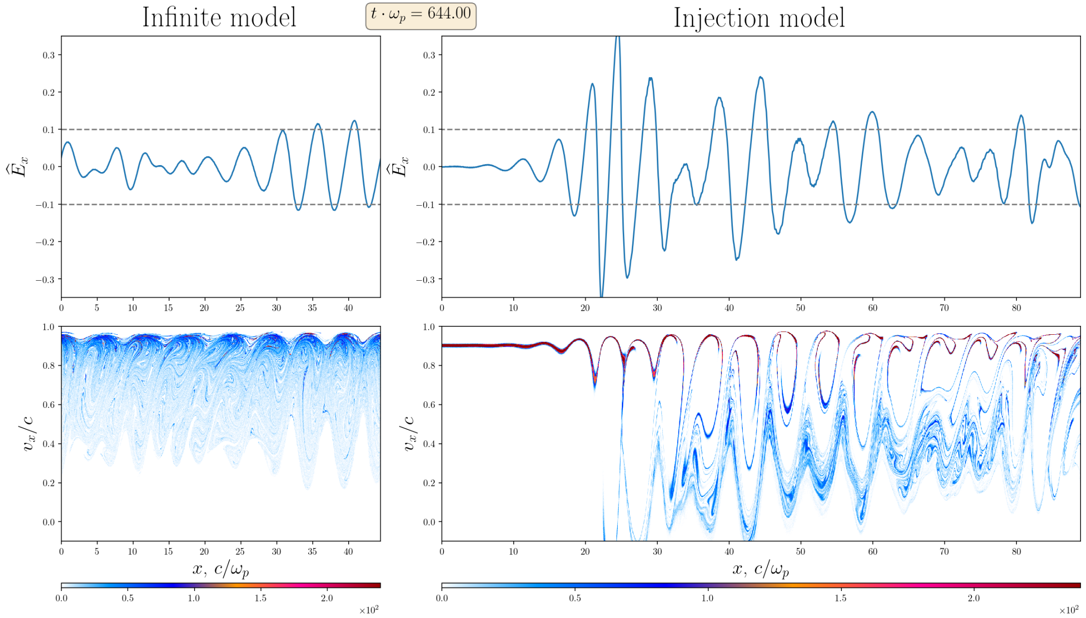
Different implementations:

- Sigov Y. S. and Levchenko V. D.// Plasma Physics and Controlled Fusion. – 1996. – T. 38, 12A. – A49—A65.
- FT. Umeda et al. // Journal of Geophysical Research: Space Physics. – 2002. – T. 107, A12. – SMP 19-1-SMP 19—16
- Mandrake L. et al. // Geophysical Research Letters. – 2000. – T. 27, No 18. – C. 2869—2872.
- Timofeev I. V. and Terekhov A. V. // Physics of Plasmas. – 2010. – T. 17, No 8. – C. 83111.



Annenkov, V. V. et al.
Phys. Plasmas 25, 113110 (2018).

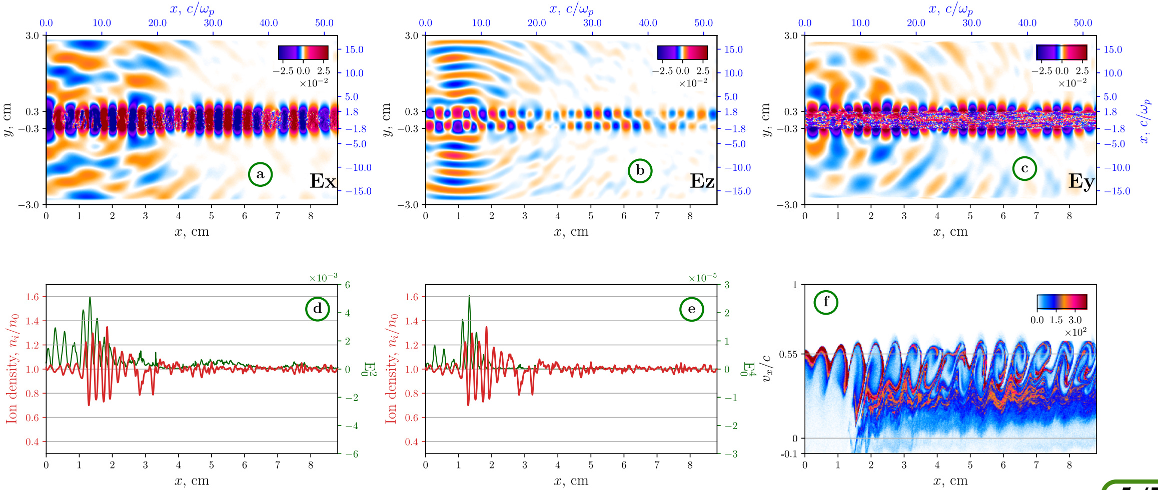

Infinite model
$t \cdot \omega_p = 0.00$
Injection model
Longitudinal field $E_x(x)$, excited by the beam through two-stream (bump-on-tail) instability.
Relaxation of an electron beam in magnetized plasma.
$n_b = 0.01 n_e$ $T_b = 1$ keV $v_b = 0.9c$
$T_e = 50$ eV $\Omega_e = 1.2\omega_p$
Beam particles phase portrait $v_x(x)$
$\widehat{E}_x$
v_x/c
$x,\ c/\omega_p$
$x,\ c/\omega_p$
$\times 10^2$
$\times 10^2$



Video: https://youtu.be/rbDYTrgGb1A

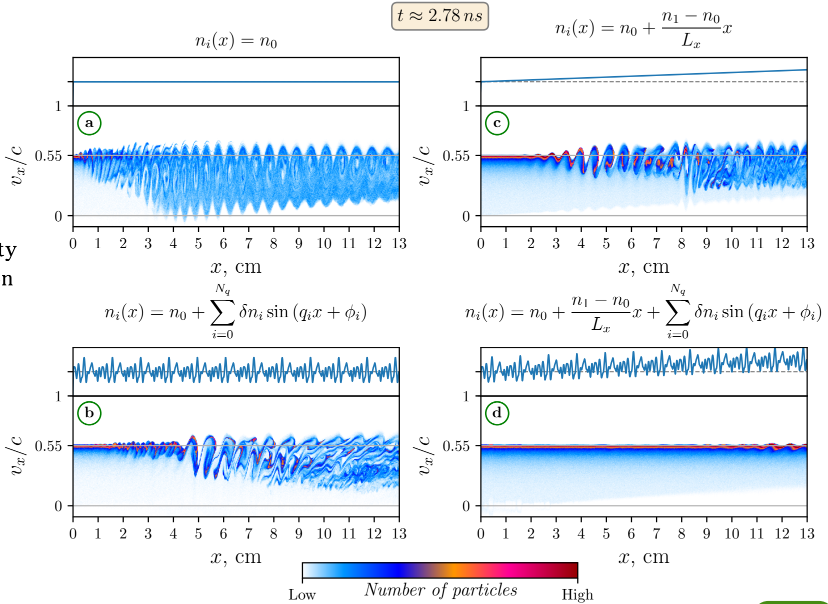
Main features of the model

- Strong localization of plasma oscillations of greater amplitude than in infinite plasma;
- The evolution of ion density is significantly different;
- No restrictions on the spectrum of excitable oscillations.



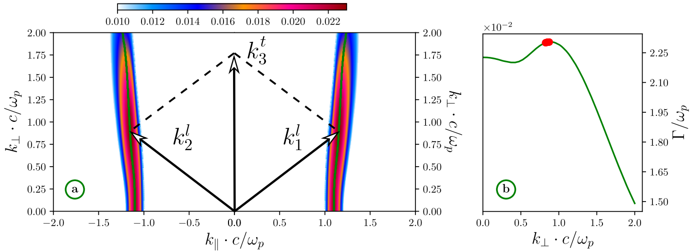
from: Annenkov, V. V. et al. Physics of Plasmas 26, 063104 (2019).

- In a homogeneous plasma, the beam relaxation region is quite close to the injection region;
- Significant disruption of instability and displacement of the relaxation region is possible due to:
  - large-scale density gradients;
  - small-scale density inhomogeneities, including those formed during beam relaxation.

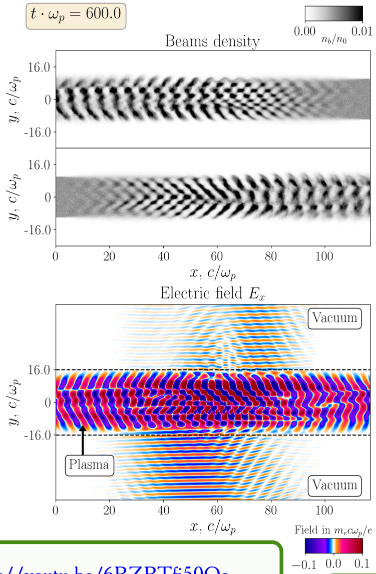


from: Annenkov, V. V. et al. Physics of Plasmas 26, 063104 (2019).

- The spectrum of plasma oscillations excited in the linear stage corresponds with good accuracy to the predictions of linear theory.
- For counterstreaming beams with density $n_b = 0.005 n_0$ a regime was found in which $2\omega_p$ EM radiation generation in the three-wave process $L + L' \to T_{2\omega_p}$ occurs at the linear stage of instability.



(a) The growth rate map for the beam-plasma instability $\Gamma(k_\parallel, k_\perp)$ in the efficient regime. The green line $k_\perp = k_\perp(k_\parallel)$ mark the maximal growth rate achieved for each $k_\perp$. (b) $\Gamma(k_\perp)$ along the green line (red points indicates the region of the three-wave interaction).



from: Annenkov, V. V. et al. The Astrophysical Journal 904, 88 (2020).

Video: https://youtu.be/6BZBTfj50Qc

For more details on our studies of processes of EM emission from beam-plasma systems using the discussed model, please refer to the papers:

- Annenkov, V., Berendeev, E., Volchok, E. & Timofeev, I. Particle-in-Cell Simulations of High-Power THz Generator Based on the Collision of Strongly Focused Relativistic Electron Beams in Plasma. Photonics 8, 172 (2021).
- Annenkov, V. V., Volchok, E. P. & Timofeev, I. V. Electromagnetic Emission Produced by Three-wave Interactions in a Plasma with Continuously Injected Counterstreaming Electron Beams. The Astrophysical Journal 904, 88 (2020).
- Annenkov, V. V., Timofeev, I. V. & Volchok, E. P. Highly efficient electromagnetic emission during 100 keV electron beam relaxation in a thin magnetized plasma. Physics of Plasmas 26, 063104 (2019).
- Annenkov, V. V., Berendeev, E. A., Timofeev, I. V. & Volchok, E. P. High-power terahertz emission from a plasma penetrated by counterstreaming different-size electron beams. Physics of Plasmas 25, 113110 (2018).
- Annenkov, V. V., Timofeev, I. V. & Volchok, E. P. Simulations of electromagnetic emissions produced in a thin plasma by a continuously injected electron beam. Physics of Plasmas 23, 053101 (2016).

Contacts: v.v.annenkov@inp.nsk.su // https://www.researchgate.net/profile/Vladimir-Annenkov

More interesting videos about beam-plasma interactions:
https://www.youtube.com/channel/UCvKOFAnpRXd511ukGbPMy2g

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