Plasma instabilities in the Fireball experiment at CERN

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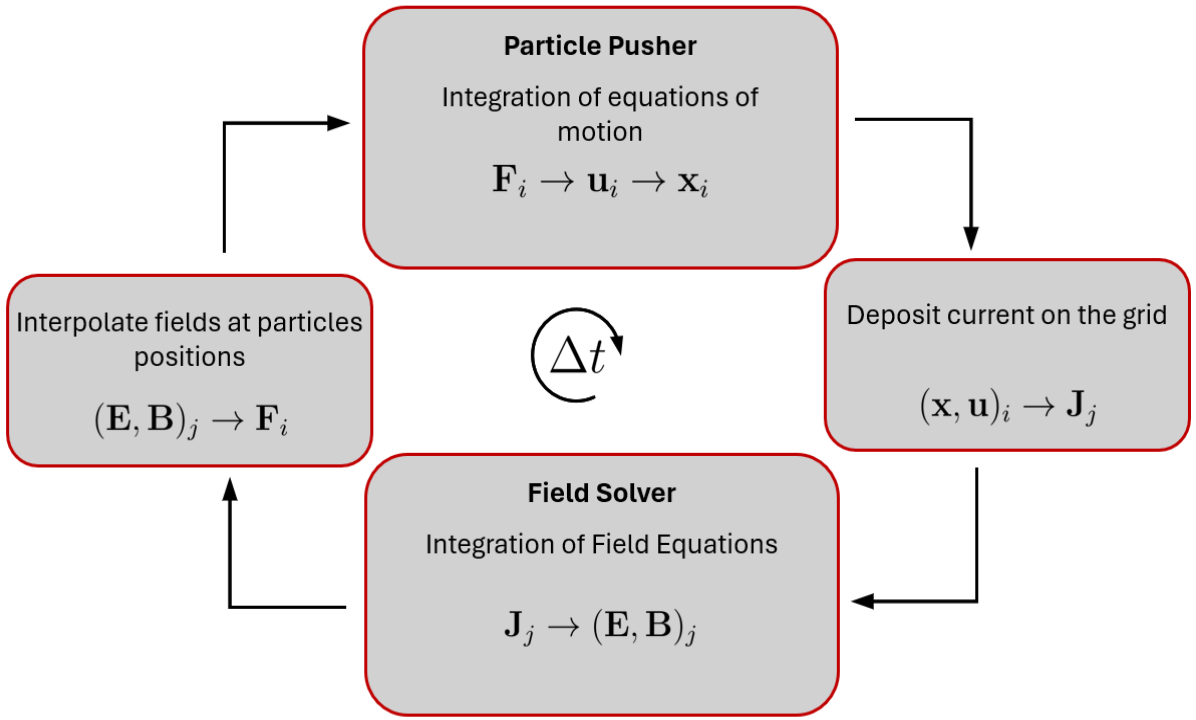
Credits: Sloan Digital Sky Survey

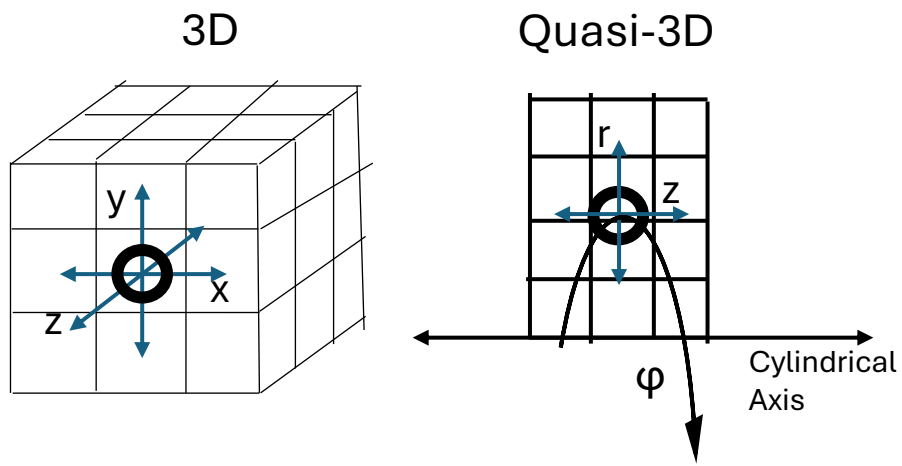
Quasi-cylindrical OSIRIS PIC code

OSIRIS: Loop Algorithm



OSIRIS Quasi-3D

$$\mathbf{F}(r, z, \phi) = \Re \left\{ \sum_{m=0}^{\infty} \mathbf{F}^m(r, z) e^{im\phi} \right\}$$



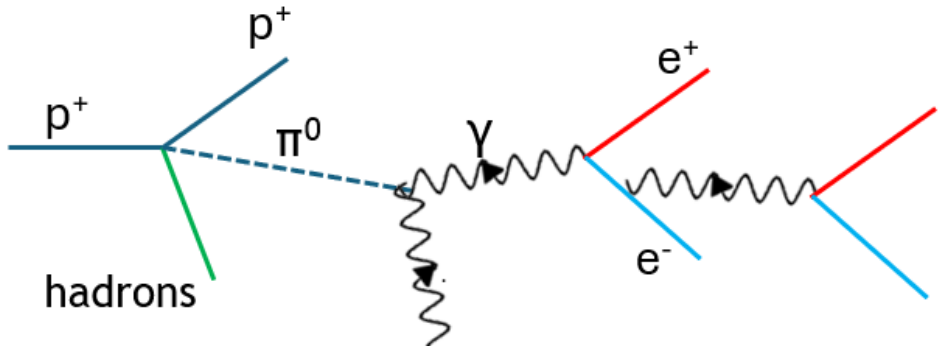
Fireball experiment at HiRadMat

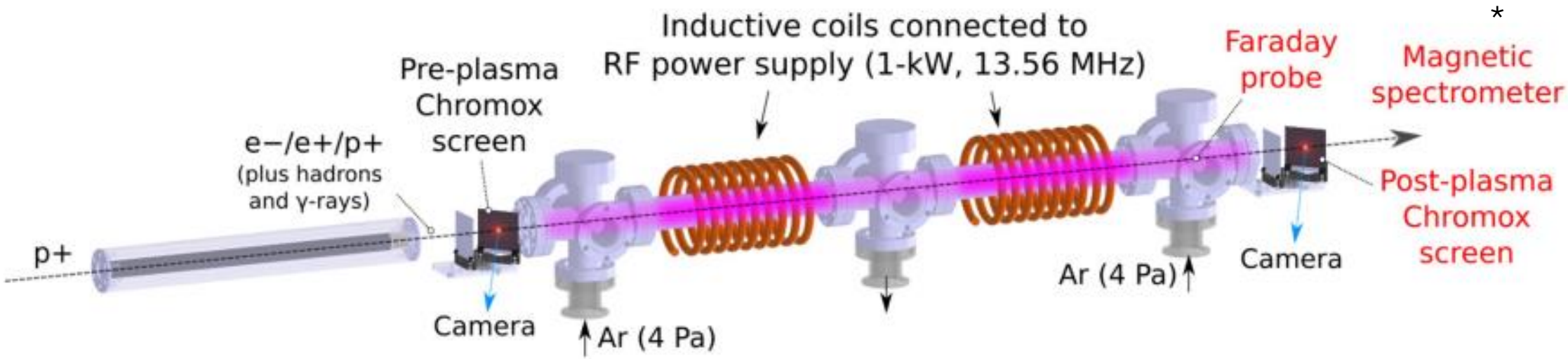
Beams and plasma generation

Beams: generated using a proton bunch through hadronization and induced electron-positron pair production (Bethe-Heitler process).

Plasma: glass tube is filled with argon gas, and copper coils are wrapped around the tube, generating strong electromagnetic fields and ionizing the gas.

Electron-positron pair production





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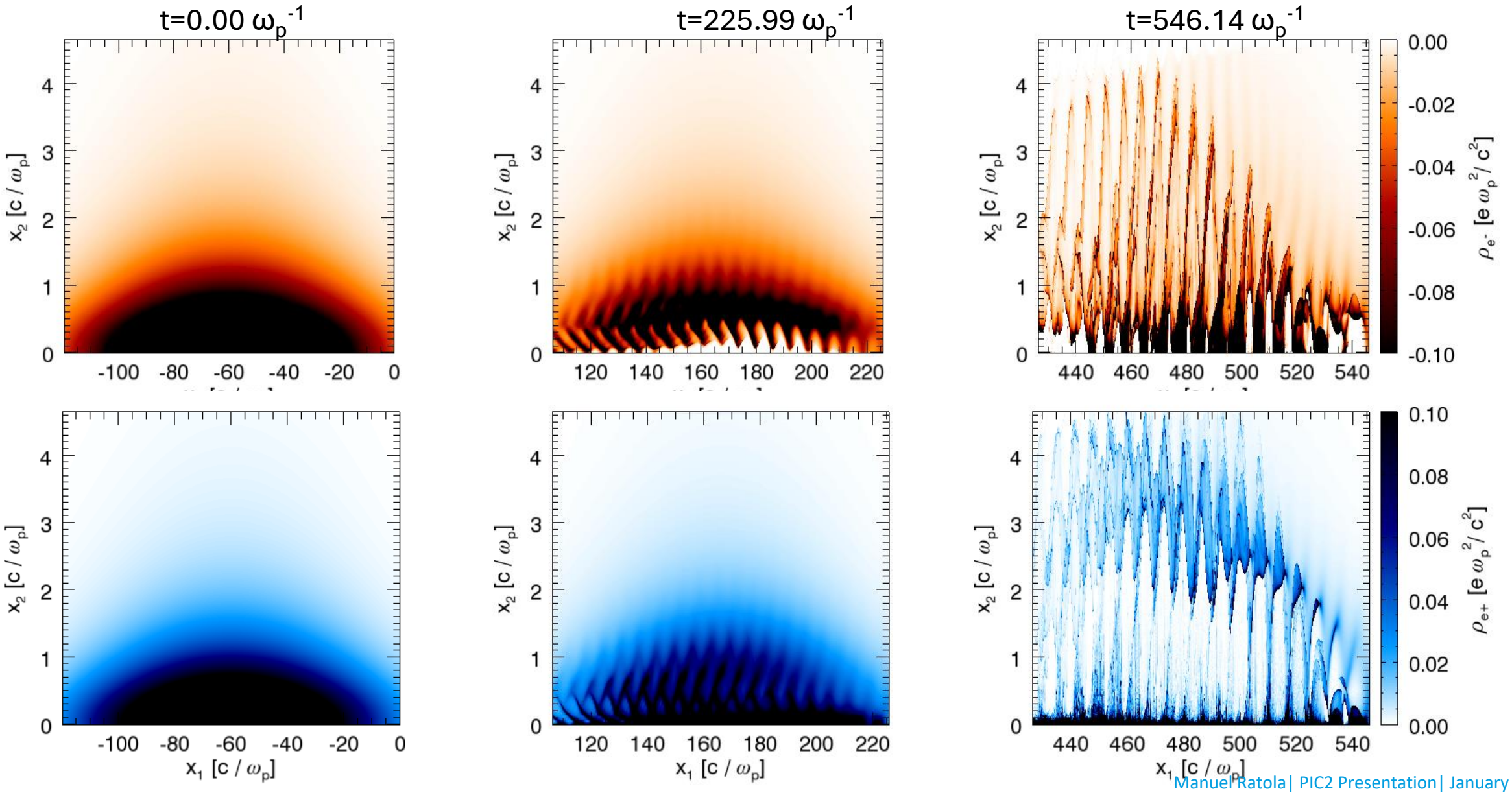
*Credits: Arrowsmith (2023)

Weibel (CFI) and Self-modulation instability in beam-plasma interaction



Conclusion and Future Work

Conclusion

- Introduced relevant plasma instabilities for the fireball experiment at HiRadMat in CERN, particularly the Weibel instability and self-modulation instability.
- Described the simulation setup relevant for the experiment, and presented some preliminary results

Future work

- Perform quasi-3D simulations with varying Fourier modes and different plasma and beam distributions, getting closer to the realistic experimental configuration.
- Analysis of the simulation data focusing on comparison with theory.
- Comparison with full 3D simulations, and identifying experimental signatures

Thank you for the attention

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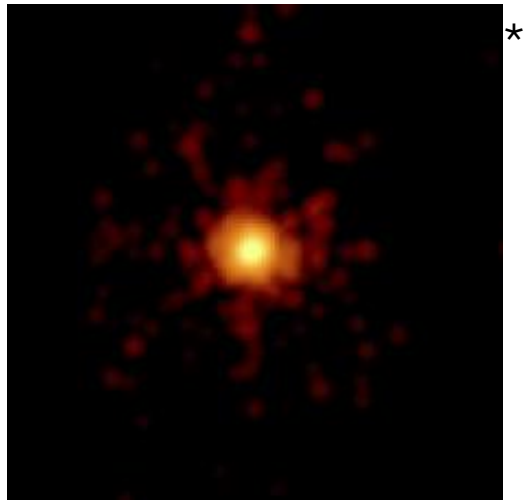
Motivation

Astrophysical scenarios are centered in the study of plasma physics. Some result in scenarios in which plasmas are out-of-equilibrium or in the presence of relativistic jets.

GRBs and Blazars are astrophysical events that emit intense gamma radiation via relativistic jets.

The Fireball model explains high-energy phenomena, where intense radiation is produced through plasma interactions and intense radiation is released in relativistic jets.

Laboratory experiments and simulations are being conducted, mimicking the dynamic of relativistic jets, using intense electron-positron beams interacting with a background plasma.



Exposure of GRB

* (Credit: NASA/Swift/Stefan Immler),

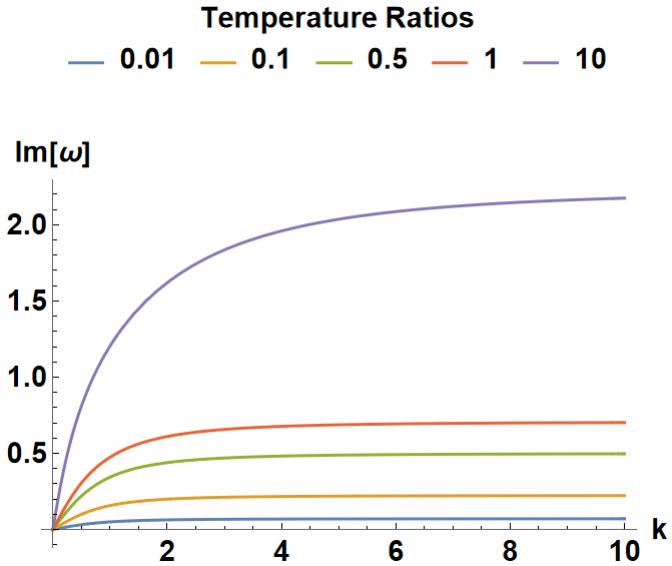
Anisotropic plasmas are unstable and generate current filaments

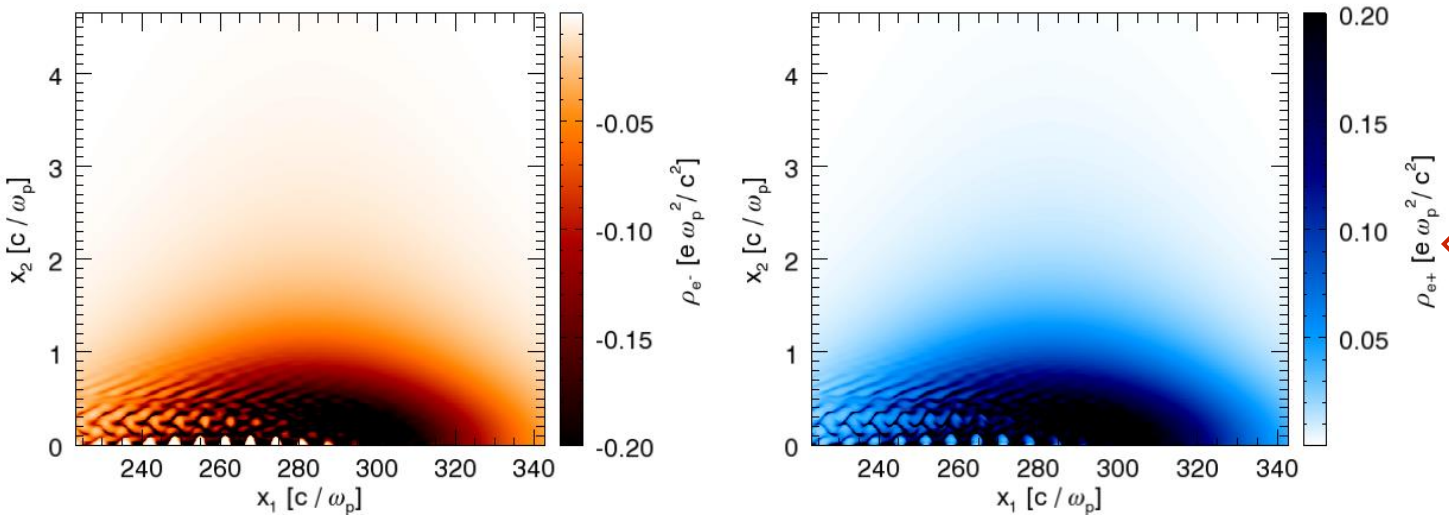
- Theoretical results allow to obtain the relationship between wave vector and the wave frequency of perturbations.

Relation dispersion : ω(k) (ω/k >>$v_{\parallel}$)

$$\omega = \pm\frac{1}{\sqrt{2}}\left(k^2c^2 + \omega_p^2 \pm \sqrt{(k^2c^2+\omega_p^2)^2 + 2w_p^2 v_{\parallel}^2 k^2 \frac{T_{\perp}}{T_{\parallel}}}\right)^{\frac{1}{2}}$$

Anisotropic plasmas can have imaginary solutions





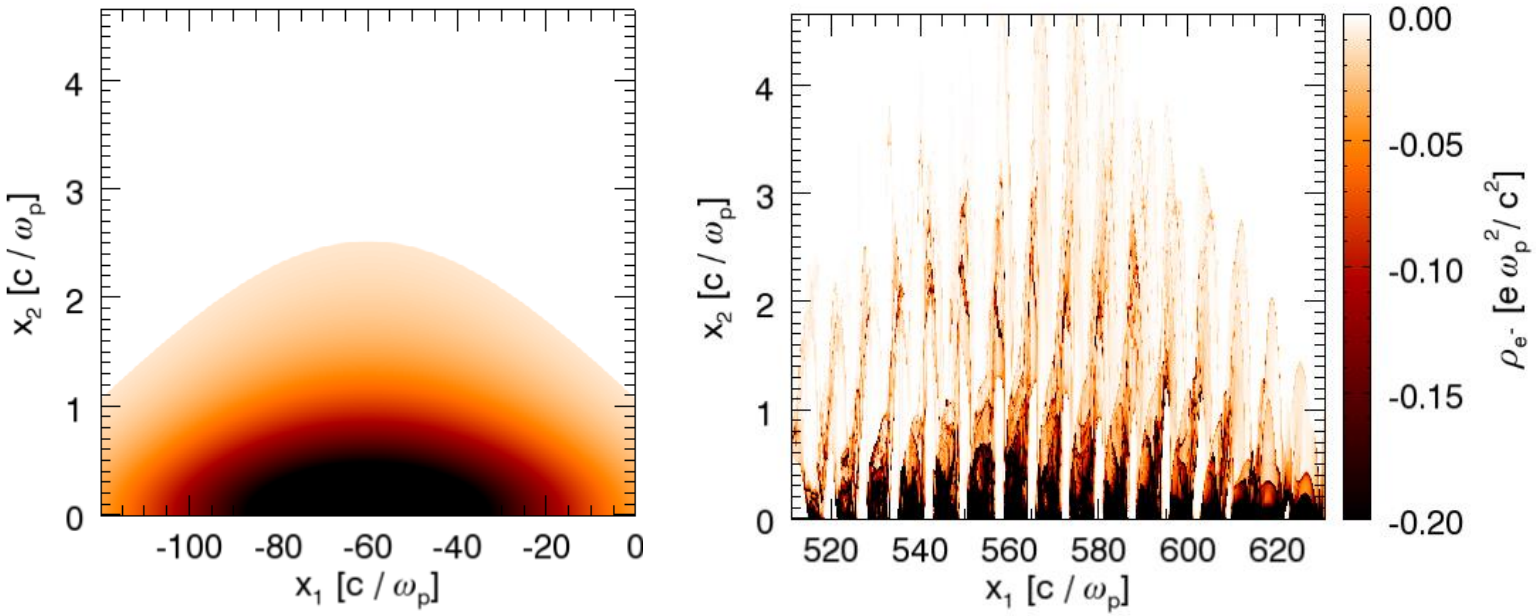
This instability also manifests in the propagation of fireball beams

Self-Modulation Instability of a beam propagating through a plasma

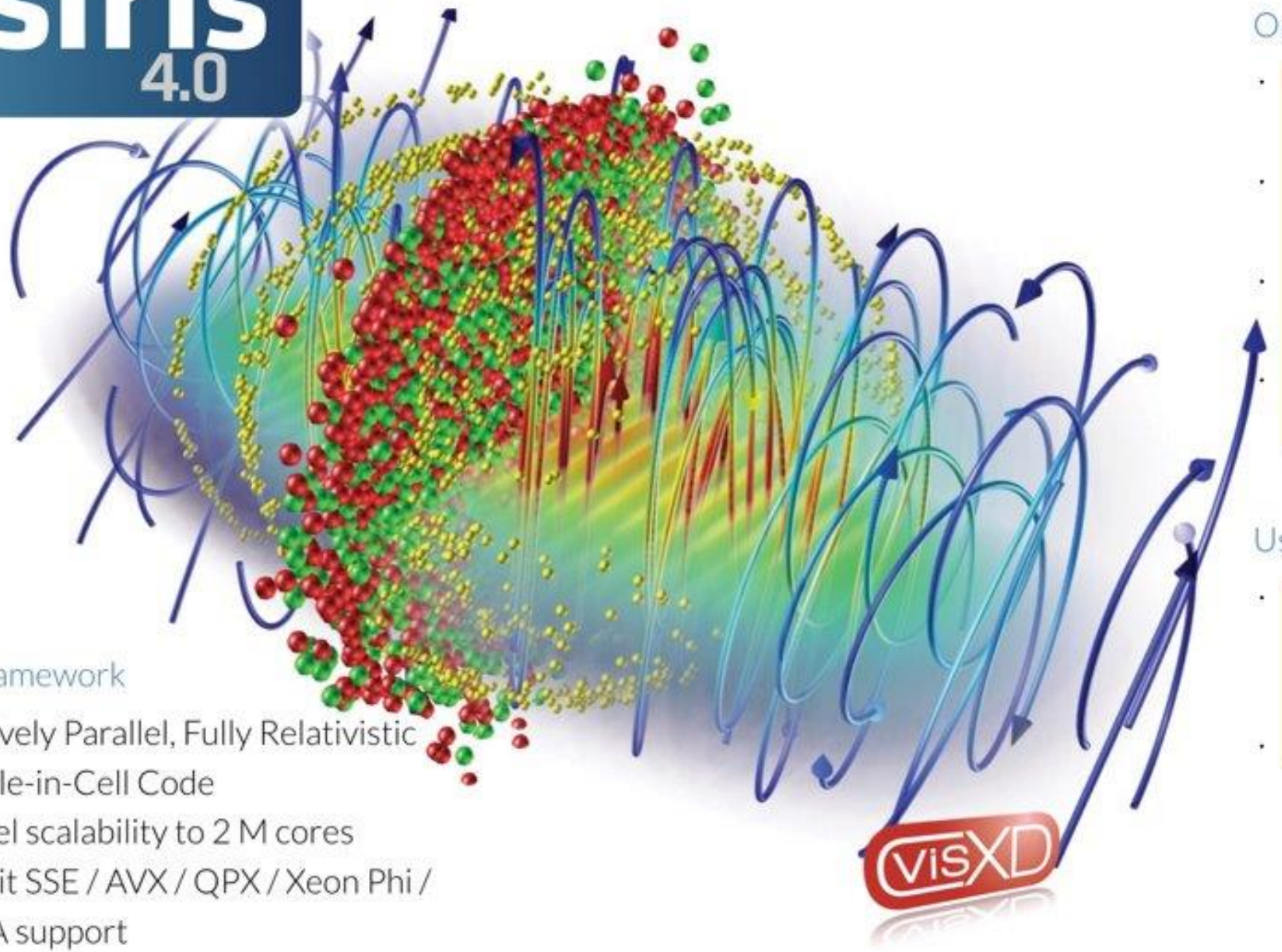
Self-Modulation Instability

Self-Modulation Instability arises from the interaction between charged particle beams, and a plasma transverse wakefield.

It is characterized by the formation of micro bunches in the beam profile.



Osiris 4.0



Committed to open science

Open-access model

- 40+ research groups worldwide are using OSIRIS
- 300+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at: **http://epp.tecnico.ulisboa.pt/osiris**

OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to 2 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / CUDA support
- Extended physics/simulation models

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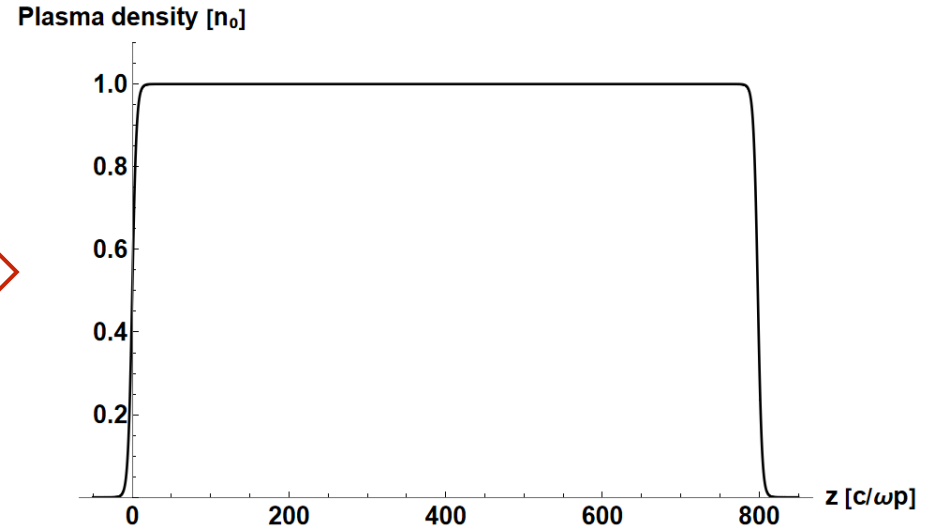
Simulation's beam and plasma initial profiles

Plasma initial profile

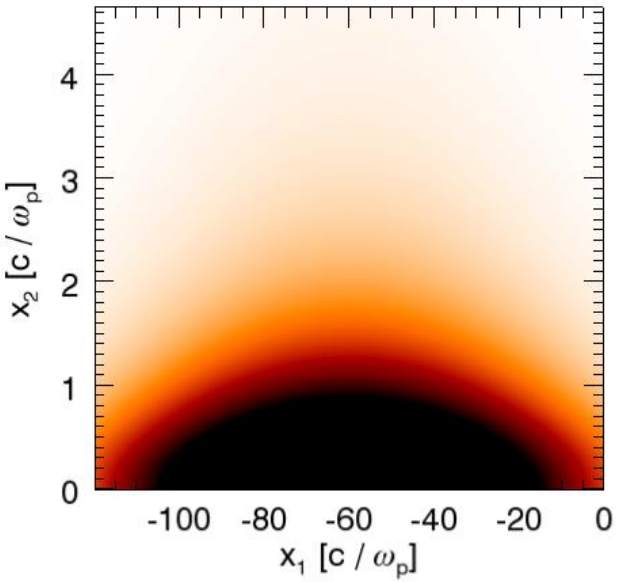
$$\frac{n_{\text{plasma}}(z)}{n_0} = \frac{1}{\left(1+\exp\left(-\frac{z}{2.7}\right)\right)\left(1+\exp\left(\frac{z-798.37}{2.7}\right)\right)}$$



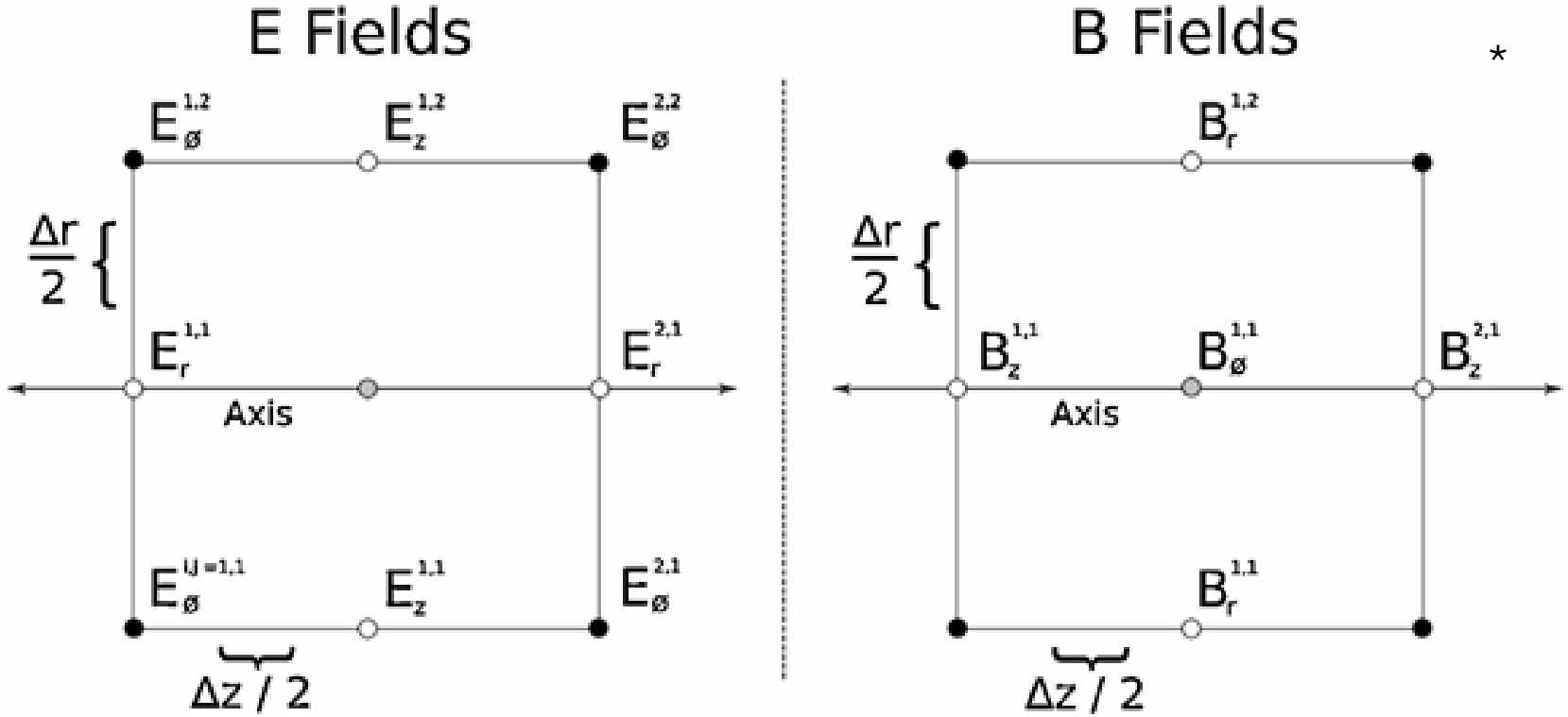
Beam initial profile

$$\frac{n_i}{n_0} = A_i \cdot \frac{l_i^3}{(r^2+l_i^2)^{3/2}} \cdot \exp\left(-\frac{(z+z_0)^2}{2\cdot\sigma^2}\right)$$

Parameter	Electrons	Positrons	Protons
A_i	0.302	0.235	0.15
l_i (c/ω_p)	0.8516	0.8516	0.2661
g (c/ω_p)	59.877	59.877	59.877
σ (c/ω_p)	29.94	29.94	29.94



Quasi-cylindrical OSIRIS PIC code



*Credits: A. Davidson (2015)

Simulations