Title: Nonlinear beam plasma simulations

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Abstract:

Beam plasma simulations in the non-linear regime

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Particle In Cell (PIC)

Kinetic evolution of collisionless plasma is governed by Vlasov-Maxwell equations

$$\partial_t f(\vec{x},\vec{u}) + \frac{\vec{u}}{\gamma}\cdot\partial_{\vec{x}} f(\vec{x},\vec{u}) + \frac{q}{m}\left[\vec{E} + \frac{\vec{u}}{\gamma}\times\vec{B}\right]\cdot\partial_{\vec{u}} f(\vec{x},\vec{u}) = 0$$

$$\begin{aligned} \nabla\cdot\vec{E} &= \rho(\vec{x},t)/\epsilon_0 \qquad & \nabla\times\vec{E} &= -\partial_t\vec{B} \\ \nabla\cdot\vec{B} &= 0 & \nabla\times\vec{B} &= \partial_t\vec{E}/c^2 + \vec{J}(\vec{x},t)/\epsilon_0 \end{aligned}$$

Scales of the problem

Problem:

Evolution of very diluted relativistic beam passing through ionized background

Typical TeV-Blazars parameter:

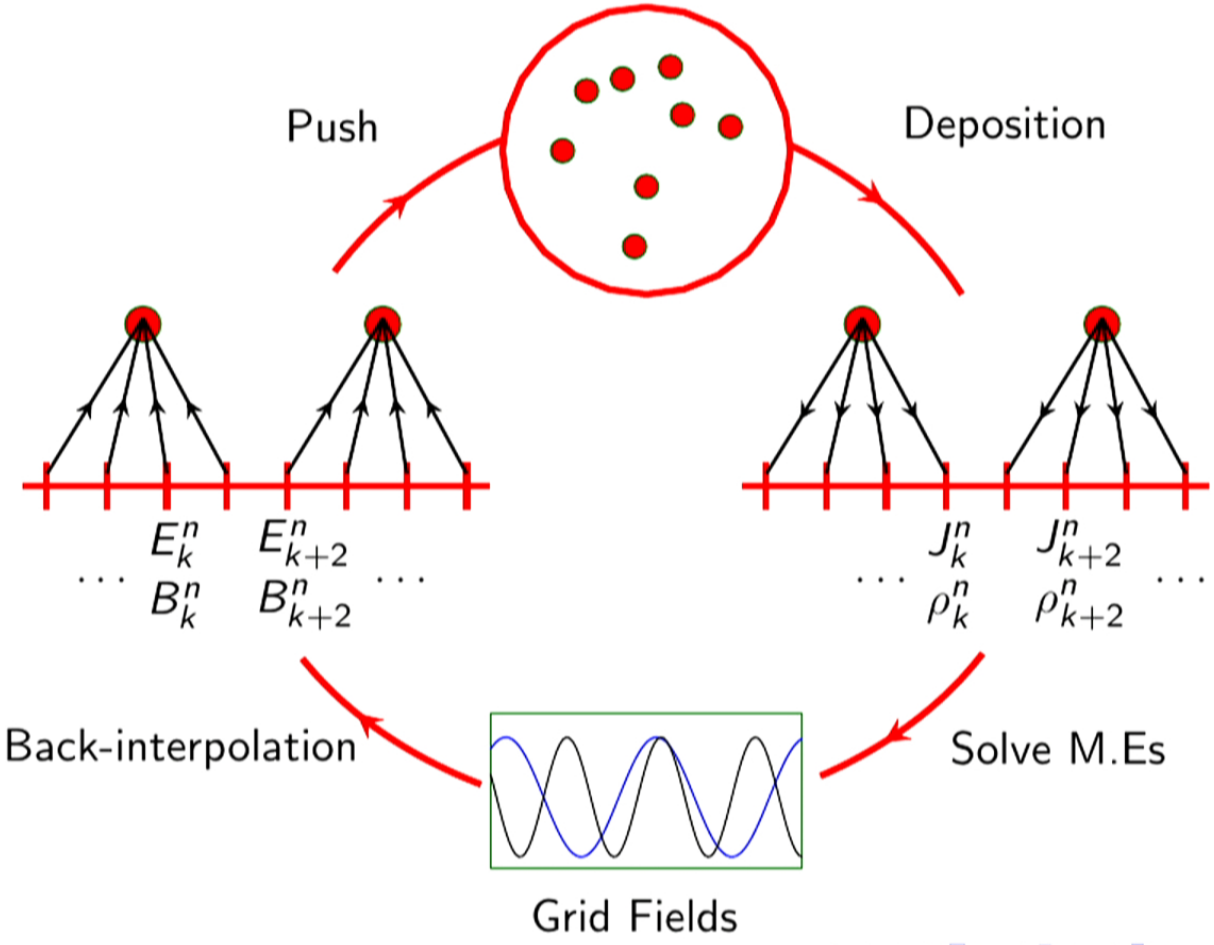
$$\gamma_b \sim 10^6 - 10^7 \quad \& \quad \alpha \equiv n_b/n_{\mathrm{IGM}} = 10^{-15} - 10^{-17}$$

Two very different scales:

$$\frac{k_b}{k_g} = \alpha\gamma_b \sim 10^{-9}$$

Linear (reactive) regime: $\Gamma_m \sim 10^{-10}\omega_g$

Particle In Cell (PIC)



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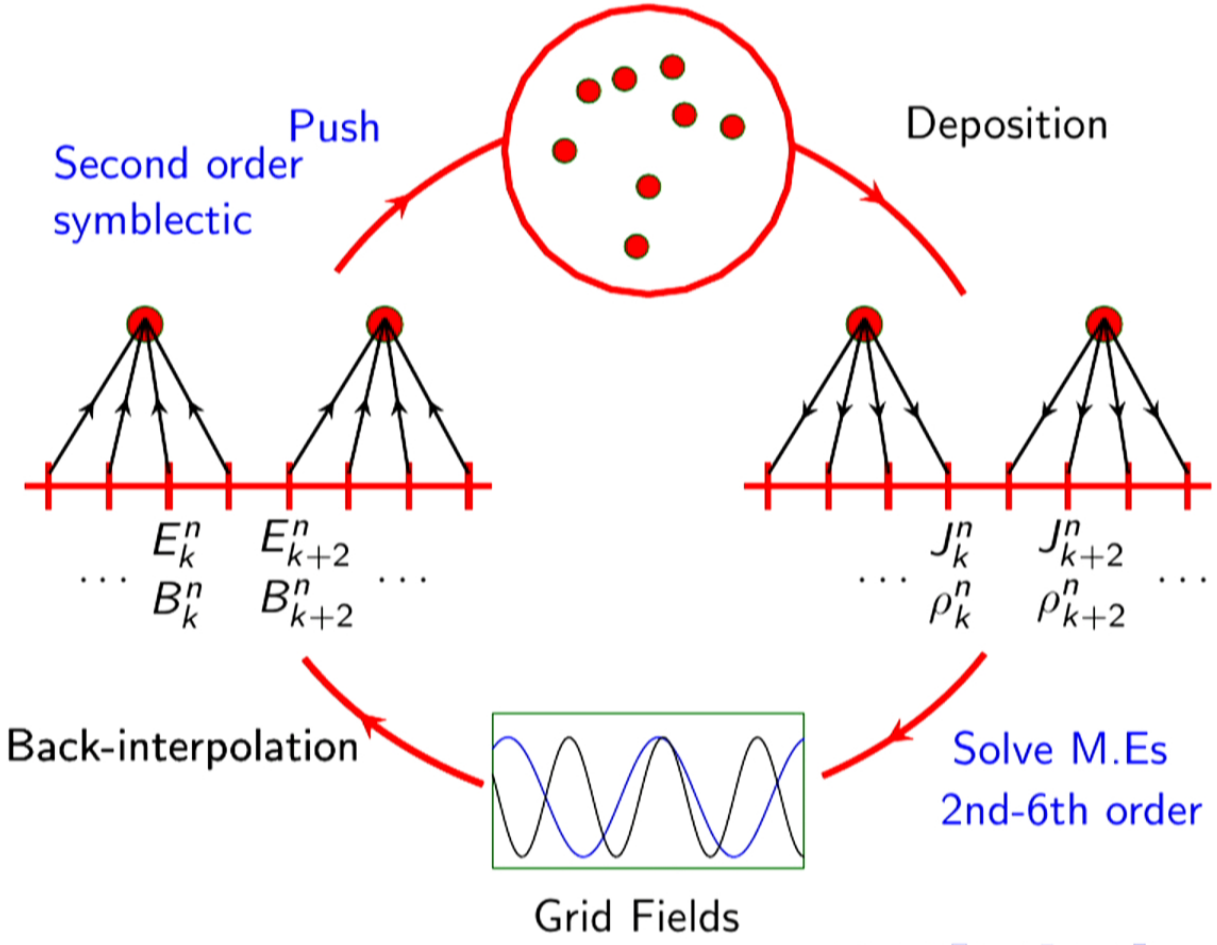

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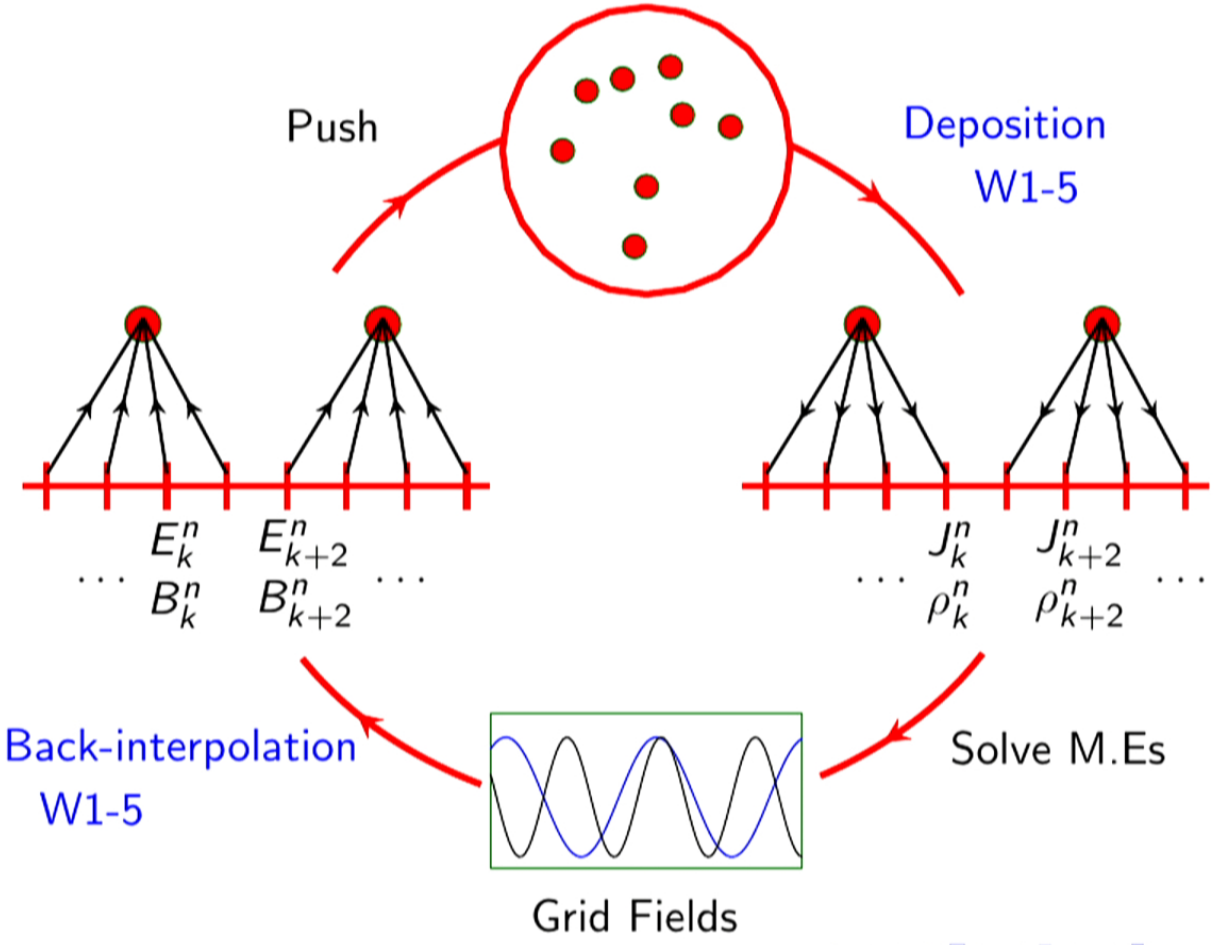
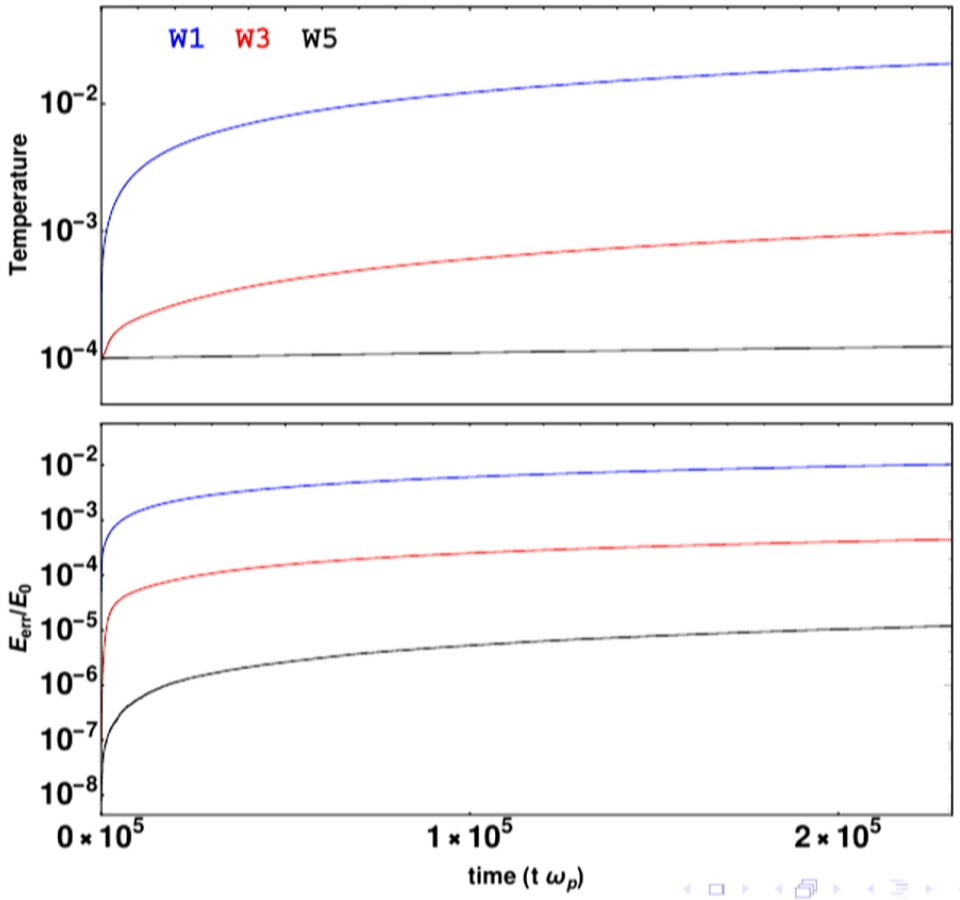


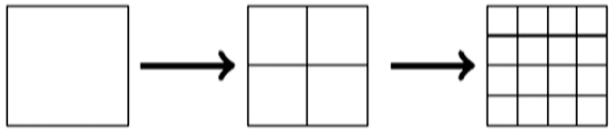
Why higher order

Numerical heating of plasma



Plasma simulation: Resolution

- Spatial resolution



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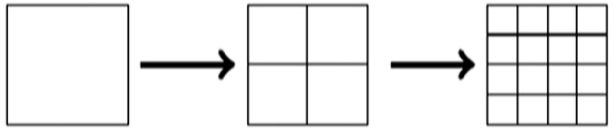
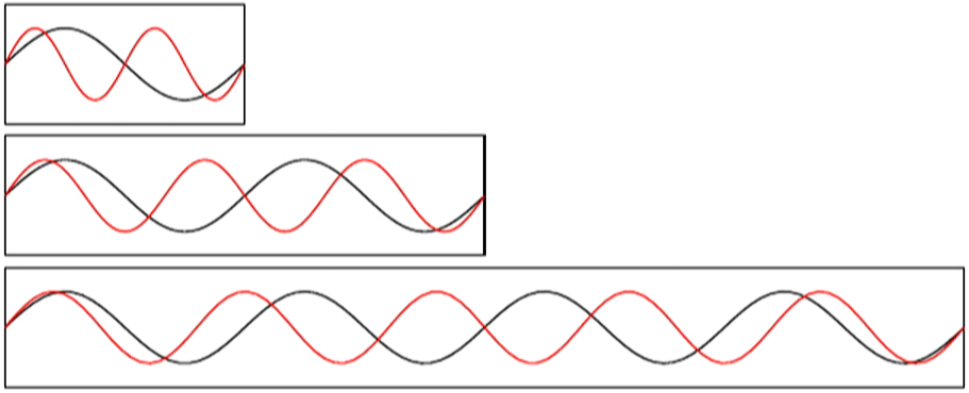


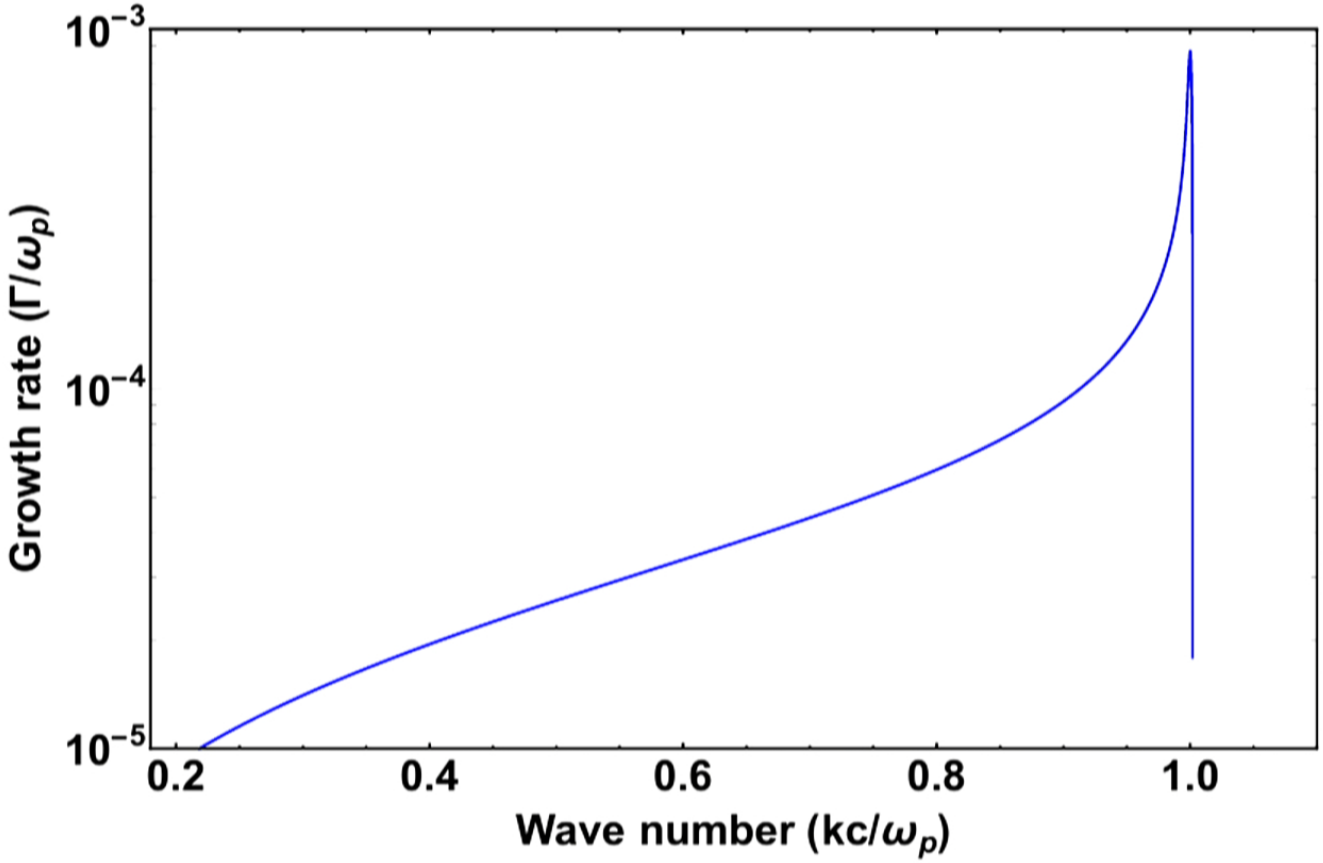
- Momentum resolution

Plasma simulation: Resolution

- **Spectral resolution**:



Plasma simulation: Resolution



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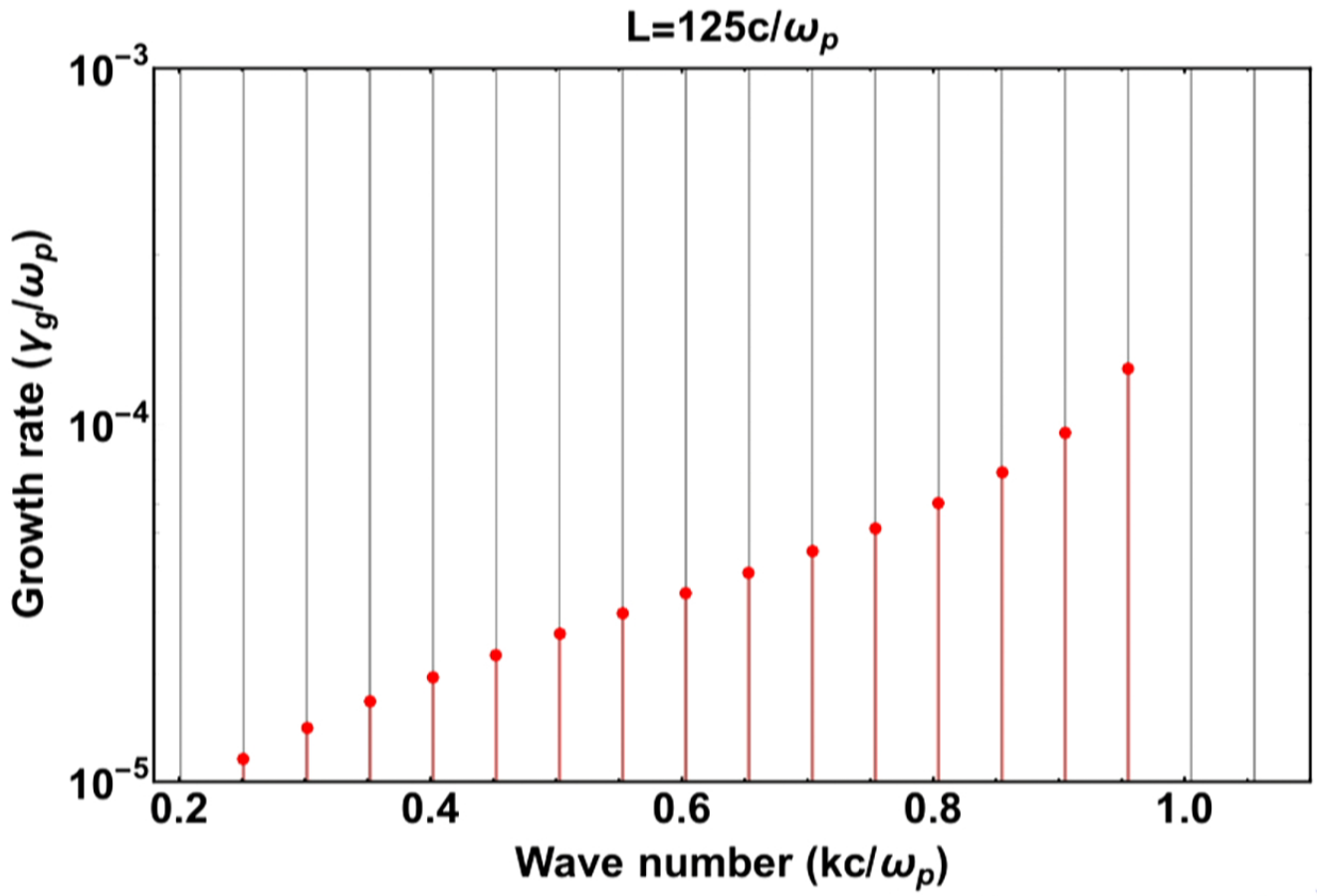

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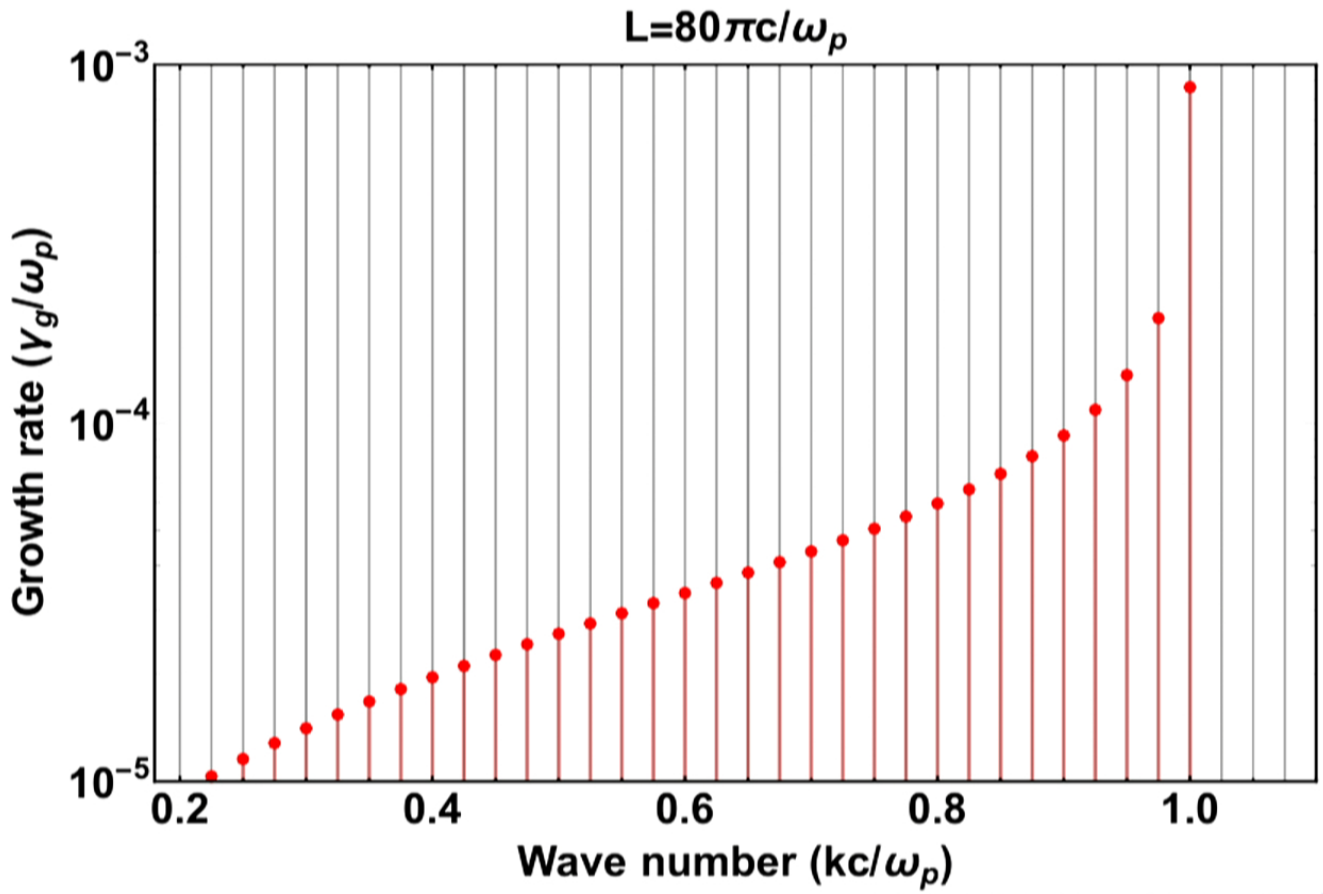
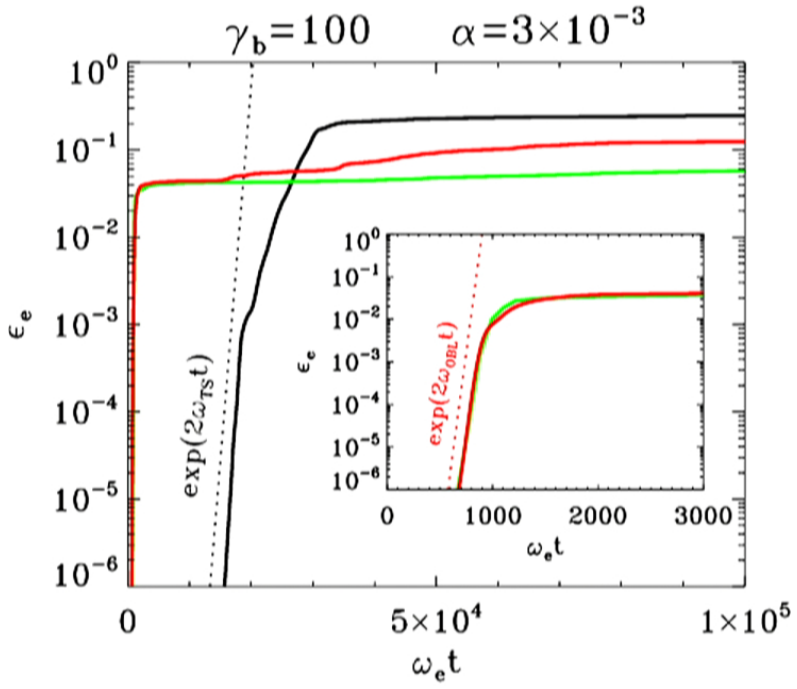


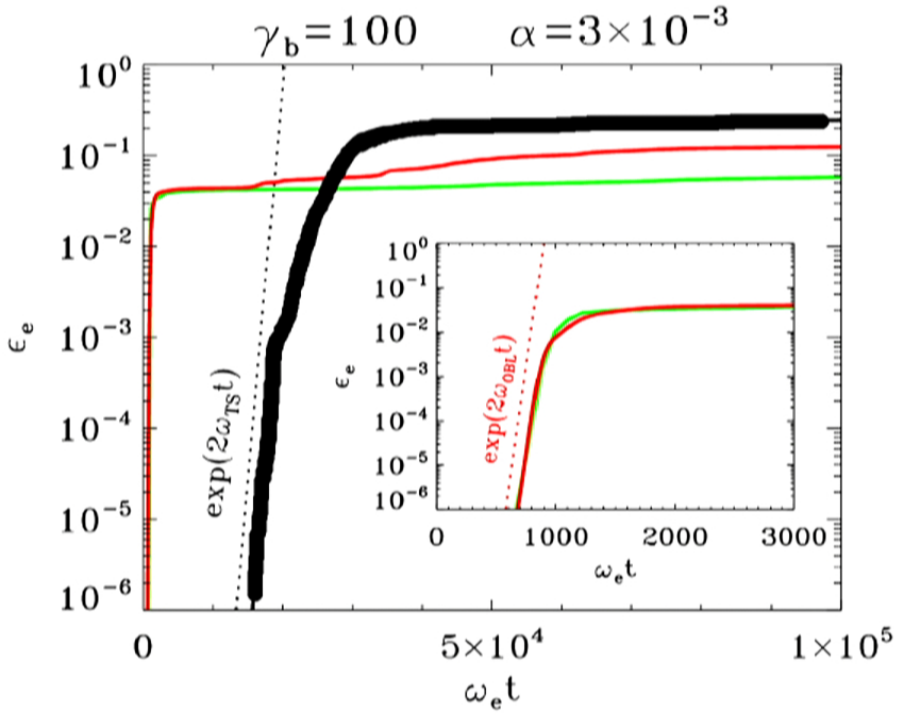
Homogeneous Background Plasma

Non-linear regime



1D: Black & green and 2D: Red. Sironi & Giannos (2013)

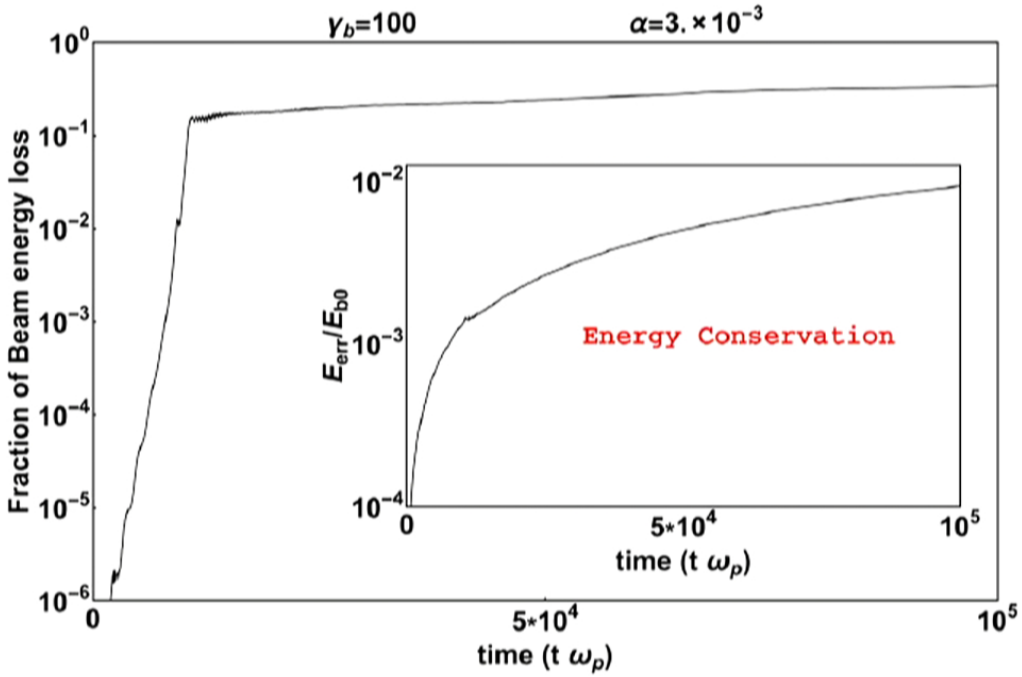
Non-linear regime



Sironi & Giannos (2013)

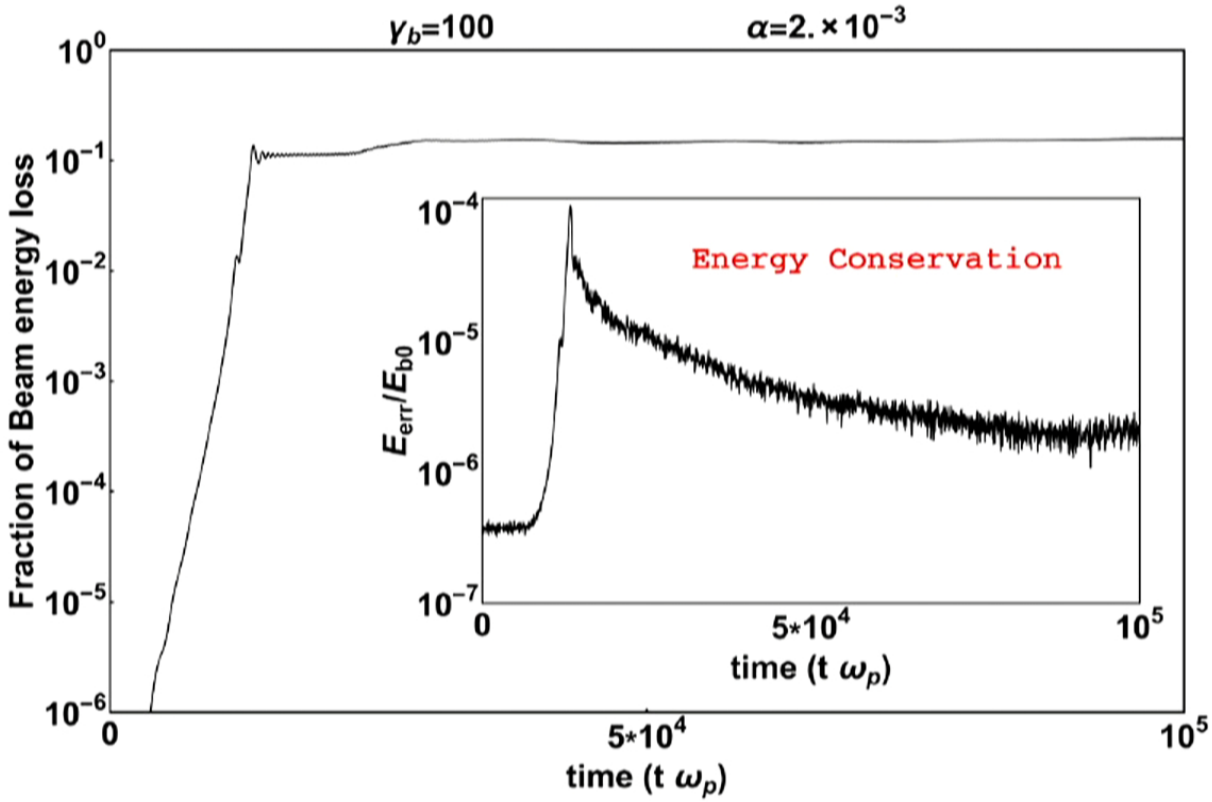
Non-linear regime

Using similar algorithm (first order interpolation):
Maximum Energy error is about 10^{-2} of initial Beam energy & secular fast energy error increase



Non-linear regime

5th-order: Maximum Energy error is about 10^{-4} of initial Beam energy & secular but much slower energy error increase.



Shalaby et al. (in prep.)

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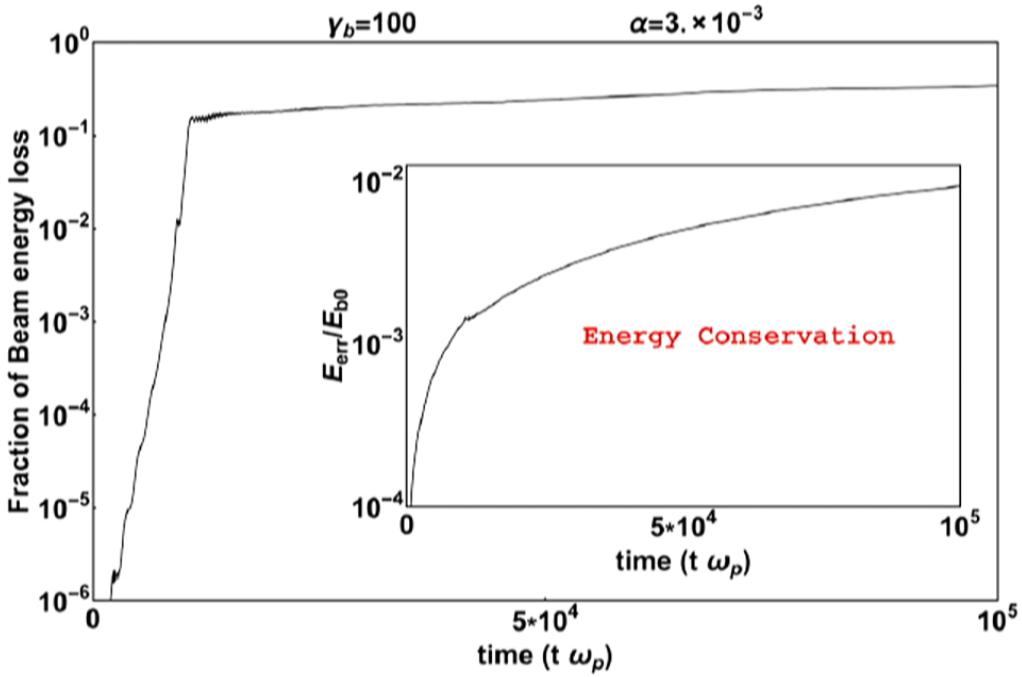

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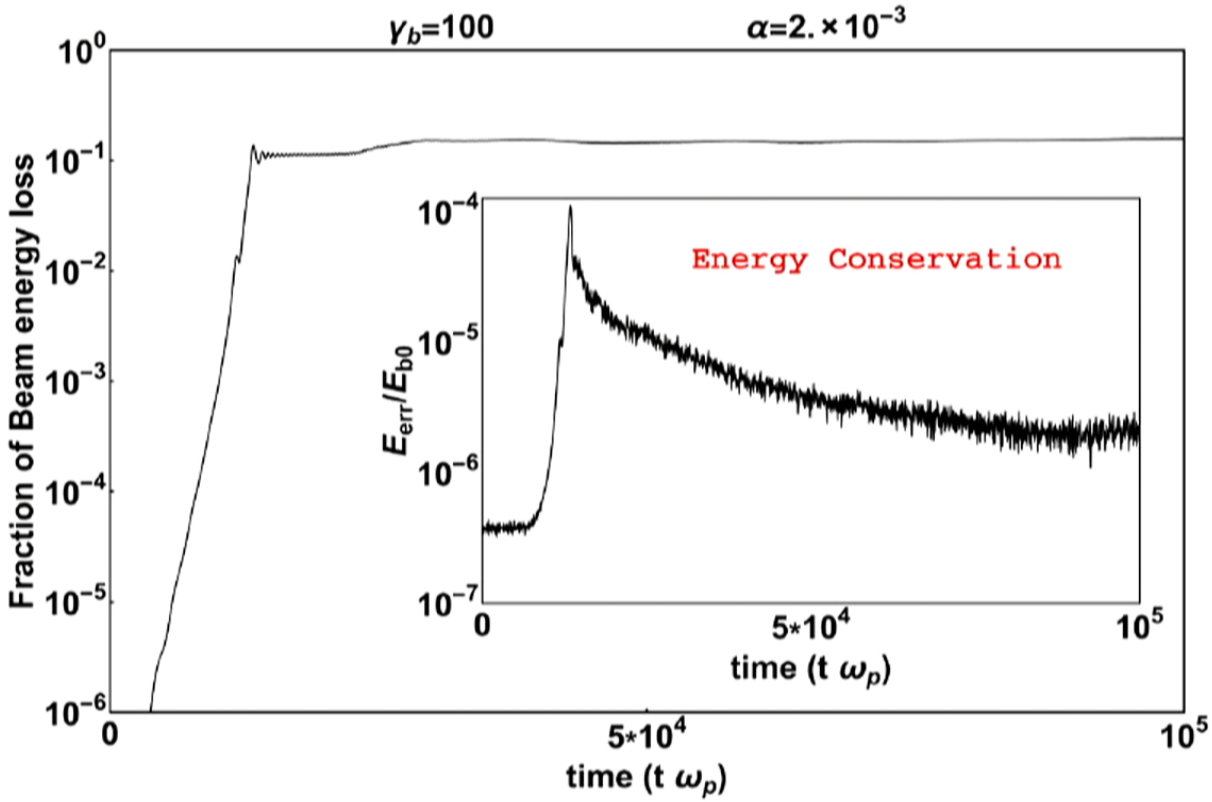

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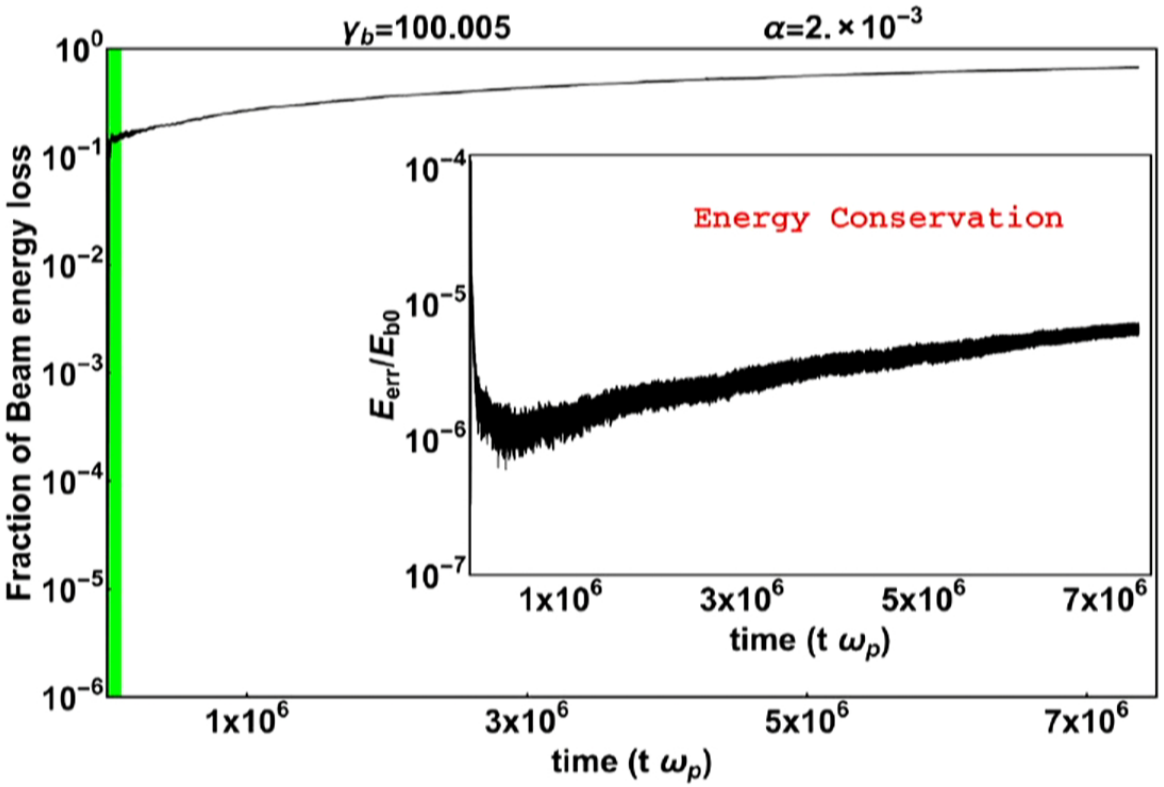

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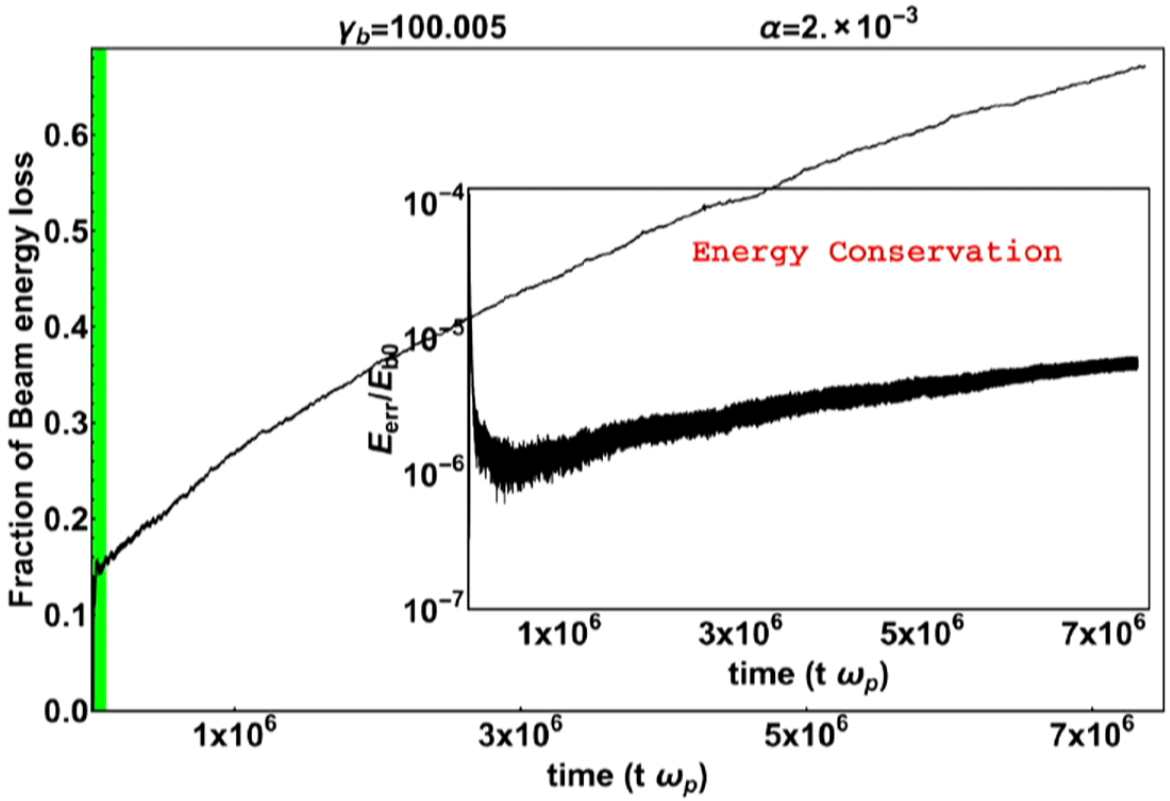

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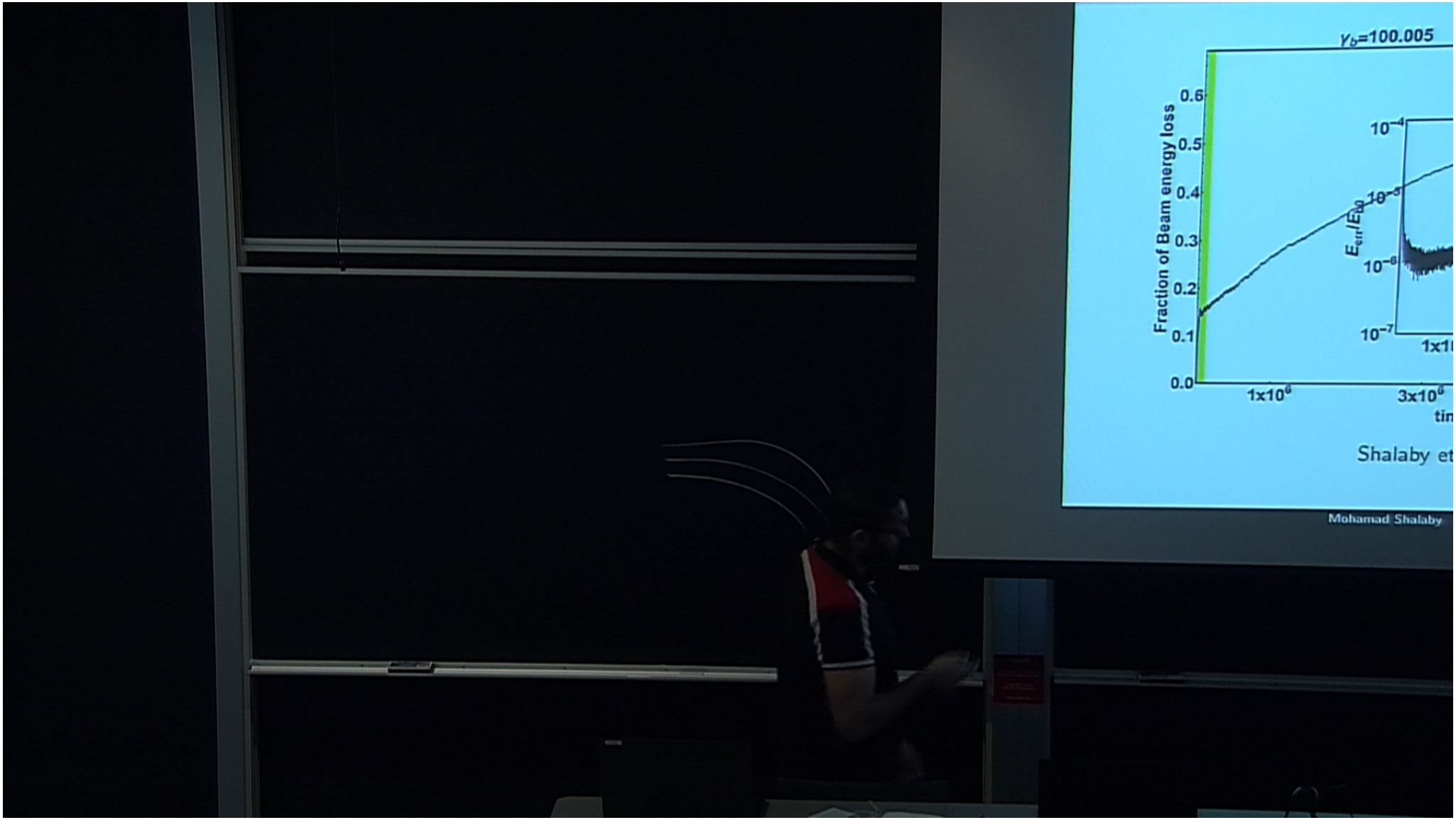
γ_b=100.005
Fraction of Beam energy loss
0.0
0.1
0.2
0.3
0.4
0.5
0.6
1x10^6
3x10^6
E_{err}/E_{b0}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
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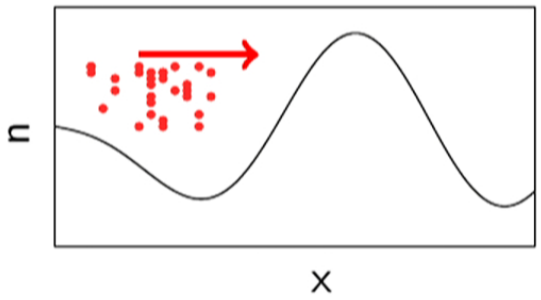
Inhomogeneous Background Plasma

Background inhomogeneity effects



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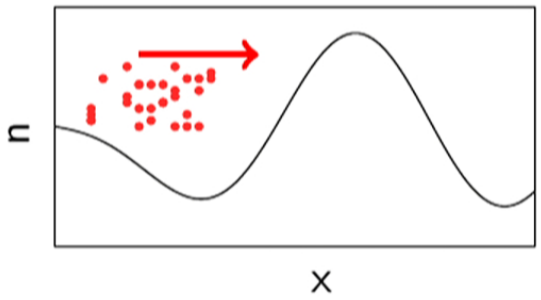

A condition for linear growth to occurs is [Miniati & Elyiv (2013)]

$$\frac{\text{few}}{\Gamma_m} < \frac{\Delta k_{\|}}{|dk/dt|} \xrightarrow[\text{modes (1D)}]{\text{electrostatic}} \frac{\gamma_b}{\alpha}\frac{c\lambda_{\|}}{\omega_p} < 1$$

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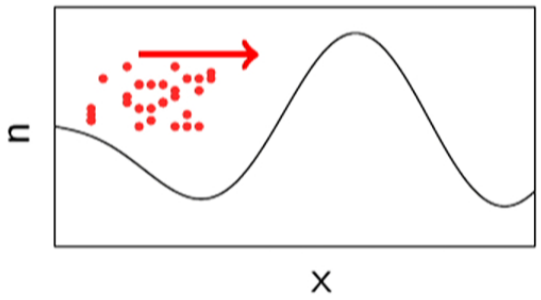

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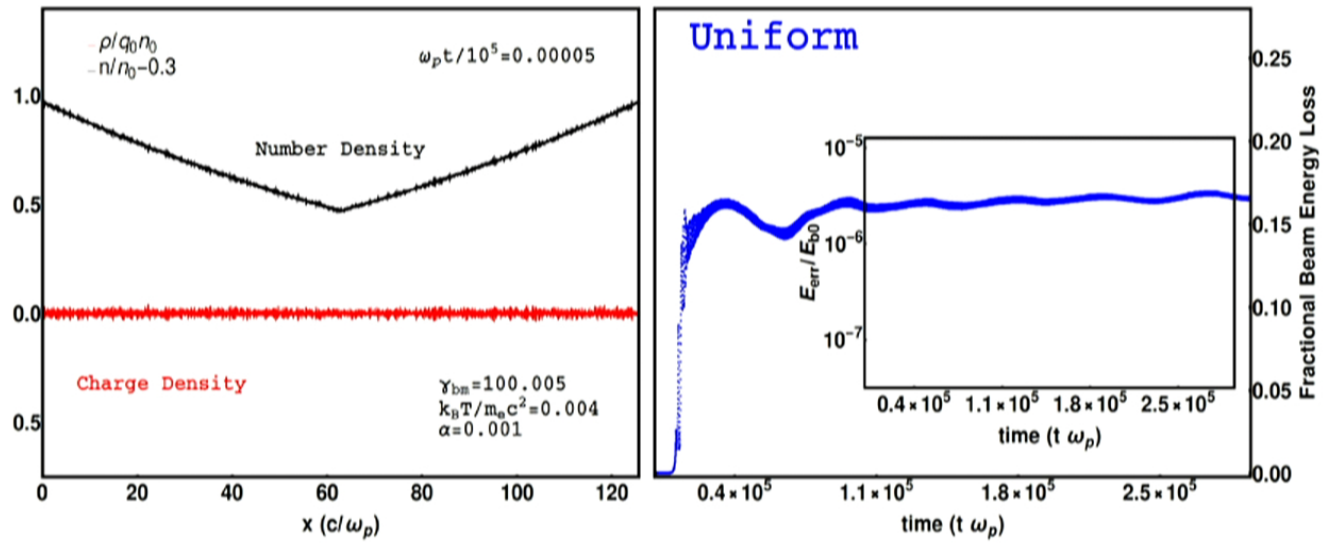
Background inhomogeneity effects

Condition $(\gamma_b/\alpha)\,(c\lambda_\parallel/\omega_p) < 1$

Simulation $(\gamma_b/\alpha)\,(c\lambda_\parallel/\omega_p) \sim 10^7$



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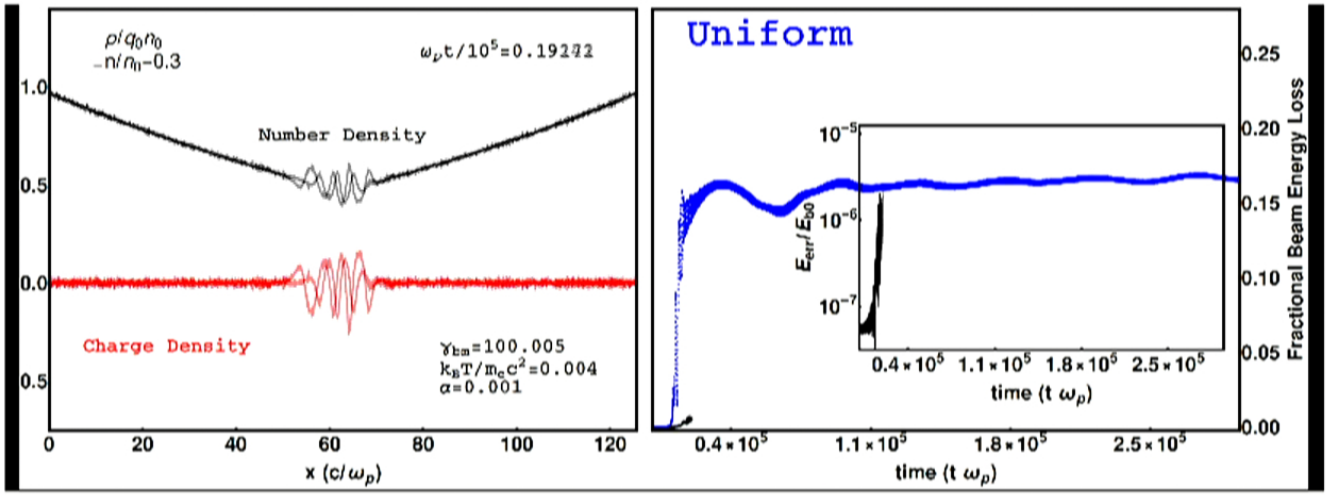

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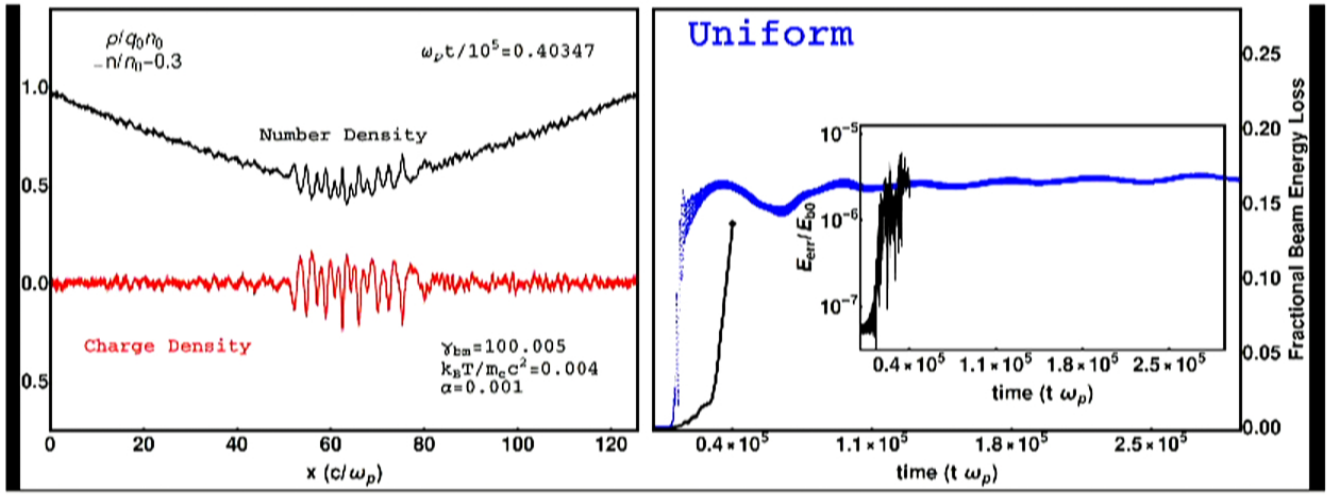

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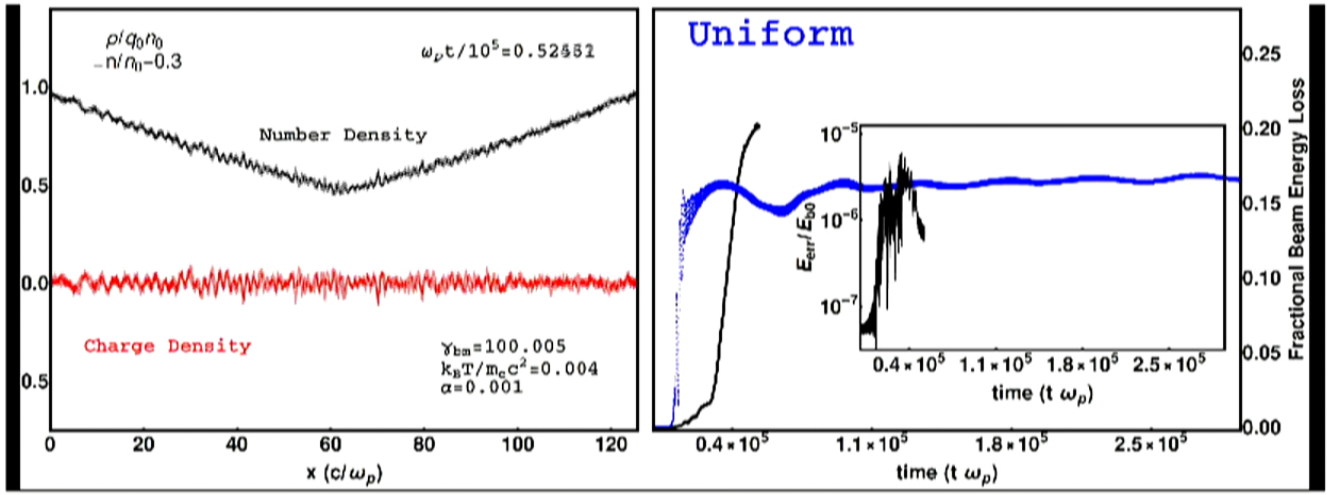
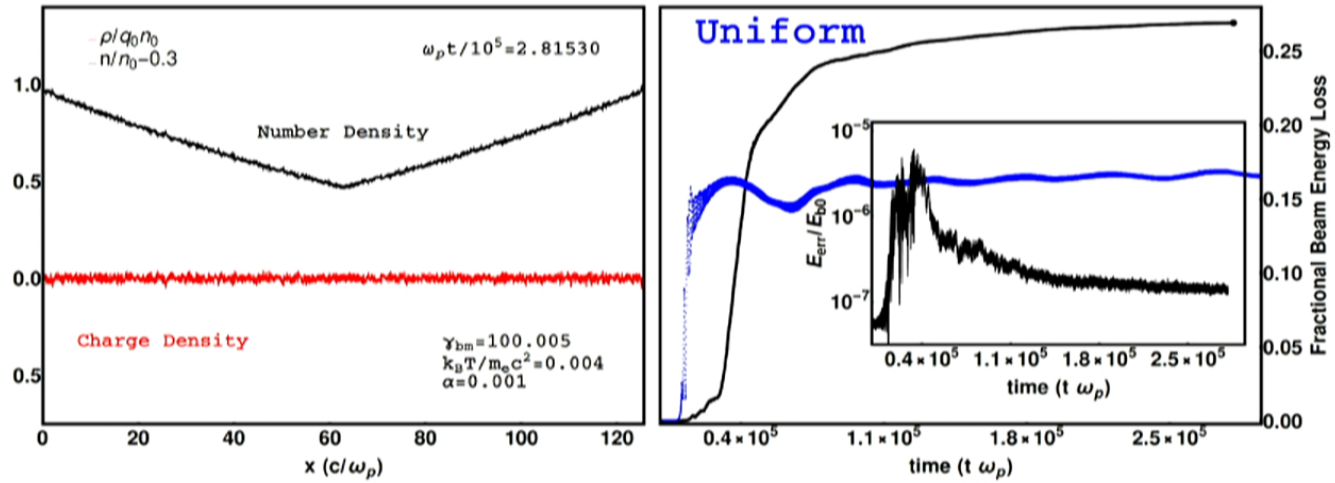


Background inhomogeneity effects

Linear waves grow, lower growth rate, more energy lost by the beam



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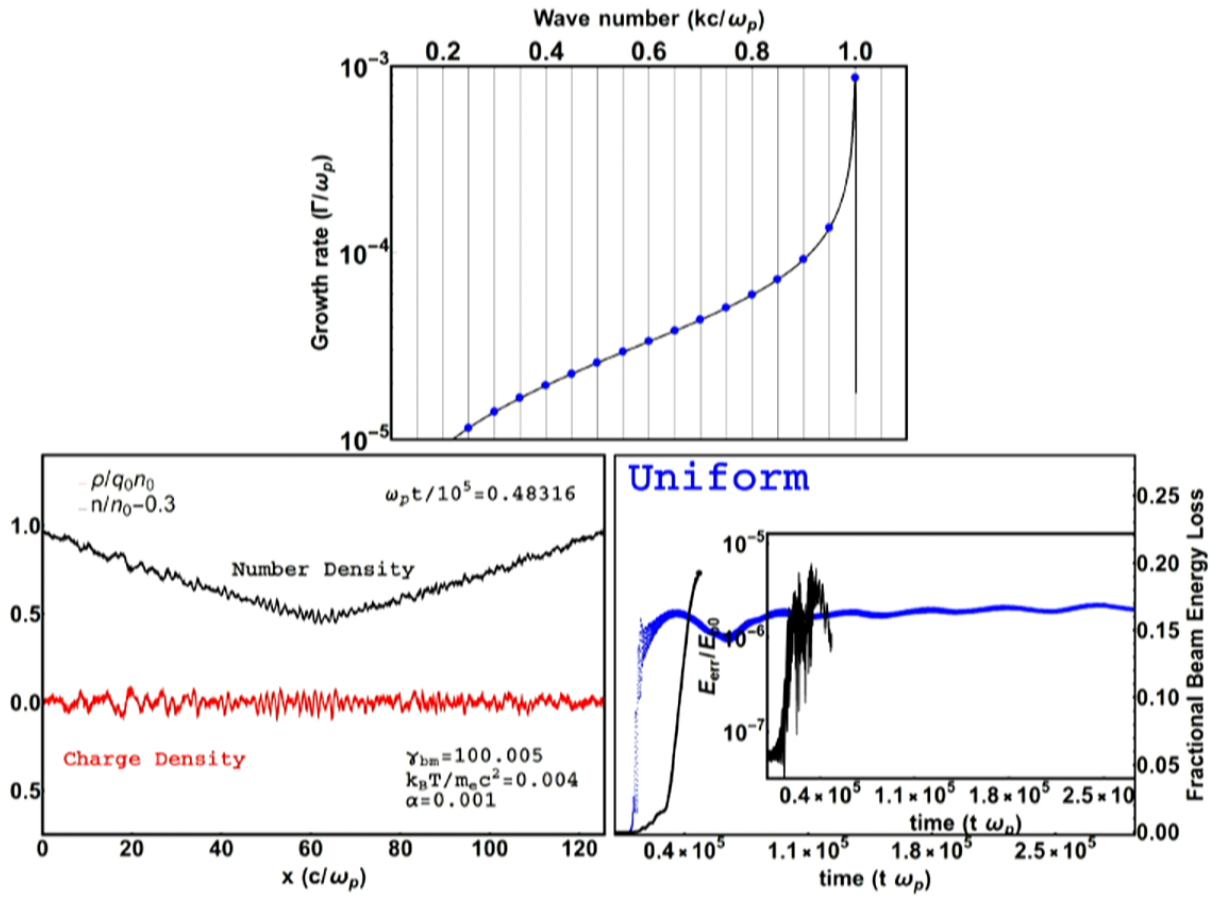

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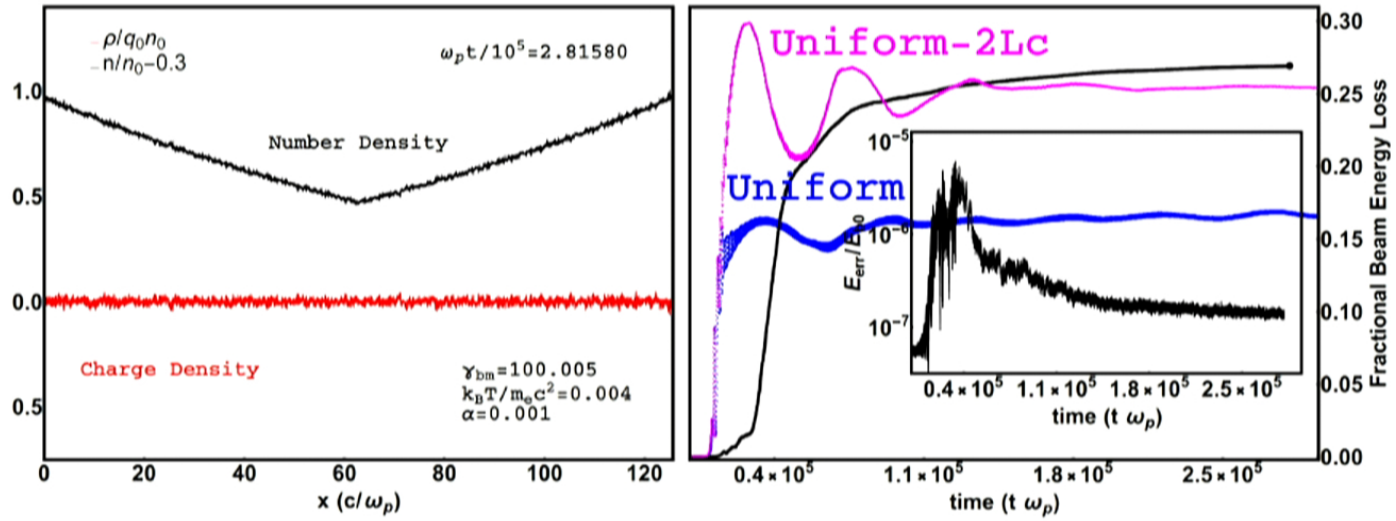

Summary

- Uncontrolled numerics can hinder the ability to study non-linear regime.
- Higher order in 1D: Beam lost O(1) to uniform background
- Background inhomogeneity lowers the linear growth rate but the beam exit the linear regime around the same level.