PhD Open Days

On the growth rates of bulk and surface modes in an e^-e^+ beam

X-Maser PhD programme

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Motivation

- Intense laser and particle beams can generate **relativistic electron– positron beams with densities approaching quasi-neutrality** [1].
- These beams offer a platform to investigate the interaction of pair beams with background plasmas, as relevant to astrophysical environments, and determine the nature of the modes.
- **Recently, laboratory-based proton beam has led to generate high number of electron-positron pairs at HiRadMat experiment, CERN** [2].
- We use the OSIRIS 4.0 Particle-In-Cell Code for simulations [3].
- The **density of background plasma and beam equal. The density profile is** $\eta = \eta_0[1 - \Theta(r - r_b)]$ [4].
- We consider fluid treatment, for perturbed field $E = E_x\hat{i} + E_z\hat{k}$. Parameters are normalized to ω_p.
- The thermal spread of the beam is neglected, i.e **cold-beam regime.**

Setup

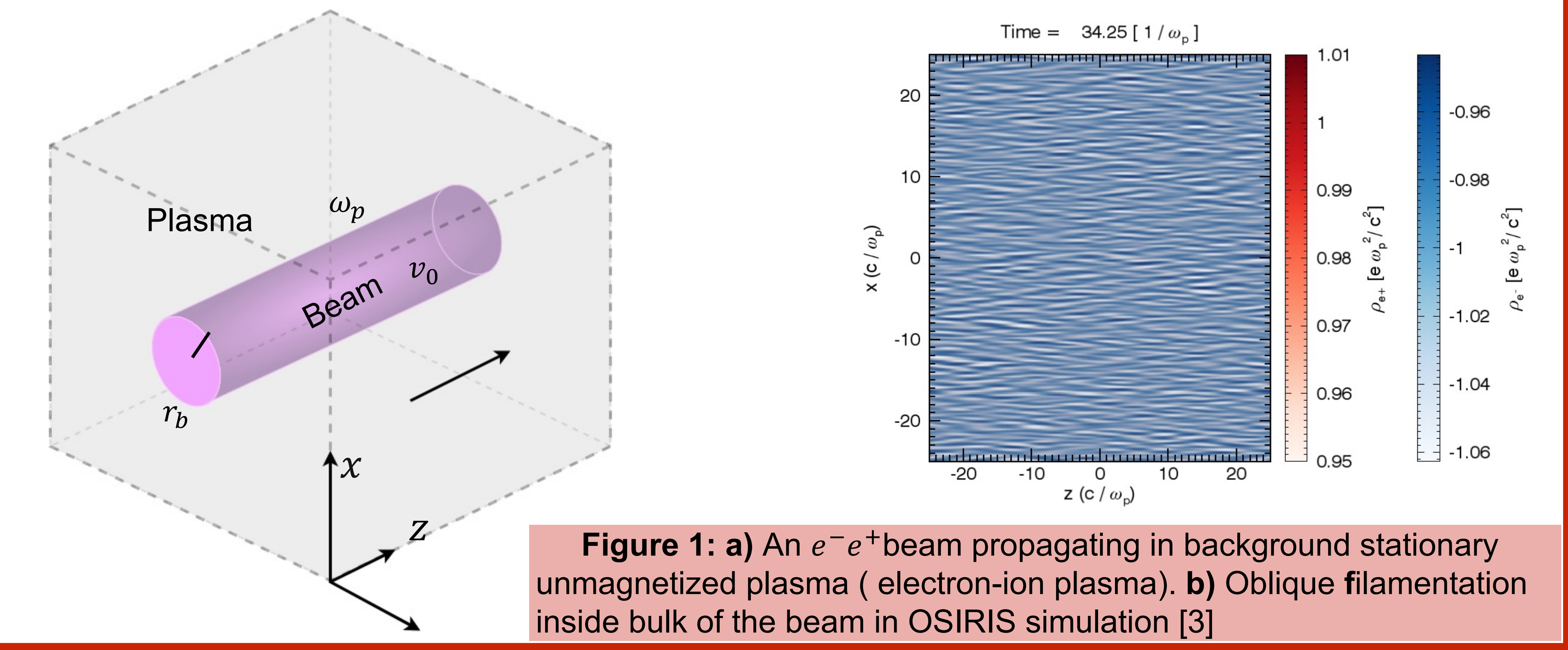

Figure 1: a) An e^-e^+beam propagating in background stationary unmagnetized plasma (electron-ion plasma). **b)** Oblique **filamentation** inside bulk of the beam in OSIRIS simulation [3]

Bulk Oblique Modes

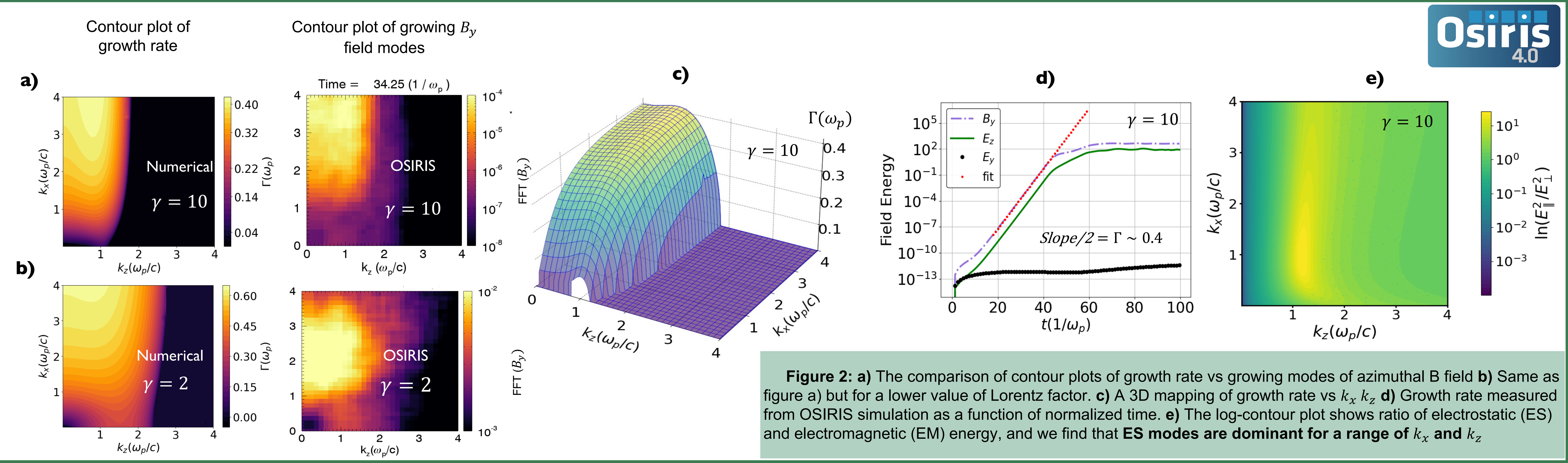

Figure 2: a) The comparison of contour plots of growth rate vs growing modes of azimuthal B field **b)** Same as figure a) but for a lower value of Lorentz factor. **c)** A 3D mapping of growth rate vs k_x k_z **d)** Growth rate measured from OSIRIS simulation as a function of normalized time. **e)** The log-contour plot shows ratio of electrostatic (ES) and electromagnetic (EM) energy, and we find that **ES modes are dominant for a range of** k_x **and** k_z

Surface Oblique Modes

Due to **beam's sharp profile,** the fields obey certain **boundary conditions**, which depend on the **cylindrical parameters . Region 1 = Beam, region 2 = plasma.**

Boundary condition found for oblique incidence

$$\frac{\partial E_{z2}}{\partial r} - \left(1 - \frac{\omega_{b\perp}^2 v_0}{k_z \Delta c^2}\right)\frac{\partial E_{z1}}{\partial r} = \frac{-i\omega_{b\perp}^2}{c^2 k_z} E_{r1}$$

The dispersion relation at the surface

$$I_0(k_1 r_b) + (1 - S)\left(1 - \frac{\omega_{b\perp}^2}{c^2 k_{R1}^2}\right)\frac{k_1 I_1(k_1 r_b)}{k_2 K_1(k_2 r_b)} K_0(k_2 r_b) = 0$$

$$\text{where}, S = \frac{\omega_{b\perp}^2 v_0}{k_z \Delta c^2}$$

Expressions of the parameters in the dispersion relation

$$A = ik_z - \frac{iv_0\omega_{b\perp}^2}{c^2\Delta} \qquad \Delta = \omega - v_0 k_z$$

$$k_R^2 = \frac{k_z^2 c^2 + \omega_p^2 + \omega_{b\perp}^2 - \omega^2}{c^2} \qquad \omega_{b\parallel}^2 = \frac{q^2 n_0}{m\epsilon_0\gamma_0^3}$$

$$k_Z^2 = \frac{\omega_p^2 + \omega_{b\parallel}^2\omega^2/\Delta^2 - \omega^2}{c^2} \qquad \omega_{b\perp}^2 = \frac{q^2 n_0}{m\epsilon_0\gamma_0}$$

$$k^2 = k_Z^2/AC$$

$$C = -\left(\frac{A}{k_R^2} + \frac{iv_0}{\Delta}\right) \qquad \omega_p^2 = \frac{q^2 n_0}{m\epsilon_0}$$

At $r_b \gg \sigma$, the dispersion relation is

$$1 + (1 - S)\left(1 - \frac{\omega_{b\perp}^2}{c^2 k_{R1}^2}\right)\frac{k_1}{k_2}\left(1 - \frac{1}{2k_1 r_b} - \frac{1}{2k_2 r_b}\right) = 0$$

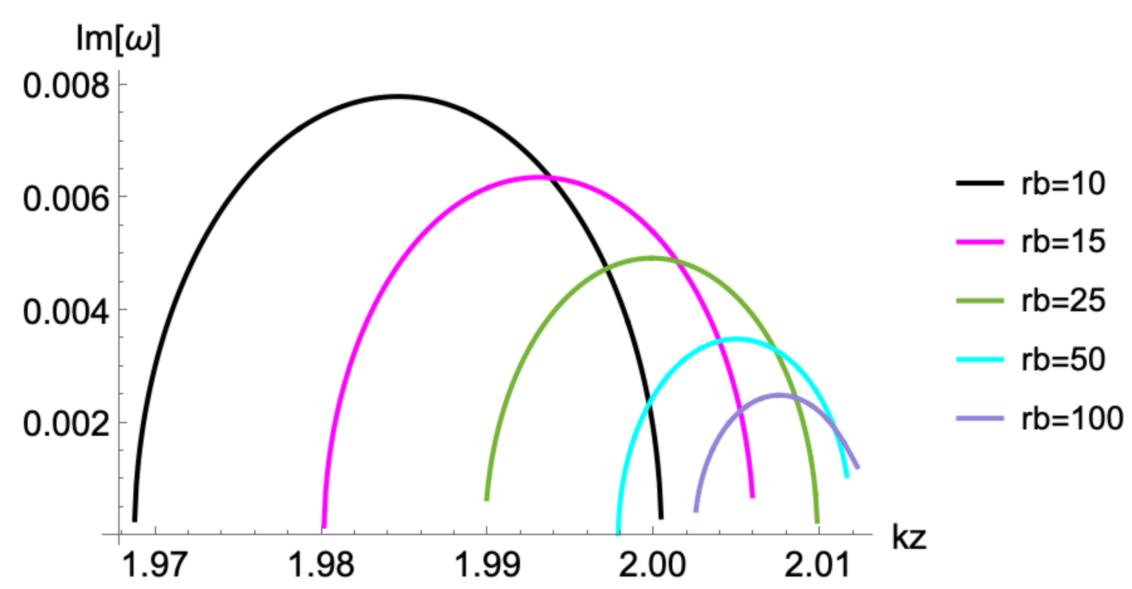

Figure 3: The plot of growing modes as a function of the radius of the beam

Conclusions & Future work

- **The bulk electrostatic modes dominate the electromagnetic modes in our cold relativistic beam setup over a range of $k_z$components, during initial stages of instability.**
- **Dispersion relation is obtained at beam surface for large radius case. The growth rate drops with beam thickness. The bulk growth is larger than the surface instabilities.**
- **Next steps include investigating surface waves from simulation results and manuscript preparation.**

References

[1] Sarri G, Poder K, Cole J et al (2015) Nat. Commun. 6 6747
[2] Arrowsmith, C.D., Simon, P., Bilbao, P.J. *et al. (2024) Nat Commun* 15, 5029
[3] Fonseca R et al (2002) Lecture Notes in Computer Science vol 2331
[4] Shanahan W R (1986) Phys. Fluids 29 1231–7

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