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Relativistic beam-plasma instabilities

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The interaction of relativistic particle beams with plasmas underpins a broad range of physical systems — from the dynamics of AGN jets and Gamma-Ray Bursts to next-generation plasma-based accelerators. In both astrophysical and laboratory scenarios, these beam-driven plasma instabilities play an important role on the interplay of kinetic and electromagnetic energy. Understanding the growth and nonlinear evolution of these instabilities is essential for predicting energy transfer, particle acceleration, and high-energy radiation generation.

In this presentation, we will introduce a novel analytical framework that captures, for the first time, the spatiotemporal evolution and coupling mechanisms of a full class of streaming instabilities —including the Current Filamentation Instability (CFI), Two-Stream Instability (TSI), Oblique Instability, and Self-Modulation Instability (SMI) —driven by relativistic beams propagating through a background plasma. The model is derived under the quasi-static approximation, exploiting the large disparity in timescales between the dilute, relativistic driver and the fast plasma response of the ambient medium.

Benchmarking against Particle-In-Cell (PIC) simulations, both quasi-static and fully kinetic, reveals excellent agreement, validating the model across a wide range of parameters. This opens a new modeling regime for highly relativistic, low-density beam–plasma systems —including those of relevance to laboratory astrophysics and advanced accelerator testbeds such as EuPRAXIA.

In addition to the theoretical and computational developments, this presentation will also outline the potential experimental campaigns that could be implemented at EuPRAXIA to study beam-plasma instabilities. These include scenarios involving relativistic electron beams interacting with underdense plasmas, where signatures of self-modulation, filamentation, and beam-induced wakefields can be diagnosed through state-of-the-art diagnostics. Such experiments would offer a unique opportunity to bridge theoretical, computational, and experimental plasma physics under controlled beam conditions.

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