9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Journey Through the World of Nonlinear Waves

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My talk is dedicated to the memory of Kunioki Mima, a respected colleague and dear friend. The scientific results I present here are either inspired by his pioneering work or were obtained in collaboration with him. They mainly relate to the theory of nonlinear waves in laser plasmas.

One of Mima's most remarkable contributions is the Hasegawa-Mima equation—co-developed with Akira Hasegawa—which describes turbulence in magnetized plasmas and the dynamics of vortices in a dispersive medium [1–3]. In laser-plasma interactions, an ultrashort laser pulse can generate a quasistatic magnetic field that lingers behind the pulse, forming a magnetic wake. This wake contains a row of electron fluid vortices governed by the Hasegawa-Mima equation. Under certain conditions, this vortex row evolves into a von Kármán-like configuration that remains stable.

In relativistically intense laser-plasma interactions, electromagnetic solitary waves are generated. In inhomogeneous plasmas, these relativistic solitons are accelerated toward the plasma-vacuum interface, where they radiate energy in the form of low-frequency electromagnetic bursts [4]. The transverse inhomogeneity of plasma within a self-focusing radiation channel contributes to the guiding of these solitary waves, which in turn excite a two-ribbon magnetic field structure in their wake.

Another area of theoretical work has been the interaction of high-intensity laser pulses with relativistic plasma mirrors, which in the case of relativistic oscillating mirror has demonstrated efficient generation of high-order harmonics—yielding bright sources of extreme ultraviolet (XUV) radiation and attosecond pulses [5]. A striking transition was observed in this process: a new regime of coherent XUV generation emerged, characterized by anomalous directional emission parallel to the mirror surface. This phenomenon is attributed to the laser-driven oscillations of relativistic electron nanobunches formed via a plasma surface instability.

The phenomenon of hole-boring by intense laser pulses plays a crucial role in fast ignition laser fusion, radiation pressure ion acceleration, and the generation of high-energy radiation. In this regime, the propagation of the laser pulse and the associated generation of relativistic electrons and magnetic fields are key processes. Simulations reveal that strong longitudinal magnetic fields are generated in front of the hole-boring region when driven by circularly polarized lasers. The polarization converts the laser into spiral electromagnetic waves, which consist of both radially and azimuthally polarized components [6–8]. The radially polarized component drives a spiral electron beam that induces the longitudinal magnetic field [7,9].

The generation of quasi-monoenergetic ion pulses via laser-driven acceleration is a prominent research topic due to their numerous applications. Achieving high-quality ion beams—characterized by narrow energy spreads—is essential. In Ref. [10], we propose the use of a double-layer target to attain such beams. The front layer consists of high-Z atoms, while the rear is a thin coating of low-Z atoms. Analytical modeling and 3D particle-in-cell simulations demonstrate the generation of high-quality proton beams from such targets under ultra-intense laser irradiation.

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