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Exploring new physics regimes with ultra-high-intensity laser-plasma interactions

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Recent advances in laser technology have brought us to the threshold of exploring physical regimes once considered exclusive to the most extreme astrophysical environments. With the commissioning of several high-power, high-intensity laser facilities around the world that are capable of delivering peak powers in the multi-petawatt range [1–3], a new generation of laboratory experiments is now within reach—experiments that probe the frontier of light–matter interactions, relativistic plasmas, and even the conversion of light into matter and antimatter.

This talk presents what can already be achieved — or is within reach — in the near term using the capabilities of current multi-petawatt laser facilities. Specifically, it highlights three interconnected phenomena that can be accessed using high-power, high-intensity laser systems: (1) the generation of extremely strong, quasi-static magnetic fields in a dense plasma [4], (2) the production of dense gamma-ray beams facilitated by these magnetic fields [4-6], and (3) the creation of electron-positron pairs directly from light using the laser-driven gamma-ray beams [7,8].

The ability to generate multi-gigagauss magnetic fields in the laboratory opens a path toward studying collective plasma behavior in extreme field environments. These fields emerge during laser interaction with overdense targets, where relativistic transparency enables laser penetration into regions that would otherwise reflect the laser. The resulting current structures drive quasi-static magnetic fields whose strength can reach values comparable to those near the surface of magnetars. This capability makes it possible to explore magnetized plasma phenomena that were previously confined to astrophysical contexts, including radiation-dominated regimes and collective plasma behavior shaped by ultra-strong magnetic fields.

Within these extreme fields, relativistic electrons can undergo direct laser acceleration, gaining energy over multiple laser cycles due to sustained phasing with the laser field. The magnetic field plays a dual role: it confines electrons transversely, supporting prolonged acceleration, and simultaneously induces intense gamma-ray emission as the electrons are redirected. As a result, high-energy photons are emitted from the same region where the electrons are energized, enabling compact and efficient gamma-ray sources. Simulations show that current laser parameters are sufficient to convert several percent of the laser energy into a directed beam of multi-MeV photons, far exceeding the capabilities of conventional synchrotrons or XFELs. Efficiency is expected to rise further with the advent of more powerful laser systems.

The availability of such gamma-ray beams enables a dramatic next step: the direct conversion of light into matter via the linear Breit–Wheeler process. In contrast to the nonlinear process demonstrated at SLAC, which requires extremely high laser intensities to become efficient, the linear process involves the collision of two photons and imposes no requirement on laser intensity. The main challenge is producing photon beams that are both energetic and dense enough to make the process observable. This is now possible: simulations show that colliding two gamma-ray beams generated by relativistically transparent plasmas can produce millions of electron–positron pairs per shot under conditions achievable at existing facilities. Even a single laser pulse can suffice, as the plasma emits both forward- and backward-directed gamma rays that overlap and collide. The resulting positrons can be accelerated by the same charge-separation field that creates the backward emission, forming a detectable, forward-directed positron beam. This opens the door to compact positron sources and laboratory studies of pair plasmas previously thought to be exclusive to high-energy astrophysical environments.

These developments mark the beginning of a new experimental frontier in plasma physics. The ability to generate extreme magnetic fields, high-efficiency gamma-ray bursts, and matter directly from light—all using current laser capabilities—brings laboratory research into regimes once reserved for neutron stars and black hole jets. As multi-petawatt facilities continue to mature, the transition from simulation to demonstration is already underway.

References

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