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Leveraging extreme laser-driven magnetic fields for intense gamma-ray generation

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Currently constructed laser facilities are expected to deliver on-target intensities approaching 10^{23} W/cm^2, which would enable experiments in a qualitatively new regime of light-matter interactions. In this regime, quantum effects will change the individual dynamics of charged particles through radiation reaction, but, even more importantly, collective effects will alter the optical properties of otherwise opaque matter through relativistically induced transparency. By performing computational and theoretical research in anticipation of experimentally achieving this novel regime, we found that the performance of laser-driven particle and radiation sources can be dramatically improved by leveraging new physics. These improvements go well beyond the incremental improvements expected from simply upscaling the laser intensity.

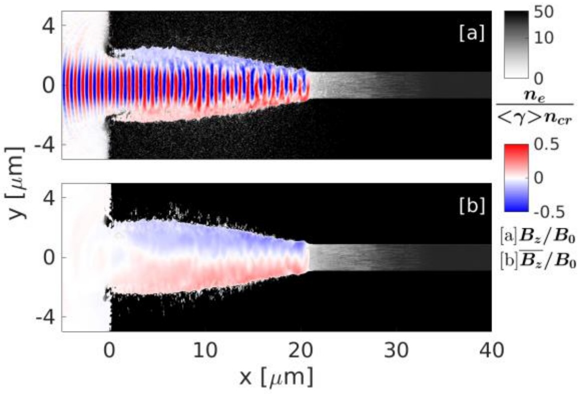

Figure 1: Instantaneous and time-averaged magnetic fields from a 2D PIC simulation where a structured target is irradiated by a laser pulse with $a_0 \approx 250$.

The relativistically induced transparency allows the laser pulse to propagation through material with an electron density that would normally be prohibitively high. We found that the resulting volumetric interaction of the laser pulse with the dense electron population generates an unprecedented slowly-evolving magnetic field that is coiled around the pulse [1,2]. Its strength can be at the mega tesla level and comparable to that in the laser pulse itself, as shown in Fig. 1. This magnetic field is shown to enhance the energy gain by laser-accelerated electrons by more than an order of magnitude. A combination of the high energy possessed by the electrons and an extreme acceleration induced on these electrons by the magnetic field leads to a strong emission of directed beams of energetic photons. The number of multi-MeV photons exceeds 10^{12} even at 5×10^{22} W/cm^2, which accounts for more than 3% of the incoming laser energy [1]. The generation of a strong magnetic field is critical for this mechanism since the energy enhancement is a threshold process. As shown in Fig. 2, the conversion rate can be further optimized for constant laser intensity by proportionally increasing the channel radius and the power of the incoming laser pulse, i.e. the size of the focal spot.

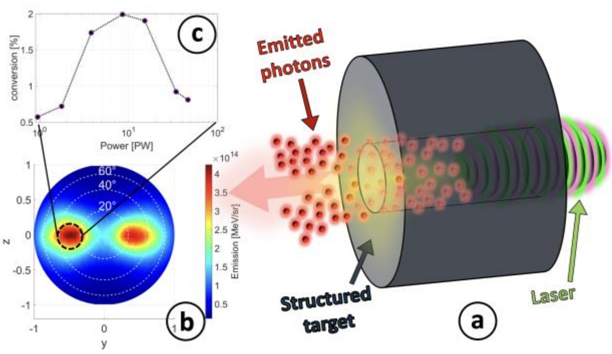

Figure 2: Laser energy conversion rate into photons with energies above 10 MeV (c) emitted into a small opening angle (b) from a structured target irradiated by a high-intensity laser pulse (a).

The novelty of the discussed regime is that the extreme magnetic field couples three key aspects of laser-plasma interactions at high intensities: relativistic transparency, direct laser acceleration, and synchrotron photon emission. Multiple applications that require a dense beam of gamma-rays, including advanced nuclear and radiological detection, can directly benefit from the development of such a photon source.

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References:

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