Abstract / Teaser

The goal of this project is to investigate the strongest electromagnetic fields using high power lasers in the laboratory. It is a fundamental prediction of quantum electrodynamics that extremely strong electromagnetic fields will produce matter, rendering the vacuum unstable. While the field strengths required for this phenomenon to occur are currently far beyond our capabilities, it is nonetheless possible to probe the physics at this scale with current high-power lasers by colliding them with high-energy electron beams. In this project we aimed at improving the electron beam quality to facilitate such high-intensity QED experiments.

Body

Introduction

With the ongoing development of ultra-intense laser technology, laser-driven plasma based particle accelerators have made tremendous progress, both for the acceleration of electrons, protons and ions. In particular, laser-wakefield acceleration (LWFA) of electrons has made enormous progress in the recent decades and is now capable of generating high quality electron beams with multi-GeV energies. Such high energy electron beams also have the capability to drive novel secondary particle and radiation sources, for instance bright X- and γ-rays, or positrons.

As the laser intensity increases further, next-generation high-power laser facilities will enter an intensity regime where quantum electrodynamics (QED) effects will play an important role [8]. This novel “QED-plasma” or “supercritical” regime is characterized by a large fraction of the plasma particles seeing electric fields in their rest frame on the order of the QED critical electric field [1]. The latter field strength can lead to a spontaneous breakdown of the vacuum by means of the so-called Sauter-Schwinger effect [2]. While the Sauter-Schwinger field strength is presently out-of-reach in laboratories, one can nonetheless probe the physics at this scale by colliding high-energy particles with laser pulses, in which the effective field strength in the particle rest-frame are boosted by factors exceeding 10000.

At these conditions quantum effects become efficient, meaning that for instance quantum stochasticity in photon emission by electrons becomes relevant. Moreover, high-energy photons interacting with such high-intensity fields are efficiently converted into matter-antimatter particle pairs. It is remarkable that the mean free path of high-energy particles in such high-intensity fields is usually only a few tens of micrometres, compared to centimetres in high-Z materials such as lead. Strong-field QED experiments can be performed in all-optical set-ups by using laser wakefield acceleration. However, they pose strict requirements especially with regards to beam energy spread, emittance and pointing stability, which requires a careful LWFA target design to allow robust injection and stable propagation.

Results and Methods

Particle-in-cell method

The method of choice for the simulation of laser wakefield acceleration is the particle-in-cell method (PIC). In PIC, the electromagnetic fields are discretized on a spatial and temporal grid, and Maxwell's equations are solved using the FDTD method. The plasma is represented by a large number of macroparticles with positions and momenta being pushed according to the Lorentz force equation with the EM fields being interpolated from the grid to the particles' positions. Then, the plasma currents are deposited onto the grid for sourcing the electromagnetic fields in the next computational loop. In this project we have used the open source PIC code SMILEI [3], which is well tested both with regard to the implemented physics modules as well as its scalability in HPC.

Gas cell design

In LWFA the laser pulse excites a plasma wave structure (bubble) with strong accelerating and confining fields into which electrons are to be injected. A stable beam quality in particular requires stable injection conditions. One option is a localized hybrid ionization/downramp-injection scheme in a novel gas cell design. Here we performed particle-in-cell simulations of laser pulses propagation through the plasma medium to find optimal conditions for stable propagation of the laser through the defocusing vacuum-plasma interface to achieve robust conditions at the injector location. The gas cell has been fully designed and was build; experiments are underway.

Pointing stability

During this project, together with experimental and theoretical efforts, we report an instability affecting the ultimate limits of beam pointing jitter. We identify a mechanism intrinsic to LWFA, coupling pointing electron beam pointing in the polarization plane to the laser carrier-envelope-phase (CEP) for the first time [4] (work submitted for publication). Previously the CEP was believed to be relevant only for near single cycle pulses, where the CEP significantly alters the shape of the laser pulses driving the accelerator. We found, however, that a significant effect also occurs for longer laser pulses due to the dynamic evolution of the driver inside the plasma medium, especially the pulse front steepening. Once steepened, the carrier wave slippage with respect to the pulse envelope excites a transverse oscillation of the accelerating structures which in turn couple to the dynamics of the accelerated electrons inside the bubble, affecting their pointing direction in the laser polarization direction. Fluctuations of the laser carrier envelope phase are eventually beam pointing jitter from shot-to shot. Eventually that means this jitter contributions is inherent to LWFA and its mitigation might require a CEP stabilization of the driving lasers.

Caption for Figure 2: PIC simulation results for the CEP-dependence of electron beam pointing jitter in the laser polarization direction.

Bibliography

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Project ID

QEDLWFA

Project title

Advanced LWFA injection schemes for strong-field QED experiments

HPC system

JUWELS