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Vacuum laser acceleration of relativistic electrons using plasma mirror injectors

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Vacuum Laser Acceleration (VLA) [1] is a promising method for accelerating electrons to very high energy in very short distances. The method is appealing because of its conceptual simplicity and most fundamental nature: electrons interact with an intense laser field in vacuum and exchange energy with the field. With intensities exceeding $10^{19} W/cm^2$, the laser electric field reaches >10 TV/m, providing the highest fields that can be produced in the laboratory. These enormous fields can then be used to accelerate charged particles with extreme accelerating gradients.

While the theoretical literature on VLA has been extremely prolific, there have been no experimental results so far showing unambiguously the acceleration of electrons to relativistic energies by VLA. This is probably because VLA occurs efficiently only for electrons injected in the laser field with specific initial conditions that are extremely challenging to fulfill experimentally. Indeed, in order to stay in phase with the laser field, electrons need to have initial velocities close to c along the laser propagation axis. In addition, they should start interacting with the intense laser beam already close to its spatial and temporal maxima, and even be injected at appropriate phases of this field. Thus, the proper injection of electrons into the intense laser field has proven difficult to solve experimentally.

We will show how by using a plasma mirror, we have been able to solve this long-standing problem. A plasma mirror is an overdense plasma with a very sharp density gradient ($L < \lambda/10$) at its front surface [2]. The interaction of an intense laser pulse with such a plasma mirror leads to the production of energetic electrons at specific phases of the field and collinear to the reflected laser pulse. This interaction provides electrons with initial conditions that are ideal for injecting electron into the reflected field and permits efficient vacuum laser acceleration.

Our experimental results clearly discriminate for the first time electrons that have explored many laser cycles and thus experienced ponderomotive scattering, from those that have remained within a given laser period and been efficiently accelerated by VLA. Simulations show that these VLA electrons surf a single laser cycle and gain about 10 MeV in a 80 µm distance. The accelerated charge in the 10 MeV beam is very large: up to 3 nC, showing that this process is quite efficient [3].

In this talk, we will explain the concept and the physics of plasma mirrors as electron injectors. We will show how our experimental results can be clearly interpreted in terms of VLA, providing clear evidence that an electron beam with a large charge can be efficiently accelerated to relativistic energies using this process.

REFERENCES

1. E. Esarey et al., Phys. Rev. E 52, 5443 (1995)
2. C. Thaury et al., Nat. Phys. 3, 424 (2007)
3. M. Thévenet et al., submitted for publication

Summary

Accelerating particles to relativistic energies over very short distances using lasers has been a long standing goal in physics. Among the various proposed schemes, vacuum laser acceleration has attracted considerable interest and has been extensively studied theoretically because of its appealing simplicity: electrons interact with an intense laser field in vacuum and can be continuously accelerated, provided they remain around a given phase of the field until they escape the laser beam. But demonstrating this effect experimentally has proved extremely challenging. Here, we solve this long-standing experimental problem by using a plasma mirror to inject electrons in an ultraintense laser field, and obtain clear evidence of vacuum laser acceleration of electrons up to 10 MeV over a distance of 80 µm, with nC of accelerated charge.

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