Detailed measurements of the time structure of a self-modulated proton bunch exiting a plasma in AWAKE

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The self-modulation of a long (>1 cm), relativistic, charged particle bunch in a dense plasma ($>10^{14}$ cm^{-3}) offers the possibility to resonantly drive wakefields to large amplitude (>1 GV/m) [1]. A witness electron (or positron) bunch can then be externally injected in the wakefields and accelerated. Because long proton bunches can carry large amounts of energy, the acceleration process can be sustained over long distances and the accelerated bunch can reach very large energies along a single plasma [2]. The witness bunch must be deterministically placed in the accelerating *and* focusing phase of the wakefields. The wakefields can be seeded, for example, by an ionization front created by a short laser pulse traveling together with the proton bunch, as in the AWAKE experiment [3]. The wakefields used for acceleration are those after the growth of the seeded modulation process has saturated, some meters into the plasma and approximately one rms bunch length behind the seed point, where they peak. It is essential to understand the variation of the phase of the wakefields with respect to the seed points and with respect to variations of the parameters of the incoming proton bunch. The phase of the wakefields is very difficult to measure. However, there is a one-to-one correspondence between the wakefields and the bunch structure driving the wakefields. We can therefore measure the time structure of the bunch exiting a first plasma, which is used as self-modulator of the drive bunch. We show that, despite variations in the bunch input parameters, the time structure of the bunch to be used to drive wakefields in a second plasma, the accelerator itself, is reproducible to within a fraction of a wakefields period (∼8 ps). Since a witness electron bunch would be generated on a photo-cathode or in a laser wakefield accelerator by a replica of the ionizing pulse used for seeding, these measurements show that the witness bunch can in principle be deterministically placed at the proper phase of the wakefields in the accelerator plasma, even when many periods behind the seed point (e.g., ∼100 at a plasma density of 7×10^{14} cm^{-3} and with σ_z=12 cm).

References

[1] N. Kumar et al., Phys. Rev. Lett. **104**, 255003 (2010)

[2] A. Caldwell et al., Phys. Plasmas **18**, 103101 (2011)

[3] P. Muggli et al., Plasma Physics and Controlled Fusion, **60**(1) 014046 (2017)