PhD Open Days

How can you control particle acceleration in plasma wakefields?

Advanced Studies Diploma in Technological Physics Engineering

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Plasma Wakefield Acceleration (PWFA)

A drive laser pulse (or particle beam) is sent into a plasma of electrons and ions. The electrons are radially repelled by the laser ponderomotive force (or beam space charge) leaving behind a positively charged cavity of ions. The cavity attracts electrons back to the propagation axis, where they repel other electrons, generating the plasma wake. Electrons can be trapped and can accelerate in the wakefields of the back of the cavity.

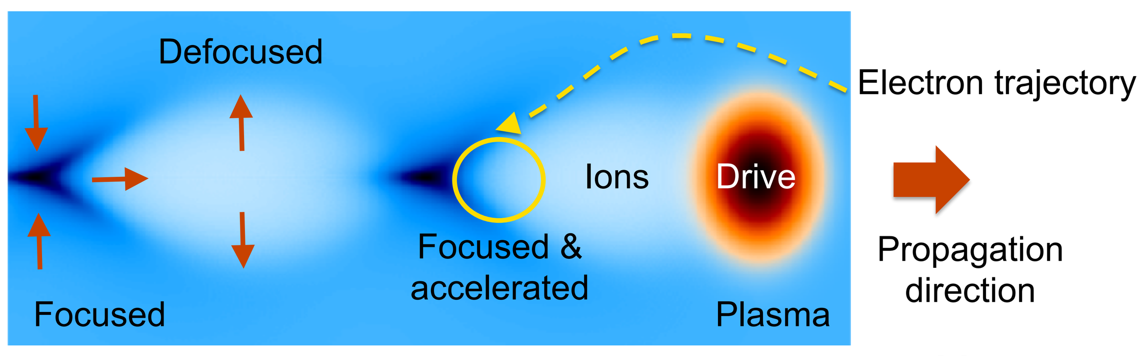

Figure 1: Illustration of standard PWFA process with OSIRIS[1].

Advantages

- Enables linear configurations precluding energy losses by radiation
- Radio Frequency (RF) cavities are limited to material breakdown before their structure melts into plasma. In PWFAs this limitation was already surpassed so higher accelerating fields can be sustained.

Challenges

- Controlling properties of the accelerated bunches, to have lower emittance and higher total charge, and of the resulting radiation, higher energy x-rays.

A) By fitting the laser pulse length to whole cavity[2]

Inside the PWFA cavity, if the trapped and accelerated electrons overlap the laser pulse they are transversely accelerated by its electric field. As the electrons become relativistic the magnetic fields of the wake and laser convert electron perpendicular momentum in additional longitudinal acceleration.

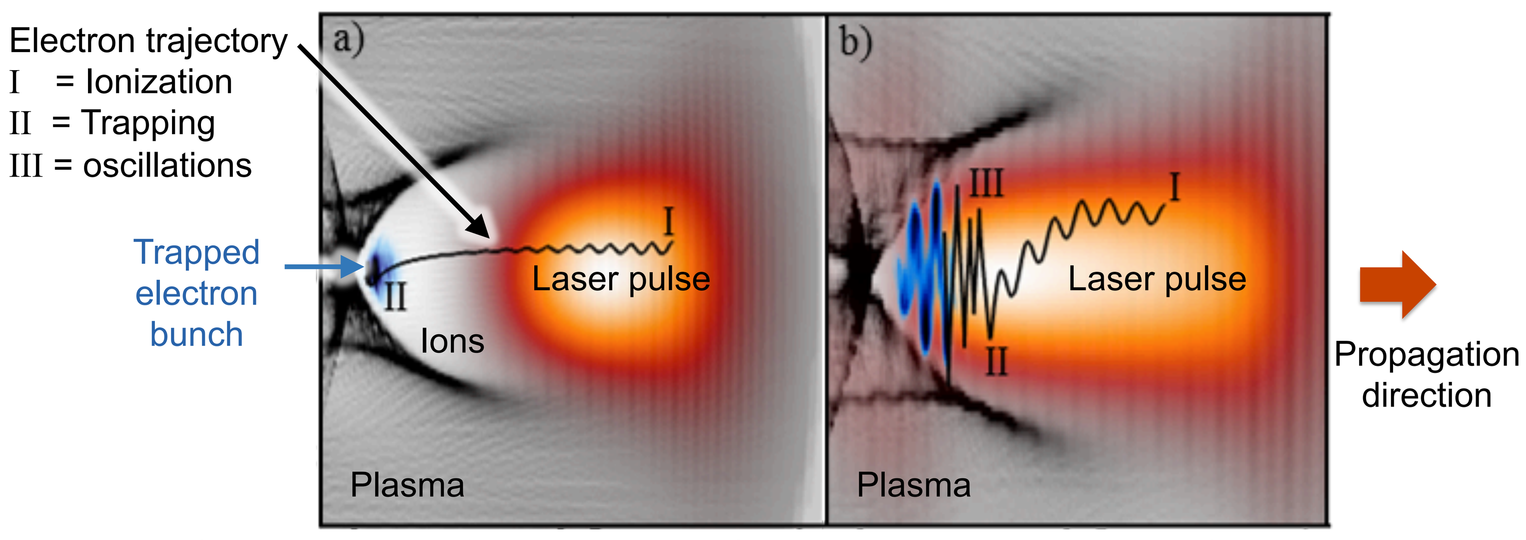

Figure 2: Comparison of PWFA with a) short laser pulse and b) laser pulse that encompasses the ion cavity and trapped electrons[2].

Advantages

- More efficient energy transfer from laser to accelerated electron bunch.
- Higher maximum bunch energy attained in same propagation distance.
- Wider perpendicular oscillations in the cavity (Fig. 2 III) (enhanced x-rays).
- Accelerated electrons micro-bunch at half laser wavelength (spectroscopy).

B) With self-modulated laser or particle beams[3-5]

Laser pulse over several plasma cavities long[3]

The laser will see locally perturbed refractive indexes due to the plasma wake density oscillations. Hence, the portions within each cavity will have varying phase velocity and the pulse radiation will compress as it undergoes the self-modulation instability. In this case electrons can be trapped and accelerated over many cavities and also react to the laser transverse electric field, as in [2]. This scheme is ideal for generating small divergence, broadband x-ray beams.

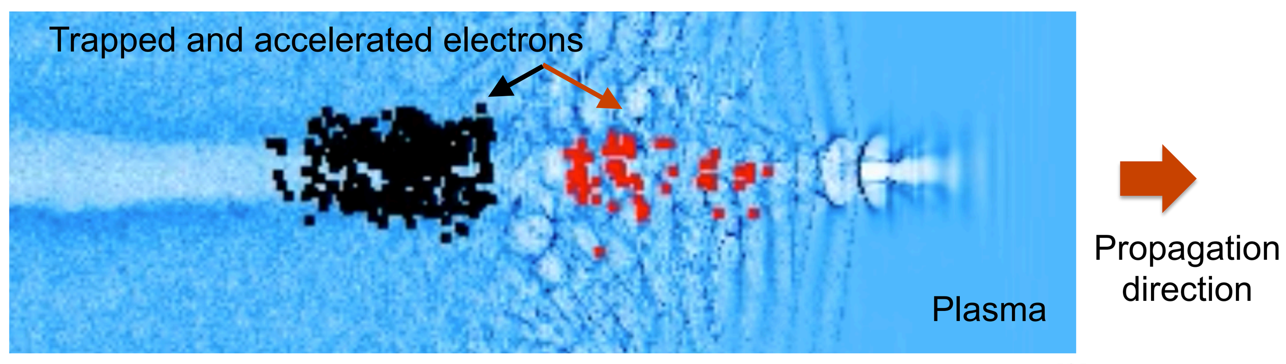

Figure 3: Plasma electron density for a self-modulated laser pulse[3].

Long electron, positron[4] and proton beams[5]

In the case of particle beams it is the plasma transverse defocusing wakefield that is responsible for splitting the beam into several beamlets, within each cavity, that resonantly excite the subsequent plasma wake. This process allows for high energy long beams, such as the CERN TeV proton beam[5].

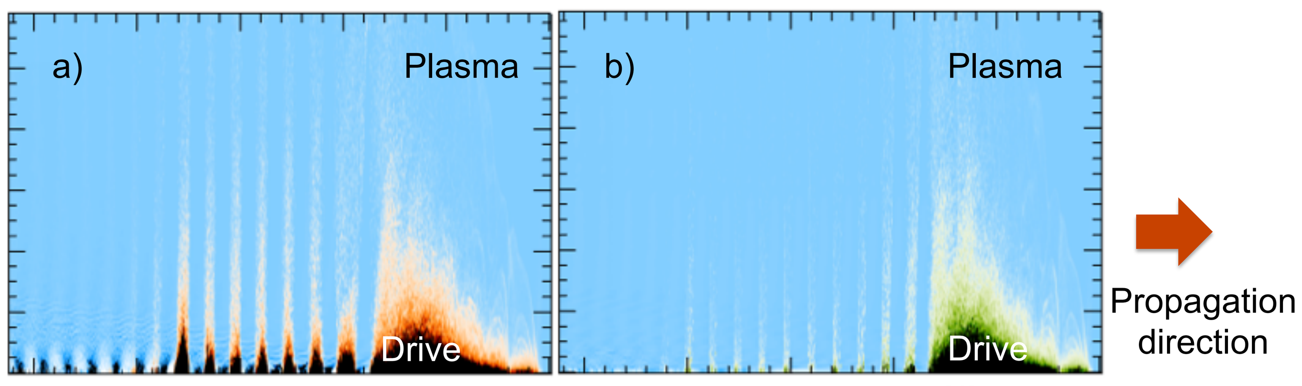

Figure 4: Self-modulated a) electron and b) positron beams[4].

C) By using tightly focused positron beams[6]

A narrow high density positron beam has the ability to excite highly non-linear plasma wakes as well as to induce significant ion motion. Because of its charge sign the beam repels the ions and generates a hollow channel that is ideal for efficient trailing positrons acceleration mitigating emittance growth.

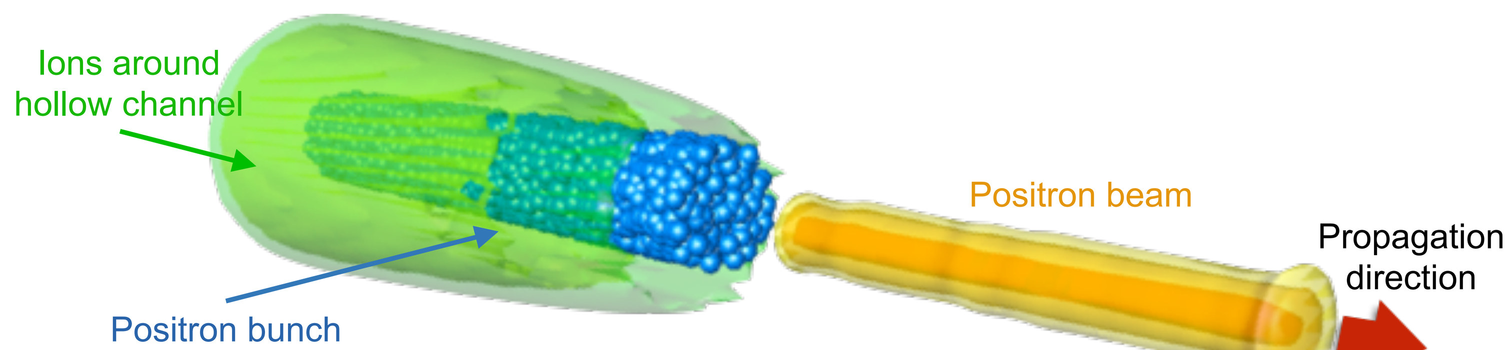

Figure 5: Hollow channel scheme for positron acceleration[6].

Advantages

- Non-linear accelerating gradients allow compact and efficient acceleration
- Transverse wakefields are mainly focusing for positron bunches
- Initial uniform plasma means no positron – neutral collisions

Main contributions - Numerical work done with the particle-in-cell code OSIRIS[1] to corroborate the experiments that took place in the University of California Los Angeles[2], Lawrence Livermore National Laboratory[3] and the Stanford Linear Accelerator[5]. Derivation and numerical study of the new acceleration scheme[6].

[1] R. A. Fonseca et al., Lecture Notes Computer Science, 2331, 342 (2002)
[2] J. Shaw, N. Lemos, L. D. Amorim et al., Physical Review Letters 118 (2017)
[3] F. Albert et al., accepted for Physical Review Letters (2017)
[4] L. D. Amorim et al. IPAC TUPME076 O5.224 (2014); E. Adli et al., NIMPR 829 (2016)
[5] K. V. Lotov et al., Physics of Plasmas 21 (2014)
[6] L. D. Amorim et al. 41st EPS O5.224 (2014); L. D. Amorim et al., to be submitted (2017)