Simulation Study for Self-modulation Experiment at PITZ

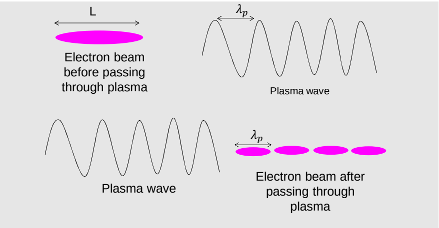
G. Pathak[1*], C. Benedetti[3], M. Gross[2], F. Gruener[1], T. Mehrling[2], A. M. de la Ossa[1], J. Osterhoff[2], C. B. Schroeder[3], F. Stephan[2],
[1]Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany
[2]Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany
[3]LBNL, Berkeley, CA 94720, USA

Abstract

Self-modulation (SM) of proton beams in plasma has recently gained interest in context with the PWFA experiment proposed by the AWAKE collaboration at CERN. Instrumental for that experiment is the SM of a proton beam to generate bunchlets for resonant wave excitation and efficient acceleration. A fundamental understanding of the underlying physics is vital, and hence an independent experiment has been set up at the beamline of the Photo Injector Test facility at DESY, Zeuthen site (PITZ), to study the SM of electron beams in a plasma.

In this contribution we present simulation results of SM experiments at PITZ using the particle-in-cell code HiPACE. The simulation study is crucial to optimize the beam and plasma parameters for the experiment. Of particular interest is the energy modulation imprinted onto the beam by means of the generated wakefields in the plasma. With the support of simulations, the observation of this information in the experiment can be used to deduce key properties of the accelerating electric fields, such as their magnitude and their phase velocity, both of significant importance for the design of self-modulated plasma-based acceleration experiments.

Self-modulation of electron beam



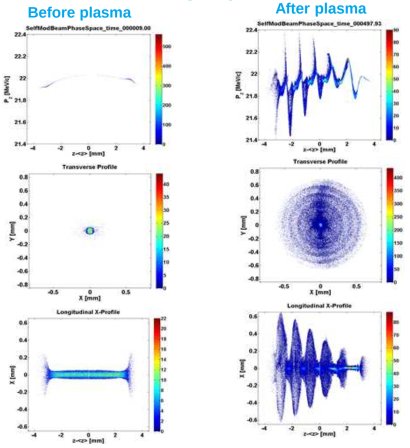
Self-modulation of the electron bunch essentially occurs due to the action of the transverse wakefields on the bunch itself.

In its simplest form of self-modulation, a long charge particle beam $(L > \lambda_p)$ when propagates through the plasma generates a wake within its body due to perturbation of plasma, which modulates the beam itself, leading to the positive feedback and unstable modulation of the whole beam along the propagation direction. This self-modulation splits the long beam into short bunches of length λ_p, which resonantly drive the plasma wake. The longitudinal electric field is given by

$$E_z = 240(MV\ m^{-1})\left(\frac{n_b}{4\times 10^{10}}\right)\left(\frac{0.6}{\sigma_z(mm)}\right)^2$$

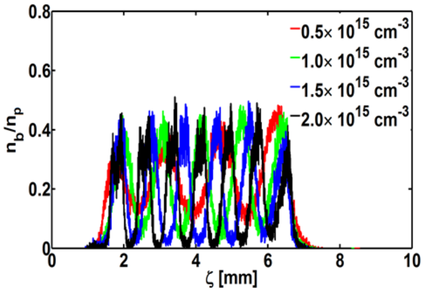
Where n_b, is beam density
σ_z is longitudinal beam size.

Beam properties

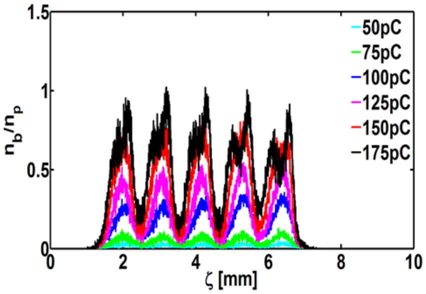


Modulation is observed more in the tail of beam.
Beam is compressed transversely due to transverse wakefield.
Different compression in x, y direction is due to asymmetrical transverse beam size.

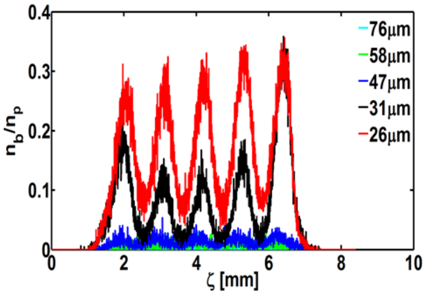
Density modulation of the electron bunch @ 15.4mm



Above Fig. shows the snapshot of the beam density modulation at $15.4mm$ in the plasma with different plasma densities when charge and beam size are kept constant. With different plasma densities (n_p) the period of modulation changes since $\lambda_p \propto 1/\sqrt{n_p}$.

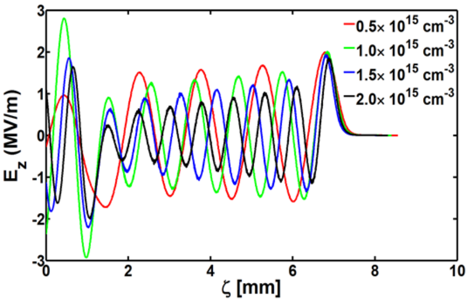


The density modulation is small for lower charge $(50pC)$. On the contrary, for the high charge case where $Q = 175pC$, the electron bunch starts modulating into small beamlets on the scale of the plasma wavelength, drives the plasma wakefield resonantly.



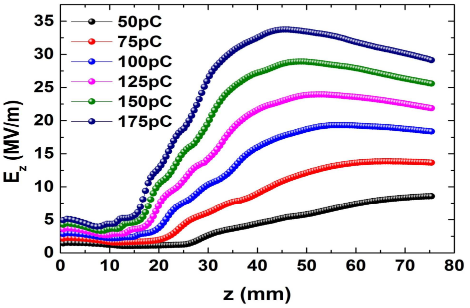
Smaller beam size expels plasma electron more strongly, generating strong transverse wakefields which in turn modulate beam energy strongly.

Longitudinal field of the plasma



$$E_z \propto \frac{n_{b0}}{\sqrt{n_p}} R(0)$$

Where $R(0)$ is a unitless transverse geometrical factor. $R(0)$ is an increasing function of $k_p\sigma_r$, the bunch transverse size σ_r relative to the plasma skin depth c/ω_p. At $5mm$ distance the amplitude of longitudinal wakefield E_z decreases from 2 to $0.5\,MV/m$ as the plasma density n_p is increased, indicating the dominance of the decreasing term $1/\sqrt{n_p}$ over the increasing term $R(0)$.



Above Fig. shows that the peak accelerating field occurs earlier for greater bunch charges, indicating a more rapid growth of the self-modulation instability. As the self-modulation instability grows, E_z saturates and the saturation distances decreases from 70mm to 40mm with increasing charge. The simulation result also indicates that within the propagation distance of $z = 15mm$, E_z remains almost constant.

Outlook

- Further optimization by simulations will be done to achieve maximum energy modulation and minimize the emittance growth e.g. with energy chirp beam and density tapered plasma.
- Experiments are ongoing for gas density measurement.
- Different methods will be implied for gas and plasma density measurement.

References

1. Proton-driven Plasma-wakefield Acceleration – A. Caldwell et.al, Nature Physics 5, 363 - 367 (2009)
2. Growth and Phase Velocity of Self-Modulated Beam-Driven Plasma Waves - C. B. Schroeder et. al. PRL 107, 145002 (2011)
3. HiPACE: a quasi-static particle-in-cellcode – T. Mehrling et. al. Plasma Phys. Control. Fusion 56 084012 (2014)
4. Preparations for a Plasma Wakefield Acceleration (PWA) Experiment at PITZ, M. Gross, et al., NIM A 740, 74-80 (2014).

*Email: gaurav.pathak@desy.de