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Progress of plasma wakefield self-modulation experiments at FACET

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ABSTRACT

Simulations and theory predict that long electron and positron beams may under favorable conditions self-modulate in plasmas. We report on the progress of experiments studying the self-modulation instability in plasma wakefield experiments at FACET. The experimental results obtained so far, while not being fully conclusive, appear to be consistent with the presence of the self-modulation instability.

1. Introduction

Plasma wakefield accelerators [1] have the potential to provide very strong accelerating fields which can be used for particle acceleration. If the particle driver density, n_b, is much less than the plasma density, n_0, then the plasma response will be in the linear regime [2,3] and the accelerating fields will be relatively weak. It has been shown in simulations that a relativistic beam, long with respect to the plasma skin depth $k_p\sigma_z \gg 1$, and with initial low density $n_b \ll n_0$, may evolve to drive relatively stronger fields in the plasma, due to the self-modulation instability (SMI) [4]. σ_z is here the bunch length, and k_p is the cold plasma skin depth. The SMI radially modulates the beam such that micro-bunches with density much higher than n_b are generated, with a spatial frequency close to the plasma electron wavelength, $\lambda_p = \frac{2\pi}{k_p}$. The wake of the micro-bunches builds up coherently, leading to much stronger fields in the plasma than those set up by the initial beam. The AWAKE experiment at CERN [5,6] will investigate the SMI with long proton bunches, and eventually exploit the SMI proton wake to accelerate electron bunches to high energy. Simulations, performed using the code OSIRIS [7], further show that also long electron and positron bunches may experience the SMI [8,9]. We have performed experiments at FACET [10] where electron and positron beams with $k_p\sigma_z \gg 1$ have been sent into pre-formed plasmas, with the aim of observing evidence for the occurrence of the SMI.

2. Experimental set-up

Fig. 1 shows the experimental set-up. FACET provides electron and positron beams with 3 nC of charge and 20.3 GeV energy [10]. Two plasma sources have been used; a laser-ionized lithium heat pipe oven [13] and tubes with laser-ionized hydrogen or argon gas. The plasma densities studied range from $8\times10^{16}\,\mathrm{cm}^{-3}$ to $7\times10^{17}\,\mathrm{cm}^{-3}$. In later discussions we will state which beam-plasma configuration was used. The final focus system of FACET provides focusing down to beta functions (β^*) of a few cm. We note that such focusing is not strong enough to match the beam into a plasma cavity in the blow out regime [14]; the matched beta function for a 20 GeV beam in a plasma cavity with ion density of $8\times10^{16}\,\mathrm{cm}^{-3}$ is 5 mm. Typical electron beam spot sizes at the plasma entrance were measured to about 40 μm rms, with some variation from day to day. Typical bunch lengths were measured to about 1.5 mm FWHM. Examples of the bunch charge profiles

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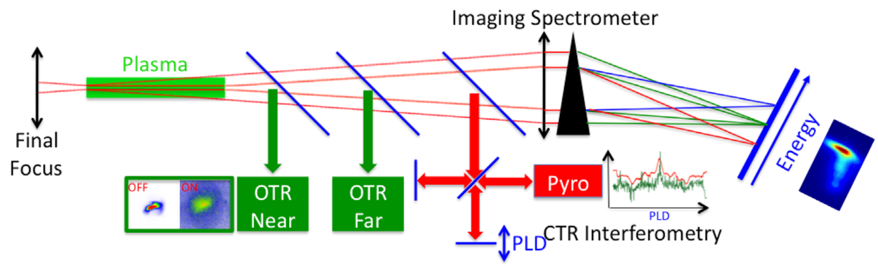

Fig. 1. In the experiment, long ($k_p\sigma_z \gg 1$) electron and positron bunches are sent into meter long plasmas generated from lithium vapor or noble gases. Signatures for the self-modulation instability are studied with three types of diagnostics; a spectrometer, transverse profile monitors (OTRs) and an interferometer.

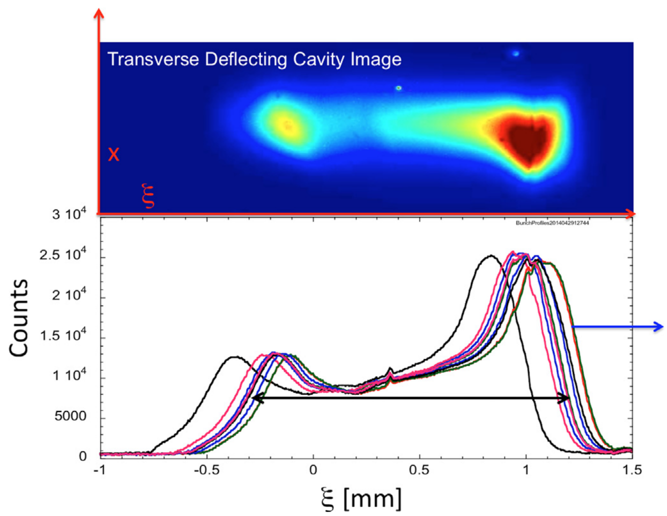

Fig. 2. Bottom inset: example bunch profiles, as measured using a transverse deflecting structure. The measured bunch length is about 1.5 mm, with a two-hump profile. The bunch is traveling towards the right. Top inset : example of the 2D beam profile measured using a transverse deflecting structure.

measured are given in Fig. 2. The shot to shot variation of the measured bunch lengths is about 1% for the measurement series shown.

A single-shot measurement of bunch modulation after passing through the plasma would be ideal for demonstrating the SMI. However, the expected modulation frequency is of the order of 100 μm, which is too small to be resolved by the fastest streak cameras available [15]. Three other types of diagnostics were used to look for signatures of the SMI; a spectrometer, transverse profile monitors and an interferometer.

The FACET imaging spectrometer consists of a dipole dispersing the beam according to energy, plus two quadrupoles which image (focus) particles of selectable energy. The spectrometer images are recorded by Lanex and Cherenkov profile monitors [16] with an energy resolution better than 100 MeV. A signature for self-modulation would be the presence of fields in the plasma which are stronger than expected than if the beam had not self-modulated.

Transverse profile monitors based on optical transition radiation (OTR) are located downstream of the plasma. The “near” OTR is 1.8 m downstream of the plasma exit, while the “far” is 3.0 m downstream. The SMI is expected to expel radially a significant fraction of the beam. Preliminary simulation results [7,11] indicate that a few 10 s of cm into the plasma, outer parts of the beam have picked up divergence of the order of one mrad. After 1.3 m of plasma propagation, roughly half of the initial charge has a large divergence and is located at large radii ($r \gtrsim 500$ μm). A signature for self-modulation would therefore be the presence of charge at large radial positions.

A Michelson interferometer with pyro detectors is installed in order to pick up coherent transition radiation generated by the beam as it passes through a titanium foil [12]. By scanning the interferometer arm, an auto-correlation signal of the incoming radiation is produced. Assuming the radiation amplitude is proportional to the charge squared for a given longitudinal slice of the beam, the auto-correlation signal will contain harmonics of eventual modulations present along the beam. Since the SMI is expected to modulate the beam density with wavelength $\sim\lambda_p$ [4], and assuming the radially expelled charge does not contribute to the radiation generated, a signature for self-modulation would be the presence of spectral content at the plasma wavelength in the auto-correlation signal.

3. Experimental results

First, we report results from electron beams in laser-ionized lithium with a plasma length of about 1.3 m FWHM and plasma density of $n_0 = 8 \times 10^{16}$ cm^{-3}. As the ionization energy for lithium is relatively low (5.4 eV), the 10 TW ~500 mJ FACET laser is expected to ionize a plasma channel of ~1 mm size [13], which is much larger than the bunch radius. Using the FACET spectrometer we observed an electron energy loss of up to 2 GeV in the plasma, corresponding to decelerating fields of almost 2 GV/m. Fig. 3 shows example experimental shots; (a) shows the energy spectrum when the beam has not passed through plasma (the ionization laser is off); (b) shows the energy spectrum when the beam has passed through the lithium plasma. Compared to predictions in [8,9] the results are reasonably consistent with a beam that has self-modulated. As further comparison, we make an energy loss estimate by calculating the wakefields originating from the measured bunch profile (Fig. 2) using linear theory [3], according to the method described in [17]. The calculated longitudinal fields are no more than 100 MV/m, much smaller than what is observed experimentally. This calculation implies that the charge density stays at the same order as the original density ($n_b \ll n_0$). However, both simulations and experiments at FACET indicate that a bunch initially with low charge density $n_b \lesssim n_0$, may strongly self-focus in a plasma, increasing the charge density by several order of magnitude [19]. This mechanism could possibly lead to significantly stronger fields than what is estimated from linear theory, also in the absence of the SMI.

Significant halo formation was observed in the electron-lithium experiments. This is illustrated in Fig. 4 where (a) and (c) show the transverse beam profile of the beam, at the “near” OTR, when not passing through plasma, while (b) and (d) show the transverse beam profile of the beam when having passed through plasma. The halo formation in the latter case is qualitatively consistent with radial expulsion of a significant portion of the beam charge. However, other sources, like beam-plasma mismatch, may also contribute to the formation of transverse beam halo. A similar halo formation has been observed in FACET experiments where short

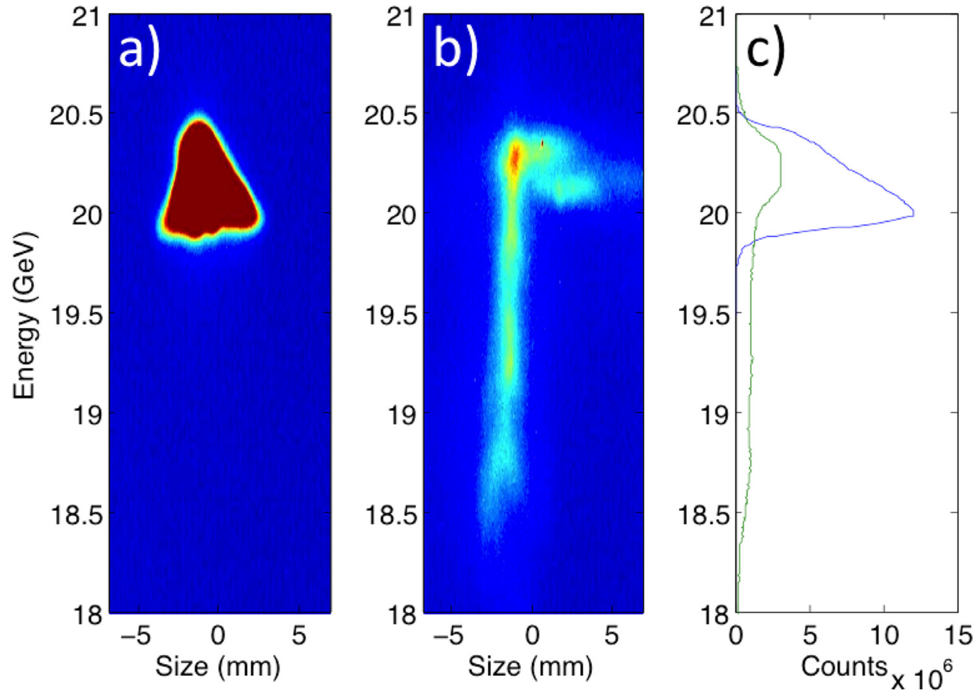

Fig. 3. Electron-lithium results: (a) the measured energy spectrum of the electron beam not passing through plasma. The beam entering the plasma has an energy spread of a few %. (b) The measured energy spectrum of the electron beam having passed through the plasma. Particles are decelerated by up to almost 2 GeV. (c) The projection of the two spectra.

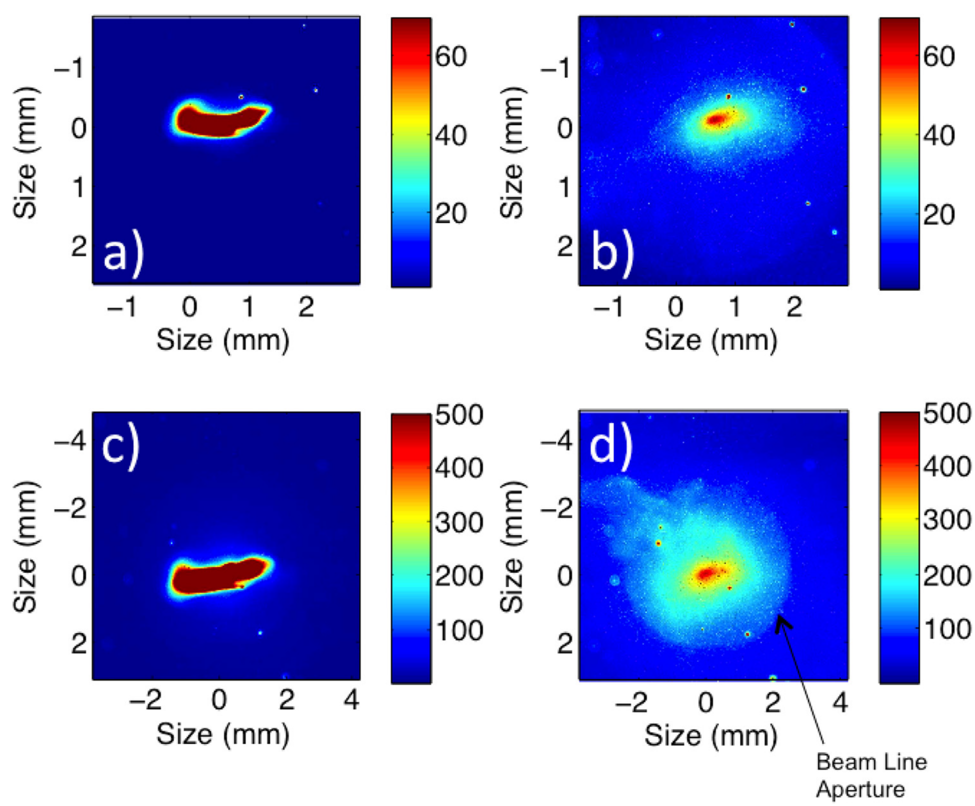

Fig. 4. Electron-lithium results: (a), (c) The measured transverse beam profile of the electron beam not passing through plasma. (b), (d) The measured transverse beam profile of the electron beam having passed through plasma. A significant amount of the charge is located at large radii, for many shots up filling the available beam line aperture.

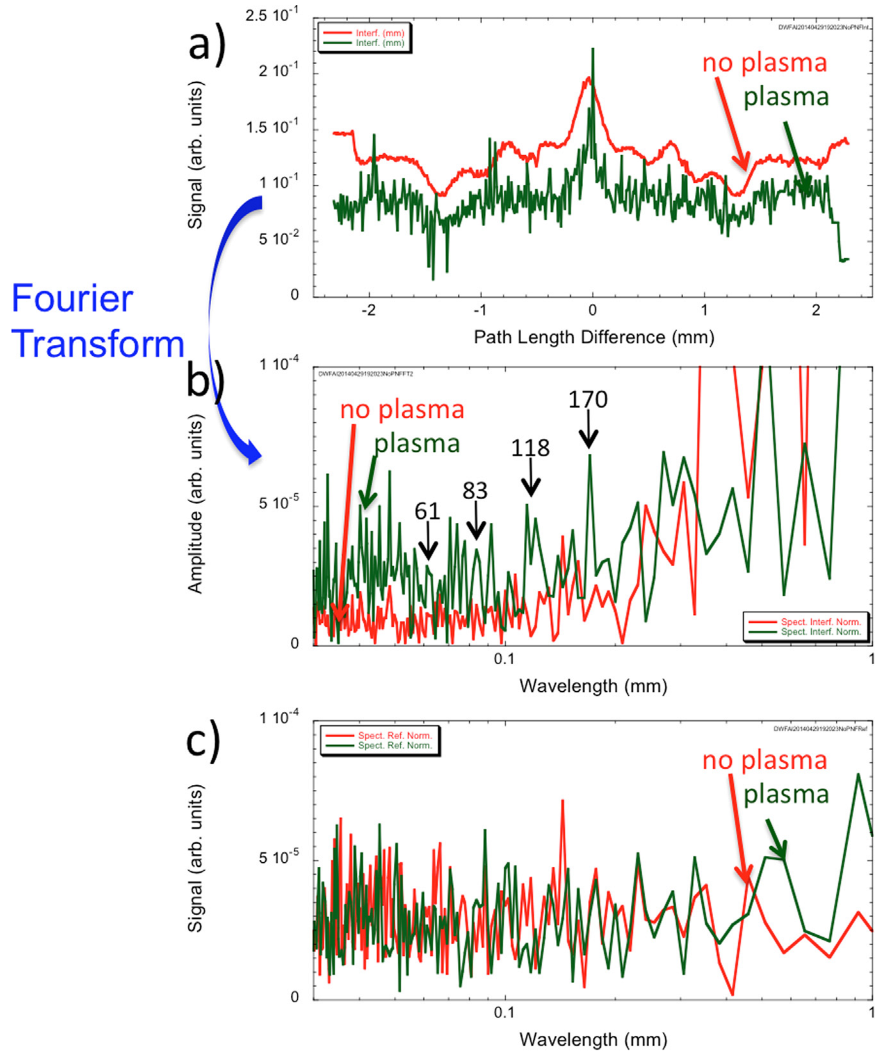

Fig. 5. Electron-lithium results: (a) auto-correlation signal for the two cases of no plasma (upper, lighter curve) and plasma (lower, darker curve). When the plasma is present, the signal contains more high frequency components. (b) The spectral content of the auto-correlation signal. The plasma wavelength is $\lambda_p = 118$ μm for the plasma density used (8×10^{16} cm^{-3}). Spectral peaks close λ_p and $\lambda_p/2$ (the first harmonic) is present in the signal. However, other wavelengths not expected from a modulation at λ_p is also present. (c) The spectral content of a reference signal that picks up the radiation entering the interferometer, without being auto-correlated. The reference signal does not contain strong peaks related to λ_p.

bunches ($k_p\sigma_z \sim 1$) were sent into plasmas with similar densities as in the SMI experiments [18].

Fig. 5 summarizes the results of an interferometry scan; (a) shows the auto-correlation signal, as measured for the two cases of no plasma (upper, lighter curve) and plasma present (lower, darker curve). When the plasma is present in the beam path, the signal contains more high frequency components. The signal is also overall less strong, which is consistent with less radiating charge. (b) shows the spectral content of the signal, found by performing a Fourier transform of (a). The spectrum analysis confirms that with plasma present, a significant amount of high frequency content is present. For the plasma density (8×10^{16} cm^{-3}) the plasma wavelength is $\lambda_p = 118$ μm. We observe that spectral peaks close λ_p and $\lambda_p/2$ (the first harmonic) is present in the signal. However, other wavelengths not expected from a modulation at λ_p are also present.

Fig. 6 summarizes interferometry measurements for positron-argon SMI experiments, with plasma densities of 7.4×10^{17} cm^{-3}, 2.4×10^{17} cm^{-3} and 8×10^{16} cm^{-3}. Spectral content close the plasma wavelength was observed for the higher two densities. Peaks at about 95 μm, compared to the expected 115 μm, was observed for the lower density. For this data as well, additional spectral content at wavelengths not expected from a modulation at the plasma density is present. To provide conclusive results it is desired that the spectra show significantly stronger signals at the expected wavelengths than elsewhere. Alternatively, an explanation for the unexpected peaks in the spectra would be needed. Thus, either improved data or improved analysis is required to bring the experimental results to conclusion.

Electron-hydrogen SMI experiments were performed in order to provide more statistics and improved data. The progress of these experiments was impeded by too narrow plasma channel formation due to a combination of less-than-nominal laser power, and the relatively high ionization potential for hydrogen (13.6 eV). Due to shot to shot beam jitter, the large majority of the experimental shots would not pass cleanly through the plasma channel.

4. Conclusions

We have investigated the development of the self-modulation instability (SMI) in experiments at FACET. The measurements of a

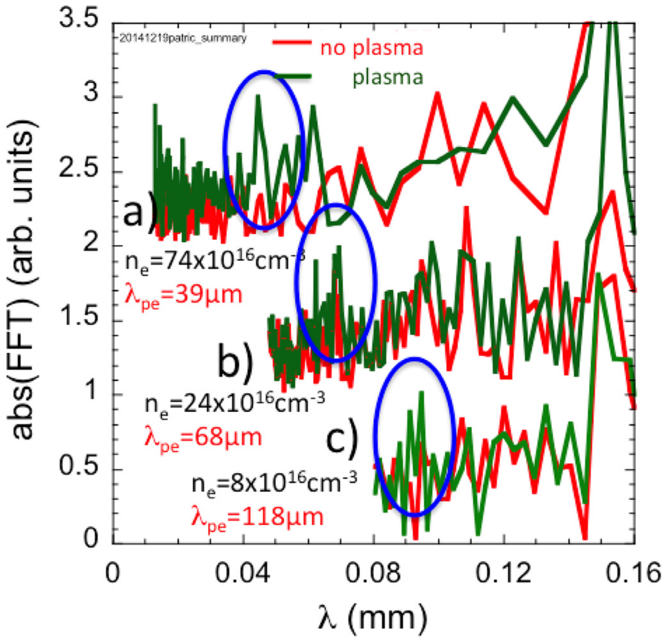

Fig. 6. Positron-argon results: spectral content of auto-correlation measurements for three different plasma densities, 7.4×10^{17} cm^{-3}, 2.4×10^{17} cm^{-3} and 8×10^{16} cm^{-3}. Spectral content close to λ_p is observed for the higher two densities.

long electron bunch having interacted with a lithium plasma are consistent with a bunch that has self-modulated. However, evidence for SMI is not fully conclusive at the time of writing. More data, or possibly improved analysis, is required to arrive at a firm conclusion.

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