X-RAY RADIATION AND ELECTRON INJECTION FROM BEAM ENVELOPE OSCILLATIONS IN PLASMA WAKEFIELD ACCELERATOR EXPERIMENTS AT FACET

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Abstract

Plasma wakefield accelerator experiments at FACET at the SLAC National Accelerator Laboratory have shown a correlation between ionization-injected electrons and the betatron x-ray yield. Emittance spoiling foils were inserted into the beam and the x-ray yield, excess charge, and beam energy loss was measured. The excess charge and x-ray yield are attributed to the beam envelope oscillations where at the minima, the field of the beam is strong enough to create secondary ionization, and at the electron oscillation maxima, the beam electrons spontaneously radiate x-rays. Large amplitude beam oscillations are expected to yield more x-rays and create more excess charge, but the results show beam head erosion strongly limits the wakefield excitation.

INTRODUCTION

An important feature of any "blow out regime" plasma-based accelerator is the strong radial fields of the ion column, which creates electron betatron motion and x-ray radiation. This effect can be used to create MeV photons [1] and the x-ray characteristics can be used as a diagnostic of the electrons transverse motion. For example, matched beam propagation would be characterized by minimizing the x-ray radiation signal. Also, mismatched beams will collapse in size to where secondary ionization produces excess charge (i.e. dark current) [2]. Larger emittance beams have larger oscillation amplitudes and therefore they are expected to produce more x-rays and more excess charge. However, large emittance beams also have shorter head erosion lengths [3], which limits the distance over which x-rays and excess charge can be generated. In this paper we study experimentally which of these factors prevail.

SETUP

The experiments were performed at FACET at the SLAC National Accelerator Laboratory during the 2013 E200 PWFA experimental run. The 20.3 GeV electron bunch contained 2.0x10^{10} electrons with an rms bunch length of ~40 um. The x and y normalized emittances, ε_N, were designed to be 50 and 5 mm-mrad, respectively. Typically, the beam betas where 0.10 meter in x and 1.0 meter in y, giving a spot size at the plasma entrance of 11 μm in x and y. The beam was sent through a ~30 cm long rubidium heat pipe oven where the plasma was formed by the field of the beam via tunneling ionization. The Rb vapor was contained using argon as a buffer. The primary diagnostic measurements discussed here are: the x-ray radiation, beam charge, and beam energy. The x-ray yield was measured with a Lanex screen and CCD camera. A 1 mm thick Tungsten foil was placed in front of the screen, which gives a photon detection threshold of 200- 300 keV. SLAC toriods were used to measure the beam charge upstream and downstream of the plasma. The excess charge was measured using the difference between the toriod signals. The change in beam energy was measured with an imaging dipole spectrometer. To study emittance effects, emitttance spoiler foils were inserted into the beam 1 meter upstream of the plasma entrance. The foils and thickness used in the experiment were: Foil 1 Nicusil 3, 25.4 μm; Foil 2 25/75Au/Cu, 50.8 μm; and Foil 3 Nocoro, 80, 38 μm. The calculated rms scattering angles are 35, 58, and 64 μrad respectively. A figure showing the set up and the data analysis and methods can be can be found in [4, 5].

DENSITY RAMPS AND BEAM MATCHING

For a plasma with a sharp boundary, the beam matching condition is $\beta_{match} = 1/k_b$, where k_b is the plasma betatron wavenumber (Eqn. 2). For our experimental parameters, β_{match} = 0.3 cm. Beam matching on this scale is difficult to produce, but as shown in [1, 6] a density ramp can significantly reduce the oscillation amplitude of an unmatched beam, thereby reducing the expected x-ray yield. For the right beam parameters, the ramp can be used to produce matched beam propagation. A larger β can be used in proportion to the scale length of the ramp. For the plasma ramp at FACET, the matched β is 3.38 cm.

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CALCULATION OF THE BEAM SIZE AND EMITTANCE WITH SPOILER FOIL INSERTED

When a foil is inserted, the new beam parameters at the plasma entrance can be calculated by propagating the no foil parameters from the beam waist back to the foil and then calculate the new beam parameter due to foil scattering θ. The new beam parameters at the foil are calculated using [7]

$$\varepsilon^2 = \varepsilon_0(\varepsilon_0 + \beta_0\theta^2)$$
$$\beta^2 = \beta_0^2\varepsilon_0 / (\varepsilon_0 + \beta_0\theta^2)$$
$$\alpha^2 = \alpha_0^2\varepsilon_0 / (\varepsilon_0 + \beta_0\theta^2) \qquad (1)$$

After scattering, the new beam parameters can be propagated back to the oven entrance. The foils increase the beam emittance and the beam size at the plasma entrance, creating a greater mismatch. The beam envelope oscillation for a mono-energetic electron beam can be calculated using Eqn. 2 and is plotted in figures 1 and 2.

$$\frac{d^2\sigma}{dz^2} + k_b^2\sigma = \frac{\varepsilon_N^2}{\gamma^2\sigma^3} \qquad k_b = \frac{\omega_p}{c}\frac{1}{\sqrt{2\gamma}} \qquad (2)$$

The figures illustrate how the beam envelope changes after inserting a foil. Figure 1 is plotted, using the experimental parameters in x, without the spoiler foil. Figure 2 shows the beam envelope with foil 1 inserted. With the foil inserted, the oscillation amplitude inside the plasma increases in proportion to the emittance ratio, $\varepsilon_{vacuum}/\varepsilon_{foil}$. Also, when the foil is inserted, the envelope minimum inside the plasma does not change. This is because, although β at the oscillation minimum is smaller, the emittance is proportionally larger and so σ_{min} is unchanged ($\sigma^2 = \beta\varepsilon$). Excess charge can be created when the drive beam pinches and the field exceeds the ionization threshold for secondary electrons from RbII and ArII. Injection of plasma electrons into the wake can limit the wake amplitude and reduce the accelerating gradient [4].

PARTICIPATING CHARGE AND, HEAD EROSION

If the head of the beam is not dense enough to ionize the Rb vapor, the beam electrons contained in that region will not participate in the wake formation. This causes a reduction in the bunch length, σ_z (but not necessarily the peak beam current).

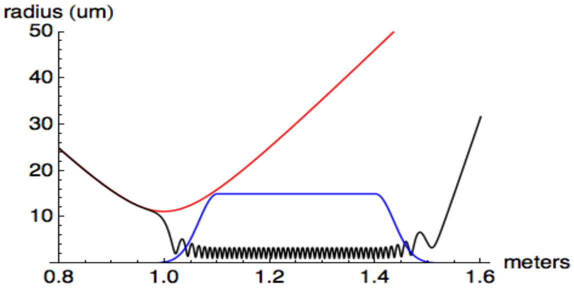

Figure 1: Plot of beam size envelope for 20.3 GeV and 2.7x10^{17} cm^{-3} plasma without spoiler foil (black). The beam envelope in vacuum (red). The plasma profile (blue).

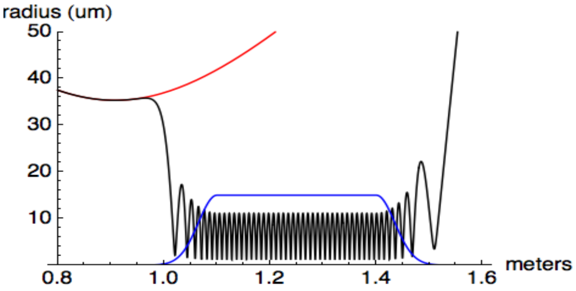

Figure 2: Same as figure 1 with spoiler foil inserted.

Head erosion is a physical effect that limits the length of the wake excitation [3]. It is due to the fact that the ionizing front of the beam is not in the blow out region and is not focused or guided by the ion channel. The unguided front of the beam expands, as it would do in vacuum, and the ionizing front moves back in the beam frame at a rate v_{etch} [3]. The head erosion length is given by $L_{he} \sim \sigma_z / v_{etch}$, where σ_z contains only the participating charge.

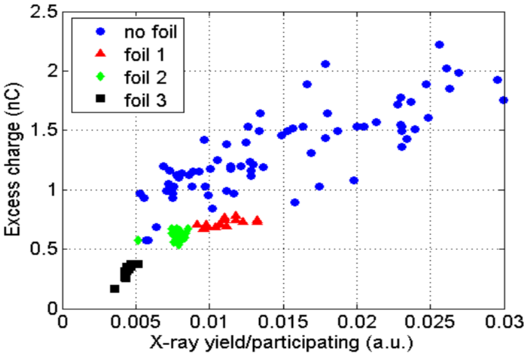

Figure 3: Experimental plot showing measured correlation of the excess charge verses x-ray yield.

EXPERIMENTAL RESULTS

Figure 3, shows the correlation between the measured x-ray yield and the excess charge which takes into account the reduced participating charge. The measured participating charge is 90% for no foil, 70% with foil 1, 65% with foil 2, and 50%, with foil 3. The inferred σ_z is reduced 30 to 50% when the foils are inserted.

Both x-rays and excess charge are reduced as foils are added. Even accounting for the lower participating charge, the x-ray yield should increase with larger emittance since the oscillation amplitude increases with larger emittance. Figure 3 shows this expectation is not the case. This is because increasing emittance reduces L_{he} in three ways. First, the large beam size will reduce the participating charge causing a reduction in σ_z, second the etch rate is higher (v_{etch}~ε_N) and third, large beam mismatch causes emittance growth as the beam propagates. Head erosion theory [3] assumes matched beam propagation. However, for these experiments the beam was not matched. Simulations show mismatched beams have emittance growth and will erode faster than matched beams. Applying Eqn. 1, to foil 1, the emittance grows from 5 to 22.5 mm-mrad in y and from 50 to 165 mm-mrad in x, thus shortening the head erosion length by 3.3 to 4.5 times. As for the x-ray production, the effective length over which x-rays are produce is ~½ L_{he}. Emittance spoiling also showed a reduction in beam energy loss. Typical energy loss without foils was >12 GeV. This indicates the beam propagated approximately the entire length of the Rb vapor. The energy loss for with foil 1, 2 and 3 was approximately 7, 5, and 3 GeV, respectively. Although some of this reduction could be due to a smaller wake amplitude (resulting from reduced participating charge) simulations show, the main effect is the reduction in the length of wake excitation as emittance is increased. This implies the length of the wake formation was reduced as foils were inserted, further emphasizing the effect of head erosion on the experiments.

SUMMARY

While emittance spoiling would seem to increase the x-ray yield, the experiment shows a significant reduction in x-ray signal. Emittance spoiling also reduces the excess charge. The reduced energy loss indicates reduced wakefield excitation length. The entirety of the results, x-rays, excess charge and energy loss, imply severe beam head erosion when spoiler foils are used. With a preionized plasma head erosion is strongly mitigated. Recent results [8] with preionization show the participating charge is nearly 100%.

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