A BETATRON-ANALYSIS TECHNIQUE FOR IDENTIFYING NARROWBAND TRAPPED CHARGE WITHIN A BROADBAND ENERGY TAIL IN PWFA EXPERIMENTS AT FACET*

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Abstract

Plasma accelerators driven by ultra-relativistic electron beams have demonstrated greater than 50 GeV/m acceleration gradients over a distance of a meter [1] though the accelerated particles typically have had a 100% energy spread when a single drive bunch was used. However, it is known that by locally producing electrons via ionization within the beam-driven plasma wake, they can become trapped and accelerated so that high-energy, mono-energetic electron bunches can be produced [2]. Prior experiments and the associated simulations [3] suggested that, by augmenting the usual He buffer gas in the heat pipe oven plasma source [4] with a moderate ionization potential (IP) gas such as Ar or Ne, local injection can indeed occur. In a recent experiment associated with the E-200 plasma wakefield accelerator (PWFA) experiment at the Facility for Advanced Accelerator Experimental Tests (FACET) [5] at SLAC, the expected energy gain of these injected electrons (initially at rest) puts them within the energy range of the accelerated tail electrons of the FACET beam. We propose a technique to help identify bunchlets of electrons at the 10's of pC level arising from the ionization injection of Ar/Ne electrons that may otherwise be lost or overlooked as part of the discrete betatron-focusing maxima or the maxima inherent the chromaticity of the imaging electron spectrometer.

OBJECTIVES OF THE EXPERIMENT

For most applications of high-energy beams, narrow energy spreads are desired. By employing spatially localized ionization to produce and inject new electrons within the plasma wake, a PWFA can produce high-energy, mono-energetic electron "bunchlets".

When these bunchlets appear at the image plane of the imaging spectrometer, there are two other types of distinct features that may mask the bunchlets having only 10's of pC of charge. First is the fact that the highly chromatically aberrated electron imaging spectrometer has a very narrow energy range for which a stigmatic focus–a focus that is simultaneous focusing in x and in y (or energy) at the same spot–is located and thus there is always a "bright feature" in the spectrum due to this. Secondly, even with a broadband spectrometer, the electrons (both the FACET beam electrons and any injected electrons; i.e., the bunchlet) exit the plasma with an energy-dependent phase advance of their betatron envelope oscillations [6] that leads to an energy-dependent divergence of the electrons at the plasma exit. This fact also puts structure onto the final spectrum, as discussed below.

Let ζ_k represent the local (within the wake) longitudinal location of the k^{th} slice of the accelerated electrons. Suppose further that this k^{th} slice exits the plasma as a nearly parallel beam having undergone $N = N_k$ betatron oscillations. Due to the finite angular acceptance of the spectrometer coupled with the strong focusing force of the ion column within the wake in the blowout regime, and the finite bit-depth of the recording CCD cameras, this slice will appear relatively bright on the spectrometer. There will be another slice, the k+1th slice at a lower energy that has undergone $N = N_{k+1} = N_k + 1$ betatron oscillations and will likewise appear relatively bright at the spectrometer. In fact, for each final slice energy such that $N_{k,m} = N_k \pm m$ where $m = \pm1, \pm2$, etc., there will be a corresponding bright spot on the spectrometer. We call this series of spots the "betatron ladder". This ladder was clearly visible in the E-167 energy-doubling experiment of Ref. [1].

In the following Sections we will describe the experimental setup, derive the energy-locations of the betatron ladder, and finally suggest a strategy for identifying the bunchlets within the other structures appearing at the image plane of the spectrometer. Specifically, by placing the stigmatic focus on one "rung" of the ladder after another over a series of data aquistion runs, we can optimize our chances of observing accelerated bunchlets, especially if they lay between or straddle the rungs on the aforementioned betatron ladder.

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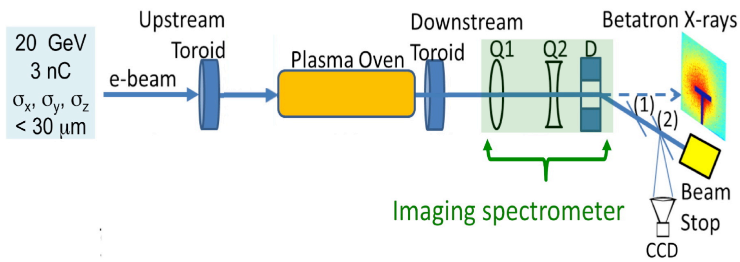

Figure 1: Schematic of portions of the E-200 experimental setup. A 20.35 GeV, 3 nC, compressed ($\sigma_z \sim 30$ μm) electron beam is focused ($\sigma_x = \sigma_y \sim 30$ μm) near the entrance of a Li-vapor column contained in the plasma oven. Toroids measure the incoming and outgoing electron charge. Betatron X-rays excite a phosphor screen located behind 1 mm of copper; the emitted light is captured by a CCD camera (not shown). The imaging spectrometer (quadrapole doublet Q1 and Q2 plus dipole D), discussed further in the text, sends the electrons to the beam stop prior to which is the Cherenkov air gap. The gap is composed of the two Si wafers (1) and (2) which are in laboratory air, thus emitting a Cherenkov-light cone that is subsequently reflected by wafer (2) to a pair of CCD cameras (two cameras for a wide vertical or energy field of view).

EXPERIMENTAL SETUP

A rough schematic of the FACET setup for the E-200 experiments is shown in Fig. 1. The fully compressed FACET beam ($\sigma_z \sim 30$ μm) is focused to a nearly round spot of $\sigma_x = \sigma_y \sim 30$ μm near the front edge of the Li vapor column which has a length of about 39 cm FWHM. The Li is contained in an oven at a temperature of nearly 1000°C, giving a Li neutral density of 2.5 x 10^{17}cm^{-3}. At each end of the oven is the buffer gas composed of He alone or He with an admixture of an intermediate IP gas such as Ar or Ne. This closed system is in pressure balance. The cooler buffer gas confines the Li by collisionally forcing the escaping Li atoms to the walls where a wick returns the (now liquid) Li back towards the oven's center. The length of the boundary region is about 10 cm on each side of the ~ 29 cm-long constant-density portion of the vapor column. The Li is easily field-ionized by the radial electric field of the (vacuum-size) FACET beam while the He is not. To obtain a mono-energetic beam from the accelerated ionization-injected electrons—the goal of this experiment—fine-tuning of the focal position of the FACET beam and the longitudinal distribution of the admixture is required. Ideally, the FACET beam would have a betatron pinch localized to where the flat-topped region of Li begins and where the availability of the admixture element nearly ends thus terminating injection.

The imaging spectrometer consists of a quadrapole doublet, a dispersing dipole magnet, a pair of Si wafers tilted at 45° to the beam, and two CCD cameras to record the Cherenkov light emitted in the air gap between the wafers and reflected to the lenses of the cameras. As mentioned before, the energy-bandwidth for which a stigmatic focus is obtained is very small.

Examples of the spectra recorded by the spectrometer cameras are shown for three different experimental conditions in Figs. 2(a)-(c). As can be seen especially in Fig. 2(b), the local brightness of the spectrum increases at an energy for which the spectrometer was set to produce a stigmatic focus. The magnification of the spatial imaging from the plasma exit to the Cherenkov air gap is about nine times larger in the *x*-direction than in the *y*- or energy-direction.

Figure 1(a) shows the aforementioned betatron ladder; the few bright spots beginning at ~ 24 GeV and up, as well as a rung near 17 GeV as evidenced by the bulge in this (purposely) saturated portion of the image. For this shot, the final focus quadrapoles were set to put the main interaction point waist about 20 cm upstream of the Li column, twice the β^*_x (= 10cm) of the vacuum waist. Since β^*_y = 100 cm, the beam had a larger *x*-size when it began to field-ionize the Li and hence the amplitude of the betatron oscillations was large in the *x*-direction. This allowed for a clear analysis of the betatron features that is discussed in the following Section.

BETATRON ANALYSIS

For a given plasma density, the number N_k of betatron oscillations experience by the k^{th} slice of the beam is related to the *initial* energy of the beam slice E_0 (which we will approximate as independent of ζ), the effective length L of the plasma and the *final* energy of that slice E_k ($z = L$).

Number of betatron envelope oscillations

A simple definition of N_k is the ratio of L to the betatron period for the k_{th} slice. The betatron period is given by [6] $\pi / k_\beta(\zeta_k,z) = \omega_p(z)/(\pi c)/\left(2\gamma(\zeta_k,z)\right)^{0.5}$. The general expression for N_k at the plasma exit is given by

$$\begin{aligned} N_k(\zeta_k)\big|_{z=L} &= \int_0^L \frac{k_\beta(\zeta_k,z)}{\pi} dz \\ &= \frac{\omega_p}{\pi c\sqrt{2}} \int_0^L \gamma(\zeta_k,z)^{-\frac{1}{2}} dz \\ &= \frac{\omega_p}{\pi c\sqrt{2}} \int_0^L \left[\gamma_0 + \frac{eG(\zeta_k)z}{mc^2}\right]^{-\frac{1}{2}} dz \end{aligned} \quad (1)$$

where we have assumed a constant density along z and a non-evolving electric field of the wake $G(\zeta)$. The final form of Eq. (1) reduces to

$$N_k(\zeta_k)\Big|_{z=L} \approx L \frac{\sqrt{2}\omega_p \left(mc^2\right)^{\frac{1}{2}} (\pi c)^{-1}}{E_k^{0.5}(\zeta_k) + E_0^{0.5}} \qquad (2)$$

where $E_k(\zeta_k)$ is again the *final* energy of the k_{th} slice.

Building the betatron ladder

As mentioned before, integer changes in N define the betatron ladder. Thus, taking $N_{k+1} - N_k = 1$ and solving for L we have

$$L = \frac{\pi c}{\sqrt{2}\omega_p \left(mc^2\right)^{0.5}} \left(\frac{1}{E_k^f(\zeta_k)^{0.5} + E_0^{0.5}} - \frac{1}{E_{k+1}^f(\zeta_{k+1})^{0.5} + E_0^{0.5}} \right)^{-1} \qquad (3)$$

where $E_{k+1} < E_k$. After substituting L from Eq. (3) into Eq. (2), and replacing N_k with $N_{k,m} = N_k \pm m$ ($m = \pm 1, \pm 2$, etc.) the expected energy-locations $E_{k,m}$ of all the other rungs on the betatron ladder are obtained. The dashed lines in Fig. 2 show this calculated ladder lying nicely on the experimentally identified locations of the betatron features.

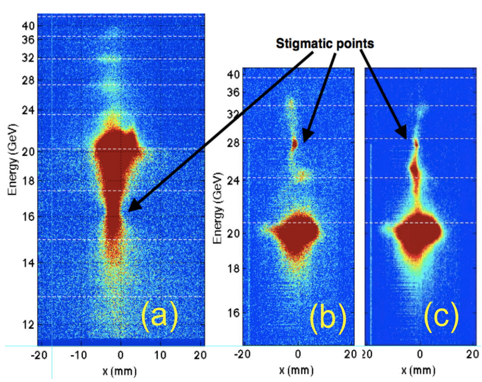

Figure 2: Three electron spectra with betatron ladders overlaid (white dashed lines, see text). (a) Buffer gas: He only, FACET waist 20 cm upstream of Li. (b) Buffer gas 50% He, 50% Ar, FACET waist 0 cm upstream of Li. (c) same as (b) but shot - by - shot difference: potential candidate shot.

The value of L is determined numerically by the measured energies of two of the rungs of the ladder; E_k and E_{k+1}. If there are multiple betatrons spots as in Fig. 2(a), one can take E_k and E_{k+2} while taking $N_k - N_{k+2} = 2$. The same value for L should obtain.

STRATEGY

To distinguish the ionization-injected and accelerated bunchlets from the other structures due to the betatron ladder as in Fig. 2(a) and the narrowband stigmatic focusing of the imaging spectrometer as seen in Fig. 2(b), it is best to place the stigmatic point on a rung of the ladder in order to reduce the complexity of the structred spectrum and thus make the identification of a bunchlet more obvious. Since the energy of the bunchlet is initially unknown, this process would be repeated over a series of data acquisition runs, each run with the stigmatic point dialed onto one of the ladder's rungs. In this way, charge that appears between rungs of the ladder or widely stradling them may possibly be attributable to the bunchlets.

It is important to note that, even if a bunchlet and accelerated FACET tail electrons in some longitudinal slice have the same energy, they will not have the same number of betatron oscillations since the initial energy $E_{0,\mathrm{trapped}}$ of the trapped charge is zero. Thus, the bunchlets could very well be focused or badly defocused at any given output energy. This is why scanning the energy-imaging point is important.

A co-called "candidate shot" for a bunchlet is shown in Fig. 2(c) where there appears to be charge both away from the stigmatic point and straddling rungs the betatron ladder; i.e., it appears that this charge is a new feature not seen in Fig. 2(b).

Although a full analysis of existing data using this strategy has only now begun, looking forward to future runs at SLAC, the plasma length L at FACET is designed to be increased by several times over the current length. While this could in principle simply scale the bunchlet-identification issue to higher energies on the one hand, on the other hand, it may result in a much cleaner measurement of these bunclets. Simulations show that the bunchlet is trapped in the high-field spike at the back of the wakefield, giving it an inherent energy-gain advantage over the FACET tail electrons. Thus, the density of the plasma can dropped to depopulate the high-gradient portion of the wakefield of FACET-beam tail electrons, potentially isolating the ionization-injected and accelerated charge on the spectrometer screen.

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