GENERATION OF BUNCH TRAINS FOR PLASMA WAKEFIELD ACCELERATOR APPLICATIONS

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Abstract

We show here that a recently demonstrated masking technique to produce trains of electron bunches can be used to generate a train appropriate for the resonant excitation of plasma wakefields, as well as for the probing of these wakefields with a witness bunch. The typical separation between bunches is in the picosecond range.

INTRODUCTION

The next significant result in plasma wakefield accelerator (PWFA) experiments is likely to be the acceleration of a witness bunch with a large energy gain and a narrow (a few %) energy spread. Previous experiments have shown that 50 GeV/m accelerating gradients can be sustained over meter-long distances. Reaching these large gradients requires short electron bunches (≈30 μm or 100 fs), and correspondingly large plasma densities (≈10^{17} cm^{-3}) for the wavelength of the relativistic plasma wave ($\lambda_{pe}=2\pi c/\omega_{pe}$, $\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$) to be approximately equal to the bunch length [1,2]. However, in this single bunch case of recent experiments, particles cover ≈2π phase of the wakefield and the resulting bunch energy spread after the plasma is extremely wide. This is particularly true after propagations in a long plasma where core bunch particles lose most of their energy and trailing particles see their energy doubled, as in [3] or [4]. The plasma density can be decreased to increase λ_{pe} to accommodate two separate bunches: a drive bunch (DB) that only loses energy and a witness bunch (WB) that gains energy and preserves a narrow energy spread. This is at the expense of the accelerating gradient. However, the constraint remains that the distance between the two bunches Δz and the plasma wavelength must be approximately equal. In addition the length of each bunch must also remain small: σ_{zD}, $\sigma_{zW}<<\lambda_{pe}$. Such bunch trains are difficult to produce, and are not readily available. It has been proposed to produce two short electron bunches distant by one wavelength of the rf accelerator (X-band) and with different energies, to separate them using a dipole or a fast magnetic kicker, and to recombine them with the appropriate delay using a two-chicane system [5], but this was never realized. Note that the first PWFA experiment was performed with two bunches with variable delay [6]. However, the bunches were relatively long, resulting in low amplitude wakefields, and in particular were not short compared to the plasma wavelength.

We have demonstrated that trains of equidistant electron bunches with sub-picosecond separation can be produced using a masking technique [7]. With this method the bunch train parameters – number, spacing, individual length, and even charge - can be chosen by adjusting the mask pattern parameters as well as the beam parameters at the mask.

ATF BEAM LINE

At the ATF, the electron beam is produced in a 1.6 cell, S-band rf-photoinjector [8] and is followed by a 70 MeV S-band linac. The electron bunch with a normalized emittance of ≈2 mm-mrad and ≈300-500 pC can be sent to three different beam lines. For the present experiment, the beam is directed to ATF Beam Line #2 using two dipoles and five quadrupoles arranged in a dogleg.

For the present application the beam energy is E_0 = 59 MeV and the dogleg quadrupoles are adjusted to obtain a region of large dispersion and low beta function (in the plane of dispersion). The beam is also accelerated off the crest of the rf wave in order to impart a correlated energy spread on the bunch (typically $\Delta E/E_0 \approx +1.5\%$). The beam line includes a limiting slit aperture located at a point in the dogleg where the dispersion is $\eta\approx$–0.5 m. This slit can be used to limit the energy spectrum of the bunch. After exiting the dogleg, the beam propagates over a dispersion-free distance of 6.5 m before entering a magnetic spectrometer with a final dispersion of η = 1 m. Before the dogleg, the bunch is about 1500 μm-long (or ≈5 ps, full width). The dogleg longitudinal dispersion function R_{56} is ≈+4 cm, which means that the effect of the dogleg is to either compress or stretch the bunch by ±400 μm (or ±1.3 ps, depending on the sign of the energy chirp) per percent of correlated energy spread.

In the dogleg, the time-correlated energy spread also corresponds to a correlation with position along the x-axis of dispersion.

BUNCH TRAIN FORMATION

The mask is placed in a region of the dogleg where the beam size is dominated by its energy spread. That is, its betatron size $\sigma_{\beta x}=(\varepsilon_N\beta_x/\gamma_0)^{1/2}$, where β_x is the beam beta-function, ε_N its normalized emittance, and γ_0 the electron relativistic factor satisfy: $\sigma_{\beta x}<<\eta_{mask}\Delta E/E_0$. η_{mask} is the magnetic dispersion at the mask location [7].

Figure 1: Picture of the wire mesh mask and frame. The wires are d=800 μm in diameter with a period of D=1650 μm. The red arrow indicated the two consecutive wires.

We have modified the mask to produce a train of equidistant (Δz) DBs followed by a WB separated from the last DB by $\Delta z'=1.5\Delta z$. The mask consists of circular stainless steel wires with diameter $d=800\ \mu m$ and stretched on metallic frame. On one side of the mask the wires are separated by $D=1560\ \mu m$. Then two wires are placed next to each other and the distance between the following wires is again D (see Fig. 1). The separation between bunches in the train is given by [7]:

$$\Delta z = D\frac{L_z + R_{56}\,\Delta E/E_0}{\eta_{mask}\,\Delta E/E_0} \qquad (1)$$

where R_{56} is the magnetic compaction factor of the dogleg, L_z is the incoming (long) bunch length. The bunch train spacing follows the mask pattern. A slit with variable width and position is placed at another location along the dogleg where β_x is small and the dispersion large. The slit determines the beam energy range that reaches the mask, and therefore also the number of bunches that are formed. In particular, it can select a number of DBs separated by Δz, followed by WB separated by $\Delta z'$. Figure 2 shows the shadow cast on the dispersed beam by the mask, a distance ≈286 cm downstream of the mask location. Three DBs and one WB are visible. "Leakage" between the two adjacent wires separating the WB from the DBs is also visible. Note that at that location (long before the CTR diagnostic and the PWFA experiment), the majority of the electrons that hit the solid parts of the mask is already lost. The separation between the DBs is 103 pixels, while the separation between the last DB and the WB is 147 pixels, or about 1.5 times larger than between the DBs. Since the energy correlation at the mask reflects the time correlation, the energy distribution of bunches reflects their time distribution (for a linear time/energy correlation, and in absence of parasitic effects such as CSR interaction). The energy arrow on Fig. 2 indicates that the witness bunch has the lowest energy in the train. This is not optimum for energy gain measurements in PWFA experiments. When the beam/plasma conditions are such that the DBs lose energy and the WB gains energy (resonance), the DBs and WB overlap in energy, therefore masking the origin of the particles gaining energy (WB or first DB?). The energy chirp of the beam can be rotated using a harmonic X-band cavity, thereby placing the WB at the highest energy in the train. Plans exist to install such a cavity at ATF. Note that this separation is in energy, and that the time separation has to be measured using coherent transition radiation (CTR) interferometry.

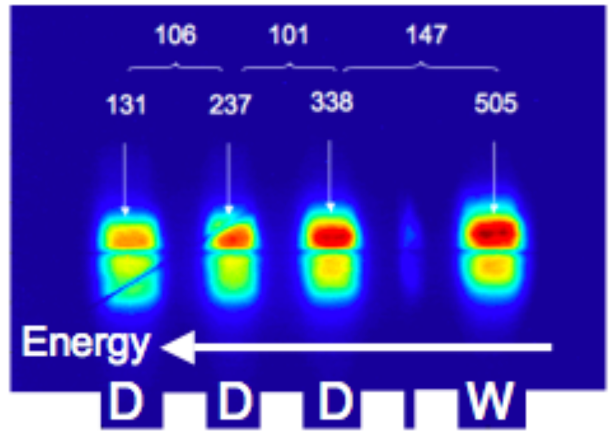

Figure 2: Shadow cast by the wire mesh captured 286 cm downstream from the mask, in the dogleg. Three DBs and one WB have been selected with the energy slit. The slit and the mask wires are schematically indicated by the white rectangles at the bottom of the image. The numbers indicate the bunch locations on the image, as well as their calculated separation (in pixels). The two lines across the image are caused by alignment wires on the screen.

TIME STRUCTURE

The bunch train produces transition radiation (TR) when entering a copper mirror located after the dogleg. The TR is sent to a Michelson interferometer where the coherent components (CTR) interfere according to the path length difference between the interferometer's two arms. The interference pattern contains information about the bunch spacing and width. Figure 3 (top) shows the CTR interference signal for the case when only the three DBs are selected by the slit. The number of DBs can be deduced from the number of peaks since N bunches produce $2N\text{-}1$ peaks. The path length difference between the peaks can be directly measured or inferred from the FFT of the interference signal (Fig. 3, bottom). In this case Δz≈390 μm. Note that $\Delta z'$ can be directly measured by selecting only the last DB and the WB with the slit for the CTR measurement. This measurement was not done in this case. However, Fig. 3 shows that a DB train was indeed produced, and since the electrons are relativistic and dephasing is therefore not an issue over the distance considered here, one can reasonably assume that the WB travels about 485 μm behind the last DB.

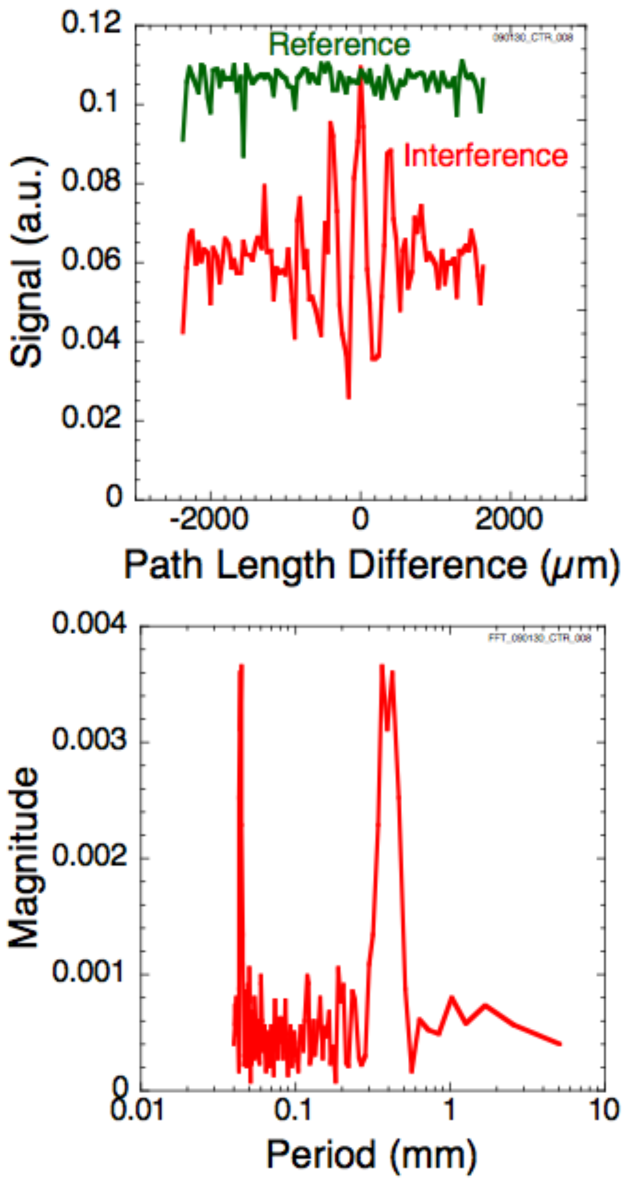

Figure 3: Top: CTR trace (red line) obtained with three DB only. The green line is the measurement of the CTR energy before the interferometer recorded for reference. Large variations in the reference signal would result from a charge (CTR~Q^2) or a bunch length variation during the scan and would compromise the DB distance measurement. Bottom: Amplitude of the Fourier spectrum of the top CTR trace. The peak shows that the distance between the peaks is about 390 μm.

SUMMARY

We used the masking technique that we previously demonstrated [7] to produce a train of bunches appropriate to demonstrate for the first time the resonant excitation of plasma wakefields in plasmas with densities in the 10^{16}-10^{17} cm^{-3} range. The train consists of a variable number of equidistant drive bunches followed by a witness bunch. Preliminary PWFA results are presented in these Proceedings [9]. Note that such a sub-picosecond separation bunch train can also be used for the study of coherent synchrotron radiation CSR in magnetic bends, and chicanes. The shape of the microbunches and therefore the amount of radiation they produce can be varied by changing the beam betatron size at the mask [10]. Suppression of CSR is particularly important for the design of electron/proton colliders [11], such as the one planned at the Brookhaven National Laboratory [12]. CSR results in an increase of the energy spread and of the emittance of the bunches in the train. CSR effects can also be studied at the picosecond scale as a function of the distance between the two bunches. In addition there trains are also useful to study the coherent emission of THz radiation in dielectric coated metallic tubes and as a picosecond x-ray camera when combined with inverse Compton scattering [12].

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