GENERATION OF ELECTRON MICROBUNCHES TRAINS WITH ADJUSTABLE SUB-PICOSECOND SPACING FOR PWFA AND FEL APPLICATIONS

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Abstract

We use a wire mesh mask placed in a dispersive region of the Accelerator Test Facility (ATF) at Brookhaven National Laboratory to produce a train of equidistant drive microbunches followed by witness bunch. This type of electron microbunch structure is appropriate for plasma wakefield accelerator experiments. These experiments aim at demonstrating the enhancement of the accelerating field when the wakefield is resonantly driven by a train of microbunches, as well as finite energy spread of the witness bunch after acceleration.

INTRODUCTION

Plasma-based particle accelerators have made extraordinary progress in the last few years. Electron bunches with narrow energy spread (<10%) have been produced in laser-driven wakefield accelerators (LWFAs). These bunches consist of background plasma electrons trapped by the large amplitude plasma wake. The energy of 42 GeV incoming electrons has been doubled in only 85 cm of plasma [1] in particle beam-driven plasma wakefield accelerators (PWFAs). In this case the single electro bunch both drove the plasma wake and experienced the accelerating wakefield, i.e., the bunch covered all the phase of the first plasma wake bucket. As a result the energy spectrum after the plasma extended from ≈10 GeV to ≈84 GeV. In order to produce high energy, high quality accelerated bunches (electrons or positrons), witness bunches will have to be injected in the plasma wake driven either by an intense laser pulse or a high-current particle bunch.

In the case of the PWFA, two linacs may be used to produce and inject the two bunches in the plasma. However, the plasma density n_e in a high-gradient PWFA is typically in the 10^{16}-10^{17} cm^{-3} range. The length of the wake bucket is typically of the order of the plasma wavelength ($\lambda_{pe}=2\pi c/\omega_{pe}$, $\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$), i.e., between ≈100 and ≈300 μm for these densities. Therefore the two bunches must be shorter than λ_{pe}, separated by $\approx\lambda_{pe}$, and travel collinearly to fit in a single plasma wake bucket. Producing such a two-bunch train is challenging.

In addition, in a PWFA driven by a symmetric Gaussian current profile bunch is limited to twice the energy of the incoming drive bunch [2]. However, the energy gain can be increased by driving the plasma wake with a bunch with a triangular current profile a few λ_{pe} long [3], or with a train of bunches with a ramped current or ramped bunch train (RBT) [4]. This RBT method is applicable to all collinear wakefield accelerators. It has recently been demonstrated experimentally in a dielectric loaded accelerator (DLA) driven by two bunches [5]. In that case, the accelerator wavelength is relatively long (23 cm), and the bunches can be separated by multiple wavelengths. The appropriate bunch train can therefore be produced by splitting and delaying the laser pulse that produces the electron bunches on the photocathode of the rf-gun. In the case of the PWFA however, the train must have a microbunch separation of the order of λ_{pe}, and producing such a train is again challenging.

We therefore explore the possibility of creating a train of microbunches suitable for multi-bunch PWFA experiments [6] out of a single initial electron bunch. Such a train should consist of a variable number of equidistant drive bunches separated by Δz, followed by a witness bunch $(m+1/2)\Delta z$, $m=1,2\ldots$ behind the last drive bunch. This ensures that the appropriate plasma density all the drive bunches lose energy to the wake, while the witness bunch extracts energy from the wake and is accelerated.

A number of methods have been proposed to produce a train of microbunches. One of them consists of sending a train of closely spaced UV laser pulses onto the photocathode of an rf electron gun [7]. The inverse free electron laser (IFEL) effect can also be used to produce trains of very closely spaced electron bunches [8]. However, in that case the bunches are all equidistant and their spacing equal to the drive laser wavelength. A method using a mask placed in the chicane of an FEL linac to block portions of the electron beam and therefore also modulate the bunch current in time was proposed [9]. However, to our knowledge it was never implemented.

The method described here uses a solid mask placed in a high-dispersion region of the accelerator beam line where the beam transverse size is dominated by the bunch energy spread. The mask spoils the emittance of the slices that hit its solid parts. These particles are subsequently lost along the beam line. When the particles energy is correlated with their position along the bunch, the mask effectively shapes the bunch current profile (in time). The bunches spacing and length can therefore be tailored for a particular application by designing the mask and adjusting the beam parameters at the mask location. At the Brookhaven National Laboratory Accelerator Test Facility (BNL-ATF), we have recently demonstrated for the first time that this method can indeed be used to produce trains of electron bunches with subpicosecond spacing [10]. We present here preliminary results showing that a drive train/witness bunch combination suitable for PWFA acceleration experiments can be produced. This masking method will also be used for high-energy experiments at the Stanford Linear Accelerator Center, and the mask and suitable beam parameters are presently investigated [11].

This method can in principle be used in all beam lines that include a magnetic chicane or a magnetic dogleg. It can be applied to higher energy beams that can be focused to tighter transverse size at the mask, and therefore produce sharper time features. It is equally applicable to electron and positron beams.

ATF BEAM LINE

At the ATF, the electron beam is produced in a 1.6 cell, S-band rf-photoinjector [12] and is followed by a 70 MeV S-band linac. The electron bunch with a normalized emittance of ≈2 mm-mrad and ≈350 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 = 50 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 $\Delta E/E_0 \approx \pm1.5\%$). 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 $\eta = 1$ 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.

MASK

We use a simple mask consisting of stainless steel wires stretched on a metallic frame. The wires have a diameter of d=800 μm. They are spaced equidistantly on either side of the mask middle with a period (center to center) of $D \approx 1550$ μm, which is also the period of the microbunches. In the middle, two wires are stretched next to each other, thereby creating a gap between the two sides microbunches of (1550+800) μm=2320 μm or approximately 1.5D, a ratio appropriate for a witness bunch in a PWFA. When placed at normal incidence with respect to the electron beam, the mask transparency is therefore (1550-800)/1550≈66% (except in the middle of the mask). This shows the main drawback of the method. The charge that strikes the wires will be lost along the beam line because the emittance growth it suffers in the wires. The mask can be angled with respect to the beam direction to vary the mesh periodicity, but at the expense of the transmitted charge. The mask can be used in conjunction with the beam line energy slit to control the number of drive and witness microbunches in the train.

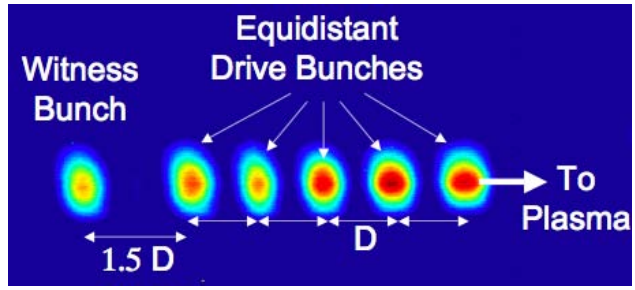

Figure 1: Picture of the beam downstream from the mask. The five drive microbunches, all separated by a distance D, and the witness microbunch following a distance $1.5D$ behind the drive train are clearly visible.

BUNCH TRAIN GENERATION

The mask is placed in the dogleg that is used to deliver the beam to the various ATF beam line. For this application, the dogleg quadrupoles are adjusted to produce a region with large x-dispersion and small beta-x function at the mask location. The small beta function is necessary for the mask to cleanly modulate the bunch charge. The bunch with a correlated energy spread (E, t) acquires a correlation between x-position and energy, i.e., between x-position and time (x, t) in the dogleg. The mask with the wires axis perpendicular to the x-z plane casts a shadow in the x-plane. The maximum number of microbunches produced depends on the bunch relative energy spread $\Delta E/E_0$, beam line dispersion at the mask η_{mask}, and wire mesh periodicity: $N \approx \eta_{mask}(\Delta E/E_0)/D$. Figure 2 shows an image of the bunch on a screen placed a short distance downstream from the mask. To obtain this image the beam line magnets have to be adjusted to produce a beam waist at the screen. Note that the image shows that at this location a short distance downstream from the mask the scattered particles are already lost. This is due to the large scattering angle (emittance growth factor >100) experienced by the electrons hitting the mask wires. For this image the number of drive bunches was chosen as five, and the number of witness microbunches as one using the limiting energy slit. As expected from the mask pattern, the drive microbunches are equidistant and the distance between the last drive microbunch and the witness microbunch is about 1.5 times longer than between the drive microbunches. Because of the time /energy correlation imposed on the bunch, this image corresponds to a bunch train traveling in time toward the right hand side of the image.

After the second dipole magnet of the dogleg that dispersion is brought back to zero, and the (x,t) correlation returned to an (E, t), correlation. That means that the mask pattern is converted from a spatial one to a temporal one. In the process the bunch length may change according to the sign of the energy chirp, as explained earlier. Note that in principle the same image can be obtained at the end of the beam line, where the beam is dispersed in energy. However, at the present time the quadrupole of the magnetic spectrometer are to weak to sufficiently reduce the beam beta function to obtained a sufficient energy resolution.

To prove that the space to time conversion occurred, we used coherent transition radiation (CTR) interferometry. Transition radiation (TR) is emitted when a relativistic particle crosses the boundary between two media with different dielectric constants. In the case of a vacuum to metal boundary, TR has an extremely broad spectrum that ranges from the plasma frequency of the metal to zero frequency [13]. For an ensemble of charges, the TR is coherent for wavelengths longer than that of the bunch, and carries information about the bunch length and time structure. Sending the TR into a Martin Puplett interferometer with a variable delay arm produces an autocorrelation of the signal from which bunch length and spacing can in principle be retrieved. However, wavelength filtering effects along the CTR transport or by the detector may lead to distortions of the autocorrelation signal [14].

Picosecond long bunches emit CTR wavelength in the THz range (>300 μm wavelengths). We use a liquid helium-cooled silicon bolometer detector. The backward CTR produced by the bunch train exits the beam line through a high-density polyethylene (HDPE) window and is focused onto the detector using an off-axis parabola.

Autocorrelation results show that the spatial mask pattern is indeed transferred into a temporal pattern [10]. The measured bunch spacing (for the drive microbunch train) is between 150 and 450 μm. The distance between the last drive microbunch and the witness microbunch can be measured by interfering the CTR signal produced by these two microbunches only. The number of bunches can be chosen by varying the width of the beam line energy slit. Detailed results will be published elsewhere [15].

SUMMARY

Experimental results show that a mask placed in a dispersive region of a beam line can be used to produce a temporal train of picosecond microbunches. The spacing between the microbunches can be adjusted through the mask design. The number of microbunches can be varied by using a variable width slit in conjunction with the mask. We have produced a train of drive bunches followed by a witness bunch appropriate for resonant, multi-bunch PWFA experiments at the ATF.

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