EXCITATION OF PLASMA WAKEFIELDS WITH DESIGNER BUNCH TRAINS

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Abstract

We show that a masking technique we recently demonstrated to shape electron bunches in time can also be used to shape the charge or current along the bunch.

INTRODUCTION

Advanced accelerator concepts, plasma or dielectric based, usually use a single bunche to either simply drive wakefields or to drive and sample the wakefields along a single bunch, about a wave period long. However, a minimum of a drive and a witness bunch, both short when compared to the wave period and separated by $m+1/2$ wave period ($m = 0, 1, 2, ...$) is needed to efficiently extract energy from the drive bunch and transfer it to the witness bunch. In addition, if the witness bunch is short enough, or when using beam loading, the witness bunch can be accelerated with a narrow final energy spread, a necessary characteristic for most applications. Single symmetric bunch produced by rf accelerators (typically with Gaussian longitudinal charge or current profile) lead to a transformer ratio R at most equal to two [1]. The transformer ratio is defined as the (absolute value of the) ratio between the peak accelerating field behind the drive bunch or drive bunch train E_+ and the peak decelerating field within the drive bunch or drive bunch train E_-. The maximum plasma length is roughly determined by the incoming particles' energy W_0 (in eVs) as: $L_{max} = W_0/eE_-$. Note that at low energy dephasing may limit L_{max} to less than this value. Thus the maximum energy gain per witness particle is $W_{gain} = eE_+L_{max} = RW_0$. For example in the recent plasma wakefield (PWFA) experiments at SLAC [2], the maximum transformer ratio was measured to be around 1.6 with a single bunch [3]. In addition, shaping of the drive bunch can help improve the energy transfer efficiency from the drive bunch to the wakefield, for example by ensuring that the decelerating field remains constant along the drive bunch, as in the triangular bunch case (see below). Shaping also improves the energy transfer efficiency from the plasma wakefield to the drive bunch by shaping the witness bunch for optimum beam loading in the nonlinear regime of the PWFA [4].

Either a single drive bunch with a tailored current profile, or a train of bunches with a particular charge/current pattern can lead to $R > 2$ and yield very large energy gain by witness bunch particles. This was demonstrated in a GHz dielectric loaded accelerator (DLA), where the bunch train separation is large enough that it can be generated from multiple laser pulses on a laser photo-cathode [5]. However, for THz frequency DLAs or PWFAs, the bunch separation and length need to be in the ps range and new methods need to be devised to generate the proper time and amplitude structure of the bunch(es). We demonstrated that a masking technique can be used to tailor in time the charge/current profile of particle bunches. This method relies on a correlated energy chirp given to the incoming bunch, as well as on the scattering of selected energy/time slices of the bunch by a solid mask placed in a high dispersion, small beta function region of the beam line [6, 7]. In these publications the mask had a large extent in the dimension transverse to the dispersion direction and each non-scattered energy/time slice of the bunch therefore retained its original charge/current. In particular, a drive bunch train consisting of a selectable number of drive bunches followed by a witness bunch, all with approximately equal charge, was produced and successfully used in resonant excitation PWFA and DLA experiments at the Brookhaven National Laboratory Accelerator Test Facility (ATF) [8, 9]. With typical ATF beam parameters ($E_0 = 60\ MeV$, correlated energy spread $|\Delta E/E_0| \cong 1\%$ and meter dispersion) the mask spatial features are mm-size (see Fig. 1) and resulting time features are in the ps range.

Note that other techniques can be used to generate similar bunch patterns, such as multiple laser pulse on the photo-cathode followed by emittance compensation [10] and emittance exchange in conjunction with a mask [11].

DESIRED BUNCH CHARGE/CURRENT PROFILES

The bunch charge/current profiles that yield $R > 2$ are well known [12, 13]. For single bunches, a triangular profile with a rise time slower than the plasma period and a fall time faster than the plasma period yields $R \cong k_{pe}L_{plasma}/2 = \pi L_{plasma}/\lambda_{pe}$, where $k_{pe} = 2\pi/\lambda_{pe}$ and $\lambda_{pe} = 2\pi c/\omega_{pe}$ are the relativistic plasma wave wavenumber and wavelength, respectively, and $\omega_{pe} = \left(n_e e^2/\epsilon_0 m_e\right)^{1/2}$ is the plasma wave angular frequency in a plasma with electron density n_e. For a bunch long compared to the plasma period, very large transformer ratios can be expected. However, such bunches are also subject to a transverse hose instability [14] that can limit the energy

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gain by destroying the bunch.

In addition, to keep the decelerating field along the triangular bunch constant an initial short perturbation, such as a delta function or a ”door-step” current is needed, otherwise the E_- field exhibits the plasma wave periodicity. This is important for maximum energy extraction efficiency.

A similar idea can be applied to a bunch train. In a ramped bunch train the density in each bunch is raised along the train and the charge ratios and final R depends on the R-value for each individual bunch, itself dependent on the bunch shape and on the number of bunches in the drive train [13].

Both of these shapes can be tailored out of a single incoming bunch.

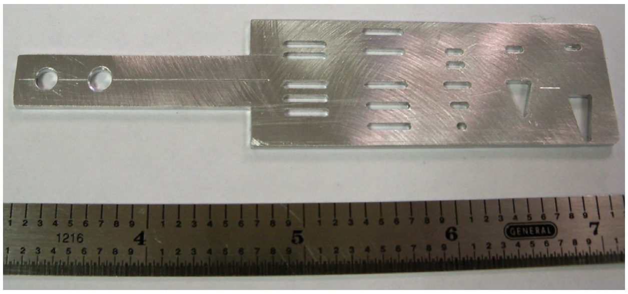

Figure 1: Picture of the mask used to produce the tailored bunches discussed in this paper. The material is aluminum, and the thickness about 2 mm. The two left-most patterns produce trains with no charge tailoring, while the three right-most patterns produce the ramped bunch train of Fig. 3 and two triangular bunch patterns followed by a witness bunch (see Fig. 2).

TAILORING OF BUNCH CURRENT/CHARGE PROFILES

The mask dimension transverse to the dispersion can be used to tailor the charge/current of each bunch slice. Figure 1 shows a picture of the mask we used to produce the tailored bunches discussed below.

Figure 2 shows the image of the bunch dispersed in energy (i.e., in time thanks to the incoming energy chirp), a short distance after the mask shown on Fig. 1. The drive bunch has a clear triangular current profile. The witness bunch is placed one triangle length behind the drive bunch in order to experience the peak accelerating field all plasma densities such that the bunch length is a multiple of the plasma length.

Figure 3 shows the image of a ramped bunch train dispersed in energy (i.e., in time thanks to the incoming energy chirp), a short distance after the mask shown on Fig. 1. The drive bunch train has an increasing charge along the bunch, as expected. In this case the witness bunch is blocked by the high-energy slit, used in conjunction with the mask to select the number of drive bunches or the presence of the witness bunch. The distance between the witness bunch and the last drive bunch is equal to that between drive bunches. At a plasma density such that the plasma wavelength is equal to the distance between the bunches the witness bunch experiences the peak accelerating field and the maximum transformer ratio. As visible from the mask the witness bunch differs from the drive bunches only by its lower charge.

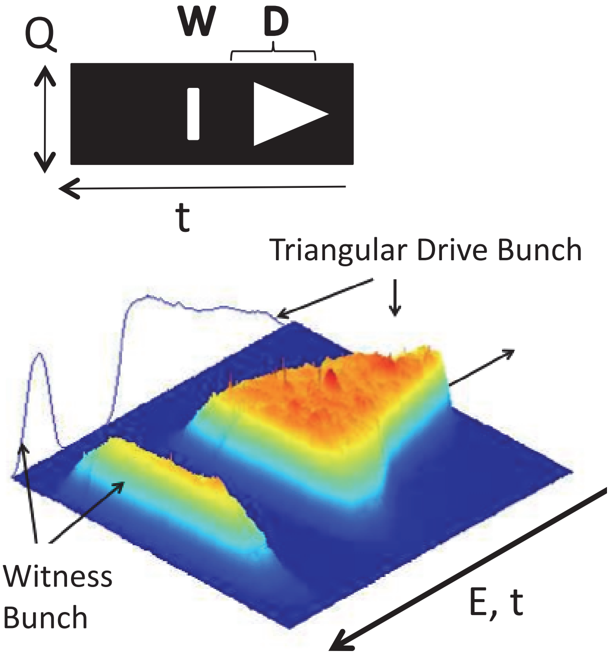

Figure 2: Image of the bunch dispersed in energy/time, a short distance downstream from the mask with triangular profile of 1. The bunch train charge/current profile is shown by the blue line. The top cartoon shows the mask ideal shape.

SPECIFIC CONSIDERATIONS

The above shows that the masking technique can be extended to also tailor the charge/current of each energy/time slice of the bunch or bunch train. However, to tailor the charge, the mask also reduces the bunch vertical size. Most publications assume that only the local bunch density changes for tailored bunch. However, with this masking technique, the bunch density remains essentially constant along the bunch or train while its radius changes. This also means that the size and density of the smallest transverse features (tip of the triangle) at the plasma entrance is limited by the bunch incoming emittance. The first effect must be taken into account when calculating the expected wakefields.

For example in 2D linear theory, the longitudinal and transverse wakefields are given by [15]:

$$W_{\parallel}(r,\xi) = Z'(\xi)R(r) = E_{\parallel}(\xi)R(r) \quad (1)$$

$$W_{\perp}(r,\xi) = Z(\xi)R'(r) \quad (2)$$

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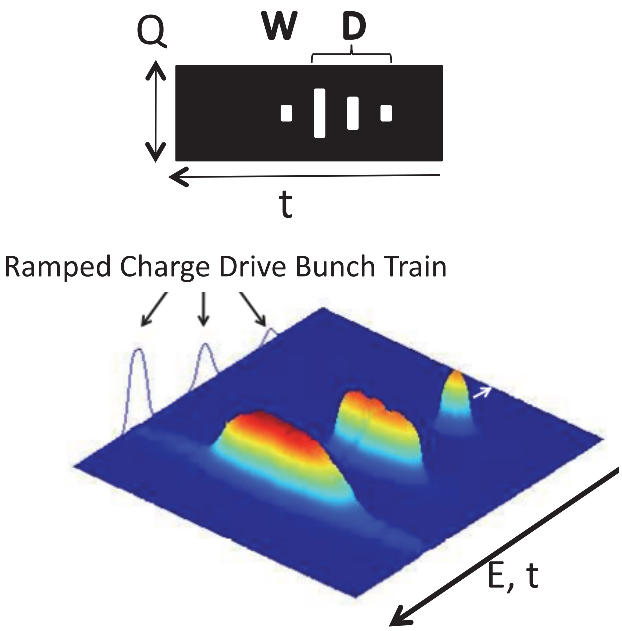

Figure 3: Image of the bunch dispersed in energy/time, a short distance downstream from the mask with the ramped bunch and witness bunch profile of 1. The blue line shows the bunch train current profile. The top cartoon shows the mask ideal shape.

where:

$$Z(\xi) = \frac{e}{\epsilon_0 k_p} \int_{-\infty}^{\xi} d\xi' n_{b\|}(\xi') sin\left(k_p(\xi - \xi')\right) \quad (3)$$

$$E_{\|}(\xi) = \frac{e}{\epsilon_0} \int_{-\infty}^{\xi} d\xi' n_{b\|}(\xi') cos\left(k_p(\xi - \xi')\right) \quad (4)$$

and:

$$R(r) = k_p^2 \int_0^r r'dr' n_{b\perp}(r') I_0(k_p r') K_0(k_p r)$$
$$+ k_p^2 \int_r^{\infty} r'dr' n_{b\perp}(r') I_0(k_p r) K_0(k_p r') \quad (5)$$

The bunch longitudinal and transverse density profiles are given by $n_{b\|}$ and $n_{b\perp}$, respectively, and I and K are the Bessel functions of the first and second kind. Therefore, as the bunch radius varies (but $n_{b\|}$ and $n_{b\perp}$ remain constant), the bunch charge must be adjusted to preserve the desired wakefield in the drive bunch or train. In addition, when the transverse size of the mask is not small when compared to the beam vertical betatron size, the incoming transverse charge distribution must also be accounted for to reach the desired charge/current profile.

These new tailored bunches have been succesfuly used for DLA self-modulation experiments [16] and will be used for PWFA experiments with large transformer ratio.

CONCLUSIONS

The masking technique we have demonstrated [6, 7] has been extended to not only tailor the bunch time structure, but also its charge/current pattern. These new bunch formats produced by this extended masking technique have already allowed new and unique DLA experiments in the THz frequency-range and will be used for PWFA experiments. In particular, the transformer ratio could be directly measured by visualizing the plasma density perturbation using techniques such as Fourier domain holography [17]. We are planing such measurements at the ATF with the various bunch shapes and at various plasma densities.

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