REPETITIVE BUNCHES FROM RF-PHOTO GUN RADIATE COHERENTLY

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Abstract

We consider injecting the plasma wake field accelerator of the Alpha-X project [1] by a sequence of low charge pancake shaped electron bunches. This solves the problem of undesired expansion due to space-charge forces of a single high charge bunch. To this end the photo-excitation laser pulse of the RF-photo-injector is split into a sequence of sub-pulses. The inter-bunch distance can be chosen such that the sub-bunches fall into successive ponderomotive wells of the plasma accelerator. In this way the total radiated output is kept as high as possible. The repetitive photo gun can be tested, at low energy, by injecting its output into an undulator and monitor the radiation. This programme is informed by results of new GPT simulations [2].

INTRODUCTION

In the ALPHA-X-project an ultra-short electron bunch, of the order of 30 μm (100 fs) will be accelerated in a laser driven plasma wake-field accelerator and then subsequently sent through an undulator [3] to produce useful radiation. The main purpose of the experiment is to demonstrate the possibility of constructing a table top FEL.

As with conventional accelerators, the first problem to attack is the production of electron bunches which are sufficiently short to inject into the accelerating potential. The ponderomotive wavelength of the wake-field accelerator is of the order of 40 μm for a plasma density, $n_e = 7 \cdot 10^{17}$ cm^{-3}. The RF-photo-injector used will deliver 5 MeV, 30 μm, bunches of several hundreds pC, but due to the space-charge forces, such bunches can not be transported over the inevitable space required for other beam line components between the gun and the accelerator. Even pancake-shaped bunches of this size with only 100 pC total charge will expand considerably.

In order to keep the total accelerated charge to an acceptable level while maintaining the bunches short we propose to split the bunch into a number, say ten, sub-bunches and to fill not one, but 10 successive buckets of the ponderomotive wave in the plasma wave accelerator. This bunch splitting is obtainable via Fourier plane filtering of the laser pulse illuminating the photocathode. The generated sequence of sub-bunches will have a total length of ≈ 1 mm, still corresponding to a small fraction in the RF-cycle of the gun (3 GHz) and thus the resulting sub-bunches can be considered almost identical. In this paper we fill every other bucket of the PMW, to ease interpretation. This results in a total length of ≈ 2 mm, still short with respect to the 3 GHz cycle.

As the plasma wave accelerator is already a quite complicated device on its own, it is useful to test the generation of sub-bunches separately. At 5 MeV, the midrange of the RF-photo gun, the ponderomotive wavelength of the generated light in the undulator is quite close to that of the wake-field accelerator. If successive PMW-well's in the undulator are filled with sub-bunches, the output radiation is in phase and adds coherently. This can be monitored with a spectrometer or THz-detector [5], and so, the repetitive photo gun can be tested with the undulator alone.

In this paper we calculate the output of the undulator for a single bunch when the bunch length is varied, and for a sequence of sub-bunches when the inter sub-bunch distance is varied.

The simulations are carried out with GPT. The electron bunch and undulator parameters used in this paper are compiled in tables 1 and 2.

Table 1: Electron bunch parameters

Energy	$E_0 = 5$ MeV
Emittance	$\epsilon_n = 3\ \mu$m
Sub bunch Charge	$q_b = 10$ pC
Total bunch Charge	$Q_b = 100$ pC
Sub bunch length	$\sigma_z = 30\ \mu$m (Gaussian)
Total bunch length	$L_b \approx 2$ mm
Tranverse size	$\sigma_r \approx 1$ mm

Table 2: FEL parameters

Undulator per.	$N_u = 96$	$\lambda_u = 15$ mm
Magnet strength	$B_u = 0.72$ T	$K_{rms} = 0.71$
Gap width	$G = 3.5$ mm	
Slot dim.	$w = 5$ mm	$d = 1$ mm
waveguide dim.	$a = 4$ mm	$b = 4$ mm
rad. wavelength	$\lambda_s = 98.5\ \mu$m	$\lambda_{pmw} = 97.9\ \mu$m

EXPANSION OF THE ELECTRON BUNCH

The longitudinal expansion of a 30 μm bunch, in the beam line between the gun and the accelerator, is shown in fig. 1 for two values of the bunch charge, 100 pC and 10 pC respectively. The transverse dimensions of the bunch

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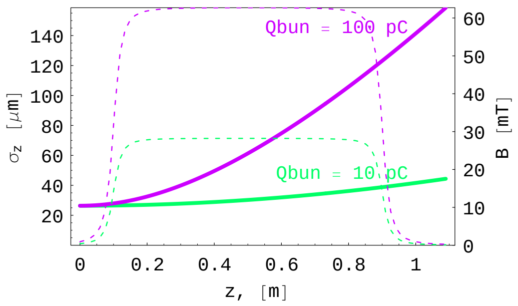

Figure 1: Longitudinal expansion of a short bunch due to the space-charge forces in one meter drift space. The bunch energy is 5 MeV, the bunch length is initially 30 μm. The bunch charge is indicated. Its transverse size in both cases, is kept at $\approx$ 1 mm with a solenoid, the field of which is shown as dotted lines.

are kept at $\sigma_r = 1$ mm using a solenoid lens, the B_z component of which is shown as a dotted line in the figure. The one meter drift space is necessary for beam line components between the gun and the plasma wake-field accelerator. It is also the approximate length of the undulator. A 100 pC bunch becomes more than 5 times longer, while the expansions of a 10 pC bunch is acceptable. Hence, in order to fill one bucket of the plasma wake field accelerator the bunch charge should be maintained at or below 10 pC.

COMPUTER MODEL

Codes	RADIA, GPT, MATHEMATICA
RADIA subdivisions	3,3,3
GPT field map divisions	0.5, 0.5, 0.375 mm
Number of modes	$100 < N_m < 1000$
No of particles	$1000 < N_p < 10\,000$

Table 3: *Simulation parameters*

3D particle tracking simulations have been carried out with the General Particle Tracer Code (GPT), in the combined field of radiation, undulator and space charge. The radiation is self consistently calculated with a custom model, similar to the one presented at EPAC[4]. The mode frequencies used in the model were chosen to be multiples of an imaginary gun repetition frequency, such that the radiation pattern repeats itself after a distance which is much longer than the electron bunch or sequence of bunches. This way the set remains complete with a reasonable number of modes.

The modes used are the HE_{nm} modes with $n = m = 1$ of a corrugated waveguide without losses.

$$E_x = sin(k_x x) sin(k_y y) sin(\omega t - k_z z)$$

$$E_y = 0$$

$$E_z = -\frac{k_x}{k_z} cos(k_x x) sin(k_y y) cos(\omega t - k_z z)$$

with $k_x = n\,\pi/a$, $k_y = m\,\pi/b$, $k^2 = k_x^2 + k_y^2 + k_z^2$.

The interaction is calculated via the innerproduct $\vec{v} \cdot \vec{E}$ for each particle at each time step for each mode without any averaging. This model is very general, includes spontaneous and stimulated emission and covers FEL-interaction from start-up to the saturated regime. The undulator field is calculated with RADIA and introduced into GPT via a field map.

RADIATION FROM ONE (SUB)-BUNCH

The shorter the bunch the stronger the spontaneous radiation from that bunch. The total radiated power decreases rapidly when the bunch length increases.[5] Fig. 2 gives the total radiated power as a function of the (initial) bunch length expressed in Joule per Coulomb *squared* for a bunch charge of 10 fC and for a bunch charge of 10 pC. We see that the radiation is proportional to the square of the bunch charge, which is typical for spontaneous emission of extremely short bunches.

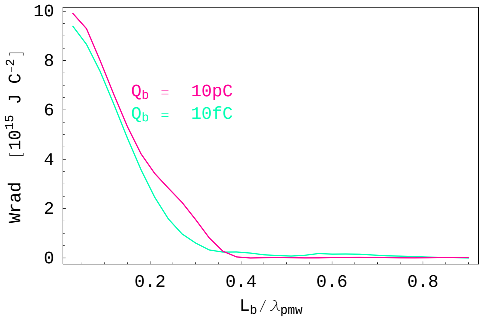

Figure 2: Radiated Energy per square Coulomb versus bunch length for a single sub-bunch. For bunch length smaller than half the PMW-length, the total radiated power is proportional to the square of the bunch charge.

The spectral evolution from "high" and low bunch charge has the same profile and is shown in fig. 3 for a bunch length of 30 μm ($0.3\lambda_{pmw}$). The 3D representation eases interpretation, while below the calibrated contour plots give contours of constant power per mode. The bunch position in the undulator (and in time) increases from bottom to top. For the low bunch charges, the final level (green) is reached at the end of the undulator, while this level is already reached only after a few cm for a high bunch charge.

RADIATION FROM SEQUENCE OF BUNCHES

The total energy radiated by a sequence of sub bunches depends on the inter sub-bunch spacing. It is maximum

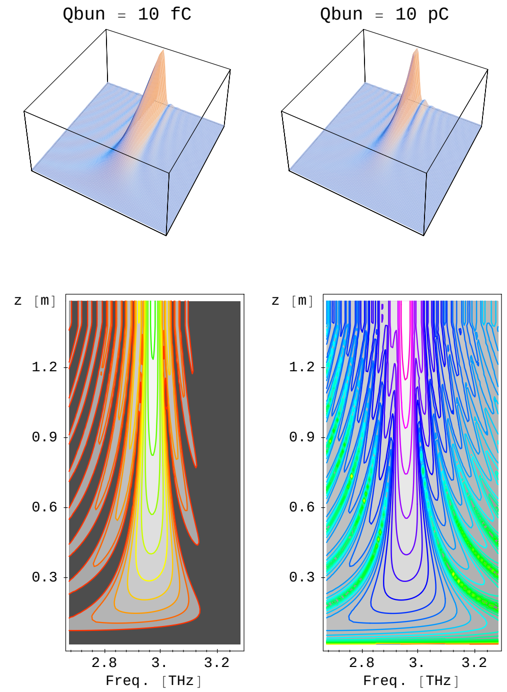

Figure 3: Spectral evolution for a single bunch of 30 μm for the indicated bunch charge. The upper plots are on a linear scale to help interpretation of the contours of constant intensity on a logarithmic scale. The contour distance is 3 dB.

when the individual bunches radiate in phase, which is when $D_{bb} = n\,\lambda_{pmw}$ with an integer value for n. This is shown in fig. 4, which shows the total radiated energy at the end of the undulator as a function of the ratio D_{bb}/λ_{pmw}. This dependence can be used to measure the inter bunch distance. At a higher bunch charge, however, the pronounced peak at $D_{bb} = \lambda_{pmw}$ disappears, because of stimulated emission.

The evolution of the spectrum radiated by a sequence of 10 sub-bunches is given in fig. 5 for the case that the inter bunch distance $D_{bb} = 2\,\lambda_{pmw}$. The bunch charge Q_{sb} is 10 fC in the plots at left and 10 pC in the plots at right. The plots are similar to those in fig. 3, however, in this case we see that at higher bunch charge the generated spectrum broadens and the power level flattens in the second half of the undulator.

HIGHER HARMONICS

The short bunches not only radiate at the first harmonic but also produce significant radiation at higher harmonics. Fig. 6 shows the spectra generated by the sequence of 30 μm sub bunches with $D_{bb} = 2.05\,\lambda_s$ for 0.1 pC and for the nominal 10 pC charge per sub-bunch. In both cases we

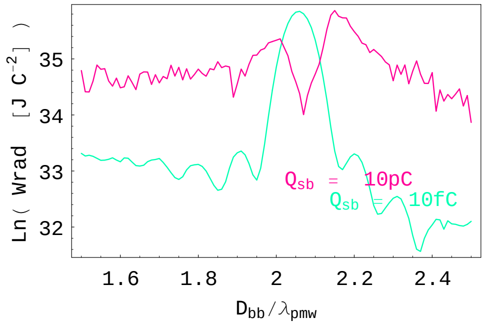

Figure 4: Total power radiated by a sequence of ten sub-bunches as a function of the distance between them. When the charge per sub-bunch is low, the maximum radiation occurs when D_{bb} is around a multiple of the PMW. However, at the nominal bunch charge of 10 pC per sub-bunch this dependence almost disappears due to stimulated emission.

see peaks at both the second and third harmonic of 3 THz but at low bunch charge these peaks are much narrower and more distinct.

CONCLUSION

The plasma wake field accelerator of the Alpha-X project requires extremely short injected bunches in order to deliver a reasonable low energy spread at its output. These bunches are produced by a RF-photoinjector but expand rapidly due to their space-charge, in the space between the gun and the wakefield accelerator. If, however, this bunch is split into a sufficiently large number of equidistant sub bunches, fitting into the buckets of the accelerating field, this problem can be solved. It is shown that, for a typical sub bunch of 5 MeV, 10 pC, 30 μm (100 fs) the parameters of the bunch sequence can be tested without the plasma wave accelerator by monitoring the radiation that it produces in the undulator.

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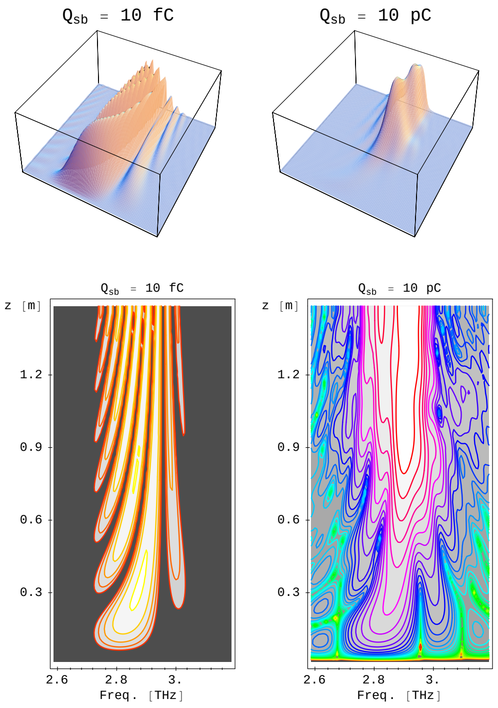

Figure 5: Spectral evolution from a sequence of ten sub-bunches separated by $2.05\,\lambda_{pwm}$, the position of the peak in fig. 4. On the left are the results for Q_{sb} = 10 fC, while on the right Q_{sb} = 10 pC. The 3D plot aids interpretation. The contour distance is 3 dB.

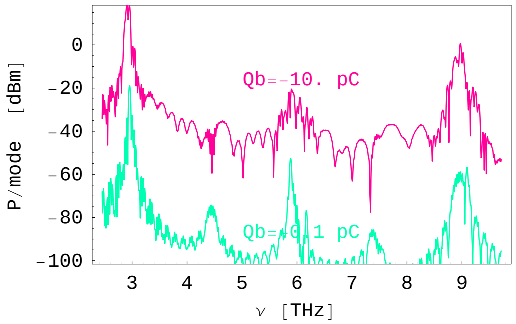

Figure 6: Spectra generated by a sequence of 10 sub-bunches, each with the indicated charge.