iMPACT, UNDULATOR-BASED MULTI-BUNCH PLASMA ACCELERATOR

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Abstract

The accelerating gradient measured in laser or electron driven wakefield accelerators can be in the range of 10-100GV/m, which is 2-3 orders of magnitude larger than can be achieved by conventional RF-based particle accelerators. However, the beam quality preservation is still an important problem to be tackled to ensure the practicality of this technology. In this global picture, the main goals of this study are planning and coordinating a physics program, the so-called iMPACT, that addresses issues such as emittance growth mechanisms in the transverse and longitudinal planes through scattering from the plasma particles, minimisation of the energy spread and maximising the energy gain while benchmarking the milestones. In this paper, a summary and planning of the project is introduced and initial multi-bunch simulations were presented.

INTRODUCTION

The particle accelerator community is in pursuit of advanced technologies that will allow more efficient, compact and cost-effective accelerators. Developing such technologies will open a new era for particle colliders as well as for medical and industrial applications. Plasma wakefield acceleration has been one of the most appealing advanced accelerating techniques during the last few decades [1–5]. Many experimental achievements were recorded more recently [6, 7].

Yet, the production and preservation of a high quality beam stays a challenge in the field. iMPACT is a feasibility study for a dedicated test stand to perform systematic and rigorous measurements on plasma and beam interaction. In beam driven plasma acceleration studies, the beam to be accelerated (the witness beam) is placed behind the driving bunch with a separation in multiples of the plasma wavelength, where the maximum gradient occurs. In such applications considering the optimum plasma densities required for inducing reasonable wakefields, a typical plasma frequency can be considered in the order of a THz. This means that a bunch separation of the order of a ps should be achieved to place a witness bunch close enough to the drive bunch to be able to surf the highest fields. In addition to two-bunch case, a multi-bunch case where more than two bunches are present, separated in some fraction of the plasma wavelength can lead to a coherent wakefield build up over all the field components induced by individual bunches. A bunch repetition of several GHz can be achieved by RF photoinjectors. In addition for a two-bunch operation in the plasma might be possible through modulating the intensity of a single laser pulse used for photoemission.

There are a number of methods how to produce multi-bunch trains from conventional linacs [8, 9] as well as via plasma interaction [10–13]. Another potential method through utilisation of an undulator magnet to microbunch a single initial bunch for investigations on two-bunch and the multi-bunch effects, namely, the field build up using such microbunches are introduced in this paper. Two-bunch and quality preservation studies are being carried out.

OBJECTIVES

The proposal aims an experimental program to demonstrate the key phenomena and address the issues of plasma wakefield acceleration technology by using an electron beam provided a medium energy injector. The project is planned as two phases in single bunch and multi bunch modes.

Phase I: Initially, the interaction between a pilot electron bunch and the plasma will be studied. This single bunch operation will reveal the maximum achievable accelerating wakefield gradients in a plasma and its relationship with beam and plasma parameters. The energy transfer from the head to the tail of the bunch through interactions with the plasma wakefield will be demonstrated. In Phase I, the divergence and energy spread of the bunch travelling through the plasma, to assess the effects of elastic and inelastic scattering from the plasma ions and electrons, will be measured. This investigation has important implications for the beam quality preservation when the technology is applied to a larger scale, such as particle colliders. These results will be compared the results with numerical studies that were previously conducted [14].

Phase II: Modulating the longitudinal intensity profile of a photocathode laser one can create a two-bunch intensity profile. Once the two-bunch scheme is provided, by adjusting the position of both bunches with respect to each other, an optimised working point will be found for efficient energy transfer from drive bunch to witness bunch. A favourable

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case can be created by maximising the transformer ratio which is defined as the ratio of the maximum value of the retarded potential in the driving bunch to the maximum accelerating potential seen by a test charge behind the driving bunch. The energy gain of the trailing bunch is $\Delta E \leq RE_0$, where R is the transformer ratio and E_0 is the incoming energy of the driver bunch.

One can also flatten the field seen by particles in the witness bunch by optimising the position of the witness bunch behind the driver bunch. The energy spread of the witness bunch will be mitigated using the fact that the resulting field on the witness bunch is a superposition of the wakefield and the electromagnetic field of the witness bunch itself. This is observed in an RF cavity as well and is known as "beam loading".

Ultimately, in order to reach higher gradients the multi-bunch scheme where the wakefield from each micro-bunch adds up coherently will be tested. The optimal conditions will be studied regarding two different analytical schemes, suggesting a particular phase advance or charge modulation for the micro-bunches [15]. To provide multi-bunches, we propose to use an undulator, long enough to reach the saturation where the free electron laser (FEL) photons produced interact with the electron bunch. This results in micro-bunching with a repetition frequency equal to the frequency of the FEL produced. The wavelength of the FEL, hence the micro-bunch frequency, can be altered by changing the undulator gap or the field strength as in $\lambda_r = \lambda_u/2\gamma^2\left(1+K^2/2\right)$, where λ_r is the radiation wavelength, λ_u is the undulator period, γ_0 is the beam energy in terms of its rest mass and K is the undulator strength depending on the undulator gap and the field. The proposed micro-bunching process will allow flexibility to vary the bunch spacing for the transformer ratio studies as the bunch frequency can be adjusted by the undulator.

UNDULATOR DESIGN

Preliminarily, the saturation length, L_{sat}, where microbunching occurs is assumed to be a factor of 20 larger than the gain length calculated using Eq.1 and the Pierce parameter given in Eq.2,

$$L_g = \lambda_u / 4\pi\sqrt{3}\rho \tag{1}$$

$$\rho = \left[\left(\frac{I}{I_A}\right)\left(\frac{\lambda_u A_u}{2\pi\sigma_x}\right)^2\left(\frac{1}{2\gamma_0}\right)^3\right]^{1/3} \tag{2}$$

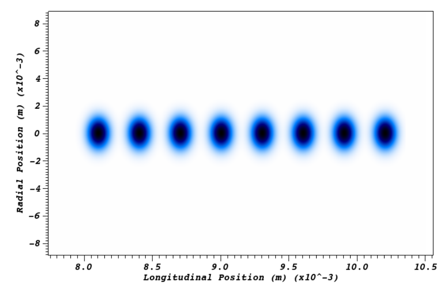
where, for the planner undulators, $A_u = a_u(J_0(\zeta) - J_1(\zeta))$ and $a_u = K/\sqrt{2}$. In the equation, J_0 and J_1 are the Bessel functions of the zeroth and the first kind, respectively, where ζ is $\zeta = a_u^2/2(1 + a_u^2)$. A general parametrisation for undulators with two different period are presented in Table 1.

Table 1: Analytical Undulator Design Parameters to Use for Microbunching the Initial Beam

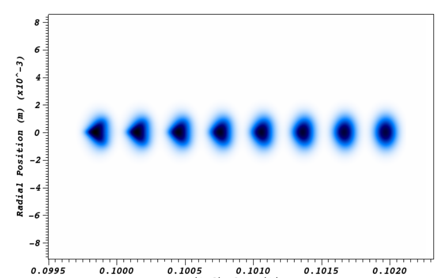
Parameter	Undulator I	Undulator II
λ (μm)	313	156
λ_u (mm)	80	40
B (T)	0.3	0.3
K	2	2
L_{1D} (m)	0.1	0.08
L_{sat} (m)	2	1.6

Table 2: Electron Beam and Plasma Parameters

Beam	
Total charge, Q (nC)	8
Charge/Microbunch, q (nC)	1
Initial bunch length, σ_{z_0} (ps)	4
Microbunch length, σ_z (ps)	0.5
Beam size (μm), σ_x	715
Beam Beta (m), β	5
Initial beam energy, E (MeV)	200
Beam number density, n_e (m^{-3})	5.2×10^{18}
Plasma	
Plasma wavelength, λ_p (μm)	300
Plasma number density, n_p (m^{-3})	1.24×10^{22}



(a)



(b)

Figure 1: a) Arrangement of eight bunches with separation of λ_p, b) same bunches after 100 mm propagation into the plasma.

PIC SIMULATIONS

Plasma simulations were performed using the particle-in-cell simulation code, VSim [16]. The microbunched beam distribution associated to the hypothetical undulator in the previous section is defined in VSim. This distribution at the first time step and after 100 mm propagation into the plasma are shown in Fig. 1. Beam and plasma parameters used were summarised in Table 2. Figure 2, presents the fields

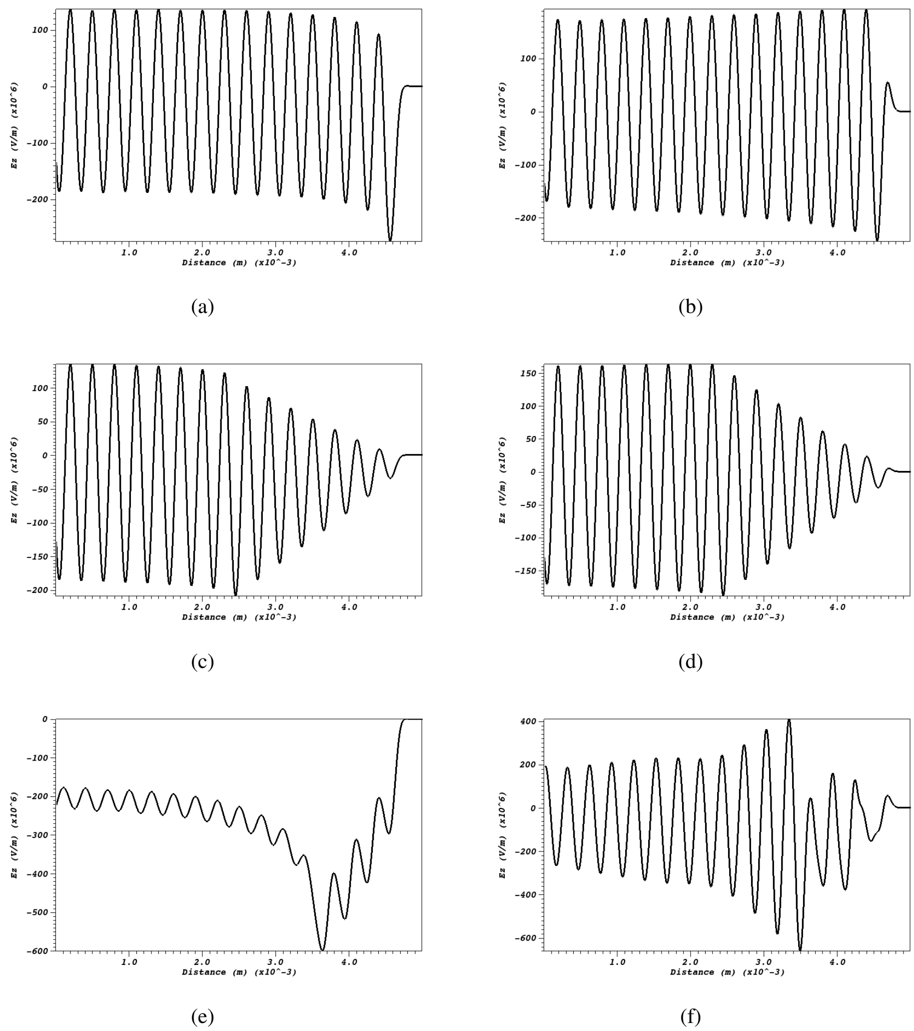


Figure 2: a,b) Single bunch of 8 nC, c,d) eight bunches with 1 nC each and separated by λ_p, e,f) eight bunches with 1 nC each and separated by $\lambda_p/2$ at the first time step and after 100 mm propagation into the plasma, respectively.

obtained for a single bunch of 8 nC, eight bunches of $1nC$ each separated by one plasma wavelength and eight bunches of 1 nC separated by half a plasma wavelength. Further simulations revealed that when the initial energy of the bunches was decreased down to 20 MeV, the resulting accelerating gradient of 200 MV/m can still be achieved. However, the value drops down to 90 MV/m after 100 mm of propagation. For higher energies, achievable gradient is relatively independent from the initial beam energy [17]. In addition, the field build-up of factor of three is observed when the microbunches are separated by half a plasma wavelength resulting into a 600 MV/m accelerating gradient behind the microbunch train.

CONCLUSIONS

A research plan to explore the beam quality preservation and multi-bunch operation for plasma acceleration was laid out. Multi-bunch production was proposed to be done by means of an undulator long enough to reach a level of microbunching of the initial single bunch. Initial simulations demonstrated a field build up of a factor of three in comparison to the single bunch operation in the case of a bunch spacing of half a wavelength is ensured by the undulator. Further studies will include FEL simulations with Genesis [18] interfaced with the plasma simulations with VSim.

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