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OPTICAL-PERIOD BUNCH TRAINS TO RESONANTLY EXCITE HIGH GRADIENT WAKEFIELDS IN THE QUASI-NONLINEAR REGIME AND THE E-317 EXPERIMENT AT FACET-II

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Abstract

Periodic electron bunch trains spaced at the laser wavelength created via inverse free electron laser (IFEL) bunching can be used to resonantly excite plasmas in the quasi-nonlinear (QNL) regime. The excitation can produce plasma blowout conditions using very low emittance beams despite having a small charge per bunch. The resulting plasma density perturbation is extremely nonlinear locally, but preserves the resonant response of the plasma electrons at the plasma frequency. This excitation can produce plasma blowout conditions using very low emittance beams despite having a small charge per bunch. To match the resonance condition, the plasma wavelength has to be equal to the laser period of a few microns. This corresponds to a high density plasma resulting in extremely large wakefield amplitudes. Matching the beam into such a dense plasma requires an extremely short focusing beta function. We present the beam-plasma interaction using quasi-static particle-in-cell (PIC) simulations and discuss the micro-bunching and focusing mechanism required for this scheme which would be a precursor to the planned experiment, E-317, at SLAC's FACET-II facility.

INTRODUCTION

Plasma wakefield accelerators have demonstrated the ability to access high gradients which are not possible using conventional accelerators. In a beam driven plasma accelerator, a plasma wave is driven by an ultra-relativistic electron beam and the fields associated with the plasma wake can be used to accelerate a trailing bunch, known as the witness beam. The accelerating gradient of a plasma wake is dependent on the plasma density and approaches the wave-breaking amplitude in the nonlinear limit, which is given by $E_{\mathrm{WB}} = mc\omega_p/e$, where $\omega_p = \sqrt{n_0 e^2/m\epsilon_0}$ is the cold plasma electron frequency.

A short bunch ($\sigma_z \ll c/\omega_p$) located in the focusing phase of the wakefield and not subject to the transverse two-stream instability [1] can permit wakefield acceleration over long distances. This imposes an additional requirement for the drive beam, which could be satisfied by increasing the wake period. However, reducing the plasma density leads to a reduction in the maximum accelerating and focusing gradients. The length requirements and efficiency considerations in enhancing the extracted energy from the drive beam motivates the use of using bunch trains instead of a single drive beam.

The use of a pulse train may resonantly excite large amplitude wakes providing the opportunity to access high accelerating gradients. These pulse trains could be created using inverse free electron bunching (IFEL) [2, 3] which can produce micro-bunches with high peak current while mitigating emittance and energy spread growth. If this density modulation occurs at the plasma wavelength, $\lambda_p = 2\pi c/\omega_p$ the bunches could be used to resonantly drive a plasma in the quasi-nonlinear regime [4, 5]. The experiment described in this paper paves a path towards the E-317 scenario which proposes driving wakefields near the TV/m level using a 2 micron laser and has stronger focusing requirements [6].

In this work, particle-in-cell (PIC) simulations have been performed using QuickPIC [7], a three-dimensional quasi-static PIC code.

RESONANT PLASMA EXCITATION IN THE QUASI-NONLINEAR REGIME

Plasma wakefield accelerators often operate in the nonlinear (blowout) regime which is characterized by the complete rarefaction of the plasma electrons by a driving particle bunch which leaves behind a "density bubble" consisting of the remaining slow moving, massive ions [8,9]. This offers a number of distinct advantages – a plasma column consisting only of a uniform distribution of ions allows for linear radial focusing and an acceleration that is independent of the transverse coordinate. However, we cannot use periodic bunch trains to drive such a wake because the period is dependent on the amplitude of the density perturbation. In contrast, the linear regime allows for the use of periodic pulse trains but, since the local density perturbation is quite small, the plasma column formed consists of both electrons and ions which create focusing and acceleration that has a transverse gradient.

A useful parameter to quantify the linearity of this beam plasma interaction is the normalized charge density $\widetilde{Q}$ [10] which is the ratio of the beam electrons over the number of plasma electrons contained in a cubic plasma skin depth $n_0 k_p^{-3}$, and it is given by:

$$\widetilde{Q} = m\frac{N_b k_p^3}{n_0} = m4\pi r_e k_p N_b, \tag{1}$$

where the factor m is the number of bunches in the train, N_b is the number of electrons in each bunch, r_e is the classical electron radius and k_p is the plasma skin depth. The parameter $\widetilde{Q}$ is less than 1 for a linear system. The advantages of both the regimes described above can be exploited by operating in the quasi-nonlinear regime ($\widetilde{Q} \sim 1$) using small beams having $\sigma_r \ll k_p^{-1}$ and $\sigma_z \ll k_p^{-1}$. The beam density

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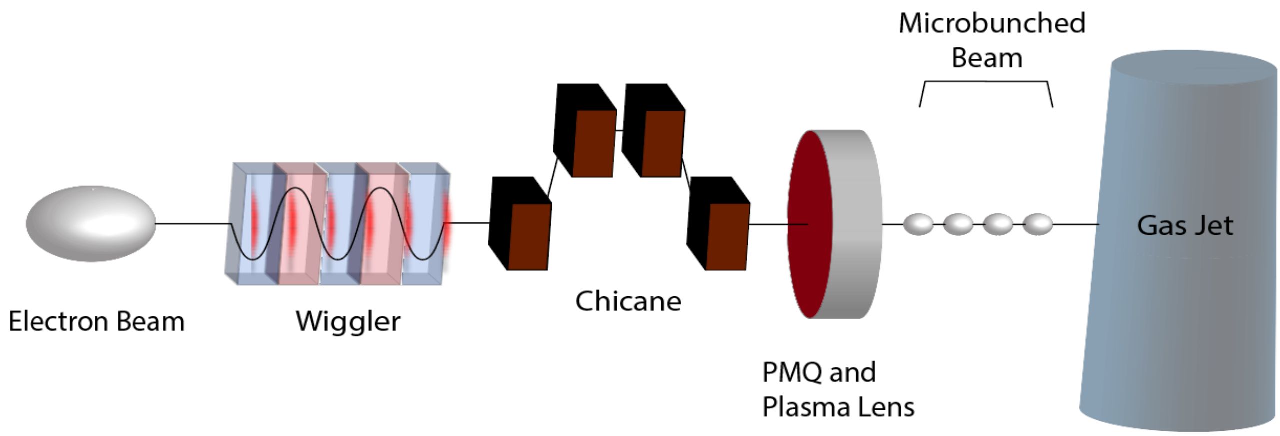

Figure 1: Schematic overview of the experiment. The electron beam is micro-bunched and focused before it enters the pre-ionized gas jet.

is chosen to have $n_b \gg n_0$ despite each micro-bunch containing a small amount of charge, which allows the global wake to be approximately linear with a concomitant linear frequency response. The periodic excitation may continue until the wake approaches the nonlinear regime ($\widetilde{Q} \gg 1$) and the resonance will break down due to the amplitude dependent expansion of the plasma wake [11].

SETUP OF EXPERIMENT

The requisite pulse train must be bunched at the optical scale to access TV/m fields. This can be achieved using IFEL, whereby the electron beam exchanges energy with the laser inside a wiggler at the laser wavelength before converting the energy modulation into a density modulation with a chicane. This technique allows for microbunching with high peak currents while maintaining control over the beam quality [3]. Realistically, the microbunching is be imperfect, *i.e.* there is non-negligible current in between the bunches which would have possible advantages and complications [6]. The laser wavelength of the IFEL determines the plasma wavelength, $\lambda_p = \lambda_l$.

Matching this micro-bunched beam into plasma [12] is difficult to achieve in practice, since the β function, $\beta = \sqrt{2\gamma}k_p^{-1}$, required at these high plasma densities is very small, sub-mm. This microbunched beam could be focused using a combination of permanent magnet quadrupoles (PMQs) [13] and an adiabatic plasma lens [14]. The emittance and focusing requirements also require modifications to the photoinjector to improve beam quality [15]. This pulse train would then be sent through a pre-ionized dense gas jet having density on the order of 10^{19} cm^{-3}, where the wakefields would be excited resonantly. A schematic of the experiment is shown in Fig. 1. In our simulations, we use a plasma wavelength λ_p of 10 µm, which corresponds to a plasma density of 1.11×10^{19} cm^{-3}.

SIMULATION RESULTS

The simulations were performed using the parameters specified in Table 1 and were run for a time equal to 5000 ω_p^{-1}, a distance of about 7.96 mm. The average energy change in the dummy witness beam shown in Fig. 2 was 880 MeV, with an average accelerating gradient of 111 GV/m. The growth of the longitudinal fields from this resonant perturbation is shown in Fig. 3. The plasma electron density spikes become narrower after each micro-bunch as the wake becomes nonlinear. The combined beam density perturbation is high enough to cause significant ion collapse and the ion distribution evolves over the course of the periodic excitation. The evolution of the ion density and electron density with the passage of each micro bunch is shown in Fig. 4. The resonant interaction was stable over the entire duration of the system, with significant head erosion in the first bunch and an observed ramping effect of the beam density profile. The ramping effect is due to the different focusing fields experienced by each bunch, which is a result of the non-uniformity of the ion distribution over the course of the resonant-plasma interaction and may lead to emittance growth [16].

CONCLUSION

In summary, we have presented a path to achieving high gradient wakefields, through resonant excitation in the quasi-nonlinear regime by using micro-bunches created from inverse free electron laser compression. Operating in the quasi-nonlinear regime at such high densities imposes certain restrictions on the beam quality and focusing systems which would need to be investigated and developed. The experiment is synergistic with existing experiments at FACET-II [17] and could be used as a platform for investigating self seeded micro-bunching in partially micro-bunched beams.

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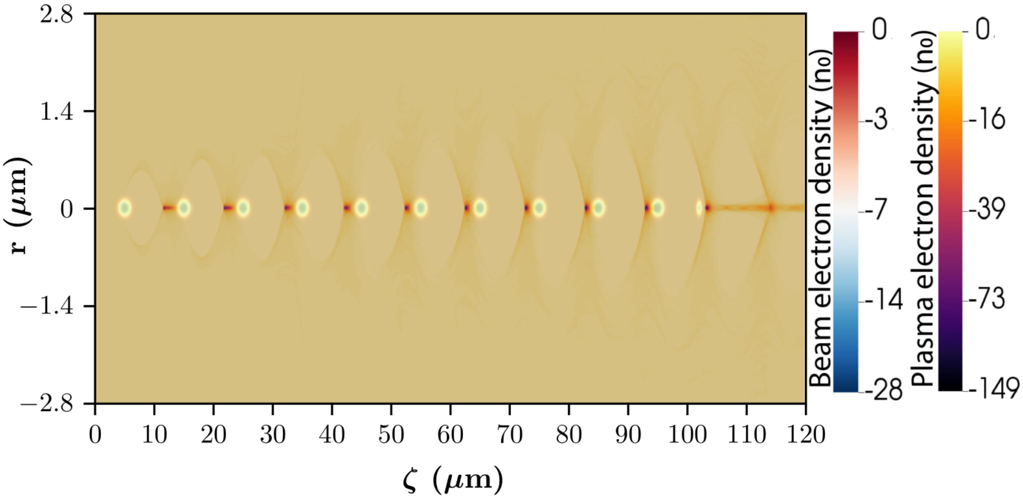

Figure 2: PIC simulation snapshot showing the resonant interaction of the micro-bunched beam with the plasma. A non-physical witness bunch was placed at 0.7 λ_p after the last drive bunch to calculate the energy gradients.

Table 1: Simulation Parameters

Parameter	**Value**	**Unit**
Plasma		
Plasma ion species	H^+	-
Plasma density, n_0	1.11×10^{19}	cm^{-3}
Plasma wavelength, λ_p	10	μm
Beam		
Total beam charge, Q_b	16	pC
$\widetilde{Q}$	2.23	-
Beam energy, E_b	10	GeV
Number of bunches, m	10	-
Peak curent, I_{pk}	348	A
σ_z	550	nm
$\sigma_\perp$	63.5	nm
$\epsilon_{n,\perp}$	250	nm-rad
Simulation		
Longitudinal resolution	58.6	nm
Trasnverse resolution	9.77	nm
Timestep	5	ω_p^{-1}
Plasma particles per cell	4	-

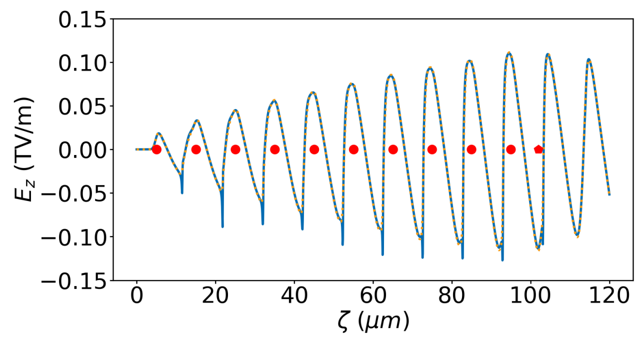

Figure 3: The axial lineout (dark blue) and the radial mean over 20 cells (dashed yellow) of the longitudinal fields showing the ten, 1.6 pC drive bunches and the witness bunch.

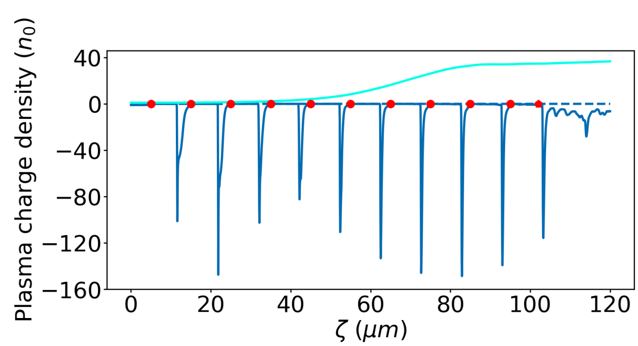

Figure 4: The on-axis plasma electron (dark blue) and ion (light blue) densities showing the ten, 1.6 pC drive bunches and the witness bunch.

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