EXPERIMENTAL RESULTS OF A PLASMA WAKEFIELD ACCELERATOR USING MULTIPLE ELECTRON BUNCHES

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Abstract

We present some preliminary experimental results of a plasma wakefield accelerator technique which utilizes multiple electron bunches in order to drive a plasma wave. The experiments were performed at the Accelerator Test Facility of Brookhaven National Laboratory where 5 – 8 equidistant bunches with a spacing that was varied between 100 – 250 μm were fed into a 6 mm long capillary discharge plasma. By varying the time delay of the bunches with respect to the discharge different plasma densities could be tuned, and the effects of the plasma on the bunches were recorded. Such multiple bunch schemes are of great interest because they can provide increased efficiencies and high transformer ratios for advanced accelerators.

INTRODUCTION

In the plasma wakefield accelerator (PWFA), a relativistic electron beam is fed into a plasma and excites electron oscillations that can support electric fields (wakefields) that can be orders of magnitude higher than those utilized in present conventional accelerator structures [1], thus providing a promising technology for the design of a future particle collider. Specifically of interest here are schemes where multiple electron bunches are used to drive the wakefield in the plasma [2], due to the possibility of multiplying the energy of an incoming trailing beam in a single PWFA stage. This can occur at a given plasma density if the number of particles in each bunch along with the bunch positions is tuned appropriately, as was theoretically explored previously in reference [3].

In this paper preliminary experimental results of the interaction between a 59 MeV multi-bunched electron beam fed into a 6 mm long capillary discharge plasma are presented, which were recorded during experiments that were performed in the Accelerator Test Facility (ATF) of the Brookhaven National Laboratory (BNL). We have observed increasing energy loss along the length of the beam as indicated by the energy shifts of the individual bunches in an magnetic energy spectrometer, demonstrating a maximum excited wakefield around 22 MV/m near the tail of the bunched beam. The results agree well with simple simulations of the beam – plasma interaction at long plasma wavelengths (low plasma densities) [4].

PLASMA & BEAM DIAGNOSTICS

Plasma Diagnostics

The plasma source consists of a 6 mm long polypropylene tube with 1 mm inner diameter, which is filled with hydrogen at a pressure of 150 Torr. A 25 kV electrical discharge breaks down the gas creating a plasma with a peak density of 1.5×10^{18} cm^{-3} that occurs approximately 200 ns after the peak of the discharge current. The plasma density is measured through the Stark broadening of the Balmer-α line of the hydrogen spectrum that is collected by inserting an optical fiber perpendicularly into the capillary body [5].

The plasma light is directed into an optical spectrometer that is adjusted such that a 1 nm spectral window with tunable central wavelength can be selected. The plasma spectrum (and density) as a function of time is retrieved in successive discharge shots. A specific plasma density can be then selected by delaying the arrival of the electron beam after the initiation of the discharge.

Electron Beam Diagnostics

The microbunches at ATF are generated by selectively blocking portions of the full 300 pC charge, 5.5 ps long (FWHM) electron beam. The beam is imparted a correlated energy spread (typically around 1.5%) and a metal mask consisting of equidistant solid wires is placed in its path in a high dispersion region of the beamline where the transverse size of the beam is dominated by the energy spread, a process which is described in detailed elsewhere [P. Muggli et al., in these proceedings and to appear in Phys. Rev. Lett.].

In order to experimentally verify the generation of the microbunches, Coherent Transition radiation (CTR) interferometry was employed [6]. The CTR signal that is emitted when the bunches pass though a copper mirror is collected and sent through an interferometer that auto-correlates the signal in time. The auto-correlation time-integrated trace is recorded for different path lengths inside the interferometer by a liquid helium cooled silicon bolometer detector. A train of N equidistant bunches (typically N is between 5 and 8) yields a symmetric trace with 2N+1 peaks as a function of the path length, while the distance between those peaks is equal to the microbunch period, typically measured around 100 – 250 μm, depending on the selected correlated energy spread. This separation corresponds to resonant plasma densities in the 10^{16} – 10^{17} cm^{-3} range.

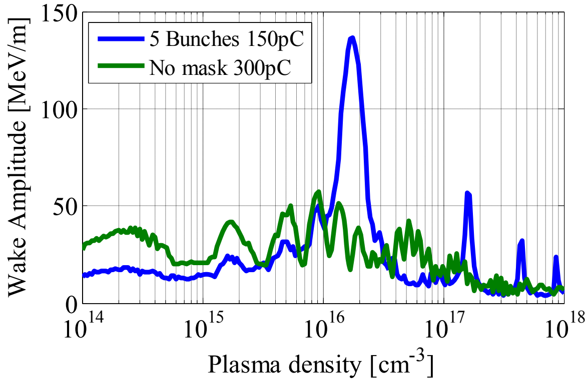

Figure 1: Plasma wakefield amplitude response as a function of the plasma density for a bunched and non-bunched longitudinally square beam. The bunches are separated by one resonant plasma wavelength (250 μm) and their width is half a plasma wavelength.

SIMULATIONS

The predicted plasma wakefield response as a function of the plasma density is shown in Figure 1. In the case without the mask inserted, the full electron beam is fed into the plasma, and the maximum wakefield amplitude peaks at 40 MV/m assuming a transverse spot size of 100 μm (rms). The envelope response appears in the $10^{14} – 10^{15}$ cm^{-3} density range, while the beating visible at higher densities appears because the model of the beam is a square bunch with sharp cutoffs at the edges.

In the case where the wire mask is blocking sections of the beam to create the bunches, the total charge remaining is 150 pC and is assumed to be distributed over N=5 identical bunches which have width equal to 125 μm (equal to half the resonant plasma wavelength). It is observed that the wakefields are very low for most densities, expect for the resonant density at 1.8×10^{16} cm^{-3} (where the wakes of all 5 bunches add in-phase) where the wake is expected to peak at 140 MV/m, even though the total charge is less in this case. Weaker wakefield peaks also appear at the plasma frequency harmonics, as each bunch is located every integer number of periods of the plasma wave.

It is important to notice that the resonance width is roughly 20% (FWHM) around the resonant density, approximately inversely proportional to the number of bunches, or ~1/N. This is the accuracy with which the plasma density must be known in order to detect the enhanced wakefield amplitudes.

BEAM – PLASMA INTERACTION

The effect of the plasma on the full 300 pC beam was first recorded at a low density of 7×10^{13} cm^{-3} (not shown), indicating an energy loss gradient of 35 MV/m compared to the plasma off case. This was deduced from the energy shift of the beam centroid over the given plasma length.

When the mask is inserted the microbunches are fed into the plasma. The experimentally recorded energy spectrum of 7 bunches after the plasma of the same density is shown in Figure 2, and it is compared to the beam spectrum without a plasma discharge. The first drive bunch has the highest energy, around 59.4 MeV. The different number of particles per bunch reflects the original non-flat charge distribution of the ATF beam. The total charge now is reduced to roughly 150 – 200 pC, which results in a measured average energy loss of 22 MV/m for the final microbunch. This is still envelope interaction at the low density, as demonstrated by the increasingly larger energy loss of the later drive bunches.

The simulated excited wakefield and energy spectra for the bunches is shown in Figure 3 and compared with the experimentally recorded energy shifts, demonstrating good agreement with the data. The bunches are shown to sample the decelerating first half-period of the plasma wave, which explains why the later bunches appear to lose more energy compared to the earlier bunches.

Operation Near the Resonance

Operation near the resonant density is more challenging because the plasma density must be stable within ≈20% for the bunches shown here over the desired plasma length in order to observe the enhanced wakefields. Variation in the plasma density larger than this value, non-uniform longitudinally plasmas or slightly non-equidistant microbunches will result in decreased values of the wakefield. In addition, for capillary discharges the density may vary by 3 – 4 orders of magnitude over a few microseconds, and the beam needs to be timed to arrive

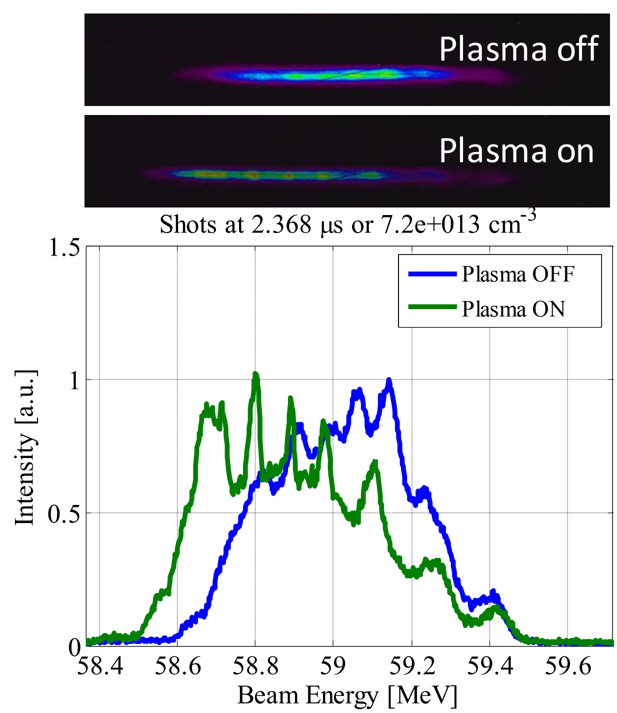

Figure 2: Recorded energy spectra of the bunched electron beam without a plasma discharge and after a 6 mm long plasma at a density of 7×10^{13} cm^{-3}. The beam crosses the capillary 2.4 μs after the peak of the plasma discharge current.

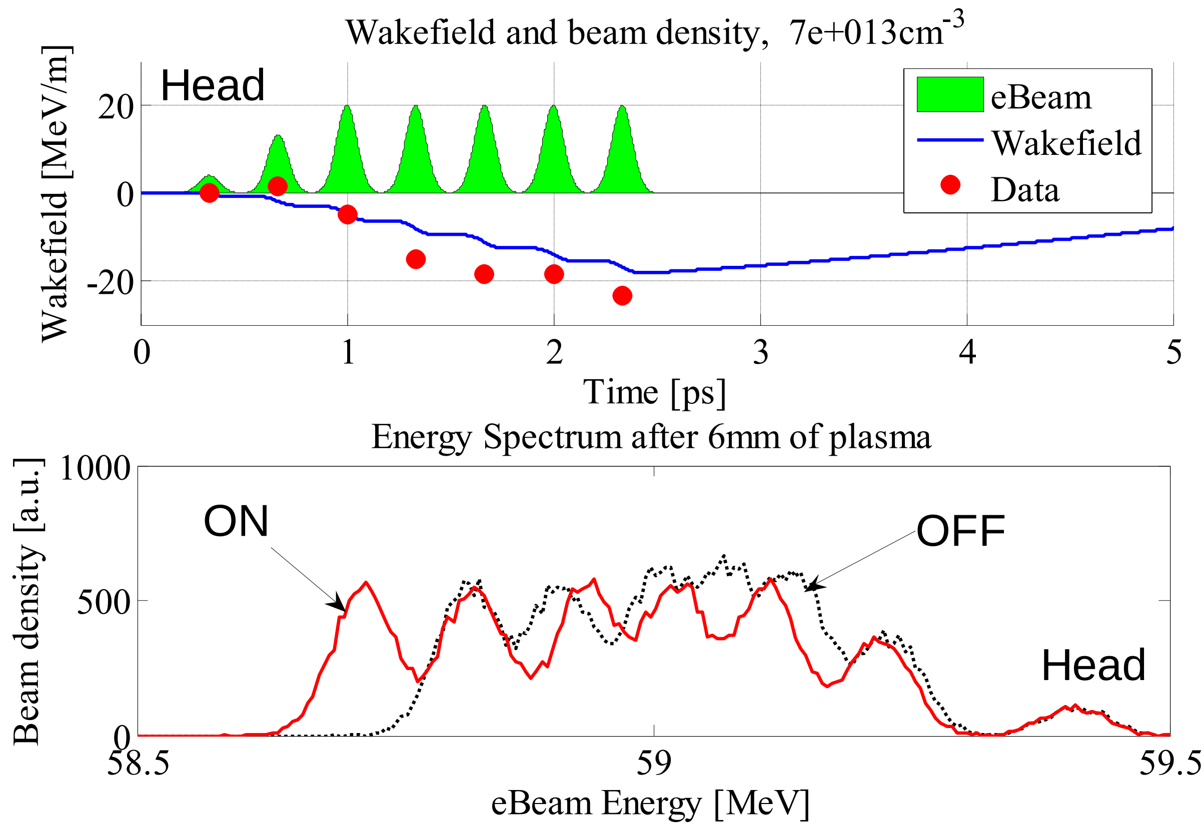

Figure 3: Simulated wakefield and energy spectra for the experimental data of the beam – plasma interaction of Figure 2. The top panel shows the 7 bunches with 200 pC total charge fed into a 7×10^{13} cm^{-3} density 6 mm long plasma. The wakefield under each bunch as deduced from the energy shifts is shown with red dots. The bottom panel shows the simulated energy spectra before and after the plasma. Small Gaussian energy spreads were added to the bunches in the simulation.

within this narrow window around the resonance.

If the plasma density after some time varies as $n_{max}\times\exp(-\alpha t)$, where α is the decay time constant, and the enhanced wakefield is to be observed in a narrow range of densities Δn around a resonant density n_0, then the time scale Δt over which the resonance will evolve is given approximately by $\Delta t \approx 1/\alpha*(\Delta n/n_0)$. For example, if there is a $\Delta n/n_0=20\%$ wide resonance and the density drops exponentially with a coefficient $\alpha=2.9\ \mu s^{-1}$, then $\Delta t\approx 70$ ns. This is the lowest time resolution with which the density must be scanned in order for the resonance to be detected. Finally, instabilities in the incoming beam energy distribution may also affect the location of the resonance as the bunch period may drift during a run.

SUMMARY

We have presented simulations that demonstrate the enhancement on the plasma wakefield amplitude when a microbunched electron beam is fed into a plasma. We have reported early experimental results of a 150 pC beam consisting of 7 bunches separated by 250 μm apart, indicating that the beam samples a 22 MV/m wakefield at a 7×10^{13} cm^{-3} density. In the near future these experiments will be extended to the resonant density where a large enhancement of the wakefield amplitude is expected.

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