MEASUREMENTS OF PLASMA WAKE-FIELDS IN THE BLOW-OUT REGIME

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Initial results from nonlinear plasma wake-field experiments at the Argonne Wake-field Accelerator (AWA) test facility are reported. This nonlinear "blow-out" regime is characterized by the complete ejection of the plasma electrons from the beam channel. The wake-fields in this case are of notably high quality for acceleration of electrons, as the acceleration is independent of transverse position, and the focusing is linear and independent of longitudinal position within the electron depleted region, allowing self-consistent guiding of the majority of the driving electron beam. Initial measurements of the energy gain in a witness beam indicate a positive shift in its energy distribution of at least 0.5 MeV.

I. INTRODUCTION

Presently, there is a great interest in experimental evidence of acceleration using the nonlinear plasma wake-field acceleration (NPWFA) concept [1]. In addition to our work, a group at KEK [2] has also been measuring this effect.

The NPWFA an electron drive beam propagates in a plasma whose initial electron density is less than the beam's density (an underdense plasma). When such a beam is short (the rms bunch length, σ_z, is less than 2 collisionless skin depths, k_p^{-1}), it is well-suited to coupling power into a plasma wave in which the plasma electrons' motion is mostly radial. Because of the underdense condition, all of the plasma electrons are pushed out of the drive beam's way, resulting in the extremely strong focusing associated with an ion channel, which guides the drive beam and also the accelerated (witness) beam. This plasma electron depleted region assures that the focusing is linear and the acceleration field independent of radius. This accelerator scheme is exciting for the high acceleration gradient predicted: a 1.5 GeV/m is possible for a plasma density, $n_0 = 1\times10^{14}$ cm^{-3} and a 100 nC beam. The characteristic wavelength of the acceleration field is somewhat longer than 3.3 mm due to relativistic effects, and is suitable for accelerating short electron bunches with collider applications in mind.

The NPWFA concept, however, requires care when considering multiple acceleration sections to increase the final energy. Krall and Joyce [3] are currently studying the electron hose instability in this context. This work suggests that very long, ramped drive beams are not desirable.

II. OVERVIEW OF THE AWA FACILITY

The layout of the Argonne Wakefield Accelerator (AWA) can be found in Ref. 4. The electron source is a single-cell L-band rf cavity, using a copper photocathode to generate the electron pulse, followed by two 1 meter linac sections. The design of this facility is optimized for high charge (up to 100 nC per pulse), and short bunch length.

In the future, an additional electron gun will be added to the AWA to produce a 5 MeV witness beam for probing the wake fields in dielectric structures and plasmas. For the initial measurements, we realized that it was feasible to generate a stably propagating witness beam in the same cavity as the drive beam by delaying a portion (approximately 20%) of the laser pulse. We found that delays as long as 70 picoseconds were possible with laser path differences of about 3 cm. Figure 1 shows a resultant streak camera trace. This data is the result of inserting a 1 mm thick fused silica Cerenkov radiator in the path of the beam (inclined 11 degrees to the normal) and directing the light to a Hamamatsu C1587 temporal disperser. Since the delay time is dependent on the amount of RF compression, and hence on the injection phase of the bunches into the linac cavity, the streak camera was necessary to calibrate this delay time for a specific set of conditions.

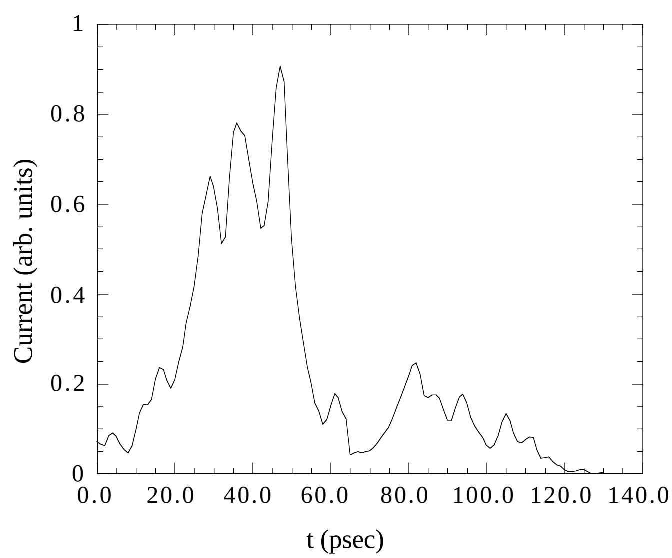

Figure 1. A streak camera image of the current profile of drive and witness beams. The data has been rescaled to reflect the charge in each pulse.

III. THE PLASMA SOURCE AND DIAGNOSTICS BEAM LINE

The plasma source used for this experiment is a modified version of that used in previous linear-regime acceleration [5] and focusing [6] studies (see Fig. 2). It is a

DC hollow cathode arc discharge with a moderate confinement magnetic field (up to 1 kG; typically 200 G,) using Argon at up to 10^{-2} Torr pressures. The plasma electron density is variable between 8×10^{12} and 1×10^{14} cm^{-3}, as measured with a Langmuir probe. The validity of the probe data is also supported by μm-wave (140 GHz) interferometry measurements, which yield an integrated plasma density along a cross section of the plasma; the two techniques agree to within 15%. The length of the plasma column is 13 cm and n_0 is within 25 % of the peak value over 11 cm of this length.

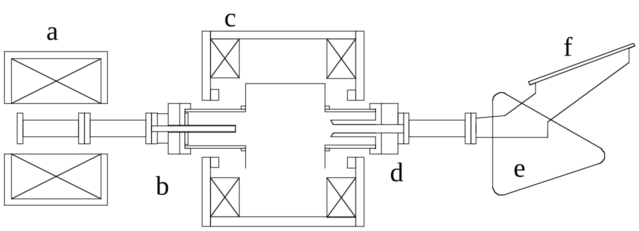

Figure 2. Experimental setup including a) focusing solenoid, b) cathode assembly, c) plasma confinement solenoid, d) anode assembly, e) bend magnet, f) phosphor screen.

In order to access the underdense regime, the beam must be brought to a tight focus - ultimately close to the betatron-matched condition for the ion channel. In order to easily control the location of this focal spot, we chose a solenoid magnet, placed about 40 cm before the start of the plasma. The beam is diagnosed with a phosphor screen before entering the solenoid. In the middle of the plasma chamber, we intercept the beam with a mirrored surface (with no plasma) and use the resulting optical transition radiation (OTR) to measure the solenoid's focal spot. After the plasma, the beam's energy distribution is measured with a spectrometer magnet. This spectrometer was designed in such a way that it has nearly point to point imaging in the bend plane from anywhere inside the plasma to the phosphor screen at the spectrometer's focal plane. The goal of this design is that the energy distribution be accurately measured regardless of the plasma caused focusing and guiding.

IV. MEASUREMENT OF WAKE FIELDS

In the first experimental run (Run I), we did not have use of the witness beam. However, this was a good opportunity to verify that energy was being deposited into the plasma, by observing the beam's deceleration. The charge per bunch was 6-8 nC, the beam was focused by the solenoid to an rms radius $\sigma_r \leq 500\ \mu m$ and $n_0 = 8 \times 10^{12}$. Assuming the bunch length to be 7.5 mm FWHM, the underdense factor, $n_b / n_0 = 1$. The result of these measurements is that the low energy half maximum point of the energy moved down by as much as 0.5 MeV, while the high energy half maximum remained within 20 keV of the no plasma case. It is encouraging that this data was shifted primarily toward the low energy side, indicating that the energy distribution was being accurately measured. The lack of the beam's self-acceleration is also supported by computer simulation results (the simulation method is explained in Appendix A.)

By the time of the second experimental run, we had developed the technique of witness beam generation, and there was more charge available from the linac. Also, because of improvements in the beam transport and emittance, the beam could be focused to σ_r=360 μm. To investigate the possibility of particles accelerated by the plasma wave, as predicted by the Run I data and simulations, we recorded images of the high energy end of the spectrometer's phosphor screen. Fig. 3 shows the intensity profiles for all possible combinations of switching on of witness beam and plasma. Each point on this plot is the result of several camera images, averaging the set of energies corresponding to a fixed intensity. With this averaging, we attempt to improve on the energy jitter, probably due to laser injection phase fluctuations in the photoinjector, evident on the phosphor screen. The plasma density for this data was 2.2×10^{13} cm^{-3}, the drive and witness beams combined had Q = 13 - 17 nC, with 20% of this charge belonging to the witness beam. The initial σ_r was 450 μm at athe entrance to the plasma.

With no plasma, the Fig. 3 distributions are identical. This suggests that prior to entering the plasma, the witness beam's high energy tail is at or below that of the drive beam nd does not appear in the plots. Without a method to diagnose the witness beam alone, we can only conclude that the lower limit on the witness beam's gain in energy as a result of the beam-plasma interaction is 0.5 MeV. Note that at lowest intensity, the gain in energy of the tail is approximately twice as large again. Therefore the average acceleration field is at least as large as 4.1 MeV/m, and the peak field measurable is perhaps twice this value.

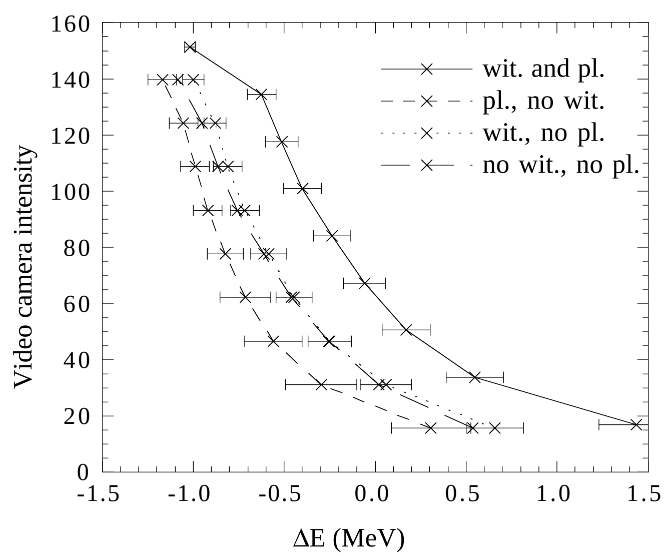

Figure 3. Observation of the high energy tail at spectrometer. In the legend, wit. indicates witness beam and pl. indicates plasma present. The curvature near the top of the plot is due to saturation of the video camera.

We also changed the plasma density to below 1×10^{13} cm^{-3} and above 4×10^{13} cm^{-3} and observed the effect on the energy distribution. From visual observation alone, the energy gain seemed weaker for these conditions.

When trying to compare this data with simulation results, we found that within the range of Q, n_0 and the length of the drive beam, it was possible to cause the acceleration of the drive beam's trailing edge. This, however, does not contradict the fact that the no witness beam high energy tail becomes depressed when the plasma is turned on - the drive beam's energy is initially likely to be negatively correlated with distance from the leading edge, due to space charge and running off-crest in the linac, but the extent of this effect is unknown. Thus, direct comparisons with simulation are not yet feasible. The simulations also reveal that a σ_r = 450 μm beam's core focuses to 180 μm in the plasma and then oscillates, staying below 330 μm. This implies that in places along the propagation the beam is 4 times more dense than the plasma, satisfying the underdense criteria. The witness beam in the experiment was positioned so far back that it overlapped with the second peak in the acceleration field. This simulation resulted in the formation of wake fields of 20 MeV/m averaged over the propagation, assuming a 13 nC drive beam, a number not in disagreement with measurements. A major possible sources of disagreement between the experiment and the simulations is the non-axisymmetry in the beam distribution due to cathode nonuniformity, space-charge and transverse wake-field effects.

V. FUTURE WORK

After improving the longitudinal shaping and transverse focusing of the drive beam, as well as reducing some aperture scraping in our beam transport system, the greater peak density of the electron beam, and more importantly shorter bunch length, should drive much more powerful fields in the plasma - on the order of 200 MeV/m. Even higher gradienst should be possible with the addition of a compressor chicage which is currently under construction. We will accompany this effort with measurements of the beam spot prior to exiting the plasma. A time resolved image of this spot [7] will confirm that the beam is propagating in a well focused state through the plasma, and that phase-mix damping leads a larger equilibrium radius near the beam's leading edge [8].

We also plan to measure the UV and VUV radiation emitted by the plasma as a result of the beam plasma interaction. The plasma wave is characterized by plasma electrons which are mildly relativistic ($v/c \leq .5$). These energetic electrons will further ionize the Ar ions and excite atoms, causing emission of UV line radiation.

APPENDIX A: COMPUTER SIMULATION METHODS

The computer simulations for this paper have used the code NOVO [9], which solves the Maxwell equations, assuming that this solution is unchanging in a frame moving with the beam. The plasma electrons are assumed to behave like a cold fluid and are modeled with the Maxwell-Boltzman equation. We have added a beam model to this code which tracks a set of super-particles, consistent with the NOVO picture [8]. This contradicts the assumption that the fields are static in the beam's frame, but this discrepancy is not very large, if we can assure that the beam changes very slowly compared to a plasma oscillation ($k_p >> 1/\beta$). A similar argument is used with spatial variations in the plasma density. In the most extreme case, the beam crosses a plasma/vacuum boundary, with the method and have been incorporated into the code. causing a transient response, which is neglected in our treatment. More gradual variations in the plasma density, like the droop at the ends of the column, are entirely consistent.

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