Expression of interest - Plasma wake-field experiments at FNPL

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I. Introduction

There has been much recent interest in studying plasma-based acceleration mechanisms. The eventual applications of this technology include ultra-high gradient acceleration for linear collider applications, high brightness electron sources, and VUV light generation.

Although using a laser driver to excite the plasma wave generates the highest recorded gradients, there are several advantages to using a beam-driven approach. The mechanism for propagating an electron beam is much simpler than for a laser beam, since the electron beam relies on the effect of ion channel focusing, In highly nonlinear cases, where the ion channel is fully formed (the blowout regime), there is no radial self-wake associated with the accelerated particles, as there would be the case if the channel still contained some plasma electrons. Such a self-wake would result in stronger focusing near the back of the accelerated bunch and thus lead to emittance dilution. In this regime, the focusing force is independent of longitudinal position over the volume of the accelerated bunch. In such a case, the Panofsky-Wenzel theorem also tells us that the acceleration force is independent of radius. One further advantage of an electron driver is the lack of dephasing present in some laser-driven schemes. Although the electron beam can suffer from erosion at the leading edge, this can be stabilized in a number of ways such that the phase relationship between the accelerating wave and the accelerated bunch is kept constant.

A measure of how strong an acceleration gradient can be produced for a particular plasma density n_0 is the wavebreaking field, $E_{wb}(\mathrm{V/m}) \cong 96\sqrt{n_0(\mathrm{cm}^{-3})}$. This is not an absolute limit, but it does show the scaling behavior of the interaction as a function of plasma density. Working with beams available today, which also have enough charge to drive high-magnitude wake-fields, a common choice for the plasma density is 10^{14} cm^{-3}, with a wavebreaking field of around 1 GV/m. At this plasma density, the characteristic wavelength of the device is 3.3 mm. Although this wavelength is shorter than is used in conventional machines (compare with ~ 1 cm of CLIC), it is much longer than is typically considered for laser-driven schemes. The use of longer wavelengths can relax the timing and transverse tolerances required to achieve staging, where a single witness beam is consecutively accelerated in a set of plasma sections.

Along with the various advantages listed above, research into beam-driven plasma wake-fields has been limited by the availability of high charge, short beams. Given the excellent beam conditions at FNPL for a plasma experiment, and the success of the ongoing program, progress on this experiment should continue and perhaps be expanded along the lines discussed in section III.

II. Progress to date

The capabilities of the A0 photoinjector facility are an ideal match for a plasma wake-field experiment. The combination of high charge and bunch compression are able to drive wake-fields above 1 GeV/m, according to simulations. Activities in the past two years have included the construction of the plasma source and its associated diagnostics, integration into the photoinjector beamline, achievement of bunch compression, and preliminary wake-field acceleration results.

Bunch compression studies have formed a sizable portion of the thesis work of Jean-Paul Carneiro and Michael Fitch, with plans to make further studies outlined in a separate EOI. For these reasons, the bunch compression results will be mentioned only in passing. The best compression achieved to date at high charge (8 nC) is 0.6 mm rms. The compression ratio, the ratio of the uncompressed to compressed bunch lengths tends to be ~5.To obtain these results, the 9-cell phase is ordinarily changed by 25-30 degrees, from the uncompressed case. Preliminary attempts to measure the emittance of the compressed bunches have been inconclusive, but have shown a large emittance increase in bend plane direction (the y-emittance).

In order to incorporate a plasma into the A0 beamline, the plasma working gas has to be separated from the upstream UHV environment. In Figure 1, this was accomplished with a 10 μm thick aluminum foil situated directly in front of the plasma column. The beam is focused onto this foil to about 200 μm transverse rms with the matching solenoid (see Figure 2), and is kept at roughly this size through ion channel focusing in the plasma. This foil is inclined at a slight angle to allow it to serve as an OTR screen.

The plasma source works according to the hollow cathode arc principle. In such a plasma source, differential pumping is used to create zone with high neutral gas pressure, where most of the plasma is produced, and a low pressure zone into which the plasma diffuses. The high pressure zone is created in the annular region between the two concentric tantalum tubes, with the gas being introduced at the closed-off downstream end and flowing toward the upstream end. In order to cause high electron emission from the tantalum, the outer tube is resistively heated with a DC 1000 Amp current from a power supply. Due to the large amount of thermal radiation at the >2100 C temperatures, the inner tube temperature is also brought close to this. To initiate the plasma arc, the gas valve is first opened for about 1 ms, and then a 0.5 μs, 160 V pulse applied to the anode 20 ms later.

Initial characterzation of the plasma parameters have shown that it is possible to produce a 10^{14} cm^{-3} plasma, and that the plasma density quickly drops away close to the region of the cathode and stays low in the downstream region. The flat top of the plasma plasma profile has an effective length of ~8 cm. However, the plasma configuration that has been incorporated into the beamline has several minor deviations from the device tested on the bench. At some point it will be necessary to add a plasma probe to the setup for online monitoring of the plasma density.

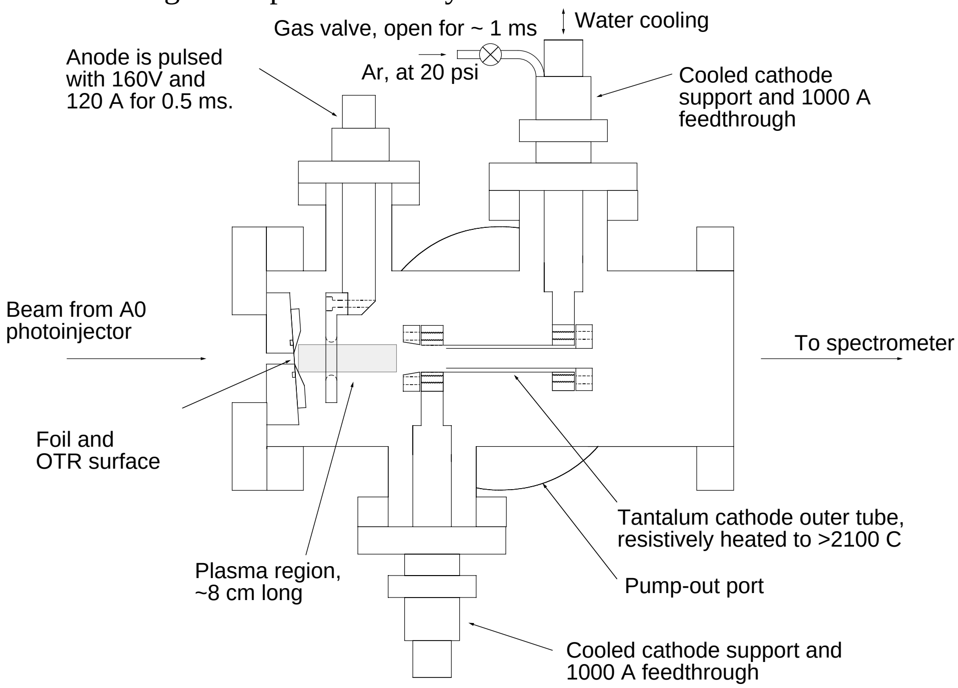

Figure 1. The plasma source.

The plasma experiment was integrated into the beamline in August 2000. Early experience with the setup demonstrated that it was easy to cause a large alteration of the energy distribution of the outgoing beam, especially toward the low end of the spectrum. While the compressed drive beam is typically near 14 MeV, we noticed a significant tail all the way down to 3 MeV. Several features of the geometry of the experiment prevent accurately looking at energies much below 3 MeV, but since this end-point could be made to happen even without the full amount of charge, there is a good chance that wakes capable of fully decelerating the trailing edge of the beam have been generated. That being the case, it is worth mentioning that the Fermilab experiment would be first in achieving such a result. At the present time, additional fundamental investigations into the linear and nonlinear mechanism of beam energy loss in plasmas in the UCLA FNPL experiment, to illuminate the parametric dependence of this effect on beam charge and dimensions, as well as plasma density.

The maximum amount of acceleration recorded in the experiment is 72 MeV/m, or a 5.7 MeV increase in energy (see Figure 3). It is surprising that when this data was taken, a large fraction of the shots had a comparable energy gain. This contrasts earlier experimental work at Argonne, where only a small fraction of the shots displayed a large energy gain. This is probably due to better stability on the part of the laser at Fermilab. Since the peak observed gradient has tended to increase as a function of getting more operational experience with the system, the number is bound to go up, very likely above 100 MeV/m, and perhaps higher. There are several reasons why the beam-plasma interaction could fail to yield a high average gradient, despite the peak gradient in the plasma being much higher:

1. A fast time-scale beam erosion of the drive beam can making a phase shift in the wave.
2. An insufficient number of electrons at the initial conditions suitable for maximum acceleration. The volume for these electrons is characterized by a radius of ~30 microns, and a longitudinal distance of 150 microns.
3. Deflection forces due to beam tail motion could distort the shape of the ion channel and further reduce this volume.

Since the available diagnostics may not be able to obtain an adequate enough picture of all these processes, attainment of higher gradients may simply be a matter of more operating experience with the device.

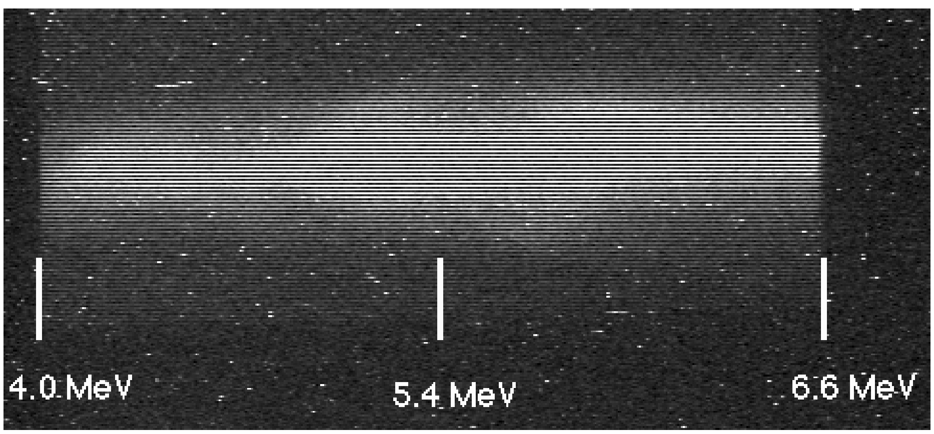

Figure 2. Decelerated electrons with 4-8 nC of beam charge.

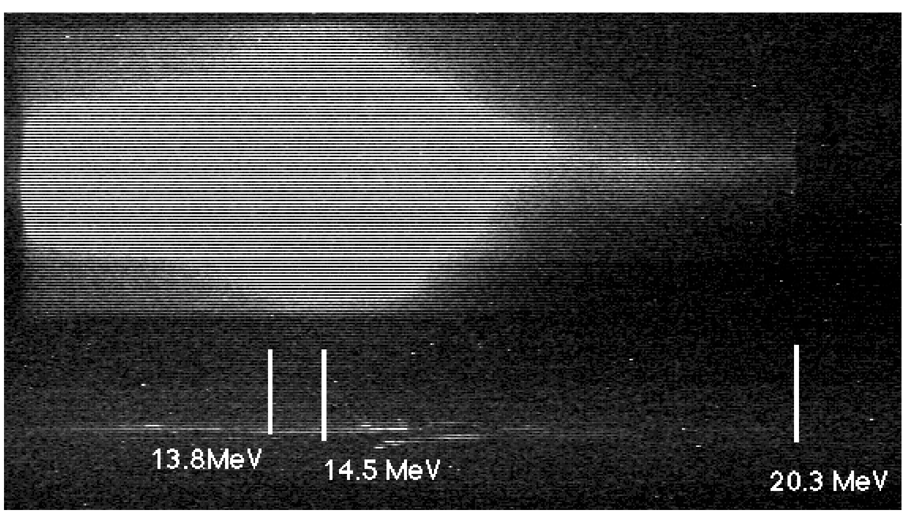

Figure 3. Accelerated electrons (shown at high enough intensity to be visible in printed form). With the plasma turned off, the beam is centered at 13.8 MeV, with a significant drop-off in intensity by 14.5 MeV.

III. Future experiments

a) Acceleration of a witness beam

If a part of the photocathode laser is split off and suitably delayed, a second beam may be accelerated in the same RF bucket in the gun as the main beam. This drive/witness pair can be used to probe the temporal structure of the plasma wave. It is also a way to maximize the number of accelerated electrons, and also to begin studying beam properties of the plasma-accelerated population, such as emittance and energy spread.

This work has already been started, with the addition of a delay arm in the pulse stacker bypass line (see Figure 4). Streak camera pictures of the uncompressed beam have clearly shown a separated in time witness beam. When the beamline was changed to allow beam compression, however, the witness beam signal could no longer be distinguished form the main beam. By itself, the witness beam appeared to have a much larger radius than the main beam. This fact is not very surprising, considering that the transverse forces in the 9-cell can b e very different for two beams that are at 25 and 30 degrees off crest.

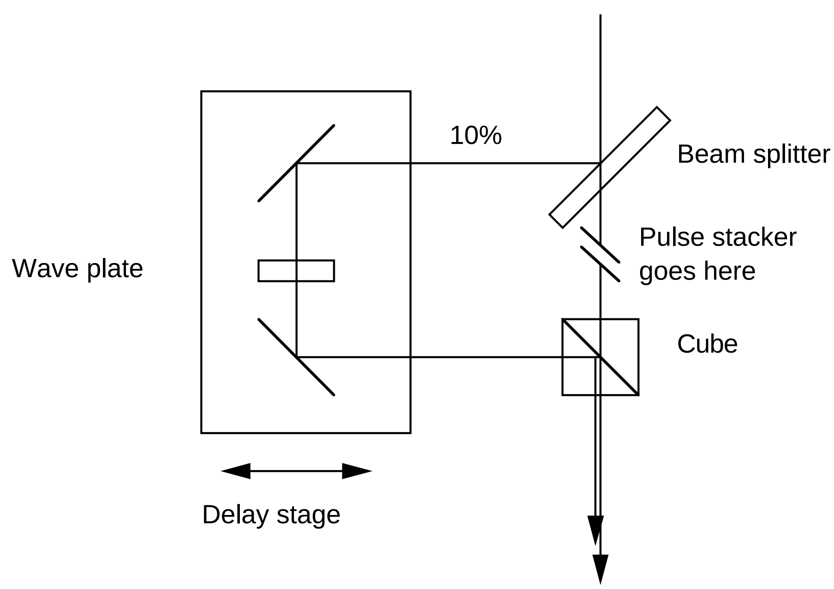

Figure 4. The laser witness pulse splitter.

These problems may be overcome with additional beam simulation work with codes like PARMELA or Astra, coupled with TraFiC4. One possible remedy would be to add a telescope to the laser witness beam delay arm, so as to establish the optimum ratio of beam sizes on the photocathode for the drive and witness beams. In this way, the differences in space-charge forces near the cathode could be used to compensate for differences in RF focusing in the 9-cell.

b) Captured electrons

There are several situations which can cause wave-breaking and trapping of electrons from rest into the plasma wave. Indeed, the laser-driven experiments are able to generate a large number of accelerated electrons, but these experiments are also characterized by a 100% energy spread. What's needed is a scheme to control the trapping so that the out-going beam can have a well-defined energy spread and phase space. A significant amount of work has been carried out recently to address this question at UCLA.

In a beam driven experiment, one way of provoking this trapping is with a longitudinal density transition (see H. Suk, *et al.* In PRL **86**, 1011 (2001)). In this scenario, the plasma electrons rephase during upstream oscillation in a higher density region, and subsequently trap in the low density downstream section. A proof-of-principle experiment is now being designed at UCLA. The plasma density optimized in simulaiton of this effect is shown in Fig. 5. The plasma density is in the 1E13/cc range, to take advantage of an existing test plasma source at UCLA. This source profile is used in the 2D electromagnetic PIC code MAGIC, along with a 5.9 nC beam compressed to 2 psec rms, to simulate the proposed experiment.

The expected results of the experiment obtained from simulation are displayed in Fig. 6. It can be seen that a 1.7 MeV(total energy) beam, with little energy spread is extracted from the plasma. The interaction length and density of the plasma has been chosen to give a maximal separation between captured and drive beam energies, to ease interpretation of the experiment. The long density droop after the transition effectively rephases the electrons, allowing the nicely minimized energy spread shown. This proof-of-principle experiment would be a major accomplishment in the creation of short-pulse, high brightness beams from plasmas.

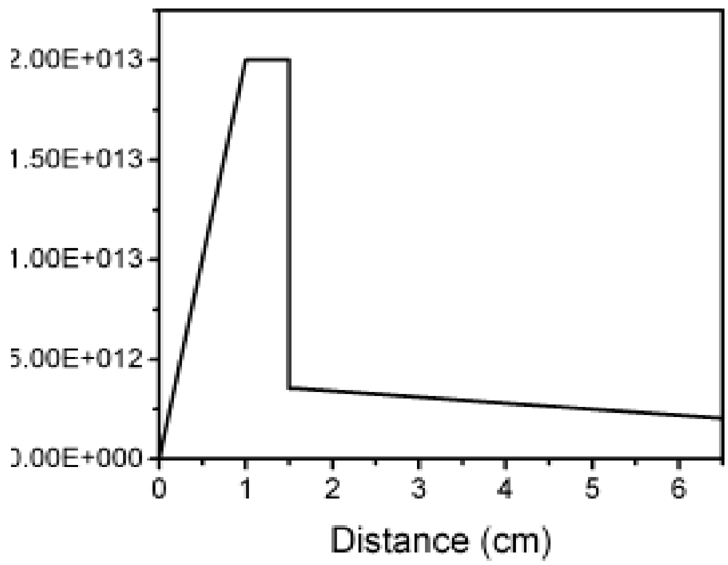

Figure 5. Plasma density profile used in simulation of optimized density transition-induced trapping experiment.

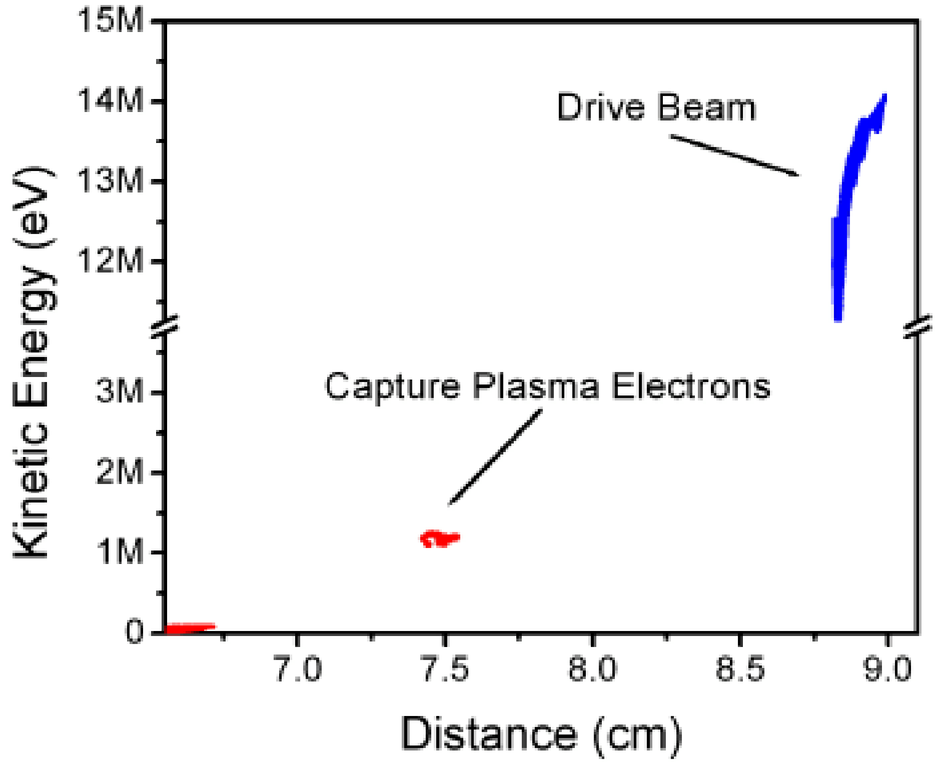

Figure 6. Longitudinal phase space at the exit of the plasma of Fig. 5, showing a drive beam and captured plasma electron population.

An entirely different way to achieve an accelerated beam is if the electrons are photoemitted from a surface. Particle-in-cell simulations show that when the drive beam crosses a thin foil directly in front of the plasma, the accelerating field lines terminate on the foil. If a laser is able to photoemit electrons from this surface at the correct phase in the wave, these electrons will be accelerated in the wave in a manner analogous to a photoinjector gun.

Since this effect was known about at the time the plasma cell was built, there is a quartz viewport in the plasma vacuum chamber facing the downstream side of the foil. Depending on the laser energy budget, a higher quantum efficiency may be obtained by evaporating some magnesium onto this foil. It should be noted that this trapping happens under conditions where the accelerating field is sufficiently close to the wave-breaking field, or ~1 GeV/m for our conditions, which is significantly higher than has been achieved.

c) Two-stage acceleration

Plasma wake-field acceleration with a symmetric in time driver is limited to a transformer ratio of 2.0. This means that a 100 MeV driver can only be used to produce a 200 MeV energy increase in a witness beam. Although the plasma cell needed to produce the 200 MeV may be really small, the overall facility size is dominated by having to produce the 100 MeV driver. In order to make the overall footprint of a plasma-based accelerator truly compact, a single source of drive electrons needs to be distributed among a collection of plasma sections in such a way that a single witness beam can gain energy from each of the sections. The overall transformer ratio, the product of the plasma transformer ratio and the "hardware" ratio (the number of sections), can now be large.

Figure 7 is a schematic of a possible two-stage plasma acceleration experiment at FNPL. In order to make the two drive bunches, the drive laser is split into two parts delayed by 1-3 RF periods. This delay time can further be adjusted to cause an energy difference between the two bunches, making it possible to separate them with a bend magnet. The alternative to this is to use a subharmonic cavity as the separator (this option was discussed in the original E890 proposal), but due to the cost and complexity this would add to the project, it may be considered if the bend magnet approach is found unsuitable.

After a witness beam is accelerated in the first plasma, it will have a large energy spread, with the tail being more energetic than the head. By carefully selecting the beam optics between the two plasmas to reverse the position of the head and tail, the longitudinal phase space tilt from the first plasma can be reversed in the second plasma. The remaining energy spread will then reflect the nonlinear component of the wake, as well as the self-wake of the witness pulse.

A fundamental difficulty in carrying out any such experiment is to insure the transverse alignment of the drive and witness pulse upon entry into the second plasma. The beam pointing jitter and longer term drifts will always make it difficult to establish good spatial alignment. However, the two drive beams are generated from the same laser pulse, and so their centroid positions along the beam line will be correlated. In order to think about how this fact can be exploited, it is useful to talk about the transfer matrix for each beam from the upstream beamline to the combining magnet. The witness beam and the second drive beam take very different paths, but the beam optics for each path could be chosen to make the two transfer matrices equivalent. This would insure a good alignment between the witness beam and the wake-field axis in the second plasma cell.

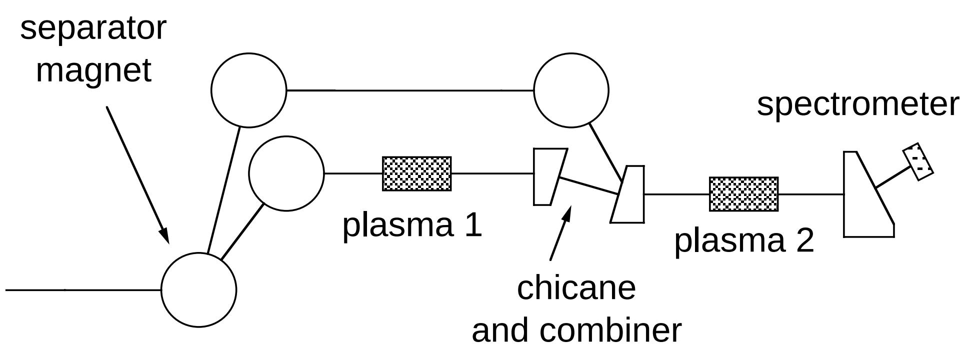

Figure 7. Schematic of two-stage plasma wake-field accelerator experiment, shown without quadrupole magnets which are needed for beta-matching and dispersion control.

As an alternative to the above described scheme, we note that instead of an externally injected witness beam, if the first stage produces an ultra-short, narrow energy spread beam from trapping injection, then an optimized beam is available for injection into the second stage.

More work is needed to obtain a detailed beamline design for such an experiment, which would determine the costs and space requirements of the project with greater accuracy. This project would also be an excellent thesis topic for one, or maybe two students.