A Novel Technique for Probing the Transverse Interactions Between an Electron Beam and a Plasma*

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Abstract

In laser-plasma interaction experiments there are a variety of effects which will scatter or deflect a probing electron beam. For example, a longitudinally probing electron beam is defocused by the ponderomotive force of a laser, but in a plasma the laser can set up fields which actually confine the electron beam. In the cases of plasma wave excitation via the beatwave or wakefield mechanisms, the thermalization of the electron distribution function can lead to large scale magnetic fields via the Weibel instability. A novel Cherenkov probe has been built and tested which measures the transverse current distribution of an electron beam with at least 50 ps time resolution. A solenoid lens is used to map angular deflections within the interaction region into *x-y* space at the location of the Cherenkov probe. This allows the cases mentioned above to be experimentally studied.

I. INTRODUCTION

The transverse current distribution of a relativistic electron beam has been time resolved to 50 ps using a novel Cherenkov probe. This probe consists of a two-dimensional mesh of optical fibers arranged in such a way that a collimated beam striking the probe chuck at a prescribed angle of incidence will inject electrons into each fiber at the Cherenkov angle with respect to that fiber's axis (Fig. 1). In addition, the mesh is square when projected onto a plane orthogonal to the trajectory of the electron beam. With this arrangement, electrons impinging upon any fiber will emit the maximum fraction of their Cherenkov cones within the numerical aperture of the fiber. The ends of the fibers are brought together in a linear array, which is imaged onto the photocathode of a streak camera. Streaking the image gives the current in every fiber as a function of time. With this information, one can obtain

$$k(x,t) = \int j(x,y,t)dy \quad \text{and} \quad k(y,t) = \int j(x,y,t)dx$$

where $j(x,y,t)$ is the unknown distribution of current density in the transverse plane, and k is lineal current density. $j(x,y,t)$ itself can only be deduced if it is assumed to be separable in x and y.

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II. PROBE DESIGN

The fibers chosen for our probe consist of a 400 μm diameter PMMA core with a 50 μm thick acrylic cladding. The overall length of the fibers is 20 cm. Plastic fibers are advantageous since in glass, electrons of less than 5 MeV would be quickly scattered out of the fiber's numerical aperture. X-ray production is also minimized in plastic. Higher energy electron beams will produce more signal in silica fibers provided UV is transmitted throughout the entire optical system.

The fibers are glued onto a 25×41 mm oval chuck of black acrylic. Machined onto the chuck are a series of nine parallel ridges running the length of the ellipse, making a 31° angle with the major axis. These are 750 μm high, 1 mm wide, and are set 3 mm apart. One set of nine fibers sits atop the ridges while the other nine tunnel through the ridges at -31° to the major axis. A beam striking the chuck at 37° to the major axis and 90° to the minor axis will see a mesh of 2.5 mm squares. Every fiber will make a 45° angle with the beam trajectory.

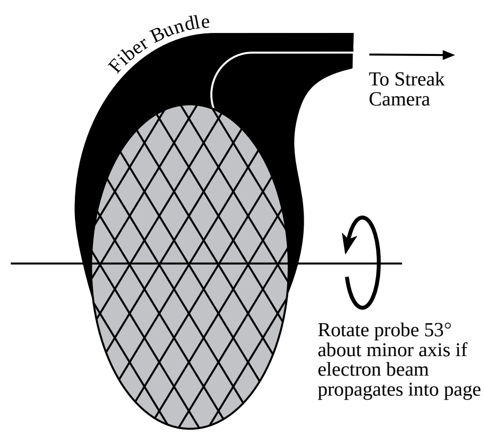

Figure 1: All fibers must make an angle of 45° with the e-beam trajectory. Therefore they must lie on the surface of any 45° cone whose axis is parallel with the e-beam trajectory. Choose two straight lines on the cone which are perpendicular when projected onto the base of the cone. The angle between these lines is the angle between the crossed fibers, and the plane they lie in is the plane of the probe chuck.

III. ELECTRON BEAMLINE

The electron beam in our experiment is generated by a 9 GHz RF linac. The beam energy is 2 MeV, and the emittance of the beam is 6π mm-mRad. The average current is 30 mA and the pulse length is 1.5 ns. The linac has been described in detail elsewhere [1].

In experiments with the Cherenkov probe, the electron beam will be propagated collinearly with a 300 ps, 100 J CO_2 laser pulse. The laser and electrons are simultaneously focused into a static fill of hydrogen gas where a plasma is formed via tunneling ionization. We are interested in measuring angular deflections of the electron beam by the plasma. To use the Cherenkov probe in this situation it is necessary to move the electrons away from the laser somewhere beyond the interaction point.

At the interaction point the electron beam is at a 500 μm waist. A collimating solenoid lens with a bore diameter of 3.2 cm is placed 20 cm from the waist. This provides a linear mapping between angle and transverse position. A 5×5 cm square dipole is situated 15 cm from the solenoid. This deflects the electron beam by about 10°. Since the focusing of the laser is f/11 this is sufficient to move the electrons off the laser beam. The Cherenkov probe is placed 25 cm from the dipole.

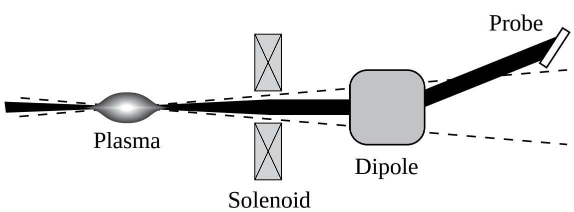

Figure 2: Cartoon of electron optics after the interaction point. The dotted lines represent the laser envelope while the black area represents the electron beam.

The beamline was characterized by inserting a hole pattern in the beam immediately prior to the solenoid. A fluorescer was placed at the position of the Cherenkov probe. It was determined that the spot size at the lens is 6 mm, and the beam is rotated 50° when collimated by the solenoid. This is convenient since the probe axes then line up with the laser polarization. It was also verified that the dipole magnet does not distort the beam, and that the beam is well centered on the lens. The only problem that emerged was that the lens smeared the shadow of the hole pattern radially as if due to chromatic aberration. However, the length of the smearing was less than an interfiber spacing, and is not resolved by the Cherenkov probe.

IV. PROBE PERFORMANCE

The Cherenkov probe has been tested within the setup described above by firing the electron beam but not the laser beam. Figure 3 shows a streak in which we consider only the temporal information. In this streak, the microbunches associated with the RF frequency of the linac are clearly shown. The time resolution of the probe in this case was evidently 50 ps since from previous measurements the microbunches are known to be less than 10 ps long. The time resolution of our setup is affected by the size of the image on the streak camera photocathode, modal dispersion in the fibers, and time of flight differences between electrons hitting different areas of the probe.

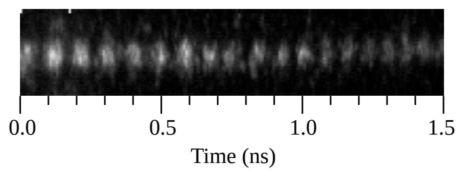

Figure 3: Streak with microbunches. The spatial information is not emphasized here. Note that the apparent chirp in the RF frequency is due to a nonlinearity in the sweep speed of the streak camera.

Figure 4 shows a streak including spatial information. On this shot the electron beam was aligned to the interaction point, collimated by the solenoid, and steered onto the center of the probe. The microbunches were not clearly visible at this sweep speed.

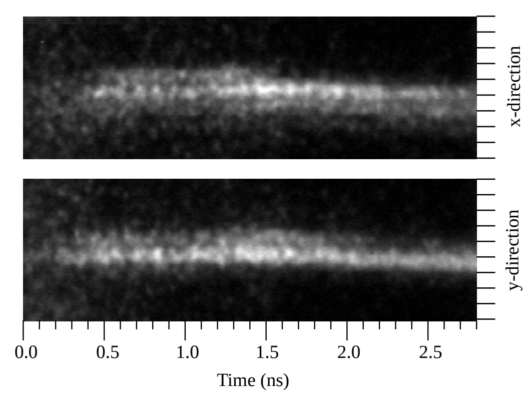

Figure 4: Streak with spatial information. White space has been artificially inserted between the upper and lower halves of the streak for clarity of viewing. The image of the fibers is arranged such that each half of the streak is an intensity plot of current with the horizontal axis time and the vertical axis one of the transverse spatial dimensions. The vertical tick marks are spaced such that the image of one fiber fits between them.

The most outstanding feature of Fig. 4 is that the electron beam is increasingly deflected in the negative *x* and *y* directions as time advances. This feature is reproducable on every shot. The reason for this deflection is that the energy of the electron beam droops in time. Thus, the dispersive electron optics both before and after the interaction point will conspire to put the beam at slightly different locations at different points in time. Since we wish to measure only deflections occuring at the interaction point, any dispersion in the electron optics is undesirable. However, since the effects of the dispersion are reproducable and small, they will not seriously affect the interpretation of future results.

Another issue associated with the dispersion in the electron optics is that when a large amplitude plasma wave is driven significant numbers of electrons in the probe beam can be drastically accelerated in the longitudinal direction. We have previously reported measurements demonstrating this effect [2]. Accelerated electrons will create a spatial variation at the Cherenkov probe which is indistinguishable from some particular angular deflection. Again, we would prefer that the spatial dimensions of the probe map only to the angles at which electrons leave the interaction point. On the other hand, accelerated electrons would lead to a specific spatial structure at the Cherenkov probe which could be easily identified, and would correspond to no plausible deflection scenario.

Finally, the sensitivity of the probe at the sweep speed associated with Fig. 4 can be easily determined. The highest number of counts produced on one pixel of the CCD was 200. The peak current of the electron beam is 250 mA. For this streak, the ratio of the area of the electron beam to the area of the section of fiber illuminated by the electron beam was 9.3. This implies that the sensitivity of each fiber is about 7 counts/mA. The background level of our CCD typically fluctuates by one or two counts. However, if we average over all the pixels illuminated by a single fiber during one microbunch we will be able to statistically resolve less than one count. Hence, we expect to be able to resolve 100 μA of current running through any fiber.

V. CONCLUSIONS

A means of using a streak camera to time resolve the angular deflections of an electron beam by a laser-produced plasma has been developed. In future experiments we will use the new probe to study a number of effects. The laser can be fired into either vacuum or plasma, and can be run in either single or dual frequency mode. When in dual frequency mode, the plasma density can be set to resonate with the beat-frequency of the laser so that a large amplitude plasma wave is excited. Probing the interaction region some time after this plasma wave breaks up may reveal evidence of the Weibel instability.

VI. REFERENCES

[1] C.E. Clayton and K.A. Marsh, “A 2 MeV, 100 mA electron accelerator for a small laboratory environment”, Rev. Sci. Instr. 64, 728-731 (1993).

[2] M.J. Everett et al., “Trapped Electron Acceleration by a Laser Driven Relativistic Plasma Wave”, Nature 368, 527 (1994).