Backward Compton scattering for probing electric fields in a plasma

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A new method is suggested for probing ultrahigh electric fields associated with relativistic plasma waves in high-density plasmas. A relativistic electron beam and an intense photon beam are collided inside the plasma. In the absence of any perturbing fields, the electrons Compton scatter some of the photons. In the backward direction, the frequency of the scattered radiation is roughly $4\gamma^2\omega_0$ with a frequency spread of $\sim 2(\Delta\gamma/\gamma)$. When strong electric fields are present, some of the electrons are accelerated and others are decelerated. This leads to broadening of the Compton-scattered spectrum. An experiment designed to probe coherent longitudinal electric fields of a beat-excited plasma wave will be described. This technique has the potential to give time-resolved information about relativistic wave particle interaction.

INTRODUCTION

The fact that collective phenomena in plasmas can lead to regions of ultrahigh potential gradients that propagate at the speed of light has lead to the new field of plasma accelerators including the plasma beat wave and the plasma wake-field accelerator concepts. In both these concepts, the accelerating field is the longitudinal field of a relativistic plasma wave (relativistic factor $\gamma$ associated with the phase velocity $\gamma c$). In a recent experiment, longitudinal fields larger than 1 GeV/m were inferred. This paper describes a new way to probe these fields with potentially ps time resolution using 180° Compton scattering of photons off a probe beam of injected electrons.

The basic idea is this: We imagine the plasma wave to be propagating near $c$. Electrons are also injected in the $z$ direction at or near the trapping-threshold energy which require that they be injected with relativistic ($\gamma \gg 1$) energies. A probing laser beam, propagating in the $-z$ direction Compton scatters off the electrons resulting in a large frequency shift when observed in the $+z$ direction. Neglecting the recoil of the electron, the shifted frequency $\omega_r$ is given by $\omega_r = 4\gamma^2(1+a_w^2)^{-1}\omega_0$, where $\gamma$ is the relativistic factor of the electrons, $\omega_0$ is the probe frequency, and $a_w = eA/mc^2$, where $A$ is the magnitude of the vector potential of the probe beam. The scattered frequency is thus a sensitive diagnostic of the changing electron energy showing, for example, a 20% variation for a 10% change in the energy of the injected electrons.

I. THEORY

Since the useful information on the electron acceleration is found in a broadening of the radiated spectrum, we must first determine what the unaltered spectrum looks like in terms of bandwidth and shape. We would also like to estimate the number of detectable photons in the radiated spectrum. We thus turn to the theory for scattering from relativistic electrons.

Applying the relativistic Doppler shift for the case where the probe beam and the electrons collide head on gives

$$\omega_r = 4\gamma^2\omega_0,$$

where we have assumed $\beta \approx 1$ and exact backscatter. We find the scattered power from the Lienard expression which, assuming the transverse acceleration due to the probe beam is much greater than longitudinal acceleration, gives

$$P = \frac{2e^2}{3c}\gamma^4a_w^2\omega_0^2 = \sigma t I_0\gamma^2,$$

where $\sigma_t$ is the usual Thomson cross section and $I_0$ is the probe laser intensity. The oscillating electrons radiate as dipoles in their own frame with angular distribution

$$\frac{dP}{d\Omega} = \frac{3}{8\pi} P_T \cos^2 \phi',$$

where $P_T$ is the total radiated power and $(\theta', \phi')$ are the polar angles in the electron's frame. From Eq. (3), there is no $\theta'$ dependence, whereas in the lab frame $(\theta, \phi)$, the radiation is sharply peaked in the electron's propagation direction, as indicated by the transformation

$$\theta = \tan^{-1}[\sin\theta'/\gamma(\cos\theta' + \beta)]$$

$$\approx \theta'/2\gamma.$$

The last approximation is true within 10% for $\theta < 60°$ and $\gamma \gg 1$. Collection in the lab frame over an acceptance angle $\Delta\theta$ implies collection of a range $\Delta\theta'$ in the electron's frame, which, in turn, implies a spectrum extending to the red from the maximum frequency shift given by Eq. (1). If we return the $\theta'$ dependence to Eq. (1), we find

$$\omega \approx 2\gamma^2\omega_0(1 + \cos \theta') \approx 4\gamma^2\omega_0(1 - \gamma^2\theta^2),$$

where we have expanded $\cos \theta'$ for $\theta' \ll 1$ and used Eq. (4). The bandwidth is easily found as a function of detector acceptance angle from Eq. (5) as

$$\Delta\omega_r/\omega_r = -\gamma^2(\Delta\theta)^2,$$

for on-axis collection. The fraction of $P_T$ collected in solid angle $\Delta\theta^2$ is found by integrating Eq. (3) over $\Delta\theta^2$, giving

$$\Delta P/P \approx 2\gamma^2\Delta\theta^2.$$

From Eqs. (6) and (7), we see that there is a power/band-
width tradeoff in choosing a collection angle.

The energy spread given by Eq. (6) is that for a monoen-
ergetic electron beam. Any real beam will have a spread of
energies so that the real spectrum will be a convolution of
the spectra from each "energy group."  

II. EXPERIMENT

In the proposed experiment at UCLA, a 100-J, 100-ps
two-frequency CO₂ laser pulse is focused into a theta-pin
ch plasma where the relativistic plasma wave is excited over
a length of 1 cm (see Fig. 1). An electron beam with γ = 2.5 is
injected through a hole in a mirror and is focused inside the
CO₂ focal spot. The electron beam, consisting of hundreds of
20-ps micropulses with 2 × 10⁷ electrons/pulse separated by
100 ps, is synchronized “by chance” with the 100-ps laser
pulse.

In the wave/particle interaction, some electrons are
slowed down while some are accelerated. Thus, the energy
spectrum of the affected micropulse is altered. The per-
turbed micropulse is passed through a foil window secured
over a hole in the laser-dumping mirror and refocused into a
second interaction volume. A second laser beam (derived
from the first-off beam splitter) is adjusted to collide peak
on peak with the electron micropulse if the micropulse was
at the peak of the first CO₂ pulse at their first foci. The
purpose of the foil is to block any bremsstrahlung radiation
from the plasma.

If the plasma is off, the (γ = 2.5) electrons and photons
will collide 10.9 ± 0.05 ns after the micropulse leaves the
first focus (assuming 300 cm between foci). If the plasma is
on and some electrons are accelerated, say to γ = 3, then
these will collide with the probe 10.6 ± 0.05 ns later. To
observe these with the probe beam, the delay of the probe
must be reduced by 300 ps. Thus, there is a time-of-flight
filtering of the observed Compton spectrum. As the delay is
reduced, the probe is sensitive to higher and higher energy
electrons.

If the electron plasma wave is driven to 1 GeV/m over
the 1-cm focal depth, then the maximum energy an electron
could gain would be around 10 MeV or γ≈20. Such accel-
eration should be attainable with our laser operating at full
power, with a focused intensity of around 10¹⁴ W/cm².
However, due to our current detection limitations and for
possible spectral brightness problems, it is desirable to per-
form these experiments initially with the driving CO₂ beam
attenuated such that acceleration can only occur up to
γ = 3–5.

For illustrative purposes, we will consider the example
of acceleration from γ = 2.5 to γ = 3. If the spread in γ of
the electrons is Δγ/γ<10% then the main contribution to the
bandwidth of the light scattered from an unperturbed elec-
tron bunch will be due to the finite acceptance angle of the
detector. For f/5 collection, we find from Eq. (6) a band-
width of 6%. A more accurate calculation shows a spectrum
with blue and red cutoffs at 461 and 493 nm, respectively.
When the energy spread of typical linacs are taken into ac-
count, the cutoff extends deeper into the red, while the blue
cutoff remains sharp. This is due to the fact that linacs typi-
cally have a sharp energy cutoff on the upper end. This is
illustrated in Fig. 2. Suppose the delay of the probe CO₂
beam is adjusted to selectively detect γ = 3 electrons. Be-
cause the probe pulse is 100 ps, it sees a range of γ's, i.e.,
γ = 3 ± 0.1, resulting in a spectrum over the range 310 ± 22
nm. This would be extended to the red by the finite collection
angle, as illustrated in Fig. 2.

It remains to be seen if these spectra are detectable. We
assume that the probe beam has an intensity of 10¹⁰ W/cm²
(10% of the main beam) and has a 1-cm focal depth. Thus
the interaction time is 33 ps—the transit time of the electrons
through the interaction volume. Equation (2) is used to cal-
culate the total radiated power which, for the γ = 2.5 elec-
trons is P = 0.009 eV/electron/33 ps. For 2 × 10⁷ elec-
trons, this gives P = 1.8 × 10⁷ eV/33 ps. From Eq. (7),
the collection efficiency is 13% for f/5 collection. If we assume
that the spectrum falls on 15 channels of a 50 channel detec-
tor (such as the 50 resolvable spots across the slit of a streak
camera), as shown in Fig. 2, then the power per channel is
1600 eV/ch/33 ps or about 600 2.5 eV photons/ch/33 ps,
which should be detectable. We follow the same calculation
for the γ = 3 electrons but use 4 eV/photon and spread the
spectrum over 20 channels. This gives about 9 photons/ch/
33 ps, assuming 1% of the electrons lies in the γ = 3 ± 0.1
energy group. Six photons/ch is marginally detectable when
one folds in the quantum efficiency of the photocathode
and the throughput of the spectrograph. However, it is not
known if taking only 1% of the electrons into the $\gamma = 3$

III. CONCLUSIONS

In conclusion, we have described a scheme for studying the energy perturbations on an electron beam due to high fields in a plasma using an optical scattering technique as a diagnostic complementary to electron spectroscopy. This technique could be applied to study the two-stream stability of the driving electron beam in plasma wake-field accelerator experiments. Here the electron bunches contain more than $10^{10}$ electrons so that there would be sufficient signal above plasma bremsstrahlung to perform the Compton scattering in the plasma rather than outside, as described here.

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