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Generation of short pulse radiation from magnetized wake in gas jet plasma-laser interaction

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Abstract: A new kind of high power tunable radiation source, where the short electromagnetic pulse is generated by a perpendicularly magnetize plasma wake is studied experimentally. A gas jet flow is used to generate the sharp boundary plasma. Wakefield is excited by a mode locked Ti:sapphire laser beam operating at 800 nm wavelength with the pulse width of 100 fs (FWHM) and maximum energy of 100 mJ per pulse with 10 Hz repetition rate. Different nozzles are used in order to generate different densities and gas profile. Strength of the applied external dc magnetic field varies from 0 to 8 kG in the interaction region normal to the direction of laser pulse propagation. Radiation is observed in the forward direction due to the axial component of the wakefield and in the normal direction due to the radial component of the wakefield, both perpendicular to the direction of the applied magnetic field. The frequency of the emitted radiation in both directions with the pulse width of 200 ps (detection limitation) is in the millimeter wave range. Radiations are polarized in the expected direction.

Introduction: There have been many different kinds of experiments on the use of intense laser pulse or electron beam to excite large amplitude (up to 100 GeV/m) plasma wakes. The energy of these wakes can be used for different purposes such as particle acceleration or radiation. Theories and experiments have shown that plasma is a capable medium to convert different initial energies to radiation. This possibility comes from the multi-mode nature of the plasma. We are studying a new kind of high power tunable radiation source. In this radiation scheme, a large amplitude electrostatic plasma wake is generated by an intense laser pulse in the presence of a modest perpendicular dc magnetic field. The initial motions of plasma electrons due to the laser ponderomotive force in the axial z and radial x directions make them rotate around the magnetic field lines and generate the electromagnetic (EM) part in the wake with a nonzero group velocity. For the axial propagation, radiation is polarized in the x direction and for the radial propagation radiation is polarized in the z

direction. The magnetized wake propagates through the plasma and couples to vacuum at the plasma-vacuum boundary. Radiation from magnetized wakes was first introduced by Yoshii *et. al.*[1] and experiments have been done by Yugami *et. al.*[2] and Dorranian *et. al.*[3]. Details about the theoretical aspects can be found in the mentioned references.

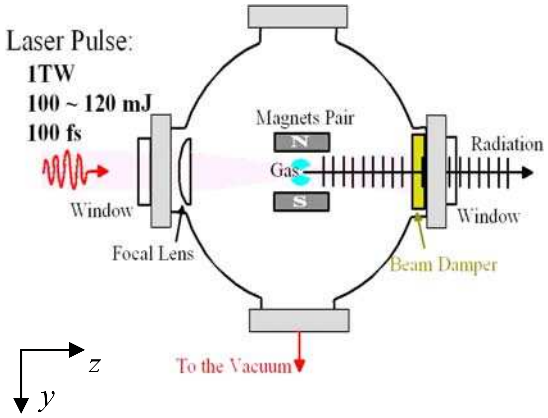

Figure 1: Experimental setup

Experimental setup: The experimental arrangement is shown schematically in Fig. 1. A mode locked Ti:sapphire laser system operating at λ = 800 nm wavelength, with the pulse width of τ_L= 100 fs (FWHM), and maximum energy of 100 mJ per pulse with 10 Hz repetition rate is used to excite wakefield. The laser pulse is irradiated into the vacuum chamber through 5 mm thickness CaF_2 window and is focused by a lens of *f*/5 at about 0.5 mm above the gas jet nozzle. The focal spot diameter is about 20 μm and the intensity is on the order of 10^{17} W/cm^2. A solenoid valve(Iota one) made by Parker instrumentation with 0.8 mm diameter exit hole was employed to generate the gas jet constant flow of 100~200 μs. The strength of the applied magnetic field is up to 8 kG. As the region of the field is much longer than the Rayleigh length, it is expected to be uniform in the interaction region. The experiment is carried out using nitrogen and helium gases at the initial base pressure of below 5 mTorr and maximum gas jet back pressure of 8 atm. The measurement system for the radiation consists of a crystal detector, horn antenna, waveguide and oscilloscope (Tektronix; TDS-694C) with limitation of minimum pulse width measurable at 200 ps and covering 10 Giga sample per second with frequency bandwidth of 3 GHz. Antenna and waveguide in U-band with cut-off frequency at 31.4 GHz for TE_{10} mode are employed to observe the temporal waveform of the radiation.

Experimental results and discussions: In Fig. 2 a typical radiation waveform is shown obtained from helium plasma at B_0 = 7.8 kG. The observed pulse duration of the order of 200 ps at FWHM, is limited by the bandwidth of the receiving equipment. From nitrogen plasma, the similar result is also obtained. The life time of the wakes in the plasma can be estimated from $\tau_p \sim L_p / v_g$, where L_p is the plasma length of the order of Rayleigh length and v_g is the group velocity of the wakes in the plasma. In this experiment with laser spot size of 20 μm, L_p is estimated to be about 1.55 mm. The electron density is about 10^{17} cm^{-3}

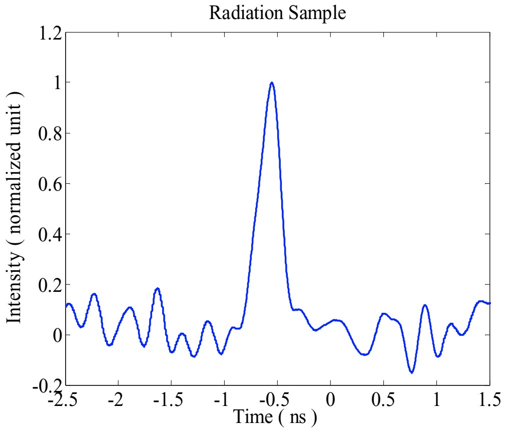

Figure 2: Radiation sample

correspondingly ω_p ~1.8×10^{13} rad/s so τ_p should be about 80 ns theoretically. But experimental results show that wake field disappears faster than the calculated life time. The reason could be explained by taking into account the gas ionization effect. In the case of preformed plasma, whose volume is larger than the laser pulse perturbation volume, when a corona electron moves away from its first position, a positive charge is created. These induce a restoring electrostatic force which is proportional to the electron displacement and produce a harmonic oscillator system at the plasma frequency. On the other hand in the tunnel ionization produced plasma, when the corona electron leaves the plasma, the number of positive charges is fixed by the laser pulse radius and Rayleigh length. Laser pulse energy is more nonuniform in this volume and electrons feel more nonuniform force. This could induces a lower restoring electrostatic force and larger number of electrons which don't come back in phase with plasma waves and destroy the oscillation faster than the expected time.

The polarization of the emitted radiation is measured by rotating the receiver horn antenna around the *z* axis in both cases of He and N_2 plasma at different gas densities. As it is predicted by the theory, the electromagnetic component of the wakes due to axial component of wakefields is in the *x* direction perpendicular to the direction of the applied external DC magnetic field. Experimental data show that the radiation is also polarized in the *x* direction, in fairly good agreement with expectation and for the propagated component due to radial component of wakefield radiation is polarized in the *z* direction. The spatial distribution of the radiation in both directions is measured by changing the position of the horn antenna in different angles. The radiation is mainly launched within the angle ±5 degree respect to the *z* axis in the *y-z* plane for the axial component as well as *x* axix in the *x-y* plane for the radial component in forward direction.

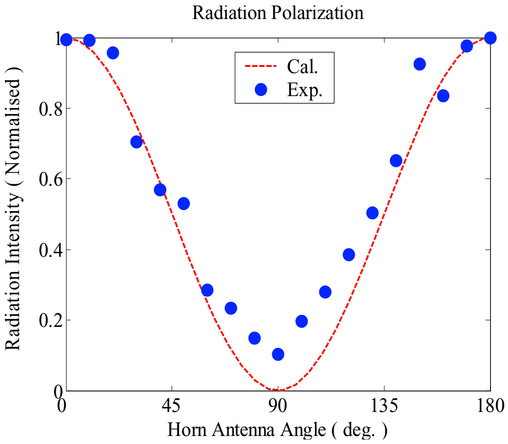

Figure 3: Radiation polarization

Pulses become weaker in larger angles up to ±8 degree and absolutely disappear after that. These results are confirmed by the fact that the group velocity of the magnetized wake is maximum in the forward direction. Data can be found in Fig. 4.

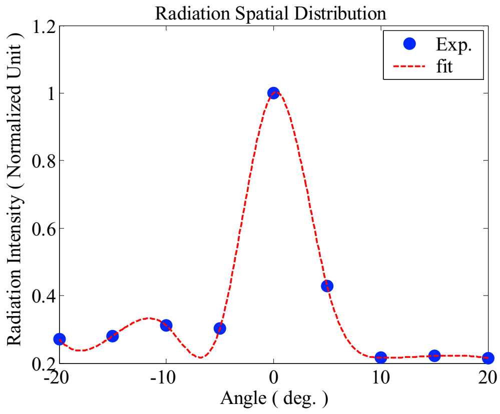

Figure 4: Radiation spatial distribution

Relative output power of the radiation versus the external magnetic field is shown in Fig. 5. The data are obtained without changing the position of the gas jet nozzle and the laser beam. The experiment is done by N_2 at the neutral gas density of 1.5×10^{17} cm^{-3}. The circles are the average of data upon six magnitude and the error bars indicate the difference between maximum and minimum of the experimental data at each magnitude of magnetic field strength. From B_0=0 to 1.7 kG, the radiation intensity doesn't change significantly with increasing the magnetic field. In this region, magnetic field is weak and unable to affect the plasma wakefield. The observed radiation in this range of B_0 might be caused by nonlinear currents. Up to 7.5 kG, the output power of the radiation increases with the magnetic field strength. Solid line indicates the theoretical values which is proportional to ω_c^2 or B_0^2. Up to now, the peak in radiation around B_0=3 kG can not be explained.

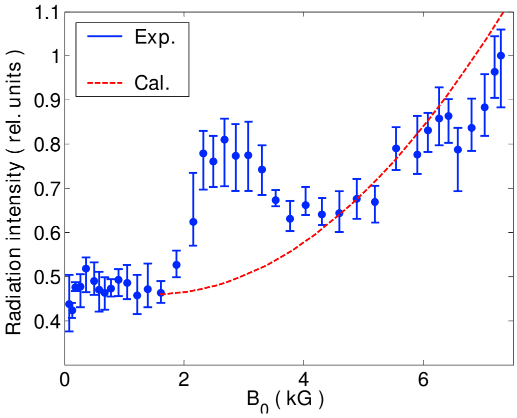

Figure 5: Radiation intensity versus magnetic field strength

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