Laser-driven beat-wave current drive in an unmagnetized plasma

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Introduction

The ability to generate an internal magnetic field in an otherwise unmagnetized plasmoid at a standoff distance is a basic yet important investigation in experimental plasma physics as well as a potentially valuable technique for fusion energy research. A seed magnetic field may be generated at a distance in a plasma using high-power lasers through a nonlinear beat-wave process. This process requires the understanding of a number of nonlinear physical phenomena, such as the wave mixing process in a plasma medium, and the wave-particle interaction through which wave energy is transferred to directed particle motion. In an experiment under development in our laboratory, an electron plasma wave will be resonantly excited, using two electromagnetic waves whose difference frequency is matched to the local plasma frequency. The excited plasma wave can drive a current in the plasma via Landau damping on the electron distribution and thus generate a seed magnetic field. One potential application of beat-wave current drive is in Magneto-Inertial Fusion (MIF). MIF takes advantage of the addition of magnetic fields to suppress cross-field thermal diffusivity in an otherwise inertially-confined plasma. It reduces energy losses during the compression of the target plasma. Realization of MIF needs the successful at-a-distance generation of a seed magnetic field that is amplified during plasma compression. A potential MIF testing facility of beat-wave current drive is the Plasma Liner Experiment (PLX) where plasma compression techniques are being studied.

Current drive by the nonlinear beat-wave process has been theoretically investigated [1, 2], but experimental investigation has been limited. The acceleration of electrons by beat waves has previously been measured in low-frequency, low-density experiments, using microwave pump wave sources [3]. In order to operate at the high densities in modern large plasma devices, higher pump wave frequencies will be necessary. For pump waves at high frequency, tunable in the THz range and at low power cost, a pair of CO_2 lasers ($\sim$30 THz) is the instrument of choice for these experiments. The multiple output lines of CO_2 laser are suitable for tuning the two pump lasers to match the local plasma frequency. The minimum frequency difference between two lines is 30 GHz and the maximum difference between two lines is 3.6 THz, which corresponds to plasma density range of 10^{13}cm^{-3} to 10^{17}cm^{-3}. In addition, the relative simplicity and high efficiency of the CO_2 laser system, and its scalability to high power levels, make it attractive for this project and future experiments.

We are currently preparing to conduct a beat-wave current drive experiment on the Compact Toroid Injection eXperiment (CTIX) using high-power CO_2 lasers, as shown in Figure 1. The experimental study will demonstrate the resonant excitation of electron plasma waves, and examine the wave-particle interaction between the beat wave and the plasma electron population. In the wave generation study, we will excite electron plasma waves via the beat-wave process. In the wave-particle interaction study, we will develop diagnostic systems to measure the modified electron velocity distribution, the generated current and magnetic field. In so doing, the experiment will investigate key issues in the beat-wave current-drive process and compare them with the prediction of theory, such as the dependence of current drive efficiency on plasma density, pump wave vectors and beam intensities.

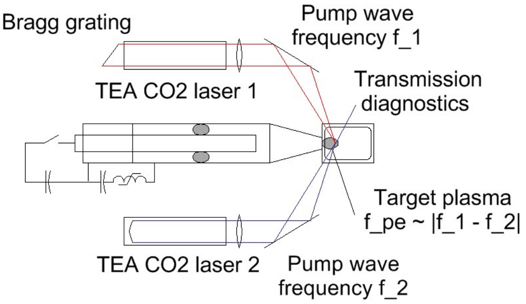

Figure 1: Overview of planned optical beat-wave current-drive experiment on CTIX

In the remainder of this paper, we will estimate the expected plasma current available with our laser system and describe the refurbishment and upgrade of the laser system.To independently examine the wave beating effect, a high density plasma test source has also been developed.

Analytical estimation

The excitation of plasma waves by nonlinear mixing two laser beams in inhomogeneous plasmas was theoretically studied by Rosenbluth, Liu [1] and Schmidt [4]. The plasma wave will grow linearly in time, then the wave amplitude will saturate by quasilinear Landau damping and trapping. For typical CTIX plasma density n=10^{15}cm^{-3}, CO_2 laser power intensity $P_{\rm in}$ =100 MW/cm^2, it will take 21 ns for the plasma wave to grow to the saturation level. The beat wave saturation time dependence has been observed in a previous low-density, low-frequency experiment [3].

Based on theoretical beat-wave current drive efficiency model of Cohen, et al. [2], we have estimated the expected driven current for the CTIX beat-wave experiment. Assuming plasma and pump-wave parameters $n_e = 10^{15}\,\mathrm{cm}^{-3}$, $P_{\rm in} = 100\,\mathrm{MW}$, $P_0^{\rm in} = (100\,\mathrm{MW})/(1\,\mathrm{cm}^2) = 10^8\,\mathrm{W/cm}^2$, $E_{\rm resonant} = 63\,\mathrm{eV}$, $q = 1$, $R_0 = 10\,\mathrm{cm}$, at an angle between pump lasers of 50°, the current drive efficiency is

$$\left|\frac{j}{c_1 W_1^{\rm in}(1+\omega_2\rho/\omega_1)}\right| = 0.15\,\frac{R_1 R_2}{(1+\omega_2\rho/\omega_1)(2\pi q R_0/10\,\mathrm{m})}\,\frac{(E_e/10\,\mathrm{keV})^{3/2}}{(n_e/10^{13}\,\mathrm{cm}^{-3})}\,\frac{\mathrm{A}}{\mathrm{W}} = 6\times 10^{-7}\,\frac{\mathrm{A}}{\mathrm{W}}$$

At the minimum expected power level of our experiment this corresponds to a current

$$I = 6 \times 10^{-7}\,\mathrm{A/W} \times 10^{8}\,\mathrm{W} = 60\,\mathrm{A}.$$

It is expected that the field created at this level of current will be well within the sensitivity of ordinary magnetic probes. In addition, an electron energy analyzer will be deployed on CTIX to determine the change in electron velocity distribution due to beat-wave absorption.

Lasers

Two Lumonics 601 TEA CO_2 lasers are being refurbished to be used as the source of pump waves for the proposed beat-wave current-drive experiments. The first laser system is now operating at its original specifications with updated high-voltage solid-state triggering systems. The other laser has been initially operated as an amplifier, in order to measure the small-signal single-pass gain as a function of operating conditions. The gain information helped us finalize the grating-tuned laser design (Littrow configuration). The second laser is now being developed as a grating-tuned laser in a multi-pass configuration. By tuning the grating, we will be able to adjust infrared line separation to match the CTIX plasma frequency at different density regimes. In addition, we have updated two low-power CW CO_2 lasers which could be used for both line tuning for the high power laser as well as for future scattering experiments for measuring the beat-wave dispersion in the target plasma.

Target plasma

We are now preparing a preliminary experiment using an independent plasma source rather than CTIX plasma for the beat-wave generation study. The main purpose of this experiment is to demonstrate enhanced beat-wave effects such as pump wave depletion at resonant plasma density. We have successfully made a high-density argon plasma source, generated by a pulsed arc discharge. The peak density as a function of time and position is measured to be higher than $10^{15}\mathrm{cm}^{-3}$ by using optical deflection diagnostics (deflectometer) [5]. The plasma duration is over 20 μs, which is much longer than the TEA laser pulse duration and thus adequate for the optical mixing experiment. This simple target plasma should prove useful in testing the nonlinear wave mixing process, since this is not affected by plasma collisionality. However, in order to measure beat wave absorption and current generation, a highly-ionized, low-collisionality plasma like CTIX will be required.

Diagnostics development

A new optical analog data acquisition system has been designed and tested to acquire data in the high noise environment of the pump laser experiment. The time-dependent relative power profile is measured by using an infrared power measurement system composed of a mercury-cadmium-telluride (MCT) detector, a preamplifier and an analog fiber-optic link. Using an integrating energy meter, we have measured laser pulse energy of 50 J under high-power operating conditions. By combining these two measurements, we obtain the absolute time-dependent laser power, as shown in Figure 2. Peak power for this shot was over 100 MW for the peak duration of over 50 ns.

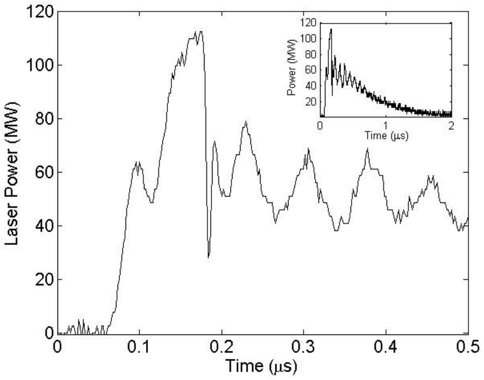

Figure 2: Time-dependent laser power of untuned CO_2 laser. Inset shows the full pulse duration up to 2 μs.

A CO_2 laser spectrum analyzer is used to measure the laser wavelength. Without grating tuning, the dominant wavelength is found to be 10.6 μm as expected. A time-integrated laser power profile has been measured on liquid crystal films and thermal paper. The observed transverse beam pattern is symmetric, which should yield good focusing, shown in Figure 3.

Future directions

The beat-wave experiments on the test plasma source will include observation of pump wave depletion and measurement of beat wave field using magnetic and Langmuir probes. The confirmation of the beat wave dispersion will be the starting point of current drive experiments on CTIX plasma. Upon the completion of the second laser with grating tunability, we shall embark on the formation of the beat wave in a plasma medium.

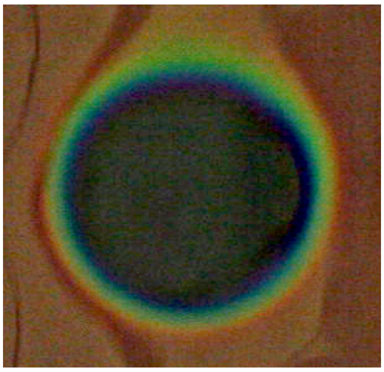

Figure 3: Transverse beam pattern of untuned CO_2 laser on liquid crystal film. The spot size is about 2 inches.

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