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THEORETICAL ANALYSIS AND EXPERIMENTAL DESIGN OF TERAHERTZ SINGLE-PULSE PICKING BASED ON PLASMA MIRROR*

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Abstract

China Academy of Engineering Physics terahertz free electron laser (CTFEL) facility needs a terahertz switch for picking of single-pulse, which can facilitate the experiments that require high peak power but low average power. At present, many researches mainly focus on resonant tunneling effects, tunable metamaterials such as graphene and vanadium dioxide, nonlinear modulation based on the principle of all-optical switching, etc. However, the frequency range of these terahertz switches is generally not applicable to CTFEL(1.87 THz-3.3 THz). In this paper, self-induced plasma switching technology is applied to CTFEL. Single-pulse is reflected by a dense plasma in a Ge, Al or fused quartz slab that is photoexcited by laser system. Theoretical analysis and numerical simulation demonstrate the feasibility of the experiment. In addition, schematic layout of the experiment setup and specifications of the major instruments are given.

INTRODUCTION

Free-electron lasers(FELs) are powerful tool as terahertz power coherent light sources.China Academy of Engineering Physics terahertz free electron laser (CTFEL) facility is the first high average power, high repetition rate and high duty ratio THz source based on FEL in China.The terahertz wave frequency is continuously adjustable from 1.87 THz to 3.3 THz. The average power is about 21 W and the micro-pulse power is more than 0.3 MW[1].

At present, some experiments of FELs on the one hand require high pulse energies,e.g.,for inducing phase transitions in biomolecules[2] and superconductors[3],on the other hand require low average power for avoiding thermal effects.Besides, some experiments involves samples featuring long-lived photoexcited states[4] that cannot return to equilibrium on a time scale of the FEL pulsing period[5]. So, a terahertz pulse picker is needed.In recent years, there have been many reports on terahertz switching[6–9]. However, the operating frequency of these THz switches is generally not suitable for CTFEL. In this paper, we describe a system for picking of THz single pulses at CTFEL, which is based on a plasma mirror,and the experimental design is given according to the theoretical analysis.

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THEORETICAL ANALYSIS

Experiment Principle

In order to induce the plasma mirror easily, we choose the materials with high absorption coefficient of 1064 nm laser, such as germanium, aluminum and fused silica. Considering that it is necessary to minimize the reflection of the terahertz before the plasma mirror is induced on the target surface, the polarization of the THz should be changed to the horizontal direction (p-polarized). What's more, the angle of incidence is chosen to be Brewster angle. Meanwhile, a Nd:YAG laser synchronized with CTFEL is used to induce the plasma mirror on the target surface. Considering the dispersion of the electromagnetic wave in the plasma, the frequency of the plasma excited by the laser gradually increases until the electron density of the plasma reaches threshold. At the critical density, terahertz cannot penetrate the plasma region where the electron density exceeds its critical density. Besides, The generated dense plasma decays sufficiently fast after 18.5 ns, in other words, only one single pulse gets picked. The gate width of the plasma mirror is approximately the same with the duration of the Nd:YAG laser pulse.

Generation Mechanism of the Laser Plasma

Generation mechanism of the laser plasma mainly includes photoionization, thermal ionization and impact ionization.At the carrier initiation stage where the temperature is low, the electrons are ionized by the multiphoton effect, and the photoionization mechanism is dominant. When the target vapor temperature is continuously increased, the atomic thermal motion is intensified, and some of the excited state electron energy exceeds the ionization potential, at this time, the thermal ionization mechanism is dominant. When the target vapor is fully ionized, the energy deposited on the critical surface mainly spread to the dense medium region by the electron heat conduction, now the collision ionization mechanism is dominant. During the generation of plasma, many ionization mechanisms are coupled to each other. If there are impurities or defects in the target, the ionization process will be more complicated.

Calculation of Critical Density of Plasma

Electromagnetic waves must satisfy the dispersion equation in the plasma:

$$\omega^2 = \omega_p^2 + c^2 k^2 \tag{1}$$

Where ω is frequency of terahertz, k is wave number, c is light speed, plasma frequency $\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$, n_e is electron

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density of the plasma. As the equation(1) shows, when $\omega_p = \omega_l$, $k = 0$. Now, there is critical density of plasma:

$$\{N_{ec}\}_{cm^{-3}} = \varepsilon_0 m_e \omega^2 / e^2 = 1.1 \times 10^{21} \{\lambda_0\}^{-2}_{\mu m} \tag{2}$$

When $\lambda_0 = 120\mu m$, we can get $N_{ec} = 7.64 \times 10^{16}\text{cm}^{-3}$. Therefore, the Nd:YAG laser needs to generate the plasma which electron density is more than $7.64 \times 10^{16}\text{cm}^{-3}$ on the target surface.

Calculation of Laser Power Density Threshold

The physical process can be simplified into two stages: the vapor ignition phase in which the laser directly interacts with the target and the plasma ignition phase in which the laser interacts with the target vapor.

In the vapor ignition phase, in order to simplify the formula of the heat transfer process, it is assumed that the material of the aluminum target is uniform and isotropic, and the thermodynamic parameters take the average value in each temperature range, the heat convection and heat radiation can be ignored. Considering the target as a semi-infinite object whose surface is uniformly heated. There is a one-dimensional heat conduction equation:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{a_t}\frac{\partial^2 T}{\partial t^2} = 0 \tag{3}$$

Where k_t is thermal conductivity, rho is density, c_p is specific heat capacity, thermal diffusivity $a_t = \frac{k_t}{\rho c_p}$. If the laser is Gaussian beam, we can get the equation of the laser:

$$I_{las}(r,t) = \begin{cases} I_0(0,t)\exp\frac{-2r^2}{\omega^2} & 0 < t < \tau_{las} \\ 0 & t < 0 \end{cases} \tag{4}$$

The boundary conditions are as follows.

$$z = 0, -k_t \frac{\partial T}{\partial z} = (1 - R)\, I_{las}(0,t)$$
$$z \to \infty, t = 0, T = 0$$

Where R is the reflectivity of the target. Target surface temperature function is as follows.

$$\begin{aligned} T(0,0,t) &= \frac{(1-R) I_{las}\omega}{k_t\sqrt{2\pi}} \arctan\frac{\sqrt{8a_t t}}{\omega} \\ &\approx \frac{(1-R) I_{las}\omega}{k_t\sqrt{2\pi}} \frac{\sqrt{8a_t t}}{\omega} \frac{2(1-R) I_{las}}{k_t}\sqrt{\frac{a_t t}{\pi}} \end{aligned} \tag{5}$$

If ambient temperature is T_0, melting temperature is T_f, evaporation temperature is T_v, latent heat of fusion is ΔH_f, we will get evaporation time.

$$\tau_v = \frac{\frac{\pi\rho}{4}\left(\frac{k_1 c_1 (T_f - T_0)^2}{(1-R_1)^2} + \frac{k_2 c_2 (T_v - T_f)^2}{(1-R_2)^2}\right) + \frac{\rho k_3 \Delta H_F^2}{c_3(1-R_3)^2}}{I^2_{las}} \tag{6}$$

In the plasma ignition phase, electron absorbs photon energy and ionizes vapor by collision with atoms.

$$\frac{dE}{dt} = \left(\frac{e^2\lambda^2}{4m_e c^3 \pi^2 \varepsilon_0} I_{las} - \frac{2m_e}{m_a} E\right)\nu_{coll} \tag{7}$$

Where E is the energy of free electrons, e is the electron charge, λ is the laser wavelength, m_e is the electron mass, m_a is the mass of the vapor atom, ϵ_0 is the vacuum dielectric constant, ν_{coll} is the collision frequency of electron and neutral vapor atom. If atomic ionization energy is E_1, vapor ionization time $\tau_1 = 10\tau_0$, we will get τ_1:

$$\tau_1 = \frac{5m_a}{m_e \nu_{coll}} \ln\left(1 - \frac{E_1}{I_{las}}\frac{8\pi^2 m_e^2 c^3 \varepsilon_0}{m_a e^2 \lambda^2}\right)^{-1} \tag{8}$$

Besides, we know that $\nu_{\text{coll}} = n_n u_{th} \sigma_{\text{coll}}$, where u_{th} is average electron speed and σ_{coll} is cross section.

$$n_n = \frac{I_{\text{las}}(1 - R_4)}{\Delta H_v u_0 m_a} \tag{9}$$

$$u_{th} = \sqrt{8k_B T_e / \pi m_e} \tag{10}$$

$$\sigma_{\text{coll}} = 7.9 \times 10^{-18}\left(\frac{E_1}{h\nu}\right)^3 \left(\frac{I_H}{E_1}\right)^{1/2} \left(\text{cm}^2\right) \tag{11}$$

Where ΔH_v is latent heat of vapor, wavefront velocity $u_0 = \sqrt{\gamma k_B T_s / m_a}$, specific heat ratio $\gamma = 1.4$, k_B is Boltzmann constant, T_s is vapor surface temperature, $h\nu$ is photon energy, ionization potential of hydrogen I_H is 13.6 eV.At the beginning of vapor ionization, the electron temperature is approximately equal to the target surface temperature. So, we can get vapor ionization time τ_1:

$$\begin{aligned} \tau_1 &= \frac{5m_a^2 \Delta H_v}{m_e \sigma_{coll} I_{las}(1-R_4)} \\ &\times \left(\frac{8}{\pi\gamma}\right)^{-1/2} \left(\frac{m_a}{m_e}\right)^{-1/2} \ln\left(1 - \frac{8E_1\pi^2 m_e^2 c^3 \varepsilon_0}{I_{las} m_a e^2 \lambda^2}\right)^{-1} \end{aligned} \tag{12}$$

The unit of I_{las} is W/cm^2,$\lambda = 1.064\mu m$. Let laser pulse width $\tau_{las} = \tau_v + \tau_1$, then we can get the laser power density threshold. It is 6.75×10^9 W/cm^2.

Numerical Simulation

Multi-1D is a good software for numerical simulation about laser induced plasma generation. In this case, laser power density is 5×10^{11} W/cm^2, the thickness of the aluminum target is 0.5 mm, time Step is 0.01 ns, number of grids is 160. The electron density distribution is shown in the Fig. 1. From the figure, we can see that the electron density is much larger than the theoretically calculated critical electron density, so the power density can meet the experimental requirements.

EXPERIMENTAL DESIGN

Device Selection

The THz laser parameters[1] and the specific parameters of the laser are shown in the Table 1 and Table 2.

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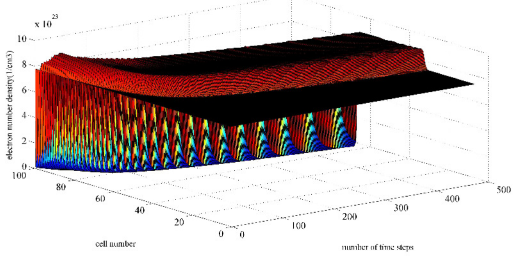

Figure 1: Electron density profile.

Table 1: THz Laser Parameters

Parameters	Value	Unit
Tunable frequency range	1.87~3.3	THz
Spectral FWHM	2~3	%
Macro-pulse average power	~20	W
Macro-pulse repetition	1~20	Hz
Macro-pulse length	0.3~2	ms
Micro-pulse RMS length	400~500	fs
Micro-pulse interval	18.5	ns
Micro-pulse power	>0.3	MW
Minimum transverse radius	<0.5	mm
Polarization	Horizontal	

Optical Path Design

Figure 2 shows the schematic layout of the experimental setup. Terahertz pulse is focused by an off-axis paraboloid mirror and then polarized to a horizontal direction (p-polarized) by a wire-grid polarizer. This experiment intends to use terahertz macro pulse for the trigger signal of Nd:YAG laser, which can realize the synchronization of terahertz and Nd:YAG-laser. Each terahertz macro pulse triggers a nanosecond laser, and then adjusts the delayed optical path to ensure that two beams of light reache the target surface at the same time. After the generation of laser plasma, the terahertz will be reflected by the plasma mirror and then focused by another off-axis paraboloid mirror. At last, the detector will collect the terahertz signal reflected by the plasma mirror.

SUMMARY

This paper applies the self-induced plasma switching technology to the single-pulse picking of CTFEL. The physical process of generating a plasma mirror and the critical electron density are analyzed. Moreover, the laser power density threshold is calculated. Multi-1D is used to calculate the electron density profile of the plasma mirror induced by Nd:YAG-laser, which demonstrates the feasibility of this experiment. At last, according to above analysis, the experimental scheme is designed.

Table 2: Nd:YAG-Laser Parameters

Parameters	Value	Unit
Wavelength	1064	nm
Pulse width	1	ns
Rep. rate	10	Hz
Pulse energy	80	mJ

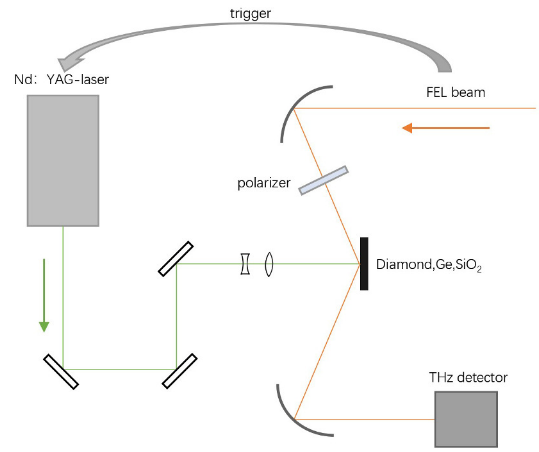

Figure 2: Experimental setup.

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