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A NOVEL TECHNIQUE FOR CONSTRUCTING A PLASMA MICRO–UNDULATOR AND A COMPACT SOFT X–RAY SOURCE

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Abstract

The plasma micro-undulator is a compact light source in which a relativistic electron beam radiates in an oscillating electric field of the rippled ion-space-charge instead of an oscillating magnetic field of conventional undulators. In the present paper, we propose a new method of creating the plasma micro-undulator: a combined technique of laser interference and resonant photoionization, where the pitch and density of plasma ripples have been controlled separately by a laser alone. A preliminary design of the undulator with the pitch of 10–100 μm, the number of ripples of 100–1000 and the undulator constant of 0.1–1.0 has been discussed.

1. Introduction

There has been a considerable attention to develop a compact free electron laser (FEL) since it has many advantages over conventional lasers, such as high output power and brightness, high conversion efficiency, tunability over wide range of wavelength and long life, all of which are quite important for applications. In general, FEL consists of a magnetic undulator and a Fabry-Perot optical resonator. In the magnetic undulator, permanent magnets whose polality changes alternately are aligned periodically.When a relativistic electron beam is injected into the undulator along the axis, it experiences a transversely oscillating force and emits an intense electromagnetic radiation along the beam path.

The wavelength of the undulator radiation /1/ is given by

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \tag{1}$$

where λ is the wavelength of radiation, λ_u is the wavelength of undulator (pitch of magnets), $\gamma = (1-\frac{u^2}{c^2})^{-1/2}$ is the relativistic factor and K is the undulator constant defined as

$$K = \frac{ecB_0\lambda_u}{2\pi m_0 c^2} = 93.4\lambda_u(\mathrm{m})B_0(\mathrm{T}). \tag{2}$$

It is to be noted that λ is proportional to the pitch of magnets and inversely proportional to the beam energy. Since it has been difficult to make λ_u much shorter than 10mm due to demagnetization of permanent magnets, a large accelerator has been required inevitably to obtain shorter-wavelength radiations extending to visible or uv region.

Recently, an alternative concept, a plasma micro-undulator has been reported /2,3/, where a relativistic electron beam has been injected obliquely into one-dimensional, plasma-density ripples. The electrons then experience a transversely oscillating electrostatic force (induced by the periodic ion-space-charge distribution) during propagation in the ripples and emit undulation radiation. The plasma micro-undulator has a potential of an extremely compact and short-wavelength FEL which is rather difficult by conventinal magnetic undulators. This paper proposes a new scheme for the formation of the plasma micro-undulator: a laser-interference, resonant-photoionization scheme using a coherent, tunable laser. In particular, we discuss a preliminary design of the undulator with λ_u = 10–100 μm, the number of ripples, N =100–1000, K = 0.1–1.0.

2. Principle

Figure 1 explains the principle /4/. A well-collimated laser beam at wavelength λ_L (wavenumber $k = 2\pi/\lambda_L$) and intensity I_0 is divided into two half-intensity beams by a half mirror A and a full mirror B. These beams interfere at the intersection with angle ϕ and create optical fringes. As is well known, the total intensity becomes

$$I = I_0\left[1+\cos\left(2kx\sin\frac{\phi}{2}\right)\right], \tag{3}$$

and the pitch of fringes is given by the formula:

$$d = \frac{\lambda_L}{2\sin\frac{\phi}{2}}. \tag{4}$$

When a plume of neutral gas is introduced into this region, a plasma will be created by photoionization. Since optical fringes correspond to a spatial modulation in the laser intensity and the plasma density should increase in proportion to the laser intensity (without saturation), we can obtain plasma density ripples which are quite regular reflecting the coherence of laser. It is worth emphasizing that the pitch of ripples is controlled only by optical parameters, λ_L and ϕ.

We have considered two photoionization schemes: resonant ionization and tunnel ionization /5/. In resonant ionization, the laser wavelength has been tuned to the energy level of a neutral atom. However, elements of interest have the ionization energy U_i of at least 5–10 eV (the minimum energy is 3.9 eV of Cs). So, the ionization occurs by absorbing two or more photons. Shibata et al. /6,7/ have developed one-wavelength multi-step resonant photoionization schemes:

Nd($U_i = 5.52$eV):	441.96 nm	two step,
Gd($U_i = 6.15$eV):	575.19 nm	three step,

which use resonant metastable states. These schemes should be most suitable for our purpose. Two-wavelength schemes developed for laser isotope separation are also considered to be applicable. The plasma created by resonant photoionization has quite low temperature ($<$ 0.1 eV). This is an important feature because the life time of plasma ripples is predominantly limited by thermal expansion.

When a neutral atom is irradiated by an intense laser beam of greater than 10^{14}W/cm^2, its coulomb potential barrier is strongly deformed and a bound electron is liberated by tunnel effect. Tunnel ionization requires strong compression (focusing and bunching) of the laser pulse to achieve a high power density above threshold. However, this leads to degradation in the periodicity of interference fringes. Therefore, we conclude that resonant-photoionization scheme is more appropriate for our purpose.

3. A preliminary design

Here, we consider design parameters of the plasma micro-undulator for a compact FEL. When plasma density ripples are of the form:

$$n = n_0 \left(1 + \sin \frac{2\pi}{d} x\right), \qquad (5)$$

an alternating force acting on a relativistic electron beam injected at an angle θ is given by

$$F = e^2 n_0 \cos k_u s \cdot \sin\theta \cos\theta / k_u \epsilon_0 \propto \frac{n_0}{k_u}, \qquad (6)$$

where $k_u = k\cos\theta = 2\pi/\lambda_u, \lambda_u = d/\cos\theta, \cos\theta = \mathbf{s}\cdot\mathbf{x}/sx$ and s is the coordinate along the beam axis. For typical $\theta = 45\,\text{deg}$, it becomes $\lambda_u = \sqrt{2}d = 1.41d$. The performance of undulators is well characterized by K of eq.(2). Since brightness of the undulator radiation is proportional to K^2, small K leads to an inefficient device, while too large K ($K \gg 1$; wiggler mode) causes quite large broadening in the radiation spectrum and increase in the emittance. So it is reasonable to assume $K = 0.1$–1.0. In addition, we employed the following parameters: $d = 10$–100 μm; $N = 100$–1000; the length of undulator, $L = Nd =$ 1 cm; Nd plasma (two-step photoionization, $\lambda_L =$ 441.96 nm). Since L is comparable to the diameter of laser beam, D, the effective volume of undulator, V becomes $V \approx L^3 = 1\text{cm}^3$. From eq.(4), the interference angle ϕ required for $d = 10\mu$m and 100μm are 2.5 deg and 0.25 deg, respectively (see also Fig. 2). When a cost-effective 10 MeV ($\gamma = 21$) linac is used, we can cover wavelengths of 20–200 nm.

Finally, we examine the requirement for the plasma density and laser energy. Suzuki /8/ calculated K for three types of electron beams: short bunch (radius r_0, length$l_0 \ll \lambda_u$), long bunch ($r_0 \ll \lambda_u \sim l_0$) and uniform beam ($r_0, l_o < \lambda_u$). He showed that the plasma density was proportional to K/λ_u^2 and was about $2 \times 10^{16}\text{cm}^{-3}$ for $\lambda_u = 10\mu$m and $2 \times 10^{14}\text{cm}^{-3}$ for $\lambda_u = 100\mu$m under $K = 1.0$. A rough estimate of the laser energy should be given by $n_p V U_i/\eta_L$ where n_p is the plasma density and η_L is the efficiency of photoionization. When typical values, $n_p = 10^{15}\text{cm}^{-3}$, $V = 1\text{cm}^3$, $U_i = 5.52$eV and $\eta_L = 0.1$, we obtain 9 mJ. The latest pulse-dye-lasers and solid-state-lasers will cover this energy without difficulty. A schematic view of the system is shown in Fig. 3.

There remain items to be further examined.

- Laser pulse length

The laser pulse length τ_L must satisfy the condition:

$$\frac{L}{c} < \tau_L < \tau_r, \qquad (7)$$

where L/c=30 ps. The life time of ripples, τ_r is predominantly determined by thermal expansion as

$$\tau_r \approx \frac{0.5d}{\sqrt{\frac{T_i+T_e}{M_i}}}. \qquad (8)$$

For Nd plasma, $T_e < T_i \simeq T_0$(vaportemperature) $\approx$ 500K has been reported. This yields $\tau_r =$ 30ns for $d = 10\mu$m, so that eq. (7) is easily satisfied.

- Beam attenuation due to neutral collisions

Rutherford scattering is dominant. The attenuation rate, $\Delta n_e/n_e$ is estimated using the cross section of Rutherford scattering, σ_R to be:

$$\frac{\Delta n_e}{n_e} = \sigma_R n_0 L < 0.1, \qquad (9)$$

where $\gamma = 21(10MeV)$, the neutral density $n_0 = 3 \times 10^{16}\text{cm}^{-3}$ (1 Torr), $L = 1$cm, and scattering angle of 10^{-2}rad are assumed.

- Repetition

Once the electron beam interacts with the plasma undulator, the plasma will break up. So, the repetition rate, f will be limited by the time for a plasma with a flow velocity u_0 to traverse a distance D as

$f \leq u_0/D$. When $u_0 \approx 1000\text{m/s}$ and $D = 1\text{cm}$, we have $f \leq 100\text{kHz}$.

4. Application to a compact soft x-ray source

We showed above that a combination of a 10-MeV linac and a 10-μm plasma undulator can generate soft X-ray radiation. However, the conventional linac is too large to realize a table-top device. Recently, there has been a rapid progress in the development of plasma-based accelerators in which the interaction between a dense plasma and a ultra-short-pulse driver beam (laser beam or electron beam) generates strong accelerating fields of order of GeV/m. For example, a LWA (laser-wake-field accelerator) experiment at KEK /9/ has demonstrated acceleration of electrons up to 18 MeV over a distance of 0.6 mm. However, there has been a problem that diffraction limits the laser-plasma-interaction distance to $\simeq \pi Z_R$ (Z_R : Rayleigh length) and optical guiding /10/ using a parabolic plasma-density profile (plasma channel) has been proposed. Our laser-interference, resonant-photoionization scheme will be useful to create plasma channel too. Two sets of plasma density ripples created with intersection at 90 deg by four laser beams form a bundle of square plasma channels /11/. It is clear that the density and diameter of plasma channel can be easily controlled by the laser intensity, laser wavelength and interference angle. A combined system of LWA and the plasma micro-undulator is quite attractive because it has a possibility of making a table-top x-ray FEL. In the beginning, proof-of-principle experiments will be needed.

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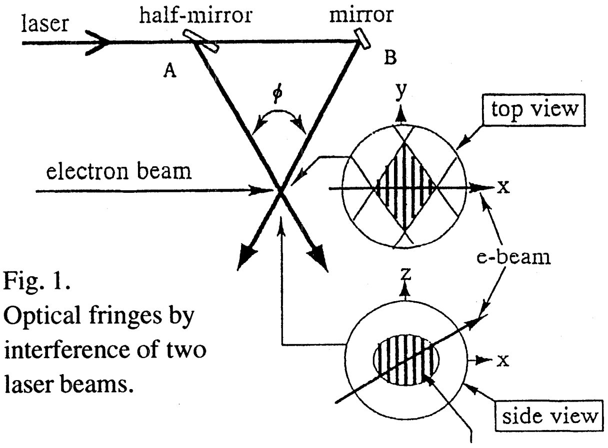

Fig. 1.
Optical fringes by interference of two laser beams.

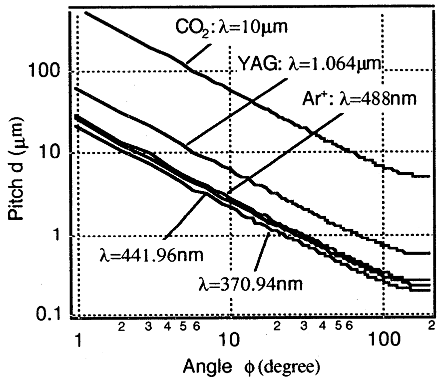

Fig. 2. Pitch d vs interference angle ϕ

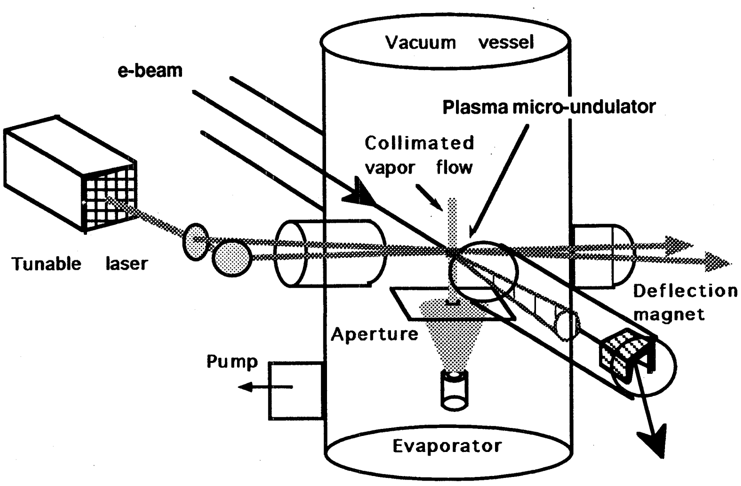

Fig. 3.
A schematic view of plasma micro-undulator.