25G02

Numerical Analyses on Atto-second X-ray Pulse Generation by Using Relativistic Flying Mirror
相対論飛翔鏡によるアト秒Ｘ線発生に関する数値解析

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The concept of flying mirror is proposed to increase the laser irradiance, and generating the tunable compact x-ray source. In this study, we showed that the Lorentz factor of flying mirror dependence on laser and plasma parameters, and how to optimize them for higher Lorentz factor. Based on the analyses, we can numerically demonstrate the generation of atto-second water-window x-ray generation by using flying mirror concept, and the parameters required for the experiments.

1. Introduction

The development of laser technology has been realized the continuous increase of its irradiance, reaching to 10^{22}W/cm^2 and more. These irradiance led to a new regime of laser-matter interaction, where relativistic electrons drive various structures such as wake wave, vortices, solitons and so on. And those structures are utilized to generate high energy electrons, ions, and photons. Then the further increase of laser irradiance is expected to investigate new and novel physics such as radiation friction effects, a pair creation from vacuum and so on.

Flying mirror concept is proposed as one of the way to dramatically enhance the laser irradiance [1]. It utilizes the dense shells formed in the electron density in a strongly nonlinear plasma wave, which could partially reflect counter-propagating laser pulse. The reflected laser pulse is up-shifted due to the double Doppler effect, where the up-shifted frequency is written as $\omega_r = (1+\beta_{ph})/(1-\beta_{ph})\omega_0 \sim 4\gamma_{ph}^2\omega_0$. Here, ω_r and ω_0 are the frequencies of reflected and incident laser pulse, and γ_{ph} is the Lorentz factor corresponding to the phase velocity of plasma wake. The proof-of-principle experiments have been performed at KPSI/JAEA [2], and further campaign achieved a frequency up-shift up to 37-66 multiplications, corresponding to the wavelength of 12-22 nm [3].

In this paper, we aim to obtain the experimental parameters realizing water-window xray generation by flying mirror concept, and numerically demonstrates the its atto-second xray pulse generation.

2. Lorentz Factor of Flying Mirror

The phase velocity of wake wave have been studied by many authors so far. In one-dimensional linear model, the phase velocity of wake wave is shown to be approximated as the laser group velocity $\gamma_{ph} \sim \gamma_L = \omega_0/\omega_p$ [4]. In relativistic intensity regime, numerical simulations showed that it is relativistically enhanced as $\gamma_{ph} \sim \sqrt{a_0}\gamma_L$ [5], where a_0 is the laser normalized intensity defined as $a_0 = \lambda^2[\mu m]\mathrm{I}[\mathrm{W/cm^2}]/(1.38\times10^{18})$. Also, recent one-dimensional nonlinear analysis showed that the Lorentz factor is lower than the linear value, as $\gamma_{ph} \sim 0.45\gamma_L$ [6]. In higher frequency up-shift

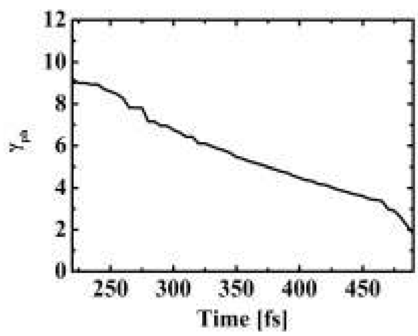

Fig.1 Temporal evolution of the Lorentz factor corresponding to the wake wave phase velocity.

by using flying mirror, we have to know the Lorentz factor including multi-dimensional effect and its nonlinear evolution towards the wave-breaking. Fig 1 shows the temporal evolution of the Lorentz factor of plasma wake wave, where background plasma density is 3×10^{19}/cc and the laser intensity is 3×10^{19}W/cm^2 and spot size of 15 μm. The Lorentz factor continuously decreases in time until the occurrence of wave-breaking at t=470fs. This is due to the increase of plasma wavelength at the laser axis via electron energy enhancement and laser energy depletion. Elongation of plasma period leads to the transverse bending of the wake structure and decrease of the phase velocity at the center. Therefore, the Lorentz factor depends on time, position of wake, and laser depletion process as well as the plasma density and laser intensity. Therefore, we performed a parametric study by using 2D PIC simulations, finding the optimum conditions of laser intensity, duration, spot size, and plasma density. Fig. 2 shows the results of parametric study, showing the Lorentz factor in α-β parameter space, where spot size is normalized as $\phi = \alpha\lambda_p$ and pulse duration is normalized as $c\tau = \beta(0.37\lambda_p)$, where the value inside the bracket corresponds to the optimum pulse duration for electron wake field acceleration [7]. The results show that the maximum Lorentz factor is realized when $\alpha \sim \beta \sim 1$. Under this conditions,

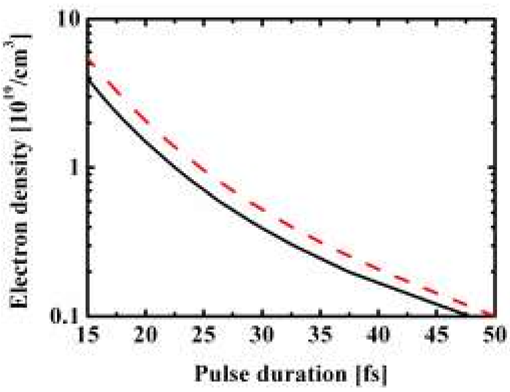

Fig.2 Relation between laser pulse duration and optimum electron density for laser energies of 1J(solid) and 2J(dotted) cases.

we can obtain the relation between laser energy, pulse duration, and plasma density. As an example, the relation between pulse duration and optimum electron density is plotted in Fig.2.

3. Atto-second Water-window Xray Genration

When the laser energy and pulse duration is fixed, we can have the optimum values of spot size and electron density from the above analyses. By using these values, we show the atto-second xray generation in water-window regime. The plasma density is 2×10^{19}/cc and driver laser intensity is 1.3×10^{20}W/cm^2 which propagates from left to right (positive in x-direction). The source light to be reflected by the mirror, propagating from right to left, has its intensity of 10^{13}W/cm^2. The system size is 60μm in x- and 100μm in y-direction. The mesh

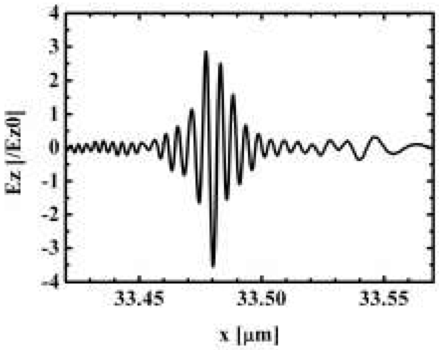

Fig3. The spatial distribution of reflected source light.

size is 0.25 nm in x- and 50 nm in y-direction, which resolves the wavelength of reflected wave. Fig 3 shows the spatial distribution of reflected light, showing the generation of atto-second water-window xray by flying mirror. The corresponding pulse duration is roughly 50 atto-seconds, and the wavelength of 4-5 nano-meter. This demonstrates that the flying mirror concept could realize the shor x-ray pulse generation with the currently available laser systems.

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