# ALL-OPTICAL COMPTON GAMMA-RAY SOURCE

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*Abstract*

We are studying a tabletop monochromatic $\gamma$-ray source using all-optical inverse Compton $\gamma$-ray source. Our system can be used for determining the concentration of nuclear materials, etc. An intense laser pulse excites a highly nonlinear plasma wave and accelerates an electron bunch up to several hundreds of maga-electronvolts within a length of a few millimeters. The key issue for applications is to stabilize laser-plasma accelerators. We successfully demonstrated the artificial injection of initial electrons into the plasma wave and the stable guiding of beams by applying a magnetic field of 1 T. Quasi-monoenergetic electrons with a maximum energy of 0.4 GeV were emitted from a 4-mm long plasma channel that was excited by a 7-TW laser pulse.

## INTRODUCTION

An inverse Compton $\gamma$-ray source, in which $\gamma - rays$ are produced by the collision of a laser pulse with a high-energy electron bunch, produced $\gamma - ray$ having superior characteristics such as monochromaticity, tunability, polarization, good directionality and a short pulse. Such characteristics are suitable for determining the concentrations of nuclear materials and minor actinides (MA) by K-edge dosimetry using monochromatic $\gamma$-rays. Since K-edge energies of nuclear materials and MA are distributed between 115-129 keV, the electron energy for producing $\gamma$-rays tuned to K-edge energies produced by the inverse Compton process using an infrared (wavelength 800 nm) laser pulse must be approximately 100 MeV. Radio frequency (rf) linacs are widely used to accelerate electrons upto 100 MeV; however, they are too large to use in a laboratory or a factory. Alternatively, laser wakefield accelerators (LWFA) can realize a tabletop Compton $\gamma$-ray source, i.e. , an all-optical Compton $\gamma$-ray source. This is possible because a wakefield, which has a high acceleration gradient of 1 $\mathrm{GeV/cm}$, is generated by an intense laser pulse. However, the stability of present LWFA is inadequate for use in application mentioned above. In order to improve the stability of LWFAs, we investigate the artificial injection of initial electrons in the wakefield, guiding of the intense laser pulse, and application of an axial magnetic field to the plasma channel to obtain high-quality electron beams.

## K-EDGE DOSIMETRY AND ALL-OPTICAL GAMMA-RAY SOURCE

Nondestructive assay measurements of nuclear materials in spent fuels is an important requirement from the viewpoint of ensuring accountability and maintaining safeguards. A hybrid K-edge/K x-ray fluorescence dosimetry (HKED) is presently being used for verifying uranium and plutonium concentrations dissolver solutions at reprocessing plants. However, it is difficult to measure minor elements in mixed solutions because the HKED does not have a wide dynamic range[1]. In an advanced fuel cycle, where plutonium and MA are processed without separation, new evaluation techniquea are required for measuring concentrations in mixed solutions.

A monochromatic K-edge dosimetry system (MKED) uses tunable monochromatic $\gamma$-rays; using this system, is possible to determine the concentrations of all elements in the solution by measuring the transmission rate of $\gamma$-rays on both sides of the K-edge energy of the target element in the solution. The concentration of an element in a given sample is evaluated by a simple formula; $\rho = \ln\left(A_1/A_2\right)/\left(\mu_2 - \mu_1\right)/L$, where $A$ and $\mu$ are a transmission rate of $\gamma$-ray and mass attenuation rate, respectively. Subscripts 1 and 2 indicate the $\gamma$-ray energies of the upper and lower sides of the K-edge energy, respectively. $L$ is the thickness of the sample. In order to accurate measurement of 1 %, the energy fluctuation of the monochromatic $\gamma$-ray must be smaller than 0.4 % (0.5 keV) ; this is because the mass attenuation rate is a steep function of the $\gamma$-ray energy. Since the K-edge energies of elements differ by 3 keV, the energy width of the monochromatic $\gamma$-ray must be smaller than 3 keV. A schematic of the MKED using the inverse Compton process is shown in Fig.1

## STABILIZATION OF LWFA

In order to stabilize the beam energy, energy width, beam pointing, and electronic charge of the LWFA, all processes of the LWFA such as the injection of the initial electron bunch, guiding of the laser pulse in the plasma channel, and ejection of the electron bunch must be controlled. Initial electrons can be injected into the wakefield in two ways: by optical injection [2] and by wavebreaking at a density ramp [3]. The optical injection of electrons into the wakefield has been successfully demonstrated [4]. However, it is difficult to achieve an accurate collision of two laser pulses in a plasma channel. In order to obtain an initial electron bunch by a simple process, we study electron injection by wave-

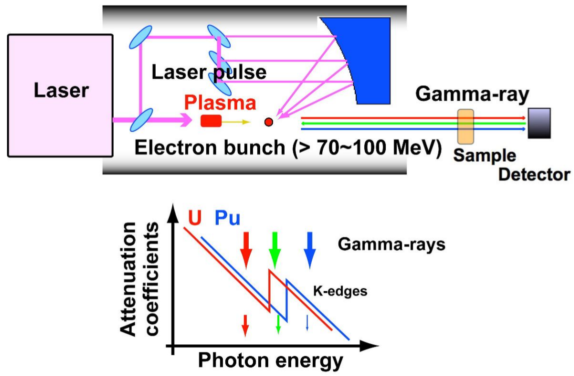


Figure 1: Schematic of tall-optical monochromatic K-edge dosimetry system.

breaking in the density ramp and the stable guidance of the laser beam and the wakefield by applying strong magnetic field to the plasma.

## *Electron Injection*

Two different processes were carried out in order to produce a density jump in the plasma for localized wavebreaking.

A density step in a supersonic jet was produced by an oblique shock wave that originated from the foot of a deflection plate that was placed on the edge of a rectangular nozzle, as shown in Fig. 2(a). The density ratios of both sides of the oblique shock and a characteristic length across the density jump measured from a fringe shift of the interferogram (Figure 2(b)) at 1.1 mm from the nozzle were approximately 1.5 and 70 $\mu$m, respectively. These parameters are functions of a Mach number and a corner angle, with respect to the supersonic flow. The number density of the gas in the undisturbed region (plateau region in Fig. 2(b)(c)) was $3 \times 10^{18}\mathrm{cm}^{-3}$. The acceleration experiment was performed using a Ti:sapphire laser that delivered 7 TW of laser power in a duration of 40 fs. The energy of nanosecond (ns)-prepulse was carefully lowered using a Pockels cell; this was done because if the intensity of the prepulse of the TW-laser were to be as high as the ionization threshold of the neutral gas, then the density step would be quickly destroyed. Although the experiment was a preliminary one, under a low ns-prepulse level of $5 \times 10^{-7}$ to the main pulse, monoenergetic electrons with small beam divergence were observed, as shown in Fig. 3(a). In contrast, under a high prepulse level of $10^{-4}$, no high-energy electron were detected (Fig. 3(b)). We investigated another process for the density step formation by using a laser initiated shock wave. A density cavity was formed in a plasma by the expansion of a shock wave due to rapid heating by a ns-prepulse. Because local heating near the focal point decreases the electron-ion collision frequency less than the electron cyclotron frequency, the plasma was magnetized near the focal point and the shape

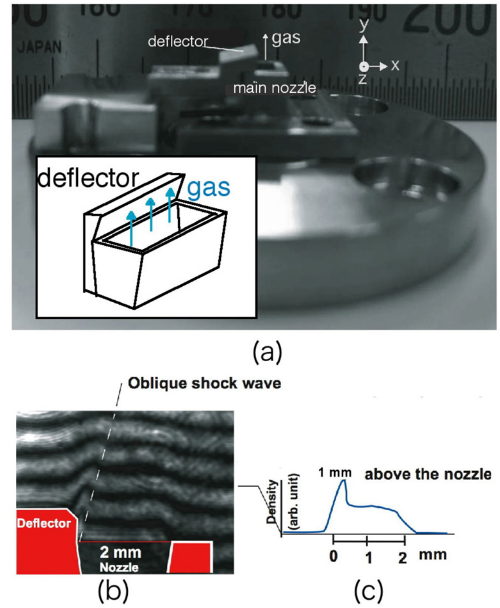


Figure 2: (a) A Photograph of the jet nozzle with a deflector. (b) Interferogram of gas jet showing a density jump produced by the oblique shock. (c) Density distribution at a distance of 1.1 mm from the nozzle exit.

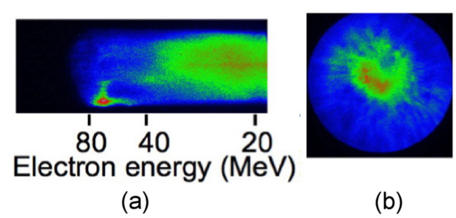


Figure 3: (a) Angle-resolved electron energy spectrum at low ns-prepulse energy. (b) Transverse distribution of electron bunch.

of the expanding cavity was deformed. The deformation of this cavity in the magnetic field restricted the direction of laser propagation and resulted in a tightly focused and directionally stable electron beam. Electrons were injected into the wakefield at the steeply decreasing density slope by the local wavebreaking. When the magnetic field was increased from 0.2 T to 1 T, the plasma dynamics near the focal point were further influenced by the strong magnetic field and the cavity was deformed into a double cone shape, as shown in the shadowgraphs in Fig. 4(a).

## *Laser Guidance in a Magnetic Field*

An improvement in the pointing stability and electronic charge of the electron bunch has been achieved by applying an axial magnetic field of 0.2 T to a plasma [6]. The introduction of the prepulse a few hundred picoseconds before the main pulse under a strong magnetic field of 1 T led to the formation of a very deep and narrow plasma channel after the conical cavity, as shown in the shadowgraphs in Fig. 4(b). The picosecond prepulse was produced by slightly detuning the pulse compressor of the laser system. Spatial profiles of electron beams obtained in the presence of a magnetic field of 1 T were narrower than $1^\circ$ for all shots, and the pointing fluctuation was less than the beam size. Whenever a structure consisting of a conical cavity with a deep and narrow channel was formed, monoenergetic peaks were observed in the electron energy spectra, as shown in Fig. 4(b). The energy of a monoenergetic electron was approximately proportional to the channel length. In the case of the longest plasma channel of length 4 mm, the electron energy reached 0.4 GeV. The appearance of a few small peaks in the spectrum can be attributed to electron injection into a few potential wells of the wakefield. The observed electron acceleration energies were considerably higher than those estimated from the empirical scaling law, by which the electron energies were estimated to be several tens of megaelectronvolts for the present experimental conditions of 7-TW laser power and the electron density of $4 \times 10^{19}\mathrm{cm}^{-3}$. A laser power of several tens of terawatts has been used to accelerate electrons to GeV levels in previous studies on LWFAs [7, 8]. Our result suggests that the plasma density in the channel dug by the picosecond prepulse might be lower than $7 \times 10^{18}\mathrm{cm}^{-3}$, and the resultant deep channel might confine a very intense laser pulse of $a_0 \approx 2$, where $a_0$ is the normalized vector potential.

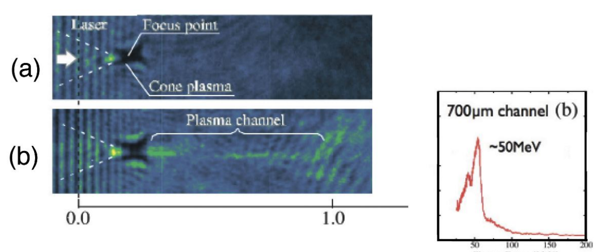


Figure 4: (a) Shadowgraph of the plasma without picosecond-prepulse in the 1-T magnetic field. (b) Shadowgraph of the plasma and the electron energy spectrum after tuning of picosecond-prepulse level in the 1-T magnetic field.

## SUMMARY

We are developing a tabletop all-optical $\gamma$-ray source that uses a LFWA instead of an rf-linac to produce a high-energy electron bunch that can deliver tunable, ultra-short, and intense $\gamma$-rays. These features are suitable for evaluating the concentrations of nuclear materials and minor actinides (MA) by K-edge dosimetry, in which $\gamma$-rays having energies of 115-129 keV are required. However, the main problem in realizing an all-optical $\gamma$-ray source is the inadequate stability of the LWFA. In order to decrease the fluctuations in the electron beam emitted from the LWFA, we are developing techniques for the injection of initial electrons by causing localized wavebreaking at the steep density ramp in the plasma. Two processes were investigated: (1) the excitation of the oblique shock wave in a supersonic jet and (2) the production of expanding shock wave in a laser-heated plasma by a nanosecond-prepulse. Although these experiments were in their preliminary stages, the desired effect of the density jump on the localized wavebreaking was successfully demonstrated. A strong axial magnetic field affected the plasma dynamics near the focal point and deformed the plasma cavity to a cone shape. Spatial profiles of electron beams obtained in the presence of the magnetic field of 1 T were narrower than $1^\circ$ for all shots, and the pointing fluctuation was less than the beam size. By introducing the prepulse a few hundred picoseconds before the main pulse under the strong magnetic field of 1 T, a very deep and narrow plasma channel was formed after the conical cavity. Whenever a structure having a conical cavity with a deep and narrow channel was formed, monoenergetic peaks were observed in the electron energy spectra. Quasi-monoenergetic electrons with a maximum energy of 0.4 GeV were emitted from a 4-mm long plasma channel that was excited by a 7-TW laser pulse.

With further improvement, the injection techniques discussed in this paper can potentially be applied to not only inverse Compton sources but also to all-optical free-electron lasers[9, 10].

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