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Observation of high-intensity X-rays in inverse Compton scattering experiment

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Abstract

We report the first results of high-intensity X-ray generation using Inverse Laser Compton scattering. This experiment was carried out by a US–Japan collaboration at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF) in September 1999. The 3.5 ps X-ray pulse at 6.5 keV, containing 3×10^6 X-ray photons was generated by the interaction of 60 MeV, 0.5 nC electron bunches and CO_2 laser pulses of 600 MW peak power.

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1. Introduction

High-intensity, short-pulse and compact X-ray sources are required in various fields of scientific, industrial and medical research. To meet these demands, R&D on the next-generation light sources has been initiated in several laboratories [1]. One of the most promising approaches to ultra-bright pulsed X-ray sources is the Laser Synchrotron Source (LSS). It is based on inverse Compton scattering via interaction between pulsed high-power laser beams and picosecond relativistic electron bunches. One of the attractive features of the laser Compton scattering is the easy control of

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polarization of the produced high-energy photons that duplicates polarization of the applied laser beam. This method has been proposed to generate circularly polarized X-rays in the prospective polarized positron source for Japan Liner Collider [2]. The US–Japan collaborative experiment on X-ray generation using inverse Compton scattering was performed at the Brookhaven Accelerator Test Facility (BNL-ATF), which is an accelerator and beam physics user facility. This experiment takes advantage of the availability of a high-brightness 60 MeV electron RF linac and high peak power CO_2 laser. The long-wavelength (ten times longer than solid-state lasers) CO_2 laser is a good choice for the LSS driver because it can generate a large number of X-ray photons for a given laser energy. In this communication, we report the first results of this experiment.

2. Experiment description

The principle design of the vacuum interaction chamber for the CO_2 laser Compton scattering experiment is shown in Fig. 1 and described in Ref. [3]. The CO_2 laser pulse and the electron bunch propagate along the same axis in opposite directions and collide at the focal point. The laser beam is focused and re-collimated inside the chamber with two off-axis parabolic Cu mirrors with focal lengths of 150 mm and 5 mm diameter holes drilled along the beam axis. These holes are necessary for the propagation of the electron beam and the backscattered X-rays. To bypass the holes, the laser beam is transformed from the Gaussian spatial profile to a "donut"-shaped profile using an axicon telescope located outside the chamber. The 600 MW, 200 ps pulsed CO_2 laser beam is introduced through the ZnSe window and focused at the center of the chamber. After interaction, laser beam is reflected from another parabolic mirror and is extracted from the chamber. The 3.5–10 ps, 0.5–1.0 nC electron bunches produced at the photo cathode RF gun and accelerated to 60 MeV ($\gamma = 120$) by the RF linac are magnetically focused in the middle point of the interaction cell to the $\sigma = 40$ μm spot. The timing jitter between the CO_2 laser and electron bunches is negligible in comparison with the electron pulse width, since a mode-locked Nd:YAG laser is used for both processes of the CO_2 pulse optical switching and the photo cathode illumination of the RF gun. To measure the electron beam size and align the CO_2 laser and the electron beam at the collision point precisely, we used a double target that has a phosphor screen and a glass fiber cross. The cross allows correlation

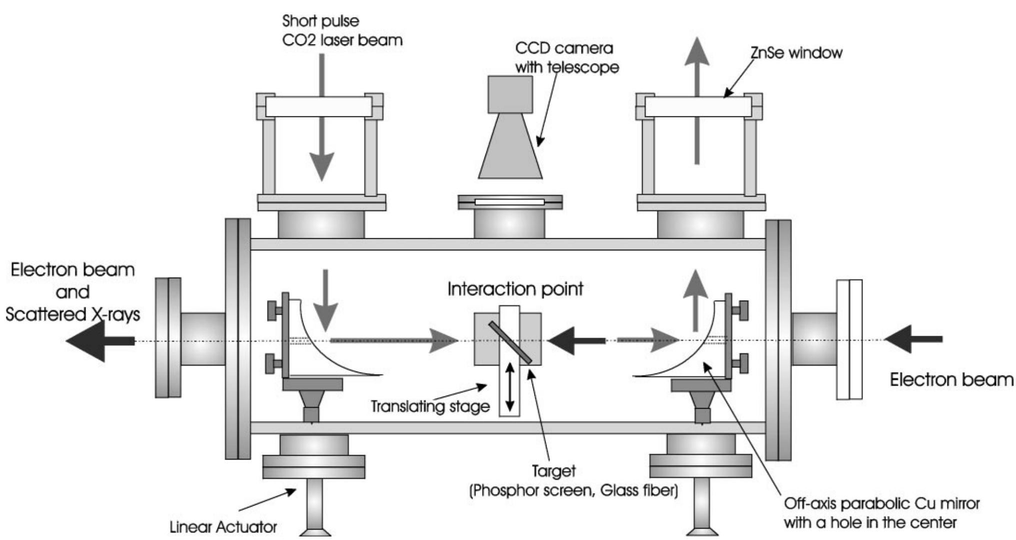

Fig. 1. Top view of the Compton chamber.

Table 1
Electron beam and CO_2 laser parameters

Electron bunch	
Beam energy	60 MeV
Bunch charge	0.5 nC
Bunch length	3.5 ps
Beam size at focus point (σ_x/σ_y)	40/40 μm
CO_2 laser	
Wavelength	10.6 μm
Energy/pulse	200 mJ
Pulse length (FWHM)	180 ps
Beam size at focus point (σ_x/σ_y)	40/40 μm

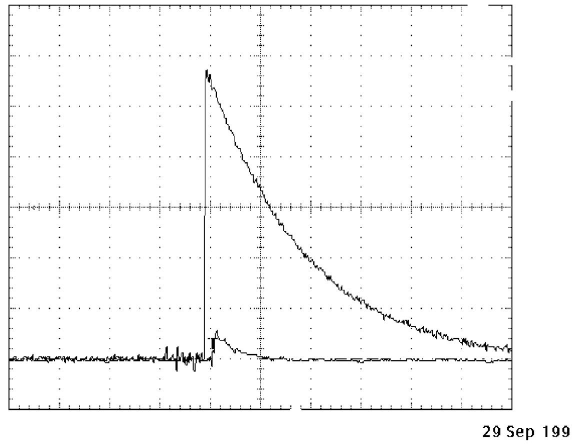

Fig. 2. Typical scope traces of the Si diode output show the Compton X-ray signal with the "laser on" (top trace, 100 mV/div scale) and the bremsstrahlung "laser off" signal (bottom trace, 50 mV/div).

between the e-beam and the CO_2 focal spot positions. This is made by viewing the electrons from fluorescence in the glass and the CO_2 by the shadow the glass makes in an IR imaging camera. The electron beam and the CO_2 laser beam parameters are given in Table 1. A dipole magnet separated the electron bunches and the scattered X-ray beam after the interaction point. The total number of back-scattered photons was measured using a silicon (Si) diode detector ($\varnothing = 25$ mm), placed 1.4 m downstream from the interaction region. Low-energy photons were attenuated by a 250 μm thick beryllium (Be) output window and 20 cm of air.

3. Experimental results

Thanks to the matched focusing and exact alignment and synchronization of the laser and electron beams, we were able to observe strong Compton X-ray signal on the Si detector, much above the background level (defined by high-energy X-rays due to the 60 MeV electron beam bremsstrahlung). The typical signal-to-noise ratio was up to 100 (see Fig. 2). The strong signal permitted a confident characterization of the observed effect and a study of the Compton yield dependence upon various experimental parameters as will be reported below. The measured maximum X-ray signal from the Si detector was about 2 V. This signal corresponds to 5×10^6 photons/pulse within an energy range from approximately 5 to 6.5 keV. In the backscattering configuration, the X-ray pulse duration is equal to the electron bunch length (3.5 ps). This brings us to 2×10^{18} photons/second. For the current experimental conditions, the maximum scattered photon energy that results from the 0.113 eV CO_2 laser photon upshift by the 60 MeV electrons was

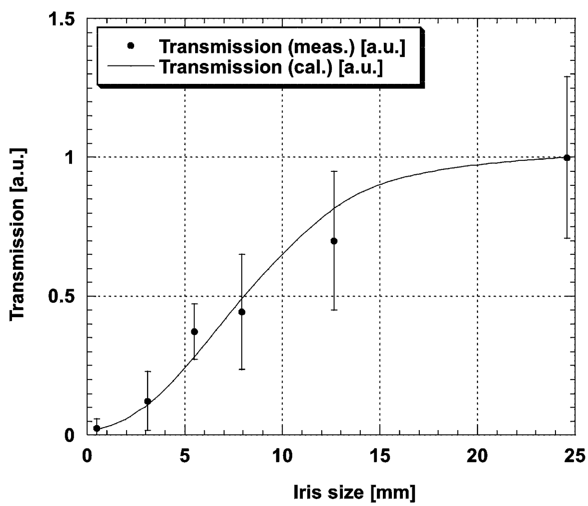

Fig. 3. Compton X-ray transmission through the iris diaphragm as a function of the diameter. Bars represent the experimental results compared with the theoretically calculated curve.

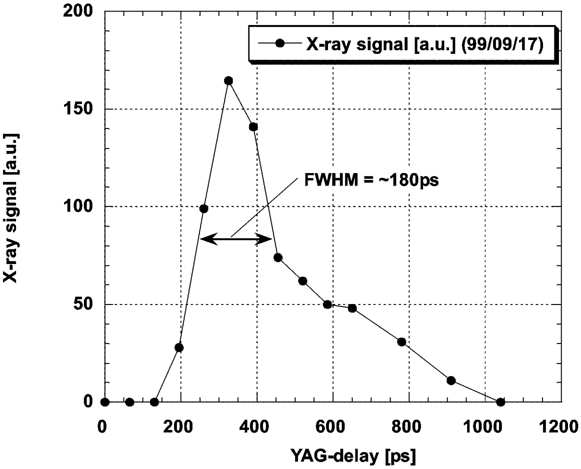

Fig. 4. CO_2 laser longitudinal profile.

6.5 keV. The detectable minimum photon energy was 5 keV. The minimum energy threshold is due to the combined effect of the angle acceptance of the Si detector and X-ray absorption in the Be window and air. The energy bandwidth is confirmed by using metal foil filters and, indirectly, by a comparison of the theoretical and experimental dependence of the X-ray flux upon the opening solid angle on the detector. To obtain the angular distribution of the scattered X-ray photons, we used a variable iris diaphragm placed in front of the Si detector. Fig. 3 shows the output signal of the Si detector versus the iris diameter and the calculation results that take into account the attenuation from the Be window and 20 cm of air. A variable delay of Nd:YAG laser pulse permits to adjust the timing between the electron bunch and CO_2 laser pulse. Incidentally, this provides a tool to measure the CO_2 laser longitudinal profile. Fig. 4 shows the CO_2 laser pulse envelope obtained by measuring the X-ray signal while scanning the Nd:YAG laser delay. On the basis of these observations, we conclude that the laser pulse has a non-Gaussian asymmetric shape and is about 180 ps FWHM. The 600 MW peak power is obtained by time integrating the plot in Fig. 4 and normalizing it to the typical 200 mJ energy in the pulse. Similarly, the size of the CO_2 laser focus is measured by observing the X-ray signal as a function of the transverse steering of the electron beam. The results of these measurements are shown in Fig. 5 and yield $\sigma = 40$ μm spot at the interaction point. For the purpose of this measurement the electron beam size was characterized on the phosphor screen.

4. Summary

We report results of the intense X-ray generation using inverse Compton scattering of CO_2 laser pulses from relativistic electron bunches. The generated number of X-ray photons within the energy range from 5 keV to 6.5 keV was 3×10^6 photons/pulse. Since pulse width is 3.5 ps, peak photon density is 2×10^{18} photons/second. We believe that this is the strongest X-ray yield observed so far in the proof-of-principle LSS experiments. This is achieved due to the availability of a combination of the high-brightness picosecond electron beam, the high mid-IR photon flux CO_2 laser at the BNL

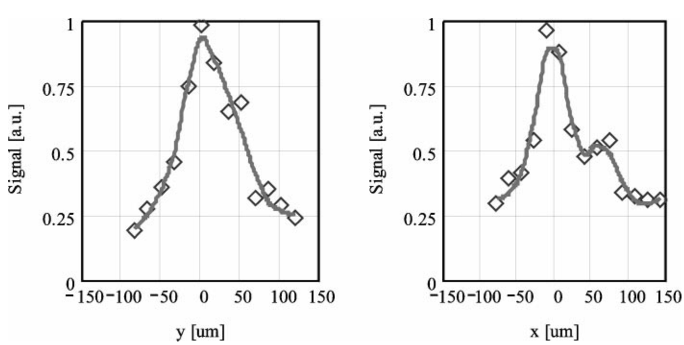

Fig. 5. Transverse scan of the laser focus with the electron beam.

ATF and the use of a backscattering configuration. Upon completion of the ongoing ATF CO_2 laser upgrade to the terawatt power and proposed electron bunch compression to femtoseconds we plan to demonstrate LSS with an X-ray yield of the order of 10^{10} photons/pulse and flux up to 10^{23} photons/s.

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