# Experimental study of nonlinear laser-beam Thomson scattering

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## Abstract

We observed $1.7\times10^8$ X-ray photons/pulse generated through relativistic Thomson scattering between the 14GW $CO_2$ laser and 60MeV electron beam at Brookhaven National Laboratory. Non-linear Thomson scattering can be observed by upgrading peak power density of the $CO_2$ laser.

## Introduction

Development of high-intensity, short-pulse, and compact X-ray sources is demanded for various fields of scientific, industrial, and medical applications.

One of the most promising methods for producing such an x-ray beam is known as Laser Synchrotron Source (LSS), which utilizes relativistic Thomson scattering via interaction between high-power pulsed laser and electron beams. We had made the first proof-of-principle experiment in 1999 using a 600MW $CO_2$ laser and a 60MeV electron beam provided at the Brookhaven Accelerator Test Facility (BNL-ATF) and demonstrated production of $2.5\times10^7$ X-ray photons/pulse with the pulse duration of 3.5psec [1, 2].

Magnitude of the non-linear process is characterized by the normalized vector potential

$$a = e\sqrt{A_\mu A^\mu} / m_e c^2 \ ,$$

where $e$ is mass of the electron, $A_\mu$ is four-vector potential of the laser, and $m_e c^2$ electron's rest energy. It can be written in more convenient form as a function of wavelength $\lambda$ and power density $I$ of the laser as follows;

$$a = 0.85 \times 10^{-9} \lambda[\mu m]\, I^{1/2}[W / cm^2] \ .$$

Thomson scattering occurs in the linear regime for $a << 1$, while the non-linear Thomson scattering is comparable to the linear process for $a \approx 1$.

In this report, we describe results of the experiment performed this year with the upgraded $CO_2$ laser and study on non-linear Thomson scattering.

## Experimental apparatus

The principle setup of the Thomson scattering experiment is shown in Fig. 1. The 60MeV electron beam from the ATF linac is focused in the middle of the interaction chamber (Compton Cell). Typical parameters of the electron beam are: bunch charge 0.5nc, normalized emittance 1mm mrad, and bunch duration 3.5ps.

The $CO_2$ laser pulse is focused with an off-axis copper parabolic mirror, whose focal length is 15cm, and collides with the electron beam at the focal point. The mirror has a 5mm diameter hole drilled along the beam axis to transmit the electron beam and generated X-rays. To bypass the hole, the laser beam is transformed from the Gaussian profile to the donut profile using a pair of ZnSe axicon lenses. The laser beam is reflected by another parabolic mirror after the interaction and extracted from the Compton cell. The spent beam is supplied to a joule meter for energy measurement. Pulse energy of the laser is measured to be 2-5J during the experiment.

To align the electron and $CO_2$ laser beams, a retractable target with a 150µm pinhole is placed at the center of the cell. The pinhole target is also used for beam size measurement.

The X-rays generated from the interaction transmit through the mirror hole and extracted from the vacuum chamber through a beryllium (Be) window (250µm) which seals the vacuum. The spent electron beam is separated from the X-rays with a dipole magnet and sent to a Faraday cup. The X-ray beam propagates through the Be window and 22cm air are detected by a silicon diode (Canberra Alpha PIPS detector A300: active area 300mm$^2$) which is placed 130cm downstream from the interaction point.

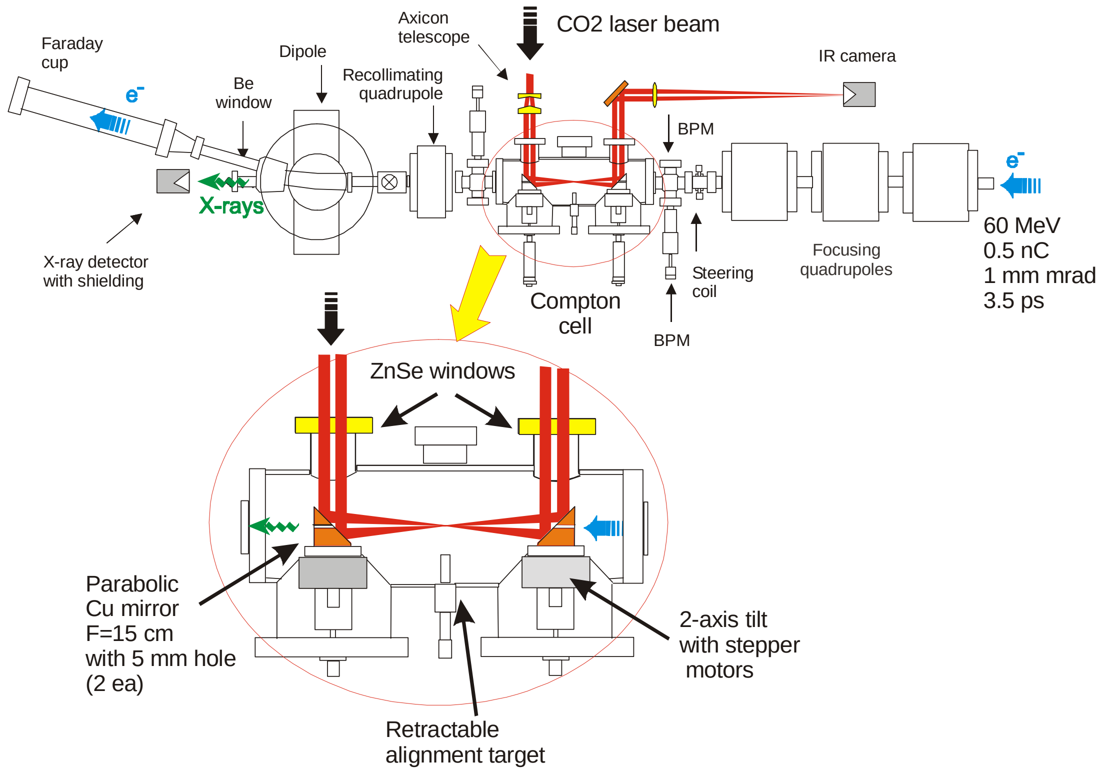


Figure 1: Principle diagram of the Thomson experiment

## Result

The maximum X-ray signal 2.4V is observed for the laser energy 2.7J. This signal corresponds to energy deposition of $1.4\times10^{11}$ eV in the Si detector in consideration of the circuit capacitance, 2500pF and average required energy to create the electron-hole pair in Si, 3.67eV. The result must be compared with a computer simulation to calculate number of generated X-ray photons.

Sizes of the laser and electron beams at the interaction point are evaluated from transmission rates through the 150mm pinhole target. Typical transmission rate of the laser (electron) beam is measured to be 30% (90%) corresponding to the beam size of $\sigma$=90$\mu$m ($\sigma$=35$\mu$m). The sizes of the beams are also measured by observing the X-ray signal as a function of the transverse steering of the electron beam. The result of 250$\mu$m (225$\mu$m) FWHM in horizontal (vertical) scan is consistent with the beam sizes obtained with the pinhole.

Fig. 2 shows the X-ray signal while scanning delay time between the electron bunch and laser pulse. The shape represents longitudinal profile of the $CO_2$ laser because the electron bunch length is much shorter (3.5ps) and therefore, pulse length of the laser is estimated to be 200ps FWHM. Thus peak power of the $CO_2$ laser is 14GW for the pulse energy 2.7J.

Production of X-rays through Thomson scattering is simulated by the computer code CAIN [3] with observed beam parameters and laser energy 3J. Fig. 3 shows simulated energy spectrum of the X-rays. Low energy X-rays are attenuated in the Be window and air, and 15% of photons reach the Si detector. Total energy on the detector $2.8\times10^{11}$ eV in the simulation is compared with the energy deposit experimentally observed, $1.4\times10^{11}$ eV, i.e. 50% of expected X-rays are observed experimentally. Namely, $2.5\times10^{7}$ photons / pulse are detected on the detector, or $1.7\times10^{8}$ photons / pulse are produced at the interaction point. Since pulse duration of the X-ray is equal to the electron bunch length (3.5ps), peak photon density is estimated to be $5\times10^{9}$ photons/second. Thus, X-ray intensity is increased by about seven times that of 1999.

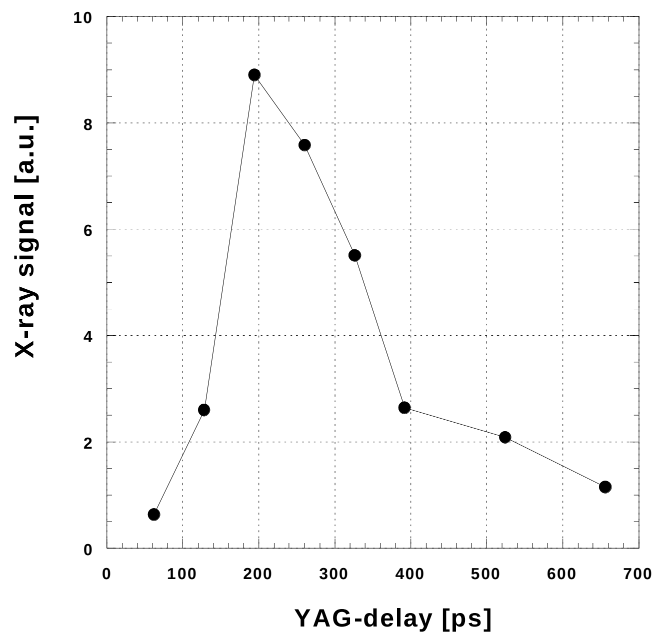


Figure 2: X-ray signal while scanning delay between the laser and electron beam.

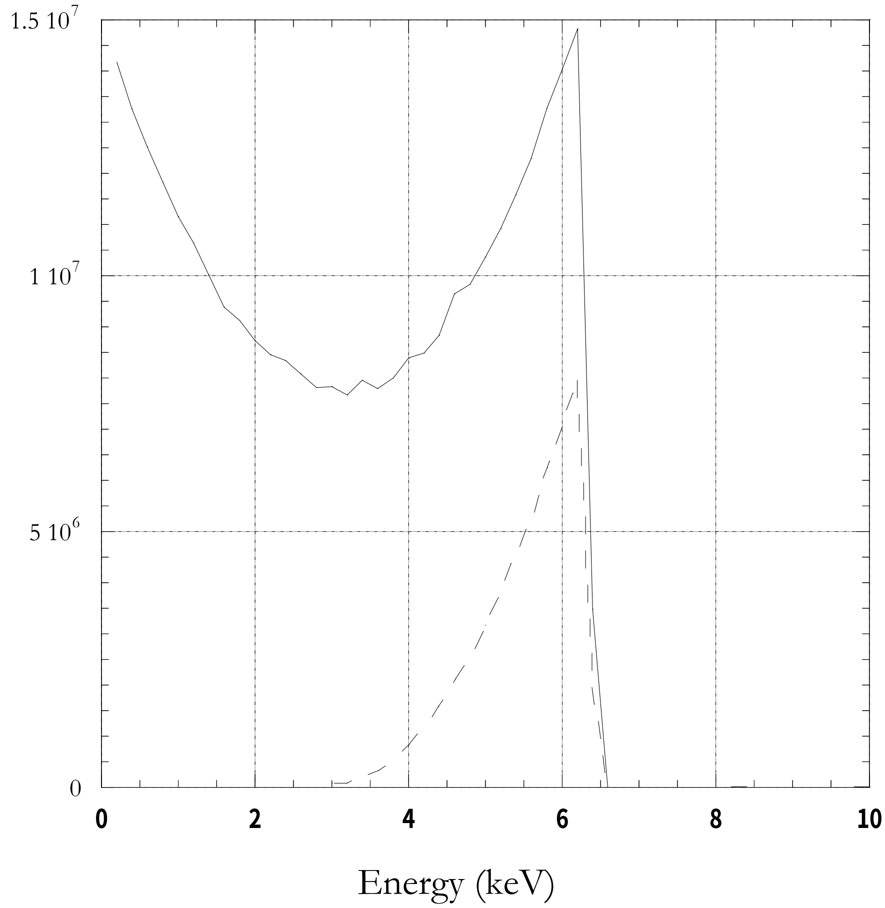


Figure 3: X-ray energy spectra simulated by CAIN. The solid line shows the spectrum of all photons generated at the interaction point ($3.4\times10^{8}$ photons, $1.1\times10^{12}$ eV per pulse), while the dashed line shows photons reach the detector ($5.0\times10^{7}$ photons, $2.8\times10^{11}$ eV per pulse).

## Non-linear effect

Fig. 4 shows a computer simulation of the X-ray energy spectrum for laser energy 30J, pulse duration 30ps, peak energy 1TW, and laser spot size 32μm corresponding to $a = 0.75$. Non-linear Thomson scattering extends the spectrum above 6keV. To observe the non-linear component, a silver foil filter is useful to cut off low energy X-rays below 6keV. Fig. 4 also shows a 20μm silver filter extracts X-rays from the non-linear process. In the experiment carried out this year, X-ray signal form the non-linear Thomson scattering was not observed. As in Fig.3, non-linear component is very small with the current laser condition ($a = 0.05$).

To observe non-linear X-rays using the silver filter, higher power density of the $CO_2$ laser which gives $a > 0.3$ is required. For example, a $CO_2$ laser with peak power of 100GW and focal spot size σ=30μm satisfies the condition. Using an energy sensitive X-ray detector, such as a crystal spectrometer, there is a possibility of observing non-linear effect with rather lower power density.

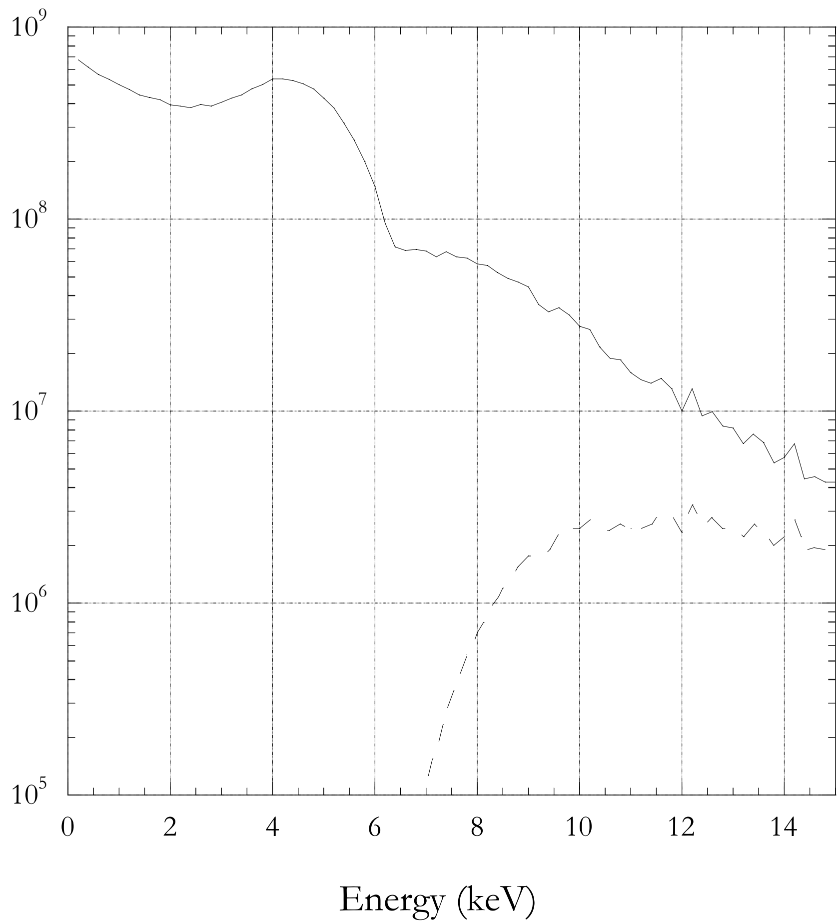


Figure 4: Simulated energy spectra for 1TW laser in logarithmic scale. The solid line shows the spectrum of photons generated at the interaction point and the dashed line shows photons transmit the 250μm Be window, 22cm air, and 20μm silver filter.

## Acknowledgement


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