

# REFRACTION CONTRAST IMAGING VIA LASER-COMPTON X-RAY USING OPTICAL STORAGE CAVITY\*

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## Abstract

We have been developing a pulsed-laser storage technique in a super-cavity for a compact x-ray sources. The pulsed-laser super-cavity enables to make high peak power and small waist laser at the collision point with the electron beam. Recently, using 357 MHz mode-locked Nd:VAN laser pulses which stacked in a super-cavity scattered off a multi-bunch electron beam, we obtained a multi-pulse x-rays through the laser-Compton scattering. Then, we performed a X-ray imaging via laser-Compton X-ray. The images have edge enhancement by refraction contrast because the X-ray source spot size was small enough. This is one of the evidences that laser-Compton X-ray is high quality. Our laser-Compton experimental setup, the results of X-ray imaging and future prospective will be presented at the conference.

## INTRODUCTION

An X-ray generation method based on laser-electron Compton scatterings (LCS) is one feasible technique for generating high quality X-rays. It utilizes a process in which energetic electrons are scattered elastically by target laser photons, with an energy transfer from the electrons to the photons. The advantage of LCS is; in order to produce the same energy, typically only one hundredth  $\sim$  thousandth of the electron energy is required thanks to its short undulation period[1]. For instance, a 30 MeV electron beam with the laser wavelength of  $\sim 1 \mu\text{m}$  can produce 15 keV X-rays. The advantage has propelled worldwide laboratories to develop compact LCS X-ray sources with a brightness equivalent to the second generation light sources.

We have been developing a compact X-ray source based on a pulsed-laser storage cavity operated with a burst amplifier[2]. The pulse train LCS X-rays were already achieved using a multi-bunch electron linac and a pulsed laser optical cavity[3]. After these successful results, our system were improved to have enough S/N and more X-ray flux. Now our LCS X-ray source was arrived to the phase of an imaging test. The contrast imagings via LCS X-ray were already performed in AIST[4], Lyncean Inc.,[5] and BNL[6]. All of these represented the enhancement of contrast by LCS and concluded the LCS X-ray was high brightness. The purpose of this imaging experiment was to

indicate our LCS X-ray quality, produced by a burst mode super-cavity and an electron linac, by observing the enhancement of edge contrast.

The paper is organized as follows: in the next section we briefly describe our experimental apparatus; this is followed by a section showing the results and discussion. In the last section, we summarize our results.

## EXPERIMENTAL SETUP

The X-ray generation experiment was performed at a LUCX accelerator facility located inside the housing of the KEK Accelerator Test Facility (ATF). Firstly, we show the parameters of electron and laser at the collision point in Table 1. The experimental setup, shown schematically in

Table 1: Electron beam and laser pulse parameters

Electron beam	
Quantity	Value
Energy	30 MeV
Charge	0.4 nC/bunch
Number of bunches	100/train
Bunch spacing	2.8 ns
Beam size (rms)	200/53 $\mu\text{m}$ (H/V)
Bunch length	10 ps (FWHM)
Repetition rate	1.56-12.5 Hz
Laser pulse	
Wavelength	1064 nm
Pulse energy	400 $\mu\text{J}$
Cavity finesse	2650
Pulse spacing	2.8 ns
Spot size (rms)	30.3 $\mu\text{m}$
Pulse duration	7 ps (FWHM)
Colliding angle	20 deg

Fig. 1, consists of three main components: a 50 MeV electron accelerator, a laser storage cavity as a LCS photon target, and an X-ray detector system. The descriptions of each electron accelerator, laser storage cavity and X-ray detector are in following subsections.

### Electron Accelerator

Our accelerator system can accelerate a multi-bunch electron beam as shown in Fig. 1. Details of our electron linac are found in reference of [7]. 100 bunch electron

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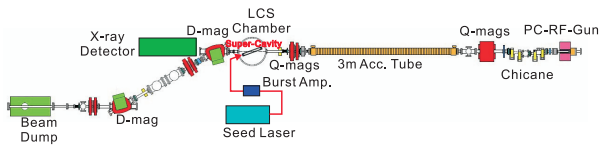


Figure 1: Schematic of LCS experimental setup.

beam is produced by irradiating the pulse train of an UV laser to a Cs-Te photo-cathode. It is accelerated up to about 30 MeV in an rf-gun cavity[8] and a 3-meter-long S-band linac. The electrons are then focused onto a laser-electron interaction point by a Q-magnet doublet. Electrons are separated from LCS X-rays by a dipole magnet and are led to a beam dump.

The multi-bunch electron beam was operated with the repetition rate of 12.5Hz and consists of 100 bunches with a bunch spacing of 2.8 ns (357MHz). We note that the energy spread over the whole train is found to be less than 1%. This value is achieved by compensating beam loading effect[9].

### Laser Storage Cavity

As a laser photon target at the interaction point, we have developed a Fabry-Perot optical cavity (super-cavity) operated with a pulsed laser. We employed a 6 W 357 MHz mode-locked laser with a wavelength of 1064 nm (High-Q IC-7000[10]) as a seed. The optical cavity consisted of two concave mirrors placed about 420 mm apart. Their reflectivity was  $R \sim 99.6\%$  and  $R \sim 99.9\%$ . The fundamental TEM<sub>00</sub> Gaussian beam was stably excited in the cavity. One notable feature of our system was the use of LD pumped burst amplifier between the mode-locked laser and the super-cavity. Detail description of the super-cavity can be found in [2].

The laser pulse and super-cavity parameters at the interaction point are summarized in Table 1. The laser pulse energies stored in the cavity of 400μJ/pulse were measured by the energy transmitted from the super-cavity. Finesse of the super-cavity was improved compared with before, thanks to the laser master system described below. The rms spot size was 30.3μm, which is smaller than that of electron beam, thus the source size of LCS X-ray was 30.3μm in rms.

Finally we comment on the electron and laser pulses mutual timing. We used special technique for the stable operation. The seed laser timing (357MHz) was employed as the master clock of the whole system. The photo-cathode irradiation laser was phase-locked to the seed laser. 8th frequency multiplied 2856MHz was used as the accelerating rf. As a result of this laser master timing system, the system was always operated stably with the timing synchronization of less than 0.3 ps.

### X-ray Detector

Around 15keV X-ray was produced via LCS of 1064nm wavelength laser and 30MeV electrons collide at an angle of 20deg. In this experiment, we used two type of micro-channel plate (MCP) detector. One was for an X-ray intensity evaluation (Hamamatsu Photonics K. K. F2224-21[3][11]), the other was imaging (see Fig. 2). We firstly evaluated LCS X-ray flux by F2224-21, then went on to imaging test by the system described below. The imaging detector setup is shown in Fig. 2. In the detector system,

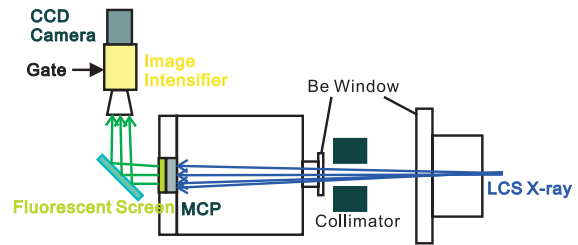


Figure 2: The schematic of X-ray imaging detector setup.

LCS X-ray photon was converted to electron and amplified by MCP, then the electron was converted to fluorescence image on fluorescence screen behind the MCP (Hamamatsu F2225-31PGFX). The fluorescence image was detected by CCD camera with a timing gating by image intensifier (I.I.:Hamamatsu C9016-23). The advantages of this setup are:

- MCP had the largest S/N detector in LCS (according to our experience [3])
- High gain in MCP and I.I. (detect low flux X-ray)
- Fluorescence can be separated from the beam line extension (BG reduction)

The spatial resolution of this system was not enough compared with other X-ray detectors, however, we believe that this provides largest S/N. The first imaging experiment was carried out by this detector, then we plan to use high resolution detector according to the X-ray flux.

## RESULTS AND DISCUSSIONS

X-ray intensity evaluation was firstly performed using MCP direct detection at the experiments. The result is shown in Fig. 3. In Fig. 3, the pulse train X-rays were found at the same timing with electron bunch. The X-ray/BG was more than 4. The X-ray flux was  $2.1 \times 10^5$  photon/sec in total bandwidth and 10% of the center part of X-rays were within detector, which is inadequate for practical use. However, we considered that this S/N was adequate for the first LCS X-ray imaging, then we moved on to the imaging test.

The X-ray imaging test was carried out by the setup shown in Fig. 2 after the evaluation of X-ray flux and S/N

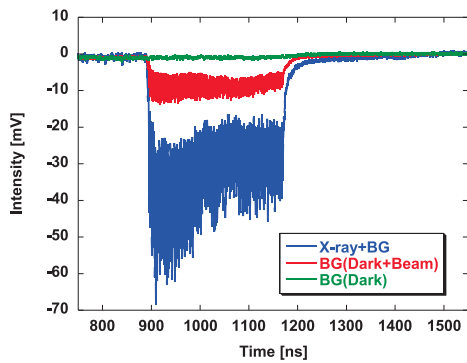


Figure 3: Raw intensity waveform of X-ray and backgrounds of MCP. The green line shows dark background i.e. beam off and rf on, the red all background and the blue X-ray and background.

of X-ray source. The resulting images were shown in Fig. 4. The images were the fish backbone. These images were

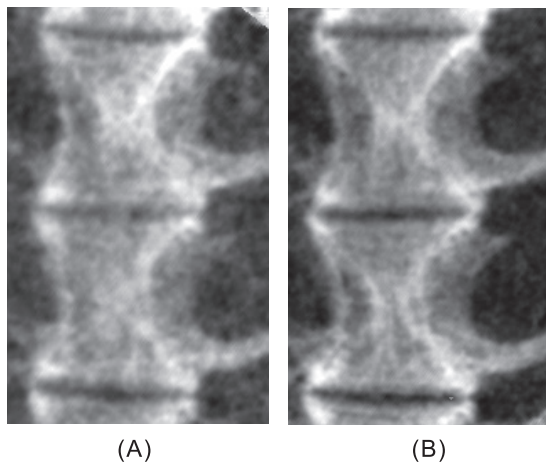


Figure 4: LCS X-ray images of fish backbone. Distances from sample to detection system are (A) 370mm and (B) 670mm.

obtained by 2700 shots accumulation to achieve the enough statistics, which corresponds to laser energy of 120J. If we would like to obtain such images with single shot, electron beam have to be interacted with 120J laser in the multi-bunch beam.

It is found that the (A) image is edge enhanced compared with (B). This is caused by the refraction contrast to set apart the detector from the sample. The line profiles of these images are shown in Fig. 5. There are some characteristic profiles, which is marked in plots, of refraction contrast in lower plots. Meanwhile, there are no edge enhancements in upper plots (Distance=370mm). The edge enhancement in such a small region corresponds the X-rays were produced from small spot. We regarded that this result indicates our LCS X-ray has very small source size i.e.

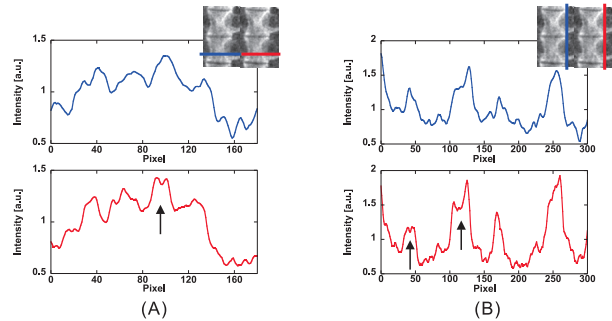


Figure 5: Line profiles of the fish backbone images. The plotted lines are shown at upper right of each plot. Upper plots are 370mm apart and lower plots 670mm.

high brightness.

## SUMMARY

In conclusion, we have firstly demonstrated a refraction contrast image by LCS X-ray in KEK-LUCX. The X-ray flux was  $2.1 \times 10^5$  photon/sec in total bandwidth. The detection of a refraction contrast constitutes indirect evidence of high brightness X-ray.

In our system, one image corresponded to the laser energy of 120J. At this experiments, we needed more than 10 minutes to obtain the image. The system have to be taken an improvements in X-ray flux. The future target is single shot (single pulse train) imaging. This results of 120J is the good target to design and upgrade the LCS system. We are now planning to upgrade the system, which are to lengthen the electron bunch train for increasing the interaction, and to redesign the optical cavity for relaxing the laser power density on mirror surface. We believe that this upgrade leads more than 2-order improvement in an X-ray flux.

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