# DEVELOPMENT OF PHOTOCATHODE RF GUN AND LASER SYSTEM FOR MULTI-COLLISION LASER COMPTON SCATTERING

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### *Abstract*

The laser cavities of Ti:Sa and Nd: YLF laser have been designed for the multi-collision laser Compton scattering (Multi-LCS) in order to enhance the X-ray yields of the LCS hard and soft X-ray source. This cavity is like the regenerative amplification including a laser crystal and a collision point for LCS. The enhanced X-ray yield was estimated more than about $1 \times 10^9$ /s using the intra-cavity stored energy. In this conference, we will describe details of the laser cavity design for the Multi-LCS and future plans of the LCS X-ray sources.

## INTRODUCTION

A short pulse X-ray source via laser Compton scattering (LCS) has been investigated for the various research fields [1-2]. The compact LCS hard and soft X-ray source have been developed based on electron linac with a photocathode rf gun system at AIST [3] and Waseda University [4], respectively. Most disadvantage of the linac based LCS X-ray source is low X-ray yields. Typical hard X-ray and soft X-ray yields were about $10^7$ and $10^5$ photons/s. Present system of LCS hard X-ray source at AIST has a high power Ti:Sa CPA laser system and a compact S-band electron linac which has a photocathode rf gun system and a 3 m S-band accelerator structure (1.5m × 2) which can generate the electron beam up to about 42 MeV. In case of the present compact LCS soft X-ray source, the electron source is only the photocathode rf gun system which can generate a electron beam up to 5 MeV and the laser system for LCS is a multi-pass Nd:YLF laser system.

We are planning to enhance the yields of X-ray photons more than $10^2$ times within a few percent band-width in order to apply the LCS soft X-ray source to the biological imaging in the "water window" region and the LCS hard X-ray source to the medical and biological uses, such as mammography, angiography and protein crystallography. Most promising approach for these purposes is the multi-pulse X-ray generation via multi-collision laser Compton scattering (Multi-LCS). Figure 1 shows the scheme of Multi-LCS is designed using multi-bunch electron beam and a laser cavity. The multi-bunch electron beam of 1 nC/bunch × 100 bunches will be obtained by Cs-Te photocathode rf gun system which is under developing at Waseda University and AIST corroborating with KEK.

The laser cavity includes a laser crystal and a collision point for LCS so that a few laser pulses are seeded into the cavity through a coupling mirror and pulse energy is built up at every pass through the laser crystal like the regenerative amplification. The laser pulse is focused at the collision point by concave mirrors in the cavity. The our designs of the Ti:Sa and Nd:YLF laser cavity and multi-pulse X-ray generation via Multi-LCS are described in this paper.

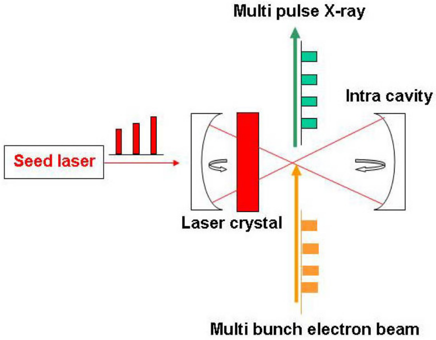

Figure 1: Scheme of multi-collision laser Compton scattering (Multi-LCS) using laser cavity.

## PRINCIPLE OF LASER CAVITY

Multi-collision laser Compton scattering (Multi-LCS) is realized between multi electron bunches and focused laser pulses in the laser cavity including laser crystal while its seed laser is built up like the regenerative amplification. In the laser cavity, the laser fluence *I* increases with *k* the number of passes through the laser crystal as

$$I_{k+1} = TI_s \ln\{G_k[\exp(I_k / I_s) - 1] + 1\},$$

where *T* is a single-pass transmission. $I_s$ is the saturation fluence obtained from $I_s = h\nu/\sigma$, where *h* is the Prank's constant, ν is the frequency and σ is the stimulated emission cross section. *G* is a small-signal gain expressed by the gain medium (laser crystal) length *L* and

$$G_k = \exp(g_k L).$$

The gain decreases after each according to

$$g_{k+1} = g_k - (p / I_s)[(I_{k+1} / T) - I_k].$$

Here, *p* is a gain recovery coefficient which is *p*=0.5 for complete gain recovery, *p*=1 for no gain recovery between pulses. In this model, we simply assumed *p*=0.72 all the while laser pulse passes. The initial small gain is derived from

$$g_0 = \frac{\eta_a \eta_q \eta_s \eta_o P\sigma}{ALh\nu} = \frac{\eta_a \eta_q \eta_s \eta_o P}{ALI_s},$$

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where *A* and *P* is cross section and power of a pump light, $\eta_o$ is the overlap efficiency between the pump light and the input laser. $\eta_s$ is the quantum defect efficiency that emission photon energy over pump photon energy known as the Stokes factor. $\eta_q$ is the quantum efficiency. $\eta_a$ is the absorption efficiency expressed by 1-exp(-$\rho L$). $\rho$ is the absorption coefficient of the laser medium.

In our model, the laser crystal is located nearby the end mirror so that the first laser pulse passes twice through the laser crystal before the second pulse reaches at the laser crystal. Cavity round loss factor *R* per 1 round is defined due to total loss of optical mirrors and other transmission medium in the cavity. In this work, the mode–locked frequency of both laser of rf gun driving and cavity seeder is assumed 79.33 MHz (36th sub-harmonic frequency of 2856 MHz) corresponding to 12.6 ns pulse spacing so that the cavity length and the number of seeded pulse are able to be chosen as a half of some harmonic of pulse spacing and the harmonic number, respectively. In this work, the number of seeded pulse and the cavity length are defined 4 pulses and 7.56 m. Consequently, the build-up waveform in the laser cavity was calculated and the intra-cavity stored energy was estimated by summing 100 build-up pulses around the peak energy pulse in each case of the LCS hard and soft X-ray sources.

## LASER CAVITY FOR MULTI-LCS HARD X-RAY SOURCE

Multi-collision laser Compton scattering (Multi-LCS) system for the hard X-ray source has been developed using a Ti:Sa laser cavity. The laser cavity design which has 7.56 m cavity length including a telescope is calculated by Winlase pro ver. 2.1. Figure 2 shows one of results of the calculations. As a result, the laser waist radius at the expanding region (laser cryastal), the contracting region of the telescope and the collision point is calculated to be apploximately 5 mm, 2 mm and 38 μm (1/e$^2$), respectively.

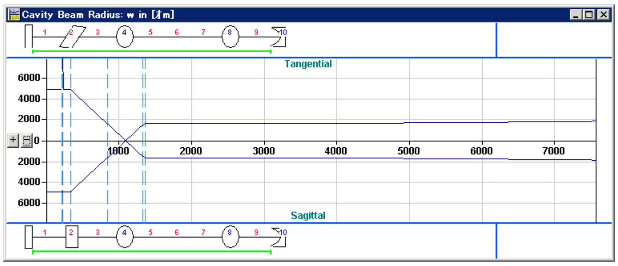

Figure 2: Ti:Sa cavity design for 4 seed pulses.

In the build-up process in the laser cavity like the regenerative amplification, the maximum energy of amplified pulse is limited by the damage threshold of the optical mirror. We assumed the mirroer usage of TLMB series (CVI Lasers) for 800 nm which has damage threshold of 8 J/cm$^2$ at 300 ps corresponding to 1.5 J/cm$^2$ at 10 ps (assuming chirped pulse by the pulse strecher) so that the maximum energy is limitted about 180 mJ/pulse due to the waist size of 2 mm in the contracting region of the laser cavity. The parameters of the Ti:Sa amplification calculation are shown in table 1. Figure 3 shows the build-up waveform in the cavity by the calculation with seed laser which has 1μJ × 4 pulses and it is clearly found that the fractuation of build-up laser energy is occered and the seed pulses modulation should be required.

Table 1: Parameters of calculation for Ti:Sa laser cavity

| Laser medium | Ti:Sa |
|---|---|
| Crystal length (*L*) | 4 mm |
| Stimulated emission cross section ($\sigma$) | $2.8 \times 10^{-19}$ cm$^2$ |
| Absorption coefficient ($\rho$) | 3.5 cm$^{-1}$ |
| Pump light wavelength | 532 nm |
| Emission light wavelength | 800 nm |
| Quantum efficiency ($\eta_q$) | 91 % |
| Overlap efficiency ($\eta_o$) | 95 % |
| Transmission (*T*) | 98 % |
| Cavity round loss (*R*) | 95 %, 90% |
| Waist radius of pump light | 5 mm |
| Pulse width (FWHM) | 10 ps (chirped) |
| Pulse spacing | 12.6 ns |
| Number of seed pulse | 4 |
| Pump light energy | 730 mJ, 820 mJ |

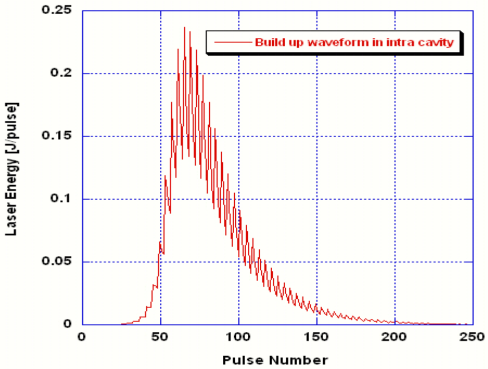

Figure 3: Build-up waveform without seed modulation.

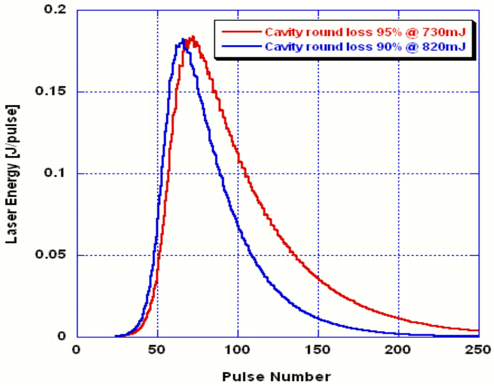

Figure 4: Build-up waveform with seed pulses modulation.

Figure 4 shows the clear build-up waveform obtained with modulated seed pulses which is 0.99, 1.25, 1.52 and 1.90 μJ. In this case, the intra-cavity stored power is calculated to be apploximately 10 J (around the peak energy pulse of 180 mJ) corresponding the average energy of 100 mJ. The yield of Multi-LCS hard X-ray on this design was estimated to be about 3.3 × 10$^9$ /s using parameters in table 2.

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Table 2: Parameters of LCS hard X-ray calculation

| | |
|---|---|
| Electron energy | 38 MeV |
| Electron charge | 1 nC/bunch |
| Bunch number | 100 |
| Electron spot size ($\sigma_x$, $\sigma_y$) | 40 µm |
| Electron bunch length | 10 ps (FWHM) |
| Laser wavelength | 800 nm |
| Stored laser power | 10 J / 100 pulse |
| Average laser energy | 100 mJ/pulse |
| Laser spot size ($\sigma_x$, $\sigma_y$) | 38 µm |
| Laser pulse width | 10 ps (FWHM) |
| Collision angle | 170 deg |
| Maximum LCS X-ray energy | 34 keV |
| LCS photon number | $3.3 \times 10^6$ /pulse |
| Repetition rate | 10 Hz |
| Total photon yield | $3.3 \times 10^9$ /s |

## LASER CAVITY FOR MULTI-LCS SOFT X-RAY SOURCE

Multi-LCS system for the soft X-ray source has been developed using a Nd:YLF laser cavity. Figure 5 shows one of results of the calculations with Winlase pro. It is found that the cavity has two focus points. One focus point (left side) is for the LCS collision point and the other (right side) is for Q-swiching point using a mecanical chopper to keep away from the spontanious emission due to its long spontaneous fluorescence lifetime of about 485 µs. As a result, the laser waist radius at the expanding region (laser cryastal), the contracting region of the telescope and the collision point is calculated to be about 5 mm, 2 mm and 50 µm ($1/e^2$) , respectively.

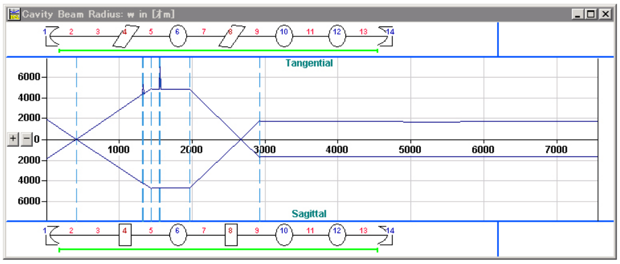

Figure 5: Nd:YLF cavity design for 4 seed pulses.

The maximum energy is also limited by the damage threshold of the optical mirror wich is assumed as Y1S series (CVI Lasers) for 1047 nm and it has damage threshold of 30 J/cm$^2$ at 20 ns corresponding to 0.67 J/cm$^2$ at 10 ps. The limitted maximum energy in the cavity is calculated to be applоximately 84 mJ/pulse. The calculation parameters concerned with terms deferent from table 2 are shown in table 3. Figure 6 shows the clear build-up waveform obtained with modulated seed pulses which is 1.1, 1.2, 1.3 and 1.4 µ J. The intra-cavity stored power is estimated to be apploximately 6 J (around the peak energy pulse of 84 mJ) corresponding the average energy of 60 mJ. The yield of Multi-LCS soft X-ray on this design was calculated to be apploximately $1 \times 10^9$ /s using parameters in Table 4.

Table 3: Parameters for Nd:YLF cavity calculation

| | |
|---|---|
| Laser medium | Nd:YLF |
| Crystal length (*L*) | 4 mm |
| Stimulated emission cross section ($\sigma$) | $1.8 \times 10^{-19}$ cm$^2$ |
| Absorption coefficient ($\rho$) | 10.8 cm$^{-1}$ |
| Pump light wavelength | 792 nm |
| Emission light wavelength | 1047 nm |
| Pump LD power | 1.36 kW@250µs |

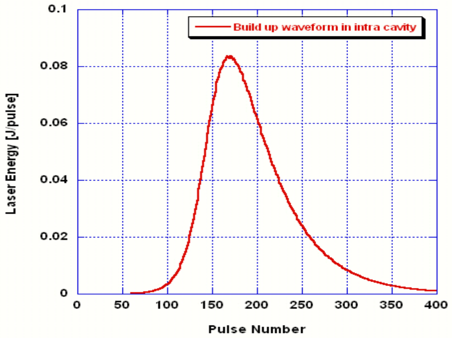

Figure 6: Build-up waveform with seed pulses modulation.

Table 4: Parameters of LCS soft X-ray calculation

| | |
|---|---|
| Electron energy | 4.2 MeV |
| Electron charge | 1 nC/bunch |
| Bunch number | 100 |
| Electron spot size ($\sigma_x$, $\sigma_y$) | 200 µm |
| Electron bunch length | 10 ps (FWHM) |
| Laser wavelength | 1047 nm |
| Stored laser power | 6 J / 100 pulse |
| Average laser energy | 60 mJ/pulse |
| Laser spot size ($\sigma_x$, $\sigma_y$) | 50 µm |
| Laser pulse width | 10 ps (FWHM) |
| Collision angle | 170 deg |
| Maximum LCS X-ray energy | 0.3 keV |
| LCS photon number | $4 \times 10^5$ /pulse |
| Repetition rate | 25 Hz |
| Total photon yield | $1 \times 10^9$ /s |

## SUMMARY

The laser cavity design for the Multi-LCS X-ray source has been successfully performed about Ti:Sa and Nd:YLF laser system. As a result, the yields of hard X-ray and soft X-ray are enhanced more than $1 \times 10^9$ /s via Multi-LCS. However, the intra-cavity stored laser power is strongly depended on the cavity round loss factor *R* from fig. 4. It is found that quite high reflectivity of optical mirrors in the cavity should be required for our Multi-LCS model.

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