SIMULATION STUDY OF COMPACT HARD X-RAY SOURCE VIA LASER COMPTON SCATTERING

R. Kuroda[#*], H. Toyokawa, M. Yasumoto, N. Sei, H. Ogawa,
M, Koike, K.Yamada AIST, Ibaraki, Japan
T. Nakajyo, F. Sakai, T. Yanagida, SHI, Tokyo, Japan

Abstract

The compact hard X-ray source via laser Compton scattering (LCS) between high intensity electron beam and high power laser beam was developed in collaboration between AIST and SHI. Maximum X-ray photon yield was accomplished about 10^7photons/s (@10Hz, MAX 40keV) at 165 degree collision angle. To enhance X-ray yields, it is necessary to increase the electron charge, so that the beam tracking and focussing simulation was performed for the high charge beam of 5 nC/bunch. In the next phase, we are planning to make the total system more compact using X-band accelerating structures. We have carried out the numerical simulation to investigate the possibility of the X-band compact system. Moreover the bunch compression study for generation of the short pulse X-ray and coherent synchrotron radiation (CSR) was calculated. In this conference, we will talk about results of the simulations, future plans and its applications.

INTRODUCTION

A short pulse X-ray source via laser Compton scattering (LCS) has been investigated for the various research fields [1-3]. The compact LCS hard X-ray source between high intensity electron beam and high power laser beam was developed at FESTA (The Femtosecond Technology Research Association) which had been organized under the framework of industrial technology development program by METI(Ministry of Economy, Trade and Industry of Japan) in collaboration between AIST and SHI [4-5]. According to completion of the project in March 2005, the compact hard X-ray source is being transferred from FESTA to AIST to upgrade the system. Main components have already been installed in AIST. Now we are planning to enhance the yield of X-ray photons up to the order of 10^8 photons/s within a few percent band-width, aiming at medical and biological uses, such as mammography and protein crystallography.

Present system of LCS hard X-ray source has a high power laser beam source and a high quality electron beam source which has an rf gun, a linac (L1 & L2), an achromatic arc section, a focusing section. The injector consists of a laser photo-cathode rf gun which has the BNL type S-band 1.6 cell cavity and a solenoid magnet for emittance compensation. The linac has two 1.5-m-long accelerating structures (L1 & L2) which is designed for 5 nC/bunches as a standing wave structure with an alternative periodic structure [6] and can generate the electron beam up to about 42 MeV. The standing wave structure has the advantage that its phase and voltage are quite stable against beam loading because of the high-energy propagation velocity. The achromatic arc section has a two 45-degree bending magnets and 4 Q-magnets. The Focusing section has triplet Q-magnets and a LCS collision chamber.

The laser system for LCS is a high power TW Ti:Sa laser system with the chirp pulse amplification(CPA) and can generate the laser beam up to 140 mJ/pulse at 800 nm, 150 fs. This system can generate a hard X-ray pulse which has variable energy of 10 keV – 40 keV with narrow bandwidth by changing electron energy and collision angle. The maximum X-ray energy and photon yield are about 40 keV and 10^7 photons/s via laser Compton scattering with about 42 MeV, 1 nC electron bunch at 165-degree collision angle.

To enhance LCS X-ray yields, it is necessary to increase the electron charge. In this study, we have performed the beam tracking simulations of high charge electron beam and the investigation of the optimum focusing parameters on the collision point using PARMELA and TRACE-3D[7]. It was also investigated to make total system compact that the 60 cm-long X-band accelerating structure could be applied instead of the S-band linac. Moreover the bunch compression study for generation of the short pulse X-ray and coherent synchrotron radiation (CSR) has been carried out.

HIGH CHARGE BEAM TRACKING AND FOCUSING SIMULATION

Our injector has an photo-cathode rf gun and a solenoid magnet for emittance compensation. Our linac has two 1.5m-long standing-wave accelerating structures (L1 & L2) which was designed to accelerate up to 5nC electron bunches (maximum) [6]. It is planning to generate the high charge electron beam in order to enhance the LCS X-ray yield. The conventional Cu photo-cathode will be exchanged to the semi-conductor cathode such as Cs-Te which has high quantum efficiency to reduce requirement of irradiating laser power. On the other hand, there is charge limitation which is 5 nC/bunch due to the divergence from space charge effect and the aperture size in the rf gun cavity. It is very difficult for the high charge bunch such as 5 nC to focus to quite small spot size on the collision point for LCS because of the large emittance growth. The beam tracking simulation in the rf gun and the linac (L1 & L2) section was performed by changing each rf phase and solenoid field using PARMELA. On the achromatic arc section and the focusing section, the

[#]E-mail: ryu-kuroda@aist.go.jp
[*]Visiting researcher at Waseda Univ. Japan

parameter matching simulations were carried out using TRACE-3D.

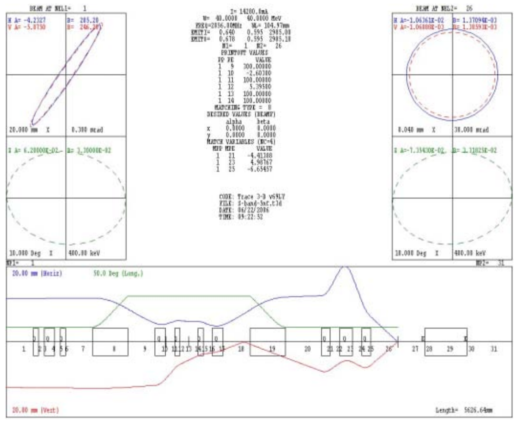

Figure 1: Focusing result of the 5nC electron beam

The rf phase of the rf gun was fixed 40 degree for the high quality electron beam which has low energy spread and low emittance. The rf phase of L1 and L2 accelerating structures was 170 degree for the low energy spread electron beam. The 5 nC electron beam after the linac has energy of 40 MeV, twiss parameters of α_x=-4.23, β_x=205.2 [m/rad], unnormalized ε_x=0.128 [mm mrad], α_y=-5.08, β_y=246.2 [m/rad], unnormalized ε_y=0.119 [mm mrad], α_z=0.062, β_z=0.033 [deg/keV], ε_z=797.1 [deg-keV]. As a results of the matching simulation in the focusing section using the triplet Q-magnets, the electron beam was focused to size of σ_x=30μm, σ_y=29μm on the collision points. On the other hand, the 1 nC electron beam was focused to size of σ_x=30μm, σ_y=24μm by the matching simulation. It means that the 5 nC beam size could almost be comparable with 1 nC beam size on the collision point and it can enhance 4.5 times on the LCS X-ray yields.

X-BAND LINAC AND FOCUSING SIMULATION

The length of our linac with S-band accelerating structures were about 3 m to accelerate the electron beam up to 30-40 MeV. However it seems that the total system as the hard X-ray source becomes a little bit large. So we have considered applying the compact X-band accelerating structure instead of the S-band linac. The 11.424 GHz X-band accelerating structure has been developed at KEK-GLCTA for the linear collider project[8]. Unfortunately, on the international linear collider (ILC) project the super conducting cavity was applied as the accelerating structure of the main linac, but the X-band technology has been already established by GLCTA. Consequently, we proposed the combination of the S-band rf gun and the X-band linac system. The 11.424 GHz X-band linac was 5/6 π mode travelling wave accelerating structure which had 53 cells. The period of one cell was about 11mm-long and total length was about 60 cm. The X-band cavity has cell length=7 mm, 2a=9.4 mmϕ, 2b=22.3 mmϕ, t=4 mm. the geometry of a input cell and a resonant first cell and the electric fields were calculated by SUPERFISH and shown in fig. 2. Figure 3 shows the electric fields as the 5/6 π mode X-band linac which has about 65 MV/m accelerating gradient assuming the 60 MW rf feed in the PARMELA simulation.

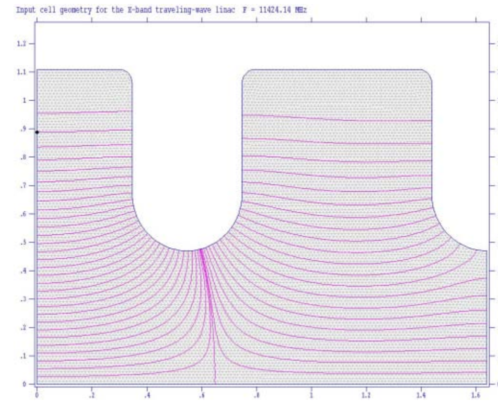

Figure 2: X-band input cell and first cell

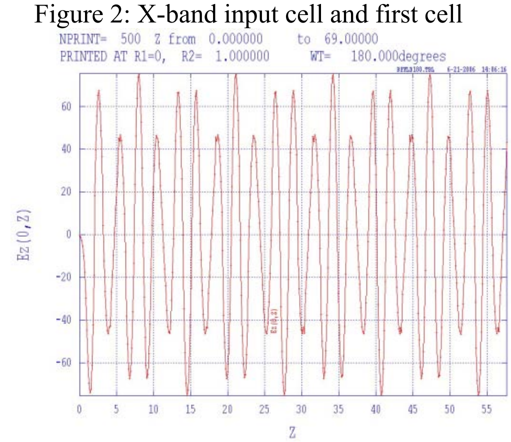

Figure 3:Electric fields of X-band linac

The rf phase of S-band rf gun was fixed about 40 degree for the low emitttance 4 MeV electron beam generation. The rf phase of the X-band linac was scanned to investigate the energy, energy spread and emittance. Figure 4 shows the electron beam characteristics as a function of the X-band rf phase. As a result, the rf phase for the highest energy and smallest energy spread was 90 degree. These characters of about 36 MeV electron beam were inputted to the TRACE-3D simulation. Figure 5 shows the focusing results of the electron beam after the matching of the achromatic arc section and the focusing section, and the spot size was focused to the σ_x=148 μm, σ_y=32 μm on the collision point. It was about 5 times larger in the horizontal direction because the energy spread and the normalized emittanc were quite large about 5 % and about 12 mm mrad, respectively. It seems that this effect was caused by the bunch length of the beam from the rf gun. It is about 4 ps (rms) and too long against about 87.5 ps = 1 λ @11.424GHz. However, the LCS X-ray yield on the X-band system was only about factor 2 less than that of S-band system, and the length of X-band linac could be 5 times smaller than S-band linac

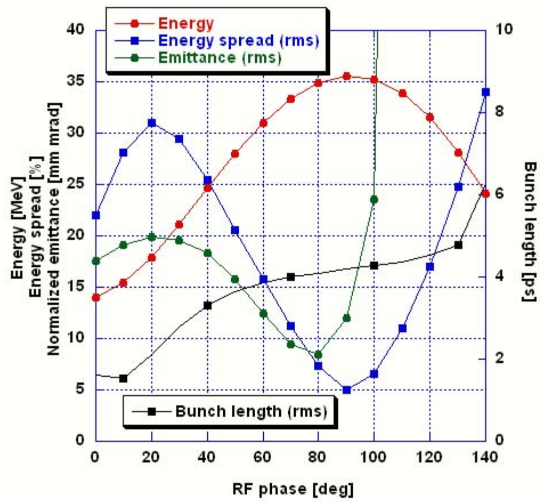

Figure 4: Beam characteristics as a function of X-band rf phase

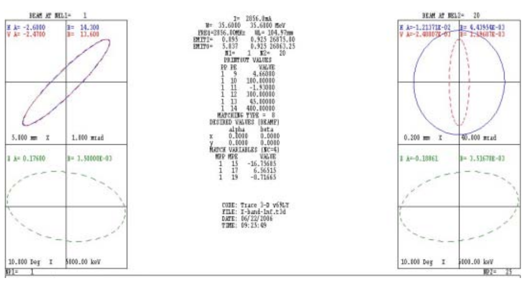

Figure 5: Focusing result for electron beam generated from X-band linac

BUNCH COMPRESSION STUDY

In case of the LCS X-ray generation especially the head on collision, the X-ray pulse length depends on the electron bunch length. So electron bunch length is the very important term for the control the X-ray pulse length. Moreover, the high intensity ultra short bunch beam is very useful for the THz radiation using the coherent synchrotron radiation (CSR). In this section, the numerical simulation for the bunch compression using the achromatic arc section was carried out about 1 nC electron beam. Figure 6 shows the top view of the achromatic arc section. The phases of the rf gun and the linac (L1&L2) were scanned to generate more than 30 MeV electron beam which has a wide energy spread. The rf gun phase was fixed at 40 degree. The L1 phase was choose 140 degree (α_z>0) and 220 degree (α_z <0) to generate 18 MeV electron beam which has about 6 % band-width at the L1 out. In case of each phase, L2 phase was scanned to be obtained more than 30 MeV beam which has about 6 % band-width and decided 120 degree (α_z >0) and 200 degree (α_z <0). The matching calculation of the achromatic arc section using TRACE3D was performed by changing the 4 Q-magnets magnetic fields to compress the electron bunch. As a result, in cases of the two L2 phase (120 deg & 200 deg), the bunch length after the compression was about 450 fs (rms) and about 550 fs (rms) and it is found that the case of α_z >0 is useful for the bunch compression rather than the case of α_z<0. Figure 7 shows the simulation results of the α_z >0 case.

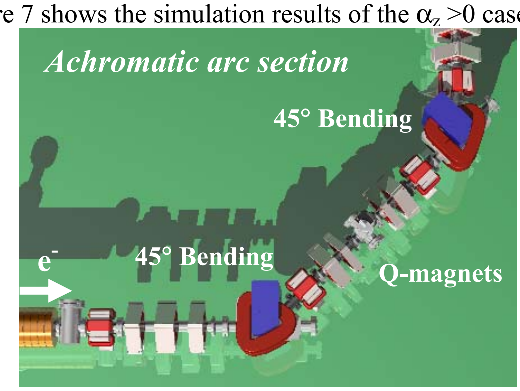

Figure 6: Top view of achromatic arc section

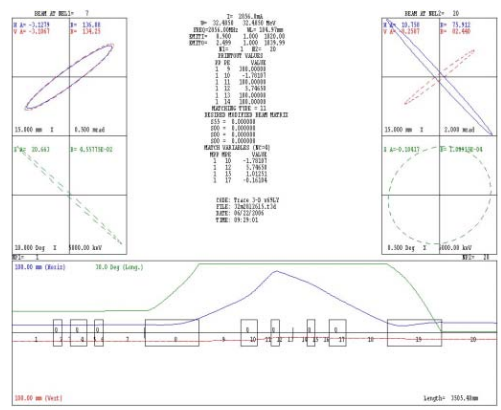

Figure 7: Matching result for bunch compression

SUMMARY

To increase the LCS X-ray yield, the beam tracking and focusing simulation for the high charge beam of 5 nC/bunch was carried out and the electron beam could be focused to size of σ_x=30µm, σ_y=29µm on the collision point, so that It can enhance the X-ray yield about 4.5 times larger than that of 1 nC/bunch. To make total system more compact, it is clearly found that X-band linac is very useful to apply instead of the S-band linac. In the bunch compression study, it is obtained that the 1 nC electron beam can be compressed about 500 fs(rms).

ACKNOWLEDGEMENT

Authors would like to express sincere thanks to Mr. K. Watanabe and Dr. T. Higo at KEK for their deep help on study of the X-band accelerating structure.

REF ERENCES

[1] R. W. Schoenlein et al, Science **274**, 236 (1996).
[2] K-J. Kim et al, Nucl. Instr. Meth. A **341**, 351 (2000).
[3] S. Kashiwagi et al., J. Appl. Phys. **98**, 123302 (2005).
[4] J. Yang et al, Nucl. Instr. Meth. A **428**, 556 (1999).
[5] M. Yorozu et al, Appl. Phys. B **47**, 327 (2002).
[6] F. Sakai et al, Jpn. J. Appl. Phys. **41**, 1589 (2002).
[7] D. P. Rusthoi et al., Proc. PAC97, 2574 (1997)
[8] T. Higo et al., Proc. PAC 2005, 1162 (2005)