X-BAND RF GUN/LINAC FOR INVERSE COMPTON SCATTERING HARD X-RAY SOURCE

Mitsuru Uesaka, Atsushi Fukasawa, N. E. R. L., University of Tokyo, Japan
Katsuhiro Dobashi, Hokuto Iijima, National Institute of Radiological Sciences, Chiba, Japan
Junji Urakawa, Toshiyasu Higo, Mitsuo Akemoto, Hitoshi Hayano, KEK, Tsukuba, Japan

Abstract

Compact Hard X-ray Source based on laser-electron collision for dynamic Intravenous Coronary Arteriography (IVCAG) is proposed and designed X-band linac is introduced to realize remarkably compact system.

We have performed the design of the X-ray system, and X-band linac is under manufacturing. CAIN code and luminosity calculation are done to estimate the X-ray yield. X-band thermionic-cathode RF-gun and RDS(Round Detuned Structure) type X-band accelerating structure are used and a 50 MeV, 20 pC/bunch electron beam with pulse length of 1 μs is generated. X-ray yield by the Q-switch Nd:YAG laser with the pulse intensity of 2 J/10 ns is 10^7 photons/RF-pulse. We will adoput a technique of laser circulation to increase the X-ray yield up to 10^8 photons/pulse.

1 INTRODUCTION

Hard X-rays of 10 $\sim$ 50 keV are now very useful for medical science, biology, material science etc. For one example of medical use, Coronary Arteriography(CAG) by a 50 keV X-ray tube for inspection and treatment of myocardial infarction has been publicly available. An coronary artery is visualized by contrast agent (contains iodine), which is injected into the artery by a catheter that is inserted into the artery. CAG is accompanied serious invasiveness of catheter and heavy irradiation dose, that are physical and mental distress for patients. A medical doctor also has heavy irradiation in the manipulation of the catheter.

These disadvantages are caused by pure contract ratio of image due to broad energy spectrum of Bremsstrahlung X-rays. Figure 1 shows the total attenuation of X-ray for various atoms. We see that Iodine has K edge at 33.169 keV[1], and monochromatic X-ray with energy just above this edge gives high contrast ratio.

On the other hand, dynamic IVCAG by monochromatic hard X-rays of Synchrotron Radiation (SR) via a monochrometer has been is proposed and tested in several institutes[2]. Actually, the clinical test has been performed by KEK and Tsukuba Univ. at KEK-AR[3]. They get clear dynamic image (33 shots/s) of the coronary artery with the intravenous injection of the contrast agent using the monochromatic X-rays of 37 keV, 10^{11} photons/s generated by the undulator at the AR ring.

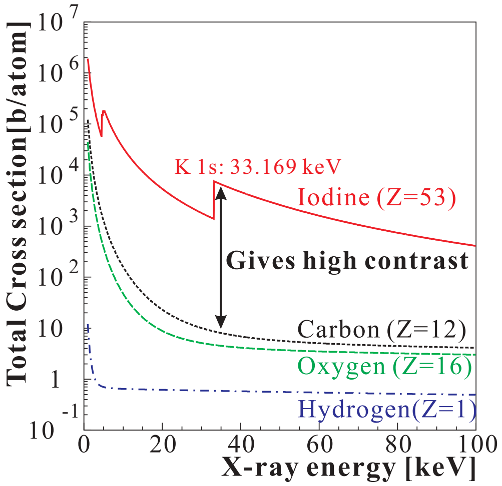

Figure 1: Total attenuation of X-ray for various atoms[1].

Intense hard X-rays are generated by the third generation light source such as ESRF, APS, and SPring-8. But most SR sources are too large to apply uses widely public IVCAG. Therefore, we are going to develop a compact hard X-ray (10 $\sim$ 50 keV) source based on laser-electron collision using by the X-band (11.424 GHz) linac system.

In this paper, we report the design and numerical analysis of the X-band RF-gun, linac, the X-ray yields of the systems, and the progress of manufacturing the X-band accelerator components.

2 DESIGN AND NUMERICAL ANALYSIS

Compact hard X-ray source based on the X-band linac that we propose is shown in Figure 2. Multi-bunch beam generated by thermionic-cathode RF-gun is accelerated by X-band accelerating structures. The beam is bent by the achromatic bends and focused at the collision point. About 10 ns hard X-ray is generated via Compton scattering on laser-electron collision. After the collision, the beam is bent and decelerated by X-band decelerating structure. The beam with the energy lower than 1 MeV is injected to a beam dump. We expect that radiation from beam dump for 1 MeV beam is less than 50 MeV. Laser system for collision includes Q-switch Nd:YAG laser and laser circulastion system to increase X-ray yield.

Photo-cathode RF-gun that can generate intense low emittance electron beam also going to be adopted to generate ultra-short pulse X-rays at the second step.

2.1 X-band linac

An X-band linac is applied to the compact hard X-ray source. RF-wavelength of the X-band is 1/4 of S-band

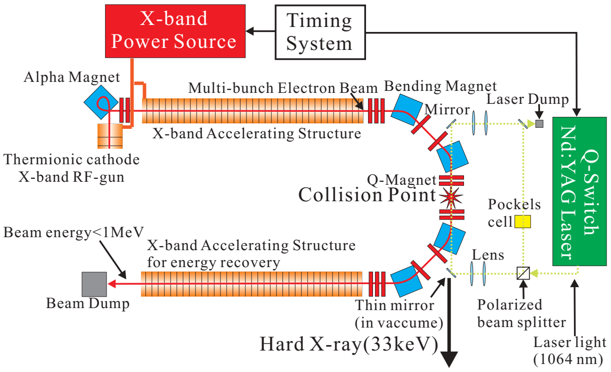

Figure 2: Schematic illustration of Compact Hard X-ray source based on thermionic-cathode X-band RF-gun, X-band accelerating structure, Q-switch Nd:YAG laser and laser circulation system.

(2.856 GHz). However, the maximum filed gradient as $\sim$ 40 MV/m enable remarkable compactness. We are going to design a thermionic-cathode X-band RF-gun and a photo-cathode X-band RF-gun. We have performed a fundamental design for the photo-cathode RF-gun using the PARMALA code. Numerical analysis of the beam transport for whole system including the photo-cathode X-band RF-gun and X-band accelerating structure at the first stage is presented[4].

Tow X-band accelerating structures with 0.7 m long is used for the X-ray source. The technologies for the X-band accelerating structure developed for future linear colliders[5] at KEK and SLAC are fully adapted for this development. At first, the RDS type accelerating structure has been adopted, which is already under manufacturing. We may consider the design the RDDS (Detuned) type to suppress the influence of the long range wakefield in the next step.

We adopt PPM(Periodic Permanent Magnet) type X-band Klystron (E3768A) designed for linear colliders[5]. Klystron Modulator is under design to fit this X-ray source. RF power is above 50MW in 1 μs.

2.2 Laser system

To concentrate on R&D of the accelerator, we choose a commercial and reliable laser for laser-electron collision.

To realize such a compact system, we adopt the Q-switch Nd:YAG laser with the intensity 2 J/pulse, the repetition rate 10 pps, the pulse length 10 ns(FWHM), and the wavelength 1064 nm.

To enhance the luminosity of laser-beam collision, we adopt the technique of circulation of laser light. The colliding laser light is bent by a mirror and its polarization plane is changed by a plckels cell. Laser light from Q-switch laser system and circulated laser light are merged by polarized beam splitter cube.

The choice of laser is a ultra-short Ti:sapphire TW laser. Single bunch short pulse electron beam and ultra short pulse laser can generate short-pulsed X-rays with the pulse length less than 10 ps(FWHM).

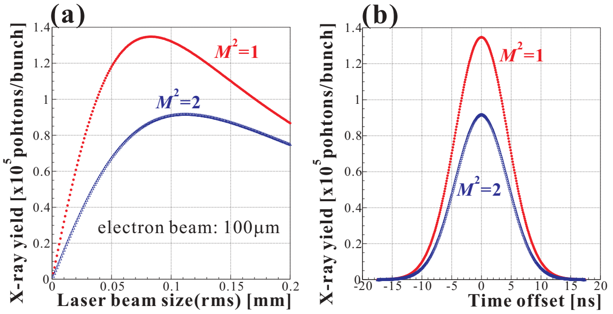

Figure 3: X-ray yield due to laser beam size for single bunch (a) and X-ray yield of each bunch due to time offset between laser and beam bunch (b).

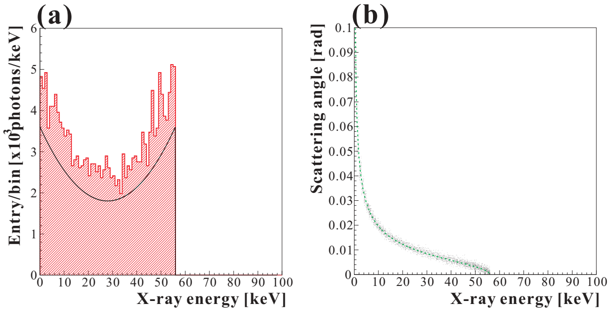

Figure 4: Total X-ray spectrum (a) and angular distribution (b) in single bunch(20 pC/bunch) collision with Q-switch Nd:YAG-laser.

2.3 X-ray yield and properties

We choose a stable system by focusing on only averaged X-ray flux. We construct the system with the thermionic-cathode RF-gun (20 pC/bunch, $\sim$ 10^4 bunches/RF-pulse, 10πmm$\cdot$mrad) and Q-switch Nd:YAG laser.

We adopt head-on collision to get the maximum X-ray yield. Figure 3(a) indicates that optimal laser beam size is 82 μm (rms) for electron beam size 100 μm (rms) at the C.P. Each bunch collides to laser light with some time offset. X-ray yield of each bunch is shown in Figure 3(b). Thus, this system generates X-rays with 1.7×10^7 photons/pulse (1.7×10^8 photons/s) that is the sum of all bunches.

Total X-ray spectrum and angler distribution is shown in Figure 4. The solid line indicates spectrum calculated by the Klein-Nishina's formula and the luminosity calculation. The histogram in (a) shows the result of beam-beam interaction Monte-Carlo simulation code CAIN[9]. Maximum X-ray energy is 56 keV at the beam energy 56 MeV In the next step, we can generate 10 ps (FWHM) short pulse X-rays with the intensity of 1.6×10^7 photons/shot (1.6×10^8 photons/s) using photo-cathode RF-gun (500 pC/bunch) and 20 TW 50 fs Ti:Sapphire laser (1 J/pulse, 10 pps, spot size 50 μm rms at C.P.).

RF-gun type	Electron beam	Laser	X-ray yield(photons)
Thermionic -cathode	20 pC/bunch $\sim 10^4$ bunches/pulse	Q-switch Nd:YAG 2J/pulse, 10ns, 10pps	1.7×10^7/pulse (1.7×10^8/s)
Thermionic -cathode	20 pC/bunch $\sim 10^4$ bunches/pulse	Q-switch Nd:YAG + Laser circulation system	1.7×10^8/pulse (1.7×10^9/s)
Photo-cathode	500 pC/bunch	20TW Ti:Sapphire 1 J/pulse, 50 fs, 10 pps	1.6×10^7/pulse (1.6×10^8/s)
Photo-cathode	500 pC/bunch	Nd:Glass 10 J/pulse, 10 ps, $\ll$1 pps	2.1×10^8/pulse
Photo-cathode Multi-bunch	500 pC/bunch 20 bunches/pulse	15 nJ/bunch+Super Cavity ($15 \times N$) nJ/bunch, 7 ps	$6.2 \times N$/pulse

Table 1: Summary of X-ray yield for various laser system.

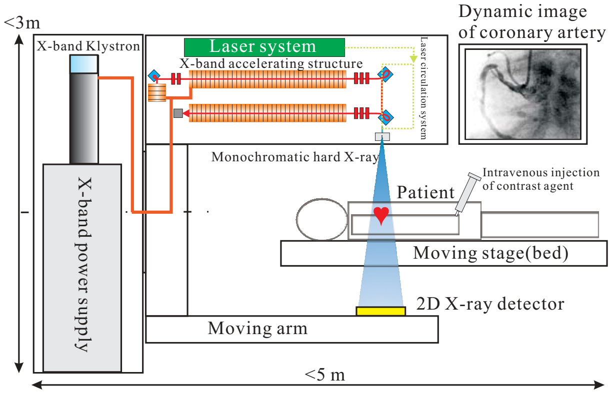

Figure 5: Final target of this study.

Calculated X-ray yields of various lasers are summarized in Table 1. The system with the thermionic-cathode and Q-switch laser is most compact and it can generate high flux X-ray with intensity 10^8 photons/s and stable.

Pulse length of Q-switch Nd:YAG laser is shoter than RF-pulse length. This mean that most of electron bunch don' t collide the laser light. The technique of circulation of laser light is effective for those situation.

The laser light collide 20 times if revolution time of laser light is 50 ns. We expect the enhancement of X-ray yield by 10 times with 90% transmission efficiency per a revolution in the laser circulation.

To achieve 10^{11} photons/s required for dynamic IVCAG, laser power and repetition rate must increase up to 10 J/pulse and 50 pps.

3 CONCLUSION

We are developing the compact X-ray source by laser-electron collision based on the X-band linac for dynamic IVCAG. To realize a remarkably compact system, we adopt the X-band system and commercial Q-switch laser and laser circulation system. We expect the X-ray yield to be 10^9 photons/s.

Final target of this study is the integrated system for dynamic IVCAG shown in Figure 5. This system has X-band RF-source and moving arm including X-band linac, Q-switch laser system and X-ray detector. We can perform dynamic IVCAG so as to to CAG and can get clear dynamic image of coronary artery with less distress for patients.

4 ACKNOWLEDGEMENTS

I would like to thanks to Dr. Emeritus Y. Hirao, Dr. S. Yamada of NIRS and M. Seya of Ministry of Education, Culture, Sports Science and Technology This study is performed in the national project of ”Development of Advanced Compact Accelerators” in Japan.

5 REFERENCES

[1] XCOM: Photon Cross Section Database, http://physics.nist/gov/XCOM

[2] E. Rubenstein, et al., E Proc. Conf Digital Radiogr. 314, 42-49(1981).

[3] S. Otsuka, et al., British Journal of Radiology 72, 25-28(1999)

[4] A. Fukasawa, et al., presented at The 2nd Asian Particle Accelerator Conference, September 17-21, 2001 Beijing, China

[5] JLC-1, KEK Report, 92-16(1992)

[6] V. O. Klein and Y. Nishina, Z. Phys. 52, 853,869(1928)

[7] C. Möller, K. Danske Vidensk. Selsk. Mat.-Fys. Medd. 23, 1(1945)

[8] T. Suzuki, KEK Report 76-3(1976)

[9] K. Yokoya, CAIN2.1e, contact Kaoru.Yokoya@kak.jp