PREPARATION FOR THE GUN TEST

The beam line for the test of the thermionic cathode X-band RF gun was constructed in this March. For the test the gun cavity must be processed by RF conditioning. After the conditioning beam experiment will be carried on.

Frequency Tuning

To check the tune of the cavity, we measured the return reflection from the gun. The pulse shapes of RF propagating forward and backward are shown in Fig. 7. The pulse propagating forward has spike in the head. Since there are no circulators which could sustain high power at X-band frequency, the reflected pulse returns back into klystron directly and come back to the gun again affecting the forward pulse.

To find a lowest reflection, frequency survey is performed. The minimum of the return loss are observed at 11.42450 GHz (Fig. 8). We changed the operation frequency 11.42400 to 11.42450 GHz.

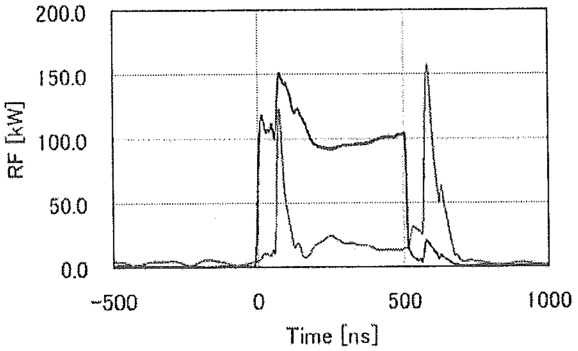

Figure 7: RF pulse shape into (blue) and reflected back from the gun cavity.

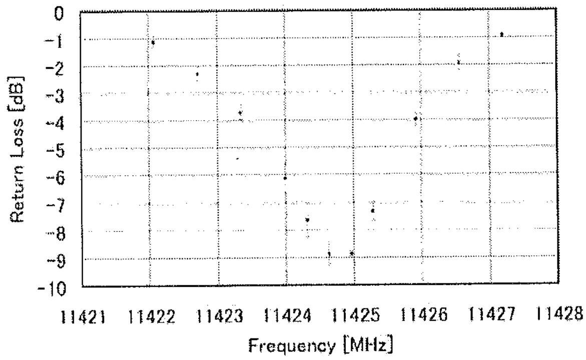

Figure 8: Return loss at the gun cavity.

RF Gun Conditioning

RF gun conditioning started in this April. The RF power 1.5 MW and the pulse length 100 ns achieved on May 13 while 6 MW and 400 ns is required for the test.

SUMMARY

We are developing a compact hard X-ray source. It requires the energy spread less than 1 %. Energy selection must be introduced and an alpha magnet with inner slits serves as that role. When the slit position came to 122mm, the condition was satisfied, however the charge became small. We are looking for better conditions.

A thermionic cathode X-band RF gun is being prepared for test. RF tuning was performed and 11.42450 GHz was chosen since the lowest reflection. RF gun conditioning began in this April. The RF status of the conditioning is now 1.5 MW 100ns while the goal is 6 MW 400ns.

ACKNOWLEDGEMENT

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Laser pulse circulation system for a compact monochromatic hard X-ray source

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Abstract

We developed a laser pulse circulation system for a compact source of monochromatic X-rays (10–60 keV) based on Compton scattering. In the X-ray source, laser pulses from a Q-switch Nd:YAG laser system collide with electron beams generated by a X-band linac. With the circulation system, a laser pulse collides with an electron beam multiple times, and the X-ray yield theoretically becomes 100 times larger than for one collision. In the proof-of-principle experiment, the laser intensity became larger by 10 times. Then, the X-ray yield will rise to at least 10^9 photons/s.

Keywords: X-band linac; Laser; X-ray source; Circulation

1. Introduction

1.1. Background

Monochromatic X-rays in the range of 10–60 keV are very useful for medical treatment, biology, material science and so on. For example, intravenous coronary arteriography (IVCAG) by monochromatic hard X-rays from synchrotron radiation (SR) has been proposed and tested in several institutes. Intense monochromatic hard X-rays (10^{11} photons/s for IVCAG) can be generated by third generation light sources. But most of SR light sources are large and expensive. Therefore, we aim to develop a compact monochromatic X-ray source (10–60 keV) based on Compton scattering shown in Fig. 1. We developed a laser pulse circulation system for the X-ray source. In the X-ray source with the circulation system, high power laser pulses repeatedly collide with multi-bunch electron beams, and the X-ray yield become larger.

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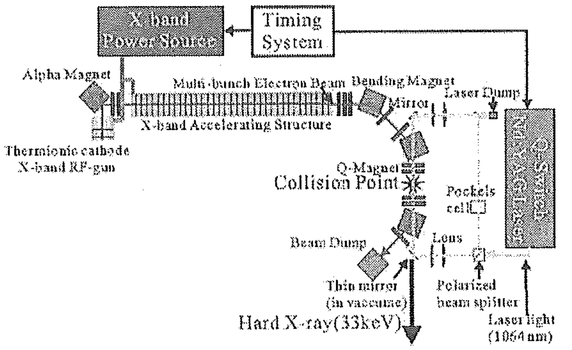

Fig. 1. Proposal for a compact monochromatic hard X-ray source.

1.2. X-ray yield

We consider the X-ray yield of our proposed system. Table 1 shows the properties of the electron and the laser beam. The X-ray yield per bunch is calculated by the known equation

$$N_{\text{X-ray}} = \sigma_{\text{comp}} L,$$

where σ_{comp} is the total cross section of Compton scattering and L is the luminosity of the laser pulse–electron bunch collision. Integrated luminosity per bunch L can be calculated by

$$L = (1 + \cos\varphi) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \rho_{\text{l}}(x, y, s, t) \rho_{\text{e}}(x, y, s, t) \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}s\, \mathrm{d}t,$$

where φ is the incident angle ($\varphi = 0$ for head-on collision), ρ_{l} and ρ_{e} are the spatial distribution function of the laser and the electron beams near the collision point, respectively. According to this equation, the system generates 10^7 photons/pulse (10^8 photons/s). The pulse length of the Q-switch Nd:YAG laser is 10 ns, and is shorter than the RF-pulse length (1 μs). This means that most of the electron bunches do not collide with the laser light. This is the reason why the laser pulse circulation system is effective to increase the X-ray yield.

Table 1
Properties of electron and laser beam of the X-ray source

Electron beam	
Kinetic energy	45 MeV
Charge	20 pC/bunch
Pulse width	1 μs
Number of bunches	10^4 bunches/pulse
Beam size	100 μm (rms)
Repeating ratio	10 pps
Laser pulse	
Wavelength	1064 nm
Pulse energy	2 J
Pulse width	10 ns (FWHM)

2. Laser pulse circulation system

Sketch of the laser pulse circulation system is shown in Fig. 2. Incident laser light passes through the polarizing beam-splitter and is focused at the collision point. After the laser pulse–electron beam interaction, the laser light is reflected by mirrors and its polarization plane is changed by the $\lambda/2$ waveplate and by the pockels cell. The polarization plane of the laser light is always vertical (s-polarization) at the polarizing beam-splitter and the laser pulse is reflected by the splitter. The laser light is led to the collision point again and can collide with the electron beam repeatedly.

3. Increase of X-ray yield

The total laser pulse energy in the laser circulation system I_N is

$$I_N = \sum_{n=0}^{N} I_0 A^n = I_0 \frac{1 - A^n}{1 - A},$$

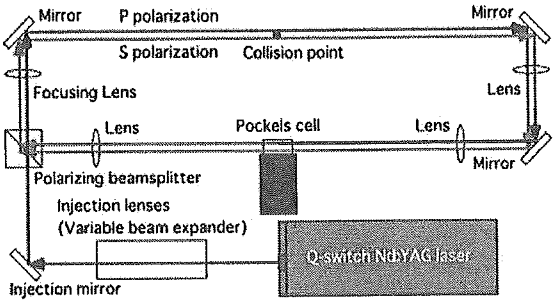

Fig. 2. Outline of the laser circulation system.

where I_0 is the initial pulse energy of the laser, A is the transmission efficiency per one circuit, and N is the total number of collisions. Since the revolving time is less than 25 ns, the laser light collides more than 40 times. With 90% transmission efficiency per collision ($A = 0.9$), we expect that the enhancement of X-ray yield becomes 10 times larger. Therefore, the X-ray source can generate 10^9 photons/s. As a next step of the laser pulse circulation, we will adopt a YAG rod as a gain medium in the circulation line to compensate the laser energy loss and achieve 100% transmission efficiency ($A = 1$). We will also utilize a higher energy laser pulse (more than 5 J) so that the X-ray yield will increase to 10^{10} photons/s.

4. Experiment

Before adding the laser pulse circulation system to the X-ray source, we are now doing a proof of experiment for the laser circulation system. The experimental setup is shown in Fig. 3. We use a relatively lower energy laser pulse (25 mJ) with ($\lambda = 532$ nm). The length of one circuit is 4 m and the revolving time is 13.3 ns.

For the laser–electron collision experiment, we have to control the laser profile and the electron beam profile at the collision point. The laser circulation system also requires high stability of the laser profile at the locus. Mirrors and lenses control the laser profile. The injection lenses (see Fig. 3) changes the beam size at the collision point, the beam size is inversely proportional to its beam size at the focusing lens. We move the angle of mirror B and the position of the focusing lens A to control the laser beam position at the collision point. We also move the mirror C and lens D to prevent an error due to the revolutions.

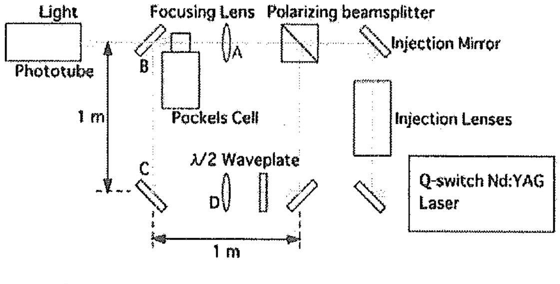

Fig. 3. Setup for the proof-of-principle experiment.

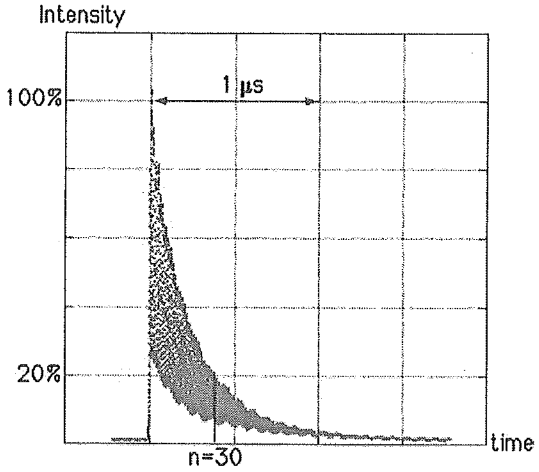

Fig. 4. Laser intensity in the circulation system.

5. Results

Fig. 4 shows the intensity of the laser pulse. This signal indicates that the laser pulse circulates more than 50 times (650 ns). The intensity of the 30th revolving pulse is approximately 20% of the incident laser pulse energy. The transmission efficiency is

$$I_0 A^{30} = 0.2 I_0,$$
$$I_0 = 94.7\%.$$

Therefore, the total X-ray yield will become more than 10 times larger, and the X-ray source will generate at least 10^9 photons/s.

6. Summary

We designed the laser pulse circulation system for the compact source of monochromatic hard X-rays. With 90% transmission efficiency, the X-ray yield becomes 10 times larger. We have been doing a proof of principle experiment and have proven that we can enhance the laser intensity by changing the laser's polarization plane. We will do further studies and experiments for the laser profiles control.

For further reading, see [1–6].

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A tunable monochromatic hard X-ray CT composed of an X-band linear accelerator and a Q-switched laser

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Abstract

A Compton scattering hard X-ray source for 10–80 keV is under construction, which consists of an X-band (11.424 GHz) electron linear accelerator and a YAG laser. The main advantages are to produce tunable quasi-monochromatic hard X-rays (10–80 keV) with the intensities of 10^{8-10} photons/s (at several stages) and its tabletop size. The second important aspect is to decelerate the beams before the beam dumper to reduce the noise radiation there. This enables a 3rd generation synchrotron radiation source to be constructed in small facilities without heavy shielding. The final goal is to load this hard X-ray source on a moving gantry. This device will realize a tunable monochromatic X-ray CT and dual energy X-ray imaging, which determines 3D distribution of electron density and equivalent atomic number. This provides real physical information to diagnostics and curative program.

PACS: 29.27.–a

Keywords: Compton scattering; Hard X-ray; Linac; Deceleration

1. Introduction

A linac-and-laser-based Compton scattering system allows quasi-monochromatic hard X-rays to be obtained with a tabletop device. If the system is small and light enough, it is possible to be loaded on a gantry. We aim to use this monochromatic

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hard X-ray source for medical applications. This system will provide clearer CT images with lower dose rate than a conventional one due to its monochromatic hard X-rays. Using two different energy X-rays, we can obtain a picture of the electron density and the effective atomic number distribution in 3D [1]. Drug delivery system is also one of the applications to be considered for our X-ray source. Putting X-ray sensitizers in nano-micells instead of drugs, the diseased part can be seen clearly or treated efficiently by using monochromatic X-ray at the required energy.

2. Development at UTNL

In our laboratory, Nuclear Engineering Research Laboratory, University of Tokyo (UTNL), a Compton scattering hard X-ray source is under construction and will start to operate in this winter. In Table 1 the design parameters of our system are listed. This system is designed at first to produce 33 keV hard X-rays for angiography [2,3] (Phase I). Tuning the accelerating phase and selecting the laser wavelength, this system will be able to produce X-rays in the range 10–80 keV (Phase II).

3. Compact hard X-ray source based on a 'soft dumping' linac

In Phase I and II system however, after the production of hard X-rays, the electron beams are dumped at high energy and produce strong radiation, which requires heavy radiation shielding, thus requiring the source to be fixed. Therefore, we propose a 'soft dumping' linac in which electron beams are decelerated to lower energy before dumped. Lower energy electrons produce much lower radiation (radiation is approximately proportional to γ^3, γ is Lorenz factor), and result in much smaller amount of shielding.

In this design we change the target X-ray energy to 40 keV, which is required for the application to dual X-ray imaging. These X-rays are produced by the collision of 47.4 MeV electrons with a 1064 nm laser which is the fundamental wavelength of Nd:YAG laser. By selecting the second harmonic generation, we can easily obtain 80 keV X-ray.

This linac is made of an X-band accelerator, which is smaller than conventional S-band one. A thermionic cathode RF gun is introduced. The main accelerator consists of four standing wave structures. Two structures are designed to have the same properties, combined through 3 dB hybrid and placed not to return the reflected RF from the cavity to the RF source.

To decelerate electron beams, we adopt counter-propagating deceleration. Both accelerating and decelerating beams travel in the same structure to the opposite direction. After the interaction point, beams are re-injected into the exit of the accelerating structure. Since the beams go to the opposite directions, standing wave structures are required to achieve both the acceleration and the deceleration.

4. Beam optics

The design of the lattice after acceleration is one of the important problems, since the transportation system could occupy larger space than the accelerating section. Also the magnets should be as few as possible. Our current lattice design is

Table 1
Design parameters of the hard X-ray source at NERL

	Phase I	Phase II
Electron beam energy	43 MeV	47 MeV
Charge	200 nC/pulse (= 20 pC × 10^4 bunches)	
Laser wavelength	1064 nm	532, 1064 nm
Laser power	2 J/pulse	5 J/pulse
X-ray energy	33 keV	10–80 keV
X-ray yield	1.7×10^9 photons/s	10^{10} photons/s

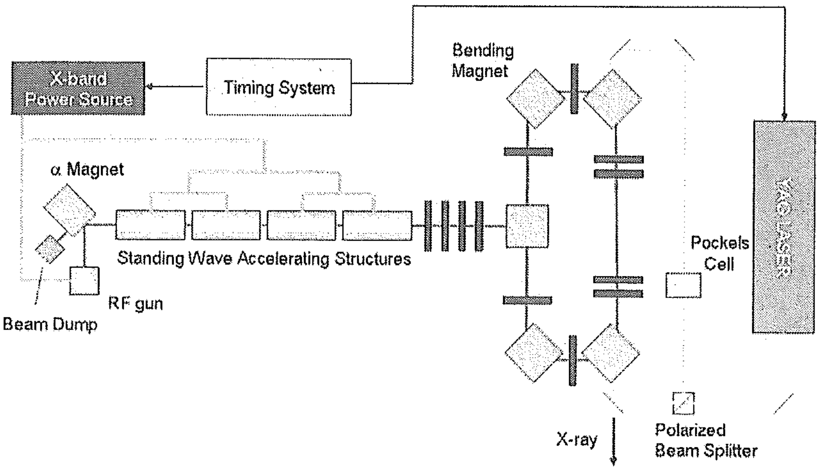

Fig. 1. Compact hard X-ray source based on a 'soft dumping' linac.

shown in Fig. 1. From the exit of the accelerating section, the beam goes through the matching section of three quadrupole magnets. All the bending magnets are the same: the bending angle is 90° and the bending radius 200 mm. The beams travel achromatically and isochronously in the bending system, and are focused at the interaction point by final doublet. Then beams go back to deceleration section through the lattice symmetrical at the interaction point.

A restriction of achromatic transportation requires $R_{16} = R_{26} = 0$ there. At the same time, the longitudinal bunch form should be the same as those right after the acceleration to decelerate the beams effectively. This requires $R_{56} = 0$ at the re-injection to decelerate the beam. We will design

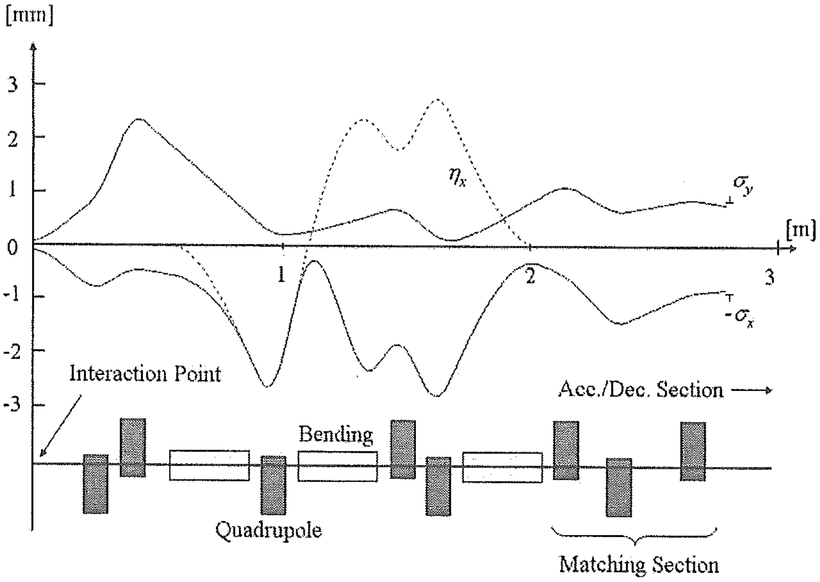

Fig. 2. Beam envelope in the arc part.

the lattice to be symmetrical at the interaction point, then $R_{56} = 0$ also required there.

PSI GRAPHIC TRANSPORT [4] (based on TRANSPORT [5]) is used to calculate the beam optics. Fig. 2 shows the beam envelope from the interaction point to the exit of the accelerating structure. The dispersion function becomes 0 after the transportation, and beams are focused into about 100 μm (rms). $R_{56} = 0$ is achieved at the exit of the accelerating structure.

In this design, the width of the transportation arc is about 1.5 m. This is still wide for a movable device, such as a hard X-ray gantry. We will proceed to minimize the lattice.

5. Beam tracking

PARMELA is used to calculate the beam motion. We used the result of the beam parameters after the alpha magnet (Table 2) to evaluate the optics and the deceleration of the beam. The rms spot size of the beam is 76×61 μm^2. This is near the designed value. This shows success in the achromatic transportation. The longitudinal bunch forms after the transportation is shown in Fig. 3. The bunch length could not be maintained after the transportation, but the main part of the bunch stays in the deceleration phase. With the RF phase tuned to decelerate the main part, the average energy becomes 4.6 MeV (Fig. 4). Taking into account on the energy dependence of radiation, γ^3, $\sqrt[3]{\langle\gamma^3\rangle}$ is about 4.9 MeV. This means the radiation power produced by this beam is equivalent to that by 4.9 MeV beam.

Table 2
Parameters of the bunch after the alpha magnet

Charge	20 pC
Energy	3.5 MeV
Emittance	10π mm mrad

The achromatic system works well while the isochronous system is not successful. In the isochronous system, the error in the longitudinal position is originated from the large bending angle. To reduce this effect we should redesign the lattice with weaker bending magnets.

6. Summary

A Compton scattering hard X-ray source for medical applications is under construction at UTNL and the experiment of the beam acceleration is planned in 2005. We also proposed a linac, which has a decelerating section before the beam

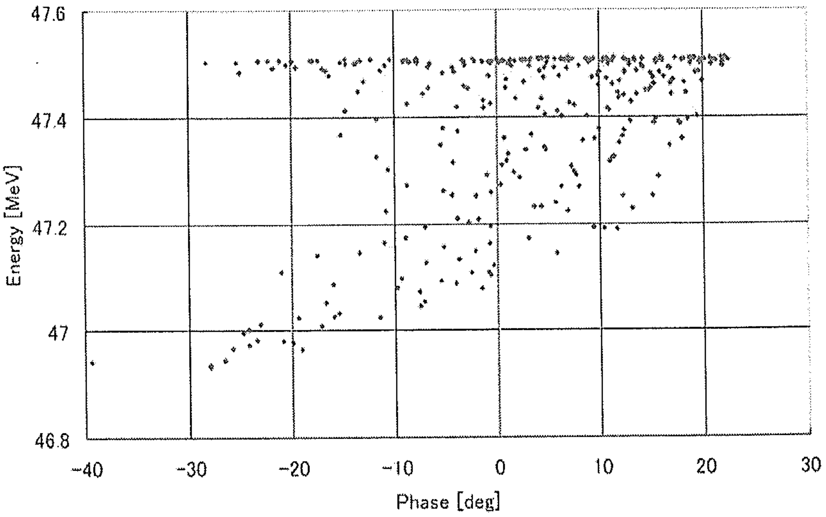

Fig. 3. Energy distribution before the deceleration.

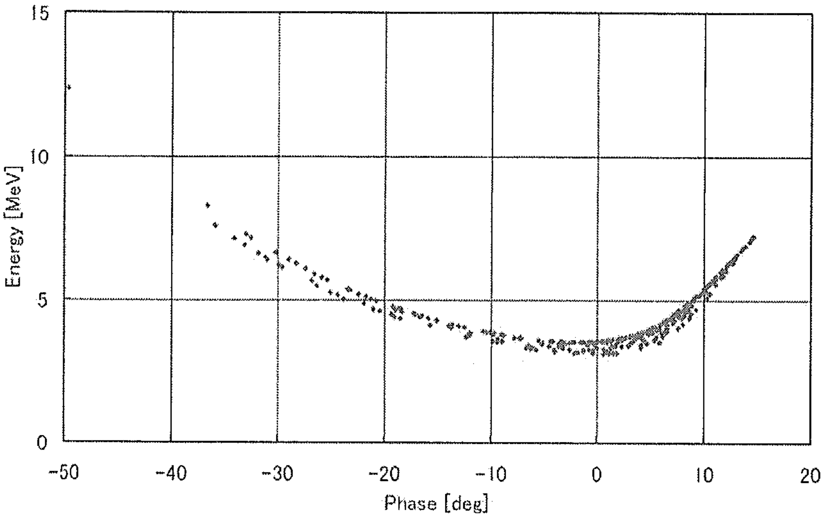

Fig. 4. Energy distribution after the deceleration.

dumper to reduce the noise radiation there. In our first design of the linac, the beam transportation is successful to make an achromatic system. We have shown the deceleration in the same structure as the acceleration, although isochronous system is not sufficient to decelerate the beam effectively.

Acknowledgements

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Design of Compact Monochromatic Tunable Hard X-Ray Source Based on X-band Linac

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A compact tunable monochromatic (1 to 10 percent bandwidth rms) hard X-ray source based on laser-electron collisions for medicine is proposed. An X-band linac is introduced to realize a remarkably compact system. We have designed a compact monochromatic tunable hard X-ray source as a demonstration. An X-band (11.424 GHz) linac for the purpose is being manufactured. Numerical considerations using CAIN code and luminosity calculations have been performed to estimate the X-ray yield. An X-band thermionic-cathode RF gun and an RDS (round detuned structure) X-band accelerating structure are applied to generate a 50 MeV electron beam with 20 pC/micro-bunch, 1 μs macro-pulse. The total X-ray yield by laser-electron collision with the electron beam and Q-switch Nd:YAG laser with a pulse intensity of 2 J/10 ns is 10^7 photons/RF-pulse (10^8 photons/s in 10 pps). We will adapt the technique of laser pulse circulating to increase the X-ray yield up to 10^8 photons/pulse (10^9 photons/s). Twenty eight percent of the photons with an energy spread of 10% rms are expected to be available by collimating the scattering angles of X-ray photons. [DOI: 10.1143/JJAP.44.1999]

KEYWORDS: Laser-beam interaction. X-band, linac, medical, monochromatic, hard X-ray, Compton scattering, X-ray imaging

1. Introduction

Hard X-rays of 10–50 keV are now very useful in medical science, biology and material science. As one example of medical use, coronary arteriography (CAG) using a 50 keV X-ray tube for inspection and treatment of myocardial infarction is publicly available. A coronary artery is visualized using a contrast agent (containing iodine), which is injected into the artery by a catheter inserted into the artery. CAG is accompanied by the serious invasiveness of the catheter and a large irradiation dose, both of which cause physical and mental distress for patients. A medical doctor also is exposed to radiation when manipulating the catheter.

These disadvantages in CAG are caused by the low contrast ratio in imaging due to the broad energy spectrum of Bremsstrahlung X-rays. The quality of the image depends on the intensity of the 33 keV X-rays and the amount of contrast agent. Figure 1 shows the total attenuation of X-rays by iodine and atoms in biomolecules, iodine has a K edge at 33.169 keV,1) and monochromatic X-rays with energy just above this edge produce a high contrast ratio. Commercial CAG systems based on X-ray tubes require injection of a contrast agent directly into the coronary artery with a catheter.

On the other hand, dynamic intravenous coronary arteriography (IVCAG) using monochromatic hard X-rays from synchrotron radiation (SR) via a monochromator has been proposed and tested in several institutes.2) Actually, a clinical test has been performed by KEK and Tsukuba University at the KEK advanced ring for pulse X-rays (PF-AR).3) They get clear dynamic images (33 shots/s) of the coronary artery with intravenous injection of a contrast agent using monochromatic X-rays of 37 keV with 10^{11} photons/s generated by the undulator at the AR ring. IVCAG is better fot a patient than CAG based on an X-ray tube.

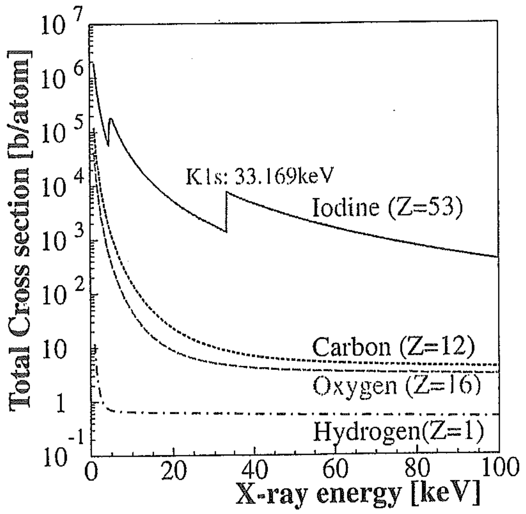

Fig. 1. Total attenuation of X-rays by various atoms.1)

Intense hard X-rays are generated by a third generation light source. However, most SR sources are too large to be applied and used widely for public IVCAG. Therefore, we are developing a compact monochromatic hard X-ray (10–50 keV) source based on laser-electron collisions with the X-band (11.424 GHz) linac system.4,5) One to ten percent narrow band X-rays are generated by collimating scattered photons that are related to the energy and scattering angle.

The final target of this study is an integrated system for dynamic IVCAG as shown in Fig. 2. This system is equipped with an X-band RF-source and a moving arm including an X-band linac, Q-switch laser system and X-ray detector. We can perform dynamic IVCAG like CAG and can get clear dynamic images of a coronary artery with less distress to patients.

A multi-bunch electron beam generated by a thermionic-cathode RF gun is collimated and compressed temporally by an alpha-magnet and accelerated by X-band accelerating structures. The electron beam is bent by the achromatic bends and focused at the collision point (CP). About a 10 ns hard X-ray is generated via Compton scattering upon laser-

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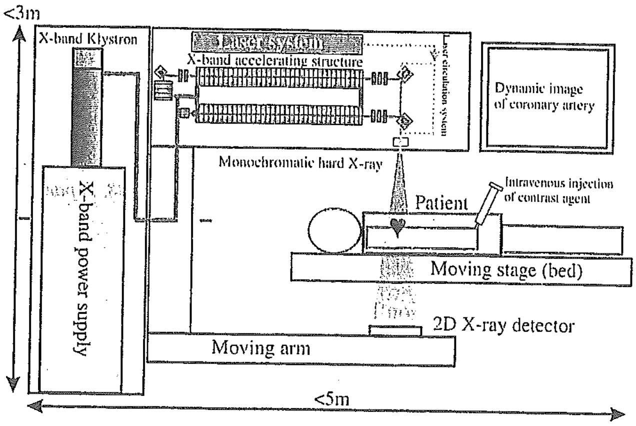

Fig. 2. Final target of this study.

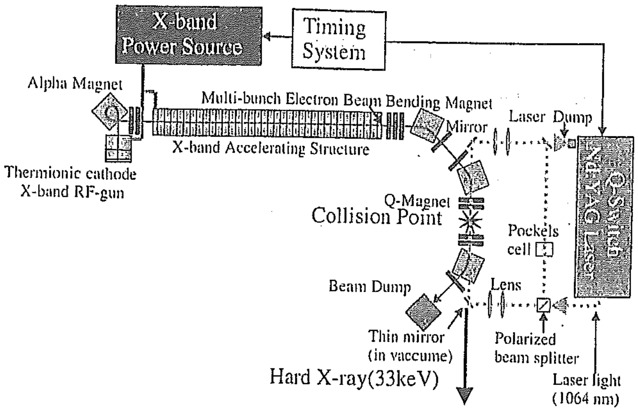

Fig. 3. Schematic illustration of the compact hard X-ray source based on a thermionic-cathode X-band RF gun, an X-band accelerating structure, a Q-switch Nd:YAG laser and a laser circulation system.

electron collision. After the collision, the electron beam is bent and decelerated by an X-band decelerating structure. The decelerated electron beam with an energy lower than 1 MeV is injected to a beam dump.

It is expected that beam loss at the beam-line is very small (less than 0.5%), because tailing of the bunch is suppressed at the beam-slit in the alpha-magnet. The radiation at the beam dump is dominant. We expect that radiation from the beam dump for a 1 MeV beam is less than 50 MeV and a heavy radiation shield is not needed. Details of the estimation for beam loss at the whole beamline in the final target system using PARMELA will be reported in another paper.

The laser system for collision is composed of a Q-switch Nd:YAG laser and a laser pulse circulating system to increase X-ray yield.

To demonstrate that the proposed X-ray sourse can be realized and will be useful in medicine, an X-band linac beamline for the proof-of-principle experiment shown in Fig. 3 is under construction.

In this paper, we present the design and numerical analysis of the X-ray source system to demonstrate hard X-ray generation and its applications.

2. Design and Numerical Analysis

2.1 *Choice of the laser systems and electron source*

First, we choose the laser system and electron source. To concentrate on the development of the accelerator, we choose a commercial and reliable laser for laser-electron collision.

X-ray yield, X-ray stability, and the size of the laser system are compared for the X-ray source with various lasers. Details of the calculation of X-ray yield are shown in §2.4. The thermionic cathode and photo-cathode RF gun can be chosen for electron source.

Calculated X-ray yields of various lasers are summarized in Table I.

The laser chosen is an ultra-short Ti:sapphire Tera watt (TW) laser. A single bunch, short pulse electron beam and an ultra-short laser pulse can generate short-pulsed X-rays with pulse lengths less than 10 ps (FWHM), but such a system requires subpicosecond timing control for X-ray stability, and the laser system is both expensive and not very stable.

Nd:Grass laser system can generate high intensity short pulse X-rays, but it is a huge system and the repetition rate of operation is very low.

A laser pulse stacking system is based on a Fabry-Perot cavity and continuous-wave (CW) mode-locked laser. The X-ray yield of this system that can enhance the laser power in the cavity depends on the enhancement factor N_{cav}. This system is not effective for a linac with a low repetition rate at $N_{\mathrm{cav}} \sim 1000$, but is effective for small electron storage rings with high bunch populations above 100 MHz.

To realize such a compact system, we adopt the Q-switch Nd:YAG laser with a pulse energy 2 J/pulse, a repetition rate 10 pps, a pulse length 10 ns (FWHM), and a wavelength of 1064 nm. The commercial Q-switch laser system is compact, stable and reasonably priced. A multi-bunch electron beam

Table I. Summary of X-ray yields for various laser systems.

RF gun type	Electron beam	Laser	X-ray yield (photons)
Thermionic -cathode	20 pC/bunch $\sim 10^4$ bunches/pulse	Q-switch Nd:YAG 2 J/pulse, 10 ns, 10 pps	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+pluse stacking ($15 \times N$) nJ/bunch, 7 ps	$6.2 \times N$/pulse

collides the long pulse laser light. The laser light can collide with about 200 micro-bunches. In this case, required timing stability is on the order of nanosecond or tens of nanoseconds. Thus, a system with a thermionic-cathode and Q-switch laser is most compact and can stably generate high flux X-rays with intention of 10^8 photons/s.

The idea of a laser pulse circulating system is based on multi-pulse laser-electron collision with laser circulation optics using a Pockels cell and a polarized beam splitter and multi-bunch electron beam from the thermionic cathode RF gun. After the first collision, laser light is turned on and reinjected into the CP. This system enhances the X-ray yield by a factor of 10 with 90% transmision efficiency of the circulation optics. To realize laser circulation optics for the intense laser pulse required for the X-ray source is challenging. Details of the laser pulse circulating system are discussed in §4.

2.2 *Requirement of beam energy*

Teh maximum energy of Compton scattered X-rays for head-on collisions depends on the wavelength (energy of photon) of the laser and the electron beam energy. The energy of the scattered photon k_s and the scattering angle of the photon $\cos\theta_s$ are derived from

$$k_s = \frac{(E_0 + P_0)k_0}{(1+\cos\theta_s)k_0 + E_0 - P_0\cos\theta_s} \tag{1}$$

and

$$\cos\theta_s = \frac{k_s k_0 + E_0 k - (E_0 - P_0)k_0}{(P_0 - k_0)k_s}, \tag{2}$$

where k_0 is the energy of laser photon, P_0 and E_0 the momentum and energy of the electron beam, and θ_s the scattering angle of the photon ($\theta_s = 0$ for the direction of the electron beam).

Figure 4 indicates that requirement of beam energy for a 33.169 KeV X-ray is above 43.5 MeV for a Nd:YAG laser with a wavelength of 1064 nm.

2.3 *X-band linac*

The X-band linac is applied to the compact hard X-ray source. The RF-wavelength of the X-band (11.424 GHz) is 1/4 of the S-band (2.856 GHz). However, the maximum filed gradient of ~40 MV/m realizes remarkable compactness.

We designed a thermionic-cathode X-band RF gun and a photo-cathode X-band RF gun. We carried out a fundamental design for the photo-cathode RF gun using the PARMALA code. Numerical analysis of the beam transport for the whole system including the photo-cathode X-band RF gun and X-band accelerating structure at the first stage has been presented.[6,7] The beam energy in this system reached 56.4 MeV.

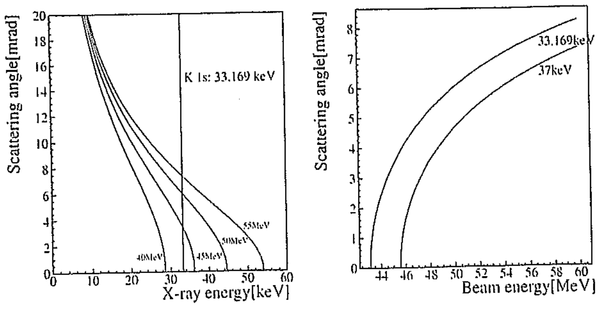

Fig. 4. Relation of beam energy and scattered photon for Nd:YAG laser (fundamental, 1064 nm) calculated using eq. (2). (a) Scattering angle of X-rays due to X-ray energy for each energy of the electron beam. (b) Scatteing angle due to beam energy for each X-ray energy.

Table II. Specifications for the X-band klystron modulator.

Output peak power	142 MW
Output voltage	500 kV
Output current	283 kA
Pulse length (FWHM)	3 µs
Flat top (±0.1%)	1 µs
Shot-by-shot fluctuation of pulse height	±0.1%
Repetition rate	50 pps
Average power	22 kW
Turn ratio of pulse transformer	1 : 32 (15.63 kV : 500 kV)
Size (PFN and control system)	1600 W × 2000 H × 1000 D
Size (with klystron)	3115 W × 2255 H × 1350 D

A 3.6-cell thermionic-cathode X-band RF gun is being manufactured by Ishikawajima Harima Heavy Industry (IHI). Two 0.7 m long X-band accelerating structures are used for the X-ray source. The technology of the X-band accelerating structure developed for future linear colliders[8] at KEK and Stanford Linear Accelerator Center (SLAC) is fully adapted to this development. At first, the RDS (detuned) type accelerating structure has been adopted, which is already being manufactured by IHI.

We adopted a periodic permanent magnet (PPM) X-band klystron (Toshiba E3768I) designed for linear colliders. klystron modulator (poulsed power supply) was designed to fit this X-ray source. Specifications for the modulator are shown in Table II. A turn ratio of 1:32 is adopted for high voltage output with low voltage PFN to realize the small size of the main body.

The RF power is above 50 MW in a 1 µs pulse width.

2.4 *X-ray yield and properties*

The X-ray yield per bunch is calculated using,

$$N_{\text{X-ray}} = \sigma_{\text{Comp}}\mathcal{L} \tag{3}$$

where σ_{Comp} is the total cross section of Compton scattering that is calculated from the Klein–Nishina's formula,[9,10] and $\mathcal{L}$ is the luminosity of the laser-electron collision per bunch. For head-on collisions in which the velocity of each beam is $\sim c$, (integrated) luminosity per collision (bunch) $\mathcal{L}$ is written as:

$$\begin{aligned}\mathcal{L} = 2N_e N_l \int_{-\infty}^{\infty} \frac{1}{2\pi}\frac{1}{\sqrt{\sigma_{\text{xe}}^2(s)+\sigma_{xl}^2(s)}}\frac{1}{\sqrt{\sigma_{\text{ye}}^2(s)+\sigma_{yl}^2(s)}} \\ \times \frac{1}{\sqrt{2\pi(\sigma_{\text{se}}^2+\sigma_{sl}^2)}}\exp\left\{-\frac{(2s)^2}{2(\sigma_{\text{se}}^2+\sigma_{sl}^2)}\right\}\text{d}s,\end{aligned} \tag{4}$$

where N_e and N_l are numbers of electrons and laser photons, and $\sigma_{(\text{x,y,s})(\text{e},l)}$ is the rms beam size of the laser (l) and electron (e) beam for x, y (transverse) and s (longitudinal) axes. Beam profiles of both beams are assumed to be Gaussian. Luminosity is calculated by integrating eq. (4) numerically for the region (±0.5 m) between each focusing-

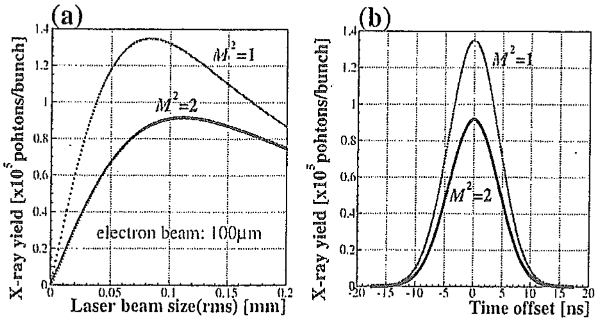

Fig. 5. (a) X-ray yield due to laser beam size for a single bunch and (b) X-ray yield of each bunch due to the time offset between the laser pulse and the electron beam bunch.

magnet of the electron beam upstream and down stream of the collision point that is large enough to be calculated with the Raylegh-length of laser light (0.11 m) and beta of the electron beam (0.1 m) at the CP.

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, 10π mm·mrad) and the 2 J/pulse Q-switch Nd:YAG laser.

We adopt head-on collisions to achieve the maximum X-ray yield. Figure 5(a) indicates that optimal laser beam size is 82 μm (rms) for an electron beam size of 100 μm (rms) at the CP. Where M^2 (≥ 1) is difference of laser profile (quality) from ideal Gaussian. Each bunch collides with laser light at some time offset. The X-ray yield of each bunch is shown in Fig. 5(b). Thus, this system generates X-rays with 1.7×10^7 photons/pulse at $M^2 = 1$ (1.7×10^8 photons/s) that are the sum of all bunches. In $M^2 = 2$, the total X-ray yield is 0.9×10^7 (0.9×10^8 photons/s).

The total X-ray energy spectrum and the realtion of X-ray energy to scattering angle (for $M^2 = 1$) are shown in Fig. 6. The solid line indicates the X-ray energy 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.[11] The maximum X-ray energy is 56 keV at a beam energy 56 MeV.

The energy of scatterd X-rays shown in Fig. 6(a) seems not narrow, but we can see the relation of the energy to the scattering angle in Fig. 6(b). That means the X-rays with higher energy can be chosen using a collimator. Figure 7 shows the relation of the scattering angle of transmitted photons at the collimator and the transmittance of photons, the number of photons transmitted (right axis), rms energy spread, and mean energy of transmitted photons (left axis) calculated by Klein–Nishina's eq. ($M^2 = 1$). It is assumed that the size of the light source is negligibly small. Figure 7 idicates that an energy spread of 10% of the rms is available at 36% transmittance for a 6 mrad scatterd angle of photon. Actually, 28% of total scatterd photon is available for application, because of the transmittance of of a 33 keV X-ray is approximately 80% at thin (1 mm) mirror to insident the laser light to the CP (Yoy can see the location of the mirror in Fig. 13). The attenuation of the X-rays at the thin (tens of μm) beryllium window that separates vacuum from air is negligibly small.

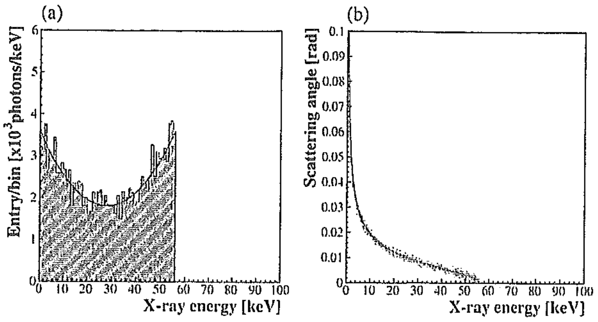

Fig. 6. (a) Total X-ray spectrum and (b) relation of X-ray energy and scattering angle of photon in single bunch (20 pC/bunch) collision with Q-switch Nd:YAG-laser (fundamental, 1064 nm).

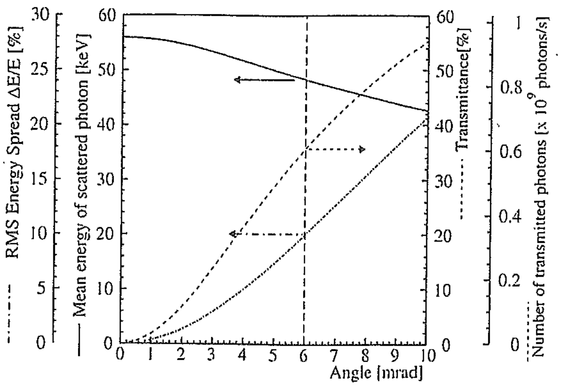

Fig. 7. Relation of collimated angle and the transmittance of photons, the number of photons transmitted (right axis), rms energy spread, and mean energy of the transmitted photons (left axis).

2.5 *Optimization of beam parameter at collison point*

The beam parameters at the CP is must be known to designs the beam line. The X-ray yield in a laser-electron collision depends on emittance, M^2, and Twiss (Courant–Snyder) parameters of the laser and the electron beam at the CP.

Figure 8 shows the maximum X-ray yield for each electron beam size at the CP. The laser spot is optimized to maximize the X-ray yield. A beam emittance of 10 mm·mrad for x and y axes is assumed to simplify the discussion. It is not effective to making the beam size less than 100 μm rms for an X-ray yield with a long pulse laser of 10 ns (FWHM).

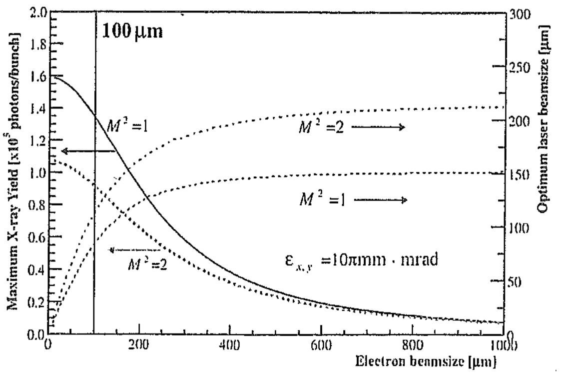

Fig. 8. Maximum X-ray yield and optimum laser size at the CP due to electron beam size at the CP for an electron emittance $\varepsilon_x = \varepsilon_y = 10\pi$ mm·mrad, and an electron charge of 20 pC/bunch.

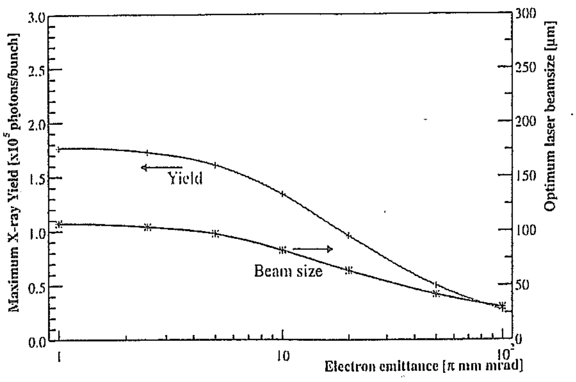

Fig. 9. Maximum X-ray yield and optimum laser size at the CP due to electron beam emittance.

The maximum X-ray yield due to electron beam emittance with a beam size of 100 μm at the CP is indicated in Fig. 9. A very small beam emittance is not effective for X-ray yield because an emittance of 8.5×10^{-8} m·rad from a laser (with a wavelength of 1064 nm and $M^2 = 1$) is larger than an optical beam emittance of 1×10^{-8} m·rad (1π mm·mrad with 50 MeV).

2.6 *Design of beam transport line*

To prove that X-band beam acceleration and the generation of intense hard X-rays using an X-band system occurs, a beam transport line is designed using the SAD[12] program.

The first results of the numerical analysis for a thermionic-cathode X-band RF gun and the alpha-magnet are used to the design of the beamline as initial beam parameters.

Requirements for the beam line are: (1) a short beam line (<6 m between the alpha-magnet and CP), (2) the beam must bend 90 degrees to reduce the background signal for the X-rays, (3) a small dispersion and chromaticity at the CP to reduce fluctuations in X-ray intensity due to beam energy, (4) a small beam size of about 100 μm at the CP, and (5) a long drift space for the laser and the electron beam monitor around the CP.

The beam line designed using the SAD program is shown in Fig. 10. Beam tracking simulations with space charge effects using SAD also indicate that a 100 μm beam size at the CP is expected.

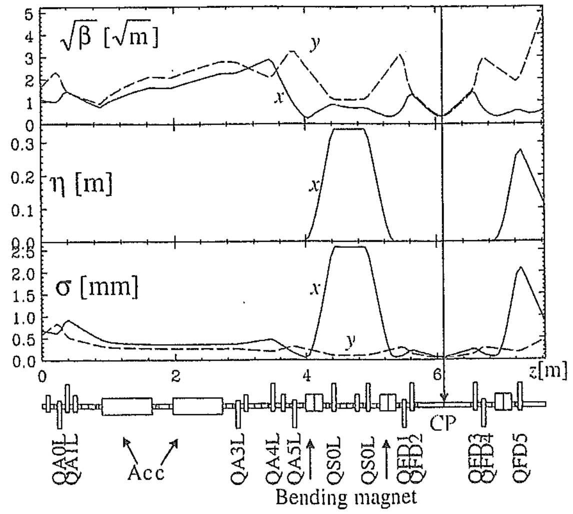

Fig. 10. Beam optics for compact hard X-ray source designed using SAD[10] program.

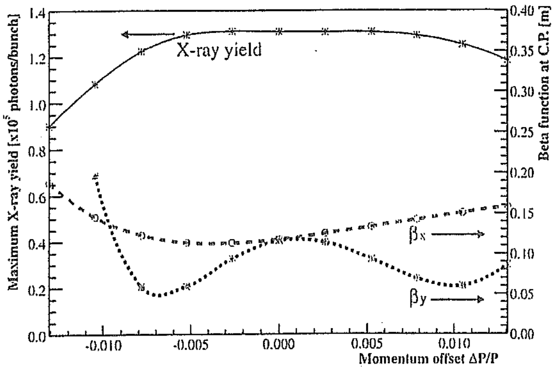

Fig. 11. The beta function (β_x, β_y) at the CP and X-ray yield due to momentum offset of the electron beam.

The effects of alignment/K-value error of the Q-magnets and bending magnets are estimated. Errors in the K-value, the transverse offset and tilt angle must be less than 0.1%, ±50 μm and 1 mrad (rms) to achive a small dispersion of less than 10 mm at the CP.

2.7 *Shot-by-shot fluctuation of X-ray yield*

Fluctuation of X-ray yield (luminosity) is caused by fluctuation in the parameters of the laser and electron beams at the C. P. Those of the electron depend mainly on the beam energy and the beam optics.

The beta function (β_x, β_y) at the CP and the X-ray yield due to the momentum offset of the electron beam are shown in Fig. 11. In the proposed system, the momentum of the electron beam depends on (1) the RF power input RF gun and accelerating structure (s), and (2) the difference between the RF phase and the length of the beam orbit between the RF gun and the accelerating structure. The momentum is independent of the RF phase shift in the klystron due to the klystron input voltage because RF gun and accelerating structure are driven by the same klystron. From the specifications of the klystron modulator shown in Table II, fluctuation in the beam momentum can be expected to ±0.125%.[13] With the X-ray yield due to beam momentum shown in Fig. 11, fluctuation in X-ray flux due to fluctuation of beam energy and chromaticity at the CP is less than 1%.

Fluctuation of the position and crossing angle of the laser and electron beams also depends on the beam energy and the dispersion functions η, η' at C. P. We expect that the small dispersion less than 10 mm are achieved by the dispersion correction technique. In this case, the position stability is about ±12.5 μm. Then the X-ray fluctuation due to momentum dispersion of electron beam optics may be ignored.

Typical fluctuations in laser energy of a Q-switch laser are ±2%. The fluctuation in X-ray yield about 50% r.m.s due to the micro structure in the temporal profile of the Q-switch Nd:YAG laser[14,15] is suppressed to less than 3.5% by a long collision region and multi (about 200)-bunch collisions.

Finally, the expected fluctuation in X-ray yield is less than 10%.

3. Applications

Among the anticipated uses of monochromatic hard X-

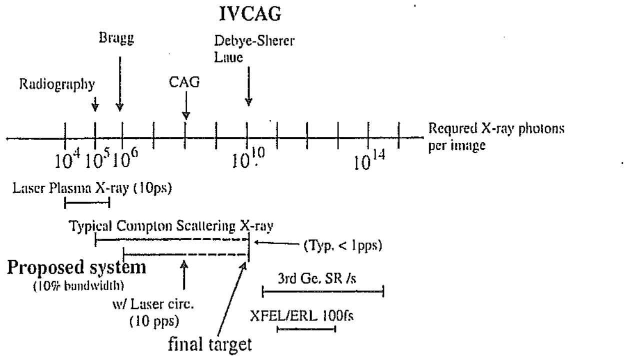

Fig. 12. Summary of required X-ray photons for various applications and X-ray yield of various X-ray sources.

rays of 10–50 keV include marked improvements not only in dynamic IVCAG but also monochromatic CT, monochromatic X-ray imaging, K-edge imaging, and protein crystallography. Required X-ray photons per image for X-ray imaging, crystallography, CAG and X-ray yield of various X-ray sources are summarized in Fig. 12.

Discussion and demonstration of advantages of narrow bandwidth X-ray beams have beem presented by Carroll.[16)] A compact hard X-ray source with X-ray yield of 10^8 photons/s (10^7 photons/pulse) can be applied to X-ray imaging.

Advantages of the proposed system are intense (10^7 photons/pulse), narrow bandwidth (1 to 10 percent), and short pulse (1 μs) X-ray generation with high (10 pps) repetition rate. This means that the system can be applied to dynamic imaging. Ont the other hand, repetition rate of most high intensity X-ray sources based on Compton scattering is low (<1 pps) that is limited by the high power laser system. A dynamic CAG experiment on animals with localization of contrast agent by catheter will be performed using the proposed hard X-ray source.

4. Upgrade of the X-ray Yield

A 33 keV monochromatic X-ray with 10^{11} photons/s (10^9–10^{10} photons/shot) is required for IVCAG. 10^4 photons/pixel/image are needed to observe meaningful differences in artery with 5% contrast agent and other tissue. The required photons for a 10 cm × 10 cm image with 1 mm resolution are 10^8.'The transmittance of X-rays in the human body of from 1 to 10% must be taken into account. Finally, 10^9 to 10^{10} photons/image of X-rays must be applied to a patient. To enhance the luminosity of laser-beam collisions, we adopt the technique of circulation of laser light shown in Fig. 13. The pulse length of a Q-switch Nd:YAG laser is shorter than the RF pulse length. This means that most electron bunches cannot collide with laser light. The laser pulse circulating system is effective to increase X-ray yield in the proposed system. The collided laser light is bent by a mirror and its polarization plane is changed by a Pockels cell. Passage of the laser light from the Q-switch laser system and circulated laser light are merged by a polarized beam splitter. Laser light can then collide with electron the beam again (see Fig. 14).

The total laser energy in the circulation I_N ($N = 1, 2, \ldots$: the times circulated) is

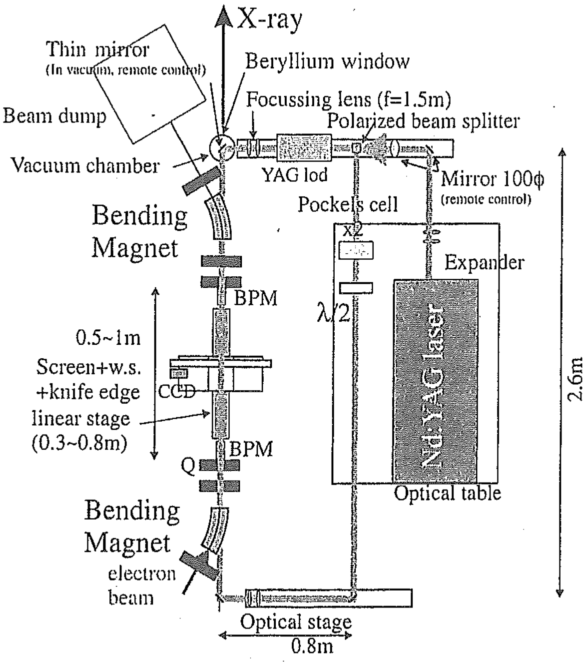

Fig. 13. Illustration of the laser pulse circulating system.

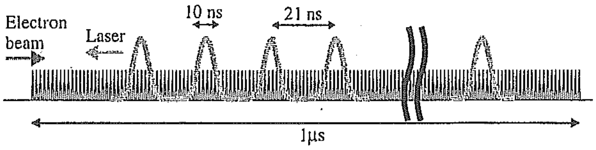

Fig. 14. Bunch structure of laser electron beams with laser circulating system.

$$I_N = \sum_{n=1}^{N} I_0 A^n = I_0 \frac{A - A^n}{1 - A} \qquad (5)$$

where I_0 is the initial pulse energy of the laser pulse; A, the transmittance of the laser pulse per revolution on the circulation line; and n, the number of revolution. The laser pulse collides 20 times if the revolution time of the laser pulse is 50 ns. We expect the enhancement of X-ray yield by a factor of 10 times with 90% transmittance of the laser pulse per revolution in the laser circulation.

For the next step in the laser pulse circulating, we adopt YAG rod as a gain medium in the circulation line to compensate for the laser pulse energy loss in the line with a 5 J laser pulse, and the revolution time is reduce to 20 ns. The X-ray yield will reach 10^9 photons/pulse (total).

A high power (above 5 J/pulse) ring laser system is best to increase the X-ray yield in the proposed system. The ring laser system will be adopted to the X-ray source in the final step.

To achieve the 10^{11} photons/s required for dynamic IVCAG, the repetition rate must by increased to 50 pps. The intensity of the electron beam will be increased by understanding and controlling the beam loading, Wakefields in the RF gun and the accelerating structure.

5. Conclusion

We are developing a compact X-ray source using laser-electron collision based on an X-band linac for dynamic IVCAG. To realize a remarkably compact system, we adopted the X-band system and commercial Q-switch laser. We expect the X-ray yield to be 10^7 photons/pulse (10^8 photons/s). A beam line for proof-of-principle experiment is designed and intensity fluctuation of X-ray is expected to be under 10%. 10^8 photons/pulse (10^9 photons/s) will be realized by a laser circulation system without power loss compensation. The laser gain medium will be applied the laser circulation to up to 10^9 photons/pulse (10^{10} photons/s). Twenty eight percent of photons with an energy spread of 10% rms will be available by collimating the scattering angle of X-ray photons.

The final target shown in Fig. 2 will be realized and widely applied to the monochromatic X-ray imaging for medicine.

Acknowledgements

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X-band RF gun and linac for medical Compton scattering X-ray source

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Abstract. Compton scattering hard X-ray source for 10-80 keV are under construction using the X-band (11.424 GHz) electron linear accelerator and YAG laser at Nuclear Engineering Research laboratory, University of Tokyo. This work is a part of the national project on the development of advanced compact medical accelerators in Japan. National Institute for Radiological Science is the host institute and U.Tokyo and KEK are working for the X-ray source. Main advantage is to produce tunable monochromatic hard (10-80 keV) X-rays with the intensities of 10^8-10^{10} photons/s (at several stages) and the table-top size. Second important aspect is to reduce noise radiation at a beam dump by adopting the deceleration of electrons after the Compton scattering. This realizes one beamline of a 3rd generation SR source at small facilities without heavy shielding. The final goal is that the linac and laser are installed on the moving gantry. We have designed the X-band (11.424 GHz) traveling-wave-type linac for the purpose. Numerical consideration by CAIN code and luminosity calculation are performed to estimate the X-ray yield. X-band thermionic-cathode RF-gun and RDS(Round Detuned Structure)-type X-band accelerating structure are applied to generate 50 MeV electron beam with 20 pC microbunches (10^4) for 1 microsecond RF macro-pulse. The X-ray yield by the electron beam and Q-switch Nd:YAG laser of 2 J/10 ns is 10^7 photons/RF-pulse (10^8 photons/sec at 10 pps). We design to adopt a technique of laser circulation to increase the X-ray yield up to 10^9 photons/pulse (10^10 photons/s). 50 MW X-band klystron and compact modulator have been constructed and now under tuning. The construction of the whole system has started. X-ray generation and medical application will be performed in the early next year.

INTRODUCTION

Medical use of monochromatic hard X-rays of 10 – 50 keV are promising for Dynamic IVCAG(Intravenous Coronary Arteriography) , monochromatic CT, monochromatic X-ray imaging, K-edge imaging, protein crystallography, etc. The first demonstration of quasi-monochromatic hard X-rays by a Compton Scatteing was performed by Carroll[1].

On the other hand, dynamic IVCAG by monochromatic hard X-rays of synchrotron radiation (SR) via a monochromator was proposed and tested in several institutes[2].

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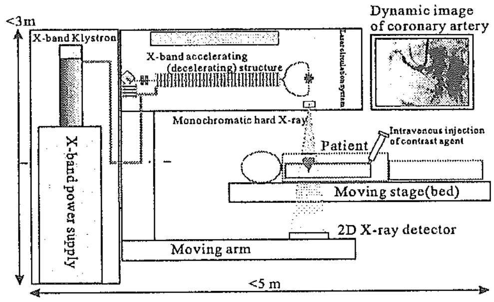

FIGURE 1. Final Target

On the other hand, the clinical test has been performed by KEK and Tsukuba Univ. at KEK-AR[3]. They got a 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.

In order to realize the medical uses of the monochromatic hard X-ray at hospital, we are going to develop a compact monochromatic hard X-ray (10 $\sim$ 50 keV) source based on laser-electron collision using by the X-band (11.424 GHz) linac system. Final target of this study is the integrated system shown in Fig. 1. This system is equipped with X-band RF-source and moving armincluding X-band linac, Q-switch laser system and X-ray detector. Demonstration experiment of the compact monochromatic hard X-ray source is going to be performed at UTNL site.

In this paper, we represent the status of the X-ray source system for the demonstration of hard X-ray generation.

COMPACT HARD TUNABLE X-RAY SOURCE

Compact hard X-ray source we have proposed[4, 5] is based on laser-electron collision by the X-band linac with a thermionic-cathode RF-gun and a commercial Nd:YAG laser. The RF-gun is collimated and compressed temporally by a alpha-magnet and accelerated by an X-band accelerating structure. The electron beam is bent by achromatic bends and focused at the collision point(C. P.). About 10 ns hard X-ray is generated via Compton scattering. After the collision, the electron beam is bent and decelerated by the X-band decelerating structure. The decelerated electron beam with the energy lower than 1 MeV is injected to a beam dump.

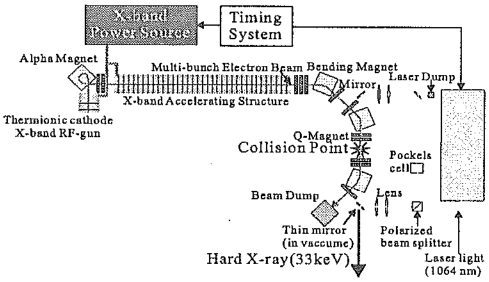

FIGURE 2. Final Target

X-BAND BEAMLINE FOR PROOF-OF-PRINCIPLE EXPERIMENT

The X-band beam-line for proof-of-principle experiment is under construction at the UTNL site shown in Fig.2.

To realize such a compact system, we adopt the Q-switch Nd:YAG laser (Spectra Physics Quanta-ray PRO-350-10) with the intensity(pulse energy) 2.5 J/pulse, the repetition rate 10 pps, the pulse length 10 ns(FWHM), and the wavelength 1064 nm. Commercial Q-switch laser system we have chosen is rather reliable pulse. Multi-bunch electron beam collides with the long laser pulse. One laser pulse can collide with about 200 micro-bunches. In this case, the required timing stability is nanoseconds order. Thus, the combination of the thermionic-cathode RF-gun and Q-switch laser can generate high flux X-ray with intensity of 10^8 photons/s most stably .

The maximum field gradient of $\sim$ 40 MV/m of the X-band linac realizes remarkable compactness. The technologies of the X-band accelerating structure developed for future linear colliders[6] at KEK and Stanford Linear Accelerator Center(SLAC) are fully adopted for this development.

X-band RF system

Block diagram of the whole X-band RF system is shown in FIG.3 50 MW X-band RF pulse with 1 μs is generated by the X-band klystron. Output RF feeded by two RF output ports of the klystron are combined by a 3-dB hybrid and transported to the beamline. The RF is derived to the thermionic-cathode -type RF-gun and X-band accelerating structure by a 7-dB hybrid.

Thermionic-cathode X-band RF-gun and X-band accelerating structure

We have designed and constructed the thermionic-cathode X-band RF-gun. Numerical analysis of the beam transport for the whole system including the photo-cathode