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DESIGN OF WAVELENGTH TUNABLE COHERENT X-RAY SOURCE*

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Abstract

KEK, Nihon University, and TOYAMA CO., Ltd. have been developing a thin-radiation shielded coherent X-ray source that can cover the X-ray energy range from 3 to 25 keV. The X-ray is the parametric X-ray radiation generated by the high energy electron beam passing through a single crystal. It has a feature that offers quasi-monochromaticity, directivity, and a large divergence angle for the incident beam. These suggest the possibility of application to medical treatments and diagnosis.

Furthermore, reduction of the radiation that is mainly generated at the beam dump will be achieved by the beam energy recovery system. This system consists of the accelerating structure, the decelerating structure, and the beam recovery transport system including four bending magnets. The RF structures are operated under low temperature of 20 K to get a high Q value in the rf recirculation system and a high energy conversion efficiency from the accelerated electron beam to the rf in the decelerating structure. Parametric X-ray radiation is generated from a single crystal that was bombarded with the electron beam accelerated up to 75 MeV. The electrons passing through the crystal is transported into a decelerating structure and then is decelerated to 3 MeV there. Quadrupole magnets are arranged to transport the achromatic beam except for in the arc sections. Simulations have been done on the beam transport, the parametric X-ray radiation intensity and the emittance growth.

INTRODUCTION

Nihon University, KEK, and TOYAMA Co., Ltd. have been developing a coherent X-ray source. This coherent X-ray means parametric X-ray radiation (PXR). This features quasi-monochromaticity, directivity and energy tunability by rotating the target crystal. A coherent X-ray is expected to be useful in a wide range of fields, for example crystal structure analysis, treatment of cancer and X-ray imaging. Nihon University group has been successful in providing PXR to users and has reported X-ray images using PXR in many papers [1, 2].

Most of the light source facilities provide synchrotron radiation to user's experiments as the X-ray sources. Due to the nature of this radiation with continuous spectrum, a monochromator is installed in the beam line to use the X-rays with a specific energy. On the other hand, the PXR X-rays are quasi-monochromatic, the energies of which are tunable with the rotation angle of the target crystal.

In the accelerator design, the decelerating structure has been employed for reducing unwanted radiation at the beam dump. The accelerating and decelerating structures are operated under the low temperature of 20 K in order to get a high efficiency of the energy conversion. Additionally, to get the coherent X-ray, the PXR generation system is used. Calculation and simulation have been carried out on the beam optics, the PXR intensity and the emittance growth. Figure 1 shows the layout of the coherent X-ray source based on the linear accelerator.

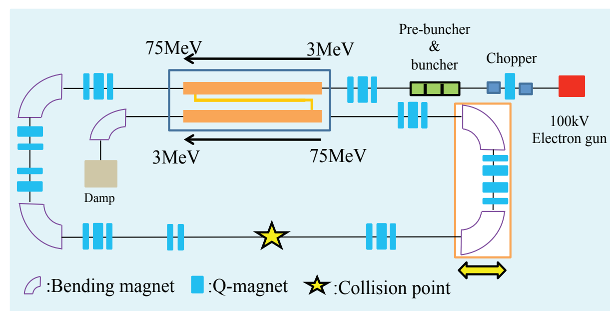

Figure 1: Layout of the coherent X-ray source based on linear accelerator.

PARAMETRIC X-RAY RADIATION

PXR is generated when relativistic charged particles pass through a crystal. This radiation can be interpreted that the virtual photon fields around the electrons are diffracted by the crystal planes. The features of PXR are beam coherence, large divergence angle with respect to the electron beam and PXR energy not affected by electron beam energy. Since the emitted X-rays satisfy the Bragg diffraction condition, the X-ray energy can be controlled by adjusting the angle between the incident beam and the specific crystal plane.

In this accelerator, the electron beam is accelerated to 75 MeV with a pulse duration of 2.5 μs and a repetition rate of 50 Hz. The average beam current is approximately 30 μA. Si or Diamond crystal will be used as the target because these crystals are heat-resistant. Furthermore, Si single crystals are readily available. The thickness of the target must be less than 0.2 mm to avoid too much emittance growth. Under this condition, the number of the PXR photons is expected to be about 10^{-9} photons/e^- [3].

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INJECTOR

The injector mainly consists of triode electron gun (100 keV), chopper, pre-buncher and buncher. The normalized beam emittance is 10 - 20 π·mm-mrad. Since the electron beam is extracted from the gun cathode continuously, a double rf chopper system is employed to control the phase spread of the beam accepted in the pre-buncher downstream. [4]

This system consists of two deflecting rf cavities, a slit and a quadruple magnet. The resonant frequency of the cavities is 5712 MHz. The first cavity kicks the electron beam to transverse direction. The electrons being deflected to one direction with nearly the maximum transverse momentum pass through the slit in the quadrupole magnet, and are reflected to the opposite direction with the focusing quadrupole field; the other electrons are dumped here. The second cavity cancels the transverse momentum gained at the quadrupole magnet.

The longitudinal displacement in the bunch Δz at the bending magnet is written as

$$\Delta z = R_{56}\frac{\Delta P}{P} \quad (1)$$

$$R_{56} = \rho\theta - \rho\sin\theta,$$

where $\theta(=\pi/2)$ is the bend angle, $\rho(=400\mathrm{mm})$ the bend radius and $\Delta P/P$ the energy displacement in the bending magnets. In the case of $\Delta P/P=\pm0.3\%$, the maximum longitudinal bunch displacement is

$$\Delta z = 4\cdot\left(400\cdot\frac{\pi}{2} - 400\cdot\sin\frac{\pi}{2}\right)\times 0.003 = 2.8\ \mathrm{mm}.$$

If the bunch length is ±3° at the exit of the buncher, the total phase spread is about 26°. In this case the electron beam energy can be decelerated to lower than 10 MeV.

The bunch after passing through the chopper system is velocity-modulated in the pre-buncher. The electrons are bunched to ±3° and accelerated up to 3 MeV in the buncher section. Figure 2 shows the designed injector.

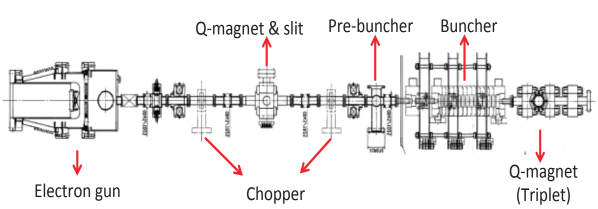

Figure 2: Layout of the injector.

ACCELERATOR AND DECELERATOR STRUCTURES

In the accelerating structure, the electron bunch is accelerated from 3 MeV up to 75 MeV, and then transported to the target crystal where the PXR X-rays are emitted. The bunch after passing through the crystal is transported to the decelerating structure. The electrons are decelerated down to 3 MeV in the structure to reduce the radiation emitted at the beam dump. The length of each structure is approximately 1.3 m. The accelerating frequency is 5712 MHz that is the same as the injector. The two structures are located in parallel in the cryostat and cooled to 20 K in order to get a higher rf efficiency in both the acceleration and the energy recovery than at the normal room temperature operation. These are exactly the same structures made of high-purity copper (6N8). The Q-value is around 5,000. Figure 3 shows the layout of the accelerating and decelerating structures in the cryostat. The rf output from the accelerating structure is connected to the input to the decelerating structure with a waveguide inside the cryostat. The source rf power from the klystron is input to a directional coupler whose another input port is connected to the output from the decelerating structure, while the output port is connected to the input to the accelerating structure; as a whole, the rf system forms a so-called resonant ring. In this system, the accelerating gradient of approximately 55 MeV/m will be achieved.

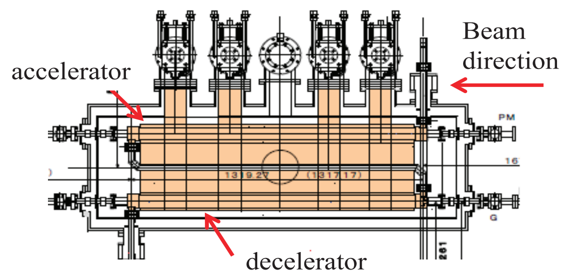

Figure 3: Accelerating and decelerating structure in the cryostat.

OPTICS DESIGN

Beam Optics for No Collision with the Crystal

Figure 4 shows the beam optics from the output of the buncher to the output of the decelerating structure. Figure 4(a) shows the beta functions in the horizontal and the vertical directions, (b) the dispersion function, and (c) the beam sizes in the horizontal and the vertical directions. This optics has been simulated by using "SAD", a computer program complex for accelerator design [5]. The normalized beam emittance assumed in the simulation is 20 mm-mrad.

At the exit of the accelerating structure, the bunch energy is about 75 MeV. The decelerating structure is located between the accelerating structure and the beam return path. Thus the length of the second arc section is shorter than that in the first arc section (see Fig. 1).

The high energy beam transport line from the exit of the accelerating structure to the crystal consists of two bending magnets and twelve quadrupole magnets. The beam size is about 1σ = 0.1 - 0.15 mm at the target. The target crystal may be broken if the beam size is too small. From the second bending magnet to the target, the dispersion function is adjusted to zero so that the beam position does not change by the change in the beam energy. The dispersion function is not zero between the first and second bending magnets.

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The bunch length is simulated by tracking particles. Figure 5 shows the bunch length at the exit of the buncher, the collision point and the entrance of the decelerating structure. Blue, red, green lines indicate the results at the exit of the buncher, the collision point, and the entrance of the decelerating structure, respectively. The beam energy can be decelerated down to lower than 10 MeV, because the bunch length is about 7 mm when the beam enters the decelerating structure.

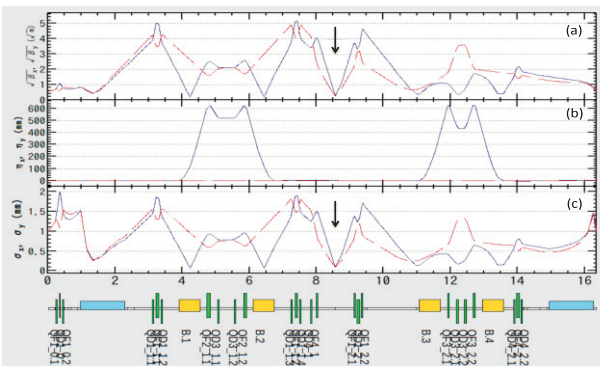

Figure 4: Optical functions of transport from buncher exit to decelerating structure exit. (a) Beta function, (b) Dispersion function, (c) Beam size. Blue and red lines indicate x-direction, y-direction. Aqua part is the accelerating and decelerating structures, green parts are Q-magnet and yellow parts are bending magnet. Arrows show the collision point.

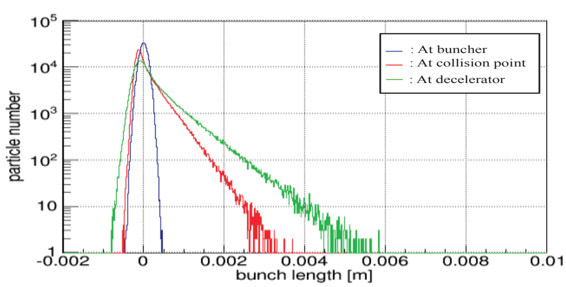

Figure 5: Bunch length at buncher exit, collision point, and decelerating structure.

Beam Optics for Collision with the Crystal

When the electron bunch passes through the crystal, the beam emittance grows due to multiple scattering, and the electrons lose their energy due to ionization loss and bremsstrahlung. The scattering angle and the energy loss were estimated by using the "Geant4", a toolkit for the simulation of the passage of particles through matters [6]. Figure 6 shows the scattering angle and the energy loss after the beam passed through the crystal. In the simulation Si and Diamond were used as the target.

As the result, if the crystal thickness is about 0.1 mm, the energy loss is less than about 100 keV and the scattering angle is less than about 4 mrad. The beam can pass through the transport line without serious energy loss. Moreover, the beam energy can be decelerated to lower than 10 MeV.

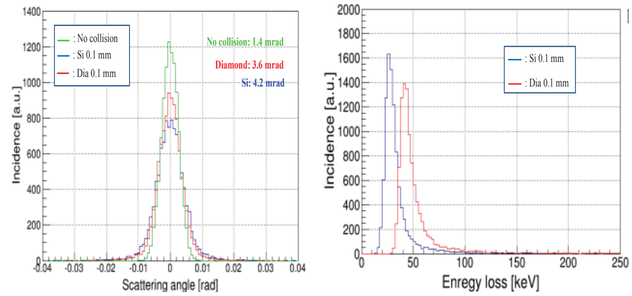

Figure 6: Scattering angle and energy loss. Left is scattering angle for Diamond and Si crystal, right is energy loss of the bunch.

Correction of the Orbital Length

To decrease the beam energy sufficiently in the decelerating structure, the electron bunch has to be in the decelerating phase of the rf wave. In the worst case, the energy will be increased to about 150 MeV (75 MeV×2). In this case, an intense radiation is generated at the beam dump. Therefore, the most important thing is that the bunch is adjusted to the correct phase. We adopt the method that moves the whole second arc section which has two bending magnets and four Q-magnets (see figure 1). This method is easy and cheap than other methods. The movable stage can slide more than one wavelength (55 mm) so that the bunch can surely be adjusted to the optimum phase of the rf wave.

CONCLUSION

We are developing the thin-radiation shielded Coherent X-ray source based on the linear accelerator. For design of the X-ray source, the optics and the emittance growth have been calculated. Moreover, the bunch length was simulated by particle tracking under the condition of no collision with the crystal. If the crystal thickness is less than 0.1 mm, the beam energy can be decelerated to less than 10 MeV without serious energy loss in the beam line.

Further simulation studies are undergoing to estimate the bunch lengthening under the condition of the collision with the crystal.

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