A PLAN OF A COMPACT HIGH-BRIGHTNESS X-RAY SOURCE AT QTF

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Abstract

We are developing a high-finesse optical cavity which stores 100-kW laser light for a compact high-brightness x-ray source. 10-MeV electrons can convert green laser light to x-rays with energy over 1 keV by the Compton scattering efficiently. We will demonstrate the x-ray production by the Compton scattering using a high duty linac. In this paper, we report our plan.

1 INTRODUCTION

High-brightness x-ray sources have many applications in various fields: material science, life science, medical care and so on. For example, x-rays in an energy range from 0.28 to 0.54 keV which is called a water window can be used to take a fine image of live cells, because proteins made of carbon and nitrogen absorb more x-rays in this range than water. Using the absorption of 33-keV x-rays by Iodine injected into the blood in advance, we can investigate the blood flow of a living human heart.

Synchrotron radiation emitted from a bending magnet, a wiggler, or an undulator in a GeV electron storage ring is currently applied to these purposes. But the Compton scattering of laser light off energetic electrons also generates x-rays efficiently. This has been proposed as an x-ray source for a long time [1, 2]. Recent progress in laser and accelerator technologies allows us to make an x-ray source much more compact. For instance, electrons of only 100 MeV are enough to generate x-rays of 33 keV.

2 X-RAY SOURCE

We are planning to develop a high-finesse optical cavity to store intense laser light [3], and to demonstrate x-ray production using a high-duty L-band linac at the QTF (Quantum Technology Development Facility) of Japan Nuclear Cycle Development Institute (JNC). This accelerator consists of a 300-mA DC electron gun, an RF chopper, a prebuncher, a buncher and seven accelerating sections with a traveling-wave resonant ring, and a beam dump. Design parameters and achieved values in 1999 are summarized in Table 1 [4]. We will install an S-chicane between the seventh accelerating section and the beam dump. The optical cavity will be set in the center of the S-chicane. Specifications of the optical cavity are summarized in Table 2. The optical cavity is used to store CW laser light with a wavelength of 532 nm and to focus it up to a beam size of 10 μm. Electrons pass across the laser beam in the cavity at the crossing angle of 90°, and interact with it.

The differential cross section of the Compton scattering is explained by the Klein-Nishina formula. That of our case is shown in Figure 1. Its total cross section is 665 mb, which is almost equal to that of the Thomson scattering. The scattered x-ray has energy of 1.78 keV at the maximum. The scattering angle of x-ray depends on the x-ray energy as shown in Figure 2, where the scattering angle is referred to the direction of the incident electron. X-rays scattered within 10 mrad are almost monochromatic. When the laser light of 100 kW in the optical cavity and the electron beam of 200 kW have a beam size of 10 μm at the interaction point, total number of x-rays reaches 2.1×10^8 s^{-1}. In this section, we describe the thermionic electron gun, the optical cavity, the laser system, the S-chicane, and the x-ray detector.

Table 1: Design parameters and achieved values at QTF.

	Design	Achieved
Beam energy	10 MeV	7 MeV
Charge per bunch	80 pC	80 pC
Bunch spacing	800 ps	800 ps
Pulse width	4 ms	1.5 ms
Repetition rate	50 pps	35 pps
Average current	20 mA	5 mA
Average power	200 kW	35 kW
Duty factor	20 %	5 %
Energy spread	< 0.5 %	not measured

2.1 Electron Gun

The thermionic electron gun is set out of the radiation shield for easy access to the gun. Inevitably, there is a 3-m drift space between the gun and the chopper. Because of this drift space, the normalized emittance is estimated to

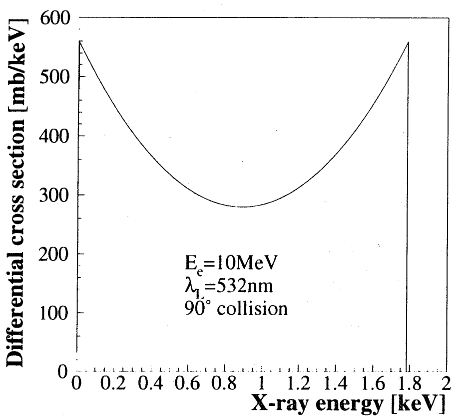

Figure 1: Differential cross section of the Compton scattering of 532-nm laser light off a 10-MeV electron.

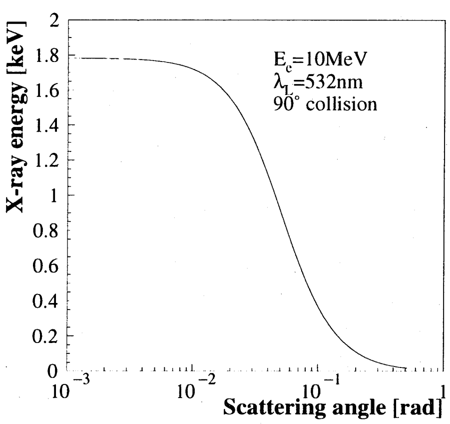

Figure 2: Energy vs. scattering angle of x-ray

grow up to 50π mm·mrad by simulation. Hence, we are planning to install a new gun in the radiation shield. The new thermionic electron gun with an RF grid modulation will be set in the place of the chopper. After this upgrade, the normalized emittance is expected to improve up to a few π mm·mrad.

2.2 *Optical Cavity*

We will use a concentric Fabry-Perot cavity with two high-reflectivity concave mirrors to store CW laser light and to focus it at the center of the cavity. When the cavity is on a resonance, the reflection of the cavity becomes minimal, and the transmission becomes maximal. At the same time, the storage of laser light in the cavity is also maximal. If two mirrors of the cavity have the same reflectivity R, the finesse of the cavity, F, is expressed as

$$F = \pi \frac{\sqrt{R}}{1-R}. \tag{1}$$

The power enhancement factor of the cavity on a resonance, S, is approximately given by

$$S \sim \frac{2}{\pi} F. \tag{2}$$

Mirror reflectivity of $R = 0.9999984$ at the laser wavelength of $\lambda_L = 852$ nm was achieved by Rempe *et al.* [5]. Moreover, the cavity of $F = 26000$ for $\lambda_L = 1064$ nm is actually used at the CEBAF [6]. We will start with mirrors of $R = 0.9999$ ($S \sim 10^4$) to achieve $S \sim 10^6$ in the future.

When the wave front of a Gaussian laser beam exactly matches to the curvature of the cavity mirrors, the laser beam has a waist in the cavity. If two mirrors with the same curvature ρ are fixed in the cavity at a distance D, the beam size at the waist, σ_0, in terms of the standard deviation is written as

$$\sigma_0^2 = \frac{1}{4} \frac{\lambda_L}{2\pi} \sqrt{D(2\rho - D)}. \tag{3}$$

Therefore, the laser beam size is adjustable by changing the cavity length. The cavity length in Table 2 is determined so that laser beam can have a waist of $\sigma_0 = 10$ μm. The beam waist of $\sigma_0 = 7.25 \pm 0.88$ [μm] was achieved with mirrors of $R = 0.99 (S = 220 \pm 20)$ at the KEK-ATF [7, 8].

The Gaussian laser beam grows up by a factor of $\sqrt{2}$ within the Rayleigh range. The Rayleigh range z_0 is given by

$$z_0 = \pi \frac{4\sigma_0^2}{\lambda_L}. \tag{4}$$

In our case, the Rayleigh range is 2.4 mm for a laser beam with $\sigma_0 = 10$ μm. This makes the horizontal tolerance loose in positioning of the optical cavity.

Table 2: Summary of the optical cavity

Wavelength	532 nm
Reflectivity	0.9999
Finesse	31414
Power enhancement factor	20000
Mirror curvature	20.000 mm
Cavity length	39.434 mm
Beam waist	10 μm
Rayleigh range	2.4 mm

2.3 *Laser System*

The laser system consists of a 10-W Nd:YAG laser, an optical isolator, steering mirrors, a telescope, photo-detectors, and a feedback system. The telescope matches the wave front of laser beam to the curvature of the cavity mirrors. The photo-detectors monitor the reflection and transmission of the cavity. The feedback system keeps the cavity on a resonance by changing the cavity length or the laser wavelength.

The finesse is defined by

$$F = \frac{c/(2D)}{\delta\nu}, \tag{5}$$

where $\delta\nu$ is the line width of the cavity. In our case, the line width is 120 kHz for $R = 0.9999$. To keep the cavity on a resonance, the cavity length must be fixed within 4 pm. At the same time, the laser is required to have such a line width for a better transmission. For our goal of $S \sim 10^6$, a laser must have a line width of $\sim$ 1 kHz. Such a narrow line width is achieved by a monolithic ring laser to which is applied the Pound-Drever-Hall locking technique [6, 9]. But its power is still low ($\sim$ 1 W).

2.4 S-Chicane

The colliding section includes several quadrupole magnets for final focusing and the S-chicane as shown in Figure 3. The S-chicane consists of four bending magnets. Two of them have a short field length, and are set at the beginning and at the end of the S-chicane. The others have a field length twice as long as short ones. These four magnets have magnetic field of the same magnitude but of alternate polarity, so that an electron beam snakes its way in the S-chicane.

The optical cavity is set at the center of the S-chicane, where laser light in the cavity collides with electrons at the crossing angle of 90°. The S-chicane reduces backgrounds from the upstream of the linac and from the beam dump. Moreover, the dispersion vanishes at the center of the S-chicane.

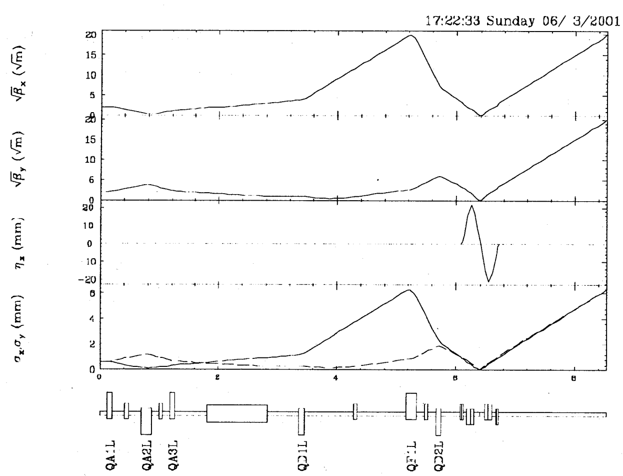

Figure 3: Beam optics in the colliding section.

2.5 X-ray detector

The total number of x-rays is 4.2×10^6 per pulse. In other words, the production rate is $1.1 \times 10^9\ \mathrm{s}^{-1}$ in every pulse. It is difficult to count x-rays at this rate. Hence, we measure the average number of x-rays by means of a silicon photodiode pulse by pulse.

The photodiode is put in a vacuum chamber to reduce the absorption of x-rays by materials in front of it. When the coverage of the photodiode is 20 mrad in half angle, the acceptance is 0.175. Consequently, 7.3×10^5 x-rays per pulse come into the photodiode, and create a charge of $\sim$ 10 pC in it, which depends on the quantum efficiency. Assuming the average quantum efficiency, we can obtain the number of x-rays from the charge.

3 DISCUSSIONS

For a high-brightness x-ray source by the Compton scattering of laser light, we are developing a high-finesse optical cavity which stores 100-kW green laser light and focuses it up to $\sigma_0 = 10\ \mu$m. The beam optics of the colliding section is designed so that 200-kW electron beams can have a beam size of 10 μm at the interaction point. The Compton scattering of the laser light off the electrons generates x-rays of 1.78 keV at the maximum. The production rate of x-rays is $2.1 \times 10^8\ \mathrm{s}^{-1}$. 17.5 % of them have a scattering angle within 20 mrad

However, there are several difficulties in the development of a high-finesse optical cavity. In manufacturing of high-reflectivity mirrors with $R > 0.99999$, we need high-quality superpolished substrates with surface roughness at the angstrom level and extremely low-loss thin-film dielectric coatings. In addition, the higher the cavity finesse is, the narrower the line width is. For example, the line width is $\sim$ 1 kHz for an optical cavity of $F \sim 10^6$. It is very difficult to develop a high-power laser with such a narrow line width. But pulse stacking in a cavity may be another way to store laser light. 35 pulses of infrared FEL has been stacked in a cavity with mirrors of $R = 0.999$ [10].

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