CHARACTERISTICS OF INVERSE COMPTON X-RAYS GENERATED INSIDE THE NIJI-IV FREE ELECTRON LASER OSCILLATORS*

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Abstract

Inverse Compton X-rays were obtained during lasing of the NIJI-IV free electron laser (FEL) in the infrared (IR) range. The position of the Compton collisions between electron bunches and laser pulses inside the FEL oscillator clearly influenced the energy spectrum of the Compton X-rays. Collisions outside the undulator magnetic field led to a sharp and clear Compton peak, while collisions inside the undulator magnetic field made it obscure. The maximum X-ray energies were 0.7 – 2.1 MeV for the FEL wavelengths of 2.6 – 0.88 μm with a fixed e-beam energy of 310 MeV. Relative energy spread was observed to be 11 % for 1.2- MeV Compton X-rays with a lead collimator of 10 mm in bore and 100 mm in thickness, when the collision point was outside the undulator magnetic field. X-ray yield was of the order of 10^6 photons/s when the NIJI-IV was operated in a three-bunch mode. Detailed characteristics of the inverse Compton X-rays are discussed in various Compton-collision conditions.

INTRODUCTION

An FEL with a very wide wavelength range from the vacuum ultraviolet (VUV) to the far infrared (FIR) has long been developed [1,2] based on the compact storage ring NIJI-IV [3] at AIST. For this purpose, optical klystrons designed for short- and long-wavelength lasing [4,5] were installed in two long straight sections of the NIJI-IV and optical cavities composed of low-loss dielectric multilayer mirrors were combined with them. After reaching the VUV range [6], we have been making experiments to realize lasing in the infrared (IR) and to obtain intra-cavity inverse Compton X-rays accompanying with IR-FEL oscillation using the long-wavelength FEL setup. Inverse Compton X-rays with high energies of the order of MeV – GeV (so-called Compton gamma-rays) are usually obtained by focusing high power external lasers on to the high-energy electron beams in the storage rings [7-12]. By utilizing intra-cavity FEL field instead of external lasers, such Compton X/gamma-rays can be effectively generated [13-15]. We previously observed [16] the Compton X-rays with relatively high energy (~3MeV) in the short-wavelength FEL setup. Here, we aim at obtaining lower-energy Compton X-rays of 0.3 – 2 MeV accompanying with IR-FELs, which can bridge the energy gap between the synchrotron light and high-energy Compton gamma-rays.

Lasing in the near IR was achieved around 1.45 μm on the NIJI-IV in February 2009 [17]. At present, the wavelength range of the IR-FEL was extended to 2.6 - 0.84 μm and the inverse Compton X-rays of 0.7 – 2.1 MeV were obtained [18] for the FEL of 2.6 - 0.88 μm with the e-beam energy of 310 MeV. Here, we investigate the characteristics of the Compton X-rays generated inside the NIJI-IV FEL oscillators.

EXPERIMENTAL APPARATUS

The long-wavelength FEL setup was mainly used in this experiment, with a few exceptions. The long-wavelength FEL is composed of an optical klystron for the IR (usually called ETLOK-III) [5] installed in the 4-m north straight section of the NIJI-IV and two highly-precise and stable vacuum mirror manipulators [19] put on both sides of the optical klystron with a distance of 14.8 m. Four sets of dielectric multilayer mirrors optimized around 0.85, 1.45, 1.5 and 2.6 μm were mounted in the mirror manipulators as an optical cavity. The FEL spectra were observed with three different spectrometers equipped with real time sensor arrays, silicon photodiode for around 0.85μm, InGaAs photodiode for around 1.5 μm and PbSe sensor for around 2.6 μm. Compton X-rays were monitored with $LaBr_3$(Ce) scintillator detection system with total energy and time resolutions of 3.1 % at 1.2 MeV and 1.3 ns which were essential to distinguish the difference between the energy spectra of X-rays scattered with different collision conditions.

EXPERIMENTS AND RESULTS

The NIJI-IV is usually operated in one-bunch mode to suppress coupled-bunch beam instability. However, to generate inverse Compton X-rays, we need at least two electron bunches in the storage ring as an FEL source and its counterpart for the Compton collision. It was found in advance that we can obtain lasing in two- or three-bunch mode as well as one-bunch mode even under the existence of the coupled-bunch instability, because the FEL gain is sufficient in the IR region. The position of Compton collisions, which will influence the X-ray energy spectra, can be determined by changing the bunch-filling pattern on the 16 RF buckets of the NIJI-IV. In the present experiment, two or three bunches selectively remained in suitable RF buckets.

Lasing of NIJI-IV FEL in the IR range

The optical klystron (ETLOK-III) has two 1.4-m undulators, including 7 magnetic periods individually, with a 0.72-m dispersive section in between. By closing the undulator gap to the minimum value, 36 mm, the deflection parameter *K* reaches ~10. The wavelength of fundamental spontaneous emission ranges from the visible to the far IR around 10 μm for the usually operating NIJI-IV energy of 310 - 340 MeV. Optical cavity was composed of several sets of dielectric multilayer mirrors mentioned above which were supplied by Japanese and German manufacturers. Though the specifications of the respective mirror coatings are different, the optical loss of the cavity was roughly 0.1 % for the wavelengths of 0.85, 1.45 and 1.5 μm, and 0.2 % for 2.6 μm. FEL gain in the IR region was estimated and found to be sufficient (typically 0.5 % at 1.45 μm even for a small beam current of 5 mA/bunch and more than 2 % is also expected for a higher current), compared with the cavity loss. As a result, lasing was obtained at wavelengths between 2.6 - 0.84 μm. Figure 1 shows the typical FEL spectrum around 1.45 μm. The linewidth is observed to be 1.2 nm (FWHM) which corresponds to 0.5 nm by taking the detector resolution into account. The average output power and intracavity power were 0.3 mW and approximately 2 W at a beam current of ~ 5 mA.

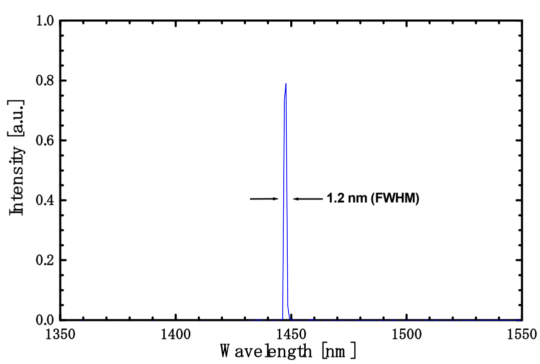

Figure 1: Typical FEL spectrum around 1.45 μm.

Generation of inverse Compton X-rays and their characteristics

Successful FEL oscillation at the near- to mid-IR regions enabled us to obtain inverse Compton X-rays from the laser cavity. Figure 2 shows the photograph of the setup for X-ray detection. Behind the vacuum mirror chamber holding the downstream mirror of the FEL cavity inside, X-rays passing through a 10-mm lead collimator aligned with the e-beam axis were observed with a $LaBr_3$(Ce) scintillation detector. It was expected that the position of the Compton collisions between electron bunches and laser pulses has some influence on the energy spectrum of the Compton X-rays, because of some difference of the collision angle and the solid angle seen through the collimator aperture. Figure 3 shows the schematic drawing of Compton collisions. Possible collision points spaced by 0.92 m are marked with solid and dotted crosses in the long-wavelength FEL setup (upper straight section).

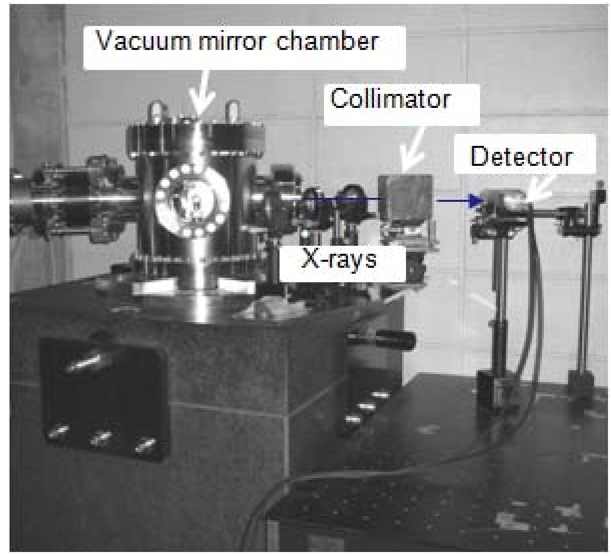

Figure 2: Setup of the X-ray detection system.

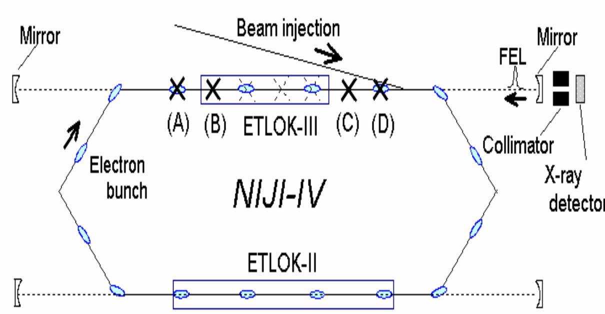

Figure 3: Schematic drawing of Compton collisions in the NIJI-IV FEL system.

The actual collision points are determined by the bunch-filling pattern on the 16 RF buckets of the NIJI-IV. In this report we mainly examine the Compton X-rays in two-bunch operation. Here, we define two bunch patterns, #1-#6 and #1- #7, according to the number of remaining bunches. For the pattern #1- #6, Compton collisions occur at points A and D, and for #1- #7, at B and C as indicated in Fig.3. Among these points, only B is inside the undulator magnetic field. The X-ray energy spectra from different collision points can be distinguished each other through the time response of the X-ray detection system.

Resultantly obtained energy spectra from A and B are shown in Fig.4 (a) and (b). In this experiment the e-beam energy and the FEL wavelength were 310 MeV and 1.53 μm, respectively, and 950 ch in the transverse axis corresponds to 1.2 MeV, Compton edge calculated for the above parameters. From these figures, it is found that a clear Compton peak can be obtained near 1.2 MeV with a relative energy spread of 11 % through the collision outside the undulator magnet (point A), while the relative energy spread of the Compton peak is made broader up to about 17 % in the collision inside the undulator magnet (point B). The X-ray signal from the point B (Fig.4 (b)) is also found to be noisy due to a smaller count rate approximately by an order of magnitude. This will be explained as follows. At the point B, electron bunches are deflected laterally by undulator magnetic field and laser-electron collisions with some oblique angle will increase, which means the e-beam emittance became larger effectively. As a result, the Compton X-rays will spread a little wider and the collimated X-ray detector receives fewer X-ray photons including off-axis lower-energy component. It should be noted that the lower-energy broad humps on the spectra are caused by the well-known escape X-ray component through Compton scattering inside the detector. In fact, such a lower-energy hump was much smaller on the spectrum of lower-energy Compton X-rays (0.7 MeV) accompanied by 2.6-μm FELs because of less amount of escape X-rays. These energy spectra are in good agreement with the results calculated using a Monte Carlo simulation combined with EGS5 code. The detailed results will be published elsewhere.

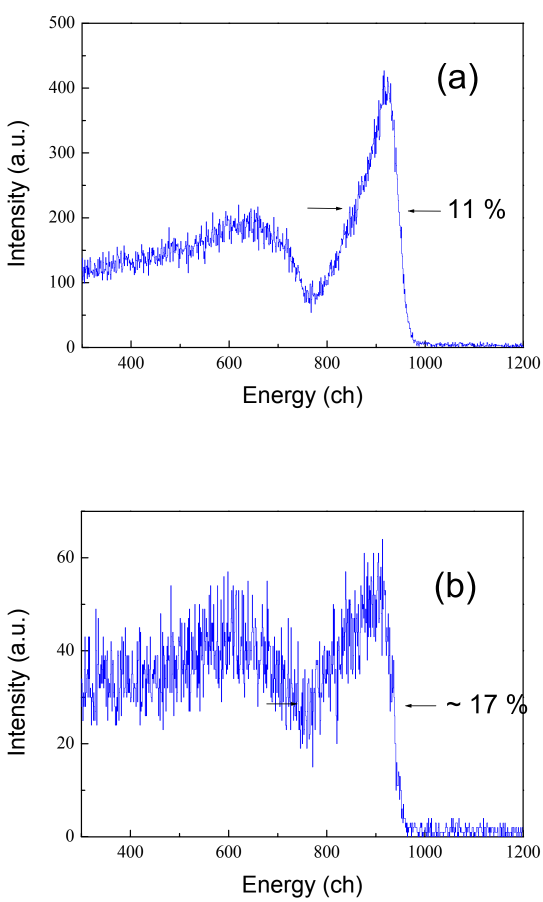

Figure 4: Energy spectra of the inverse Compton X-rays scattered from the points outside the undulator (A) and inside the undulator (B). 950 ch in the transverse axis corresponds to the photon energy of 1.2 MeV.

To consider the effect of collision condition on the Compton X-ray spectra, we performed an additional experiment using short-wavelength FEL setup (the lower straight section in Fig.3). In this experiment, NIJI-IV was operated in full-bunch (16-bunch) mode at 310 MeV and the parameters of the optical klystron (ETLOK-II) and the optical cavity were set to generate ultraviolet (UV) FEL around 300 nm. Though we cannot achieve FEL oscillation in this condition because of a large beam energy spread through the coupled-bunch instability, we can expect enough growth of the spontaneous-emission power in the low-loss FEL cavity to obtain significant amount of Compton photons without any bunch-pattern control and fine laser-cavity tuning. In this case, Compton collisions occur at random positions in the straight section, most part of which is inside the undulator magnetic field. Figure 5 indicates a typical X-ray spectrum in such random-collision mode. Here, 350 ch in the transverse axis corresponds to the photon energy of 6.1 MeV, Compton edge in this case. The X-ray detection system was almost the same as shown in Fig.2 except that the collimator aperture was a little larger (15 mm in diameter). In this figure, we cannot find any sharp Compton edge at the expected energy (6.1 MeV) and the spectrum has more gradual slope as a function of the X-ray energy. The reason for this is now investigated. One possible explanation is as follows. In this random-collision mode, collision condition is always changing according to moving collision point, while it is fixed in case of Fig.4 (b). This can cause a considerable increase of the effective beam emittance and solid angle seen through the collimator aperture. This will make the Compton edge quite obscure. Contribution of the escape X-rays must be taken into account also on this spectrum. Detailed study including computer simulation will be necessary to analyze such a spectral feature much more exactly.

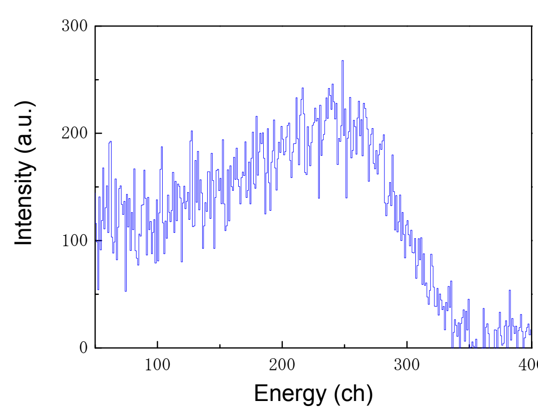

Figure 5: Typical X-ray spectrum in the random collision mode. 350 ch in the transverse axis corresponds to the photon energy of 6.1 MeV.

SUMMARY

Characteristics of the intra-cavity inverse Compton X-rays were investigated during lasing of the NIJI-IV FELs in the IR region. The energy spectra of the Compton X-rays were clearly influenced by undulator magnetic field. Compton collisions outside the undulator scattered the X-rays within a narrower solid angle and brought better monochlomaticity with a sharp Compton edge, while collisions inside the undurator spread the X-rays much wider and the monochromaticity became worse due to an effective growth of the beam emittance. A specially arranged Compton experiment tried in the short-wavelength FEL setup, which we call "random-collision mode", was simple and convenient to generate energy-tunable X-rays. However, it was found that the lack of a sharp Compton edge would degrade their monochromaticity even if a narrow collimator was used. It will be important to select the Compton collision condition carefully, to obtain X-rays with suitable specifications necessary for each application research.

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