WAVELENGTH TUNABILITY OF JAERI-FEL

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Abstract

Wavelength tunability of JAERI-FEL has been demonstrated by adjustment of the undulator parameter at the electron beam energy of 16.4 MeV. The wavelength has been rapidly and continuously varied without any readjustment of the electron beam. The demonstrated spectral range is between 17 μm and 23 μm against the undulator parameter of between 0.25 and 0.70. The FEL properties such as relative rms spectrum width and extraction efficiency are measured at each undulator parameter. The relative rms spectrum width is estimated from extraction efficiency using the universal brightness. The measured spectrum width is compared with the estimated value for verification of the measurement.

1 INTRODUCTION

A free-electron laser (FEL) is a very useful light source in many applications due to its potential of high power, short pulse width and continuous wavelength tunability [1-4]. An important feature of FEL is the property of rapid and continuous tunability over a wide spectral range. The resonance wavelength of the FEL λ is given the following equation [5],

$$\lambda=\lambda_u(1+a_u^2)/(2\gamma^2)\,, \quad (1)$$

where λ_u is the period length of the undulator field, γ is the Lorentz factor and a_u is the undulator parameter. Therefore the wavelength tunability is achieved by adjustment of the electron beam energy and/or the undulator parameter.

Recently, high power, high efficiency and ultrashrot pulse generation was achieved at a superconducting rf linac based FEL in Japan Atomic Energy Research Institute (JAERI-FEL) [6,7]. In order to show the usability of JAERI-FEL for many applications, the wavelength has been varied by adjustment of the undulator parameter. The FEL properties such as relative rms spectrum width and extraction efficiency are measured at each undulator parameter. This paper reports property of the wavelength tunability.

2 EXPERIMENTS AND RESULTS

The layout of JAERI-FEL is shown in Fig. 1. Typical parameters of JAERI-FEL in this demonstration are listed in Table 1. The injector consists of a 230 kV thermionic triode gun driven by a grid pulser at width of 1 ns, a 83.3 MHz subhermonic buncher, and two 499.8 MHz 1-cell superconducting modules. In the injector, the electron beam is accelerated to an energy of 2 MeV and compressed over a long drift space, thus minimizing the emittance growth due to the bunch compression [8]. Two 499.8 MHz 5-cell superconducting modules are used to increase the beam energy to 13-20 MeV. Power requirements limit the macropulse duration and repetition to 1 ms and 10 Hz, respectively. The macropulse consists of a train of short mircrobunches, hence, the optical beam also consists of short, intence micropulses. The microbunches have a repetition of 10.4125 MHz with a charge of up to 0.6 nC and a width of less than 5 ps. Behind the linac, the electron beam is led into an undulator. The undulator is a hybrid type with a period number of 52 and a period length of 33 mm [9]. Two mirrors placed at opposite side of the undulator define the resonator. The mirrors are gold-coated to ensure high reflectivity in the wide spectral range. The distance between the mirrors can be adjusted in order to synchronize the circulating optical pulse with the electron bunches. Behind the undulator, the electron bunches are bent out of the resonator and dumped.

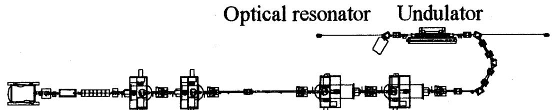

Figure 1: The Layout of JAERI-FEL.

Table 1: Typical parameres of JAERI-FEL.

Kinetic energy	16.4 MeV
Average current	5.3 mA
Bunch charge	0.51 nC
Bunch width (FWHM)	<5 ps
Energy spread (rms)	1.2 %
Normalized emittance (hor.)	40 mm-mrad
Normalized Emittance (ver.)	22 mm-mrad
Bunch repetition	10.4125 MHz
Length of undulator period	33 mm
Number of undulator period	52
Undulator parameter	0.70-0.25
Length of optical resonator	14.4 m
Rayleigh range	1.00 m
Mirror radii	6 cm
Output coupler	4 mm ϕ, Center-hole
Output wavelength	23-17 μm

Adjustment of the electron beam energy while maintaining the excellent beam quality needed for FEL oscillation is nontrivial, and involves careful adjustment of the amplitude and phase of the rf field of the linac. In addition, the excitation of beam transport magnets, which is used to inject the electron beam into the undulator, has to be scanned simultaneously with the adjustment of the energy. In contrast, the method of variation of the

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wavelength by adjustment of the undulator parameter dose not suffers from these limitations. This method allows rapid and continuous wavelength tunability. The undulator parameter a_u means normalized field strength of the undulator and is given by $a_u=eB_u\lambda_u/2\pi mc$ [5], where e is the elementary electric charge, B_u is the rms magnetic field on axis, m is the rest mass of electron and c is the speed of light in vacuum. The undulator is constructed from permanent magnets and magnetic poles, and the field on axis is varied by adjustment of the gap between the two rows of magnetic circuits. The undulator parameter as a function of the gap is shown in Fig. 2. The crosses denote measured value. The solid line is fitted to the measured values by a function of $a_u=C_1Exp\{(-g/\lambda_u)(C_2+C_3g/\lambda_u)\}$ [10], where C_1, C_2 and C_3 are the free parameters, and g is the gap length. The result of the curve fitting, C_1, C_2 and C_3 are 2.520, 1.215 and 1.593, respectively. The movement of the undulator rows has a high mechanical accuracy in the presence of large magnetic force. The adjustment of the undulator parameter form 0.70 to 0.25 takes about 30 sec. The moving speed of the row is restricted to ensure the high accuracy.

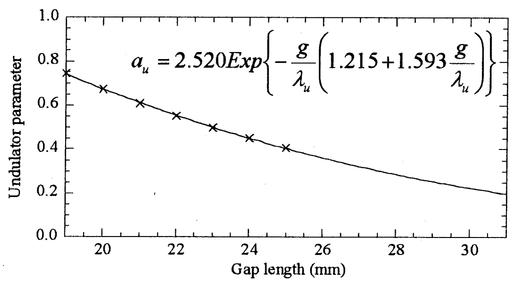

Figure 2: The undulator parameter against the gap. The crosses denote the measured undulator parameter. The solid line denotes the fitted cureve.

The variation of wavelangth is performed by the adjustment of the undulator parameter without any readjustment of the electron beam. The spectral range is from 23 μm to 17 μm at the energy of 16.4 MeV. A monochromater with a HgCdTe detecter is used for the measurement of spectra of various undulator parameters. Sensitivity of the monochromater is corrected by using black-body radiation. The FEL radiation is coupled out through a 4 mm diameter center-hole in one of the mirros and extracted to the air through a KRS5 window. The radiation is guided via transport system in the air to the monochromater, which is installed near the output window in the accelerator room. For minimizing absorption in ambient water vapor, the transport distance is about 3m as short as possible. The monochromater signal is averaged over the macropulse duration. The spectra are shown in Fig. 3. There are some dips due to the absorption in ambient water vapor. The spectra are measured at desynchronism of peak power. The desynchronism means difference between the round-trip time of optical pulse and the repetition of the electron beam. The FEL properties such as the extraction efficiency and spectrum width are largely depend on the desynchronism [11].

Figure 4 shows mean wavelength of the measured spectra and the resonance wavelength against undulator parameters. The mean wavelength is slightly longer than the resonance wavelength, which is derived from Eq. 1. The deference of the mean and the resonance wavelength is good agreement with the Madey theorem [12].

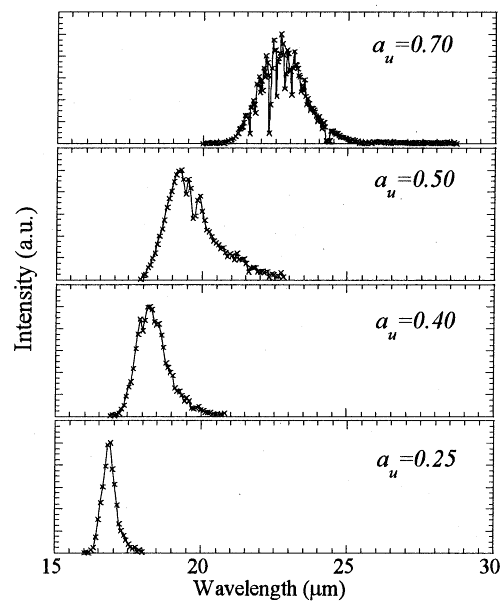

Figure 3: The spectra for various undulator parameters.

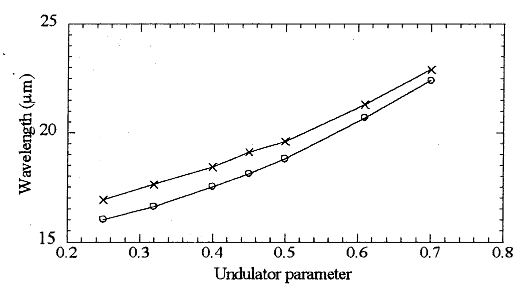

Figure 4: The mean wavelength of the measured spectra and the resonance wavelength. The crosses and the open circles denote measured mean wavelength and resonance wavelength, respectively.

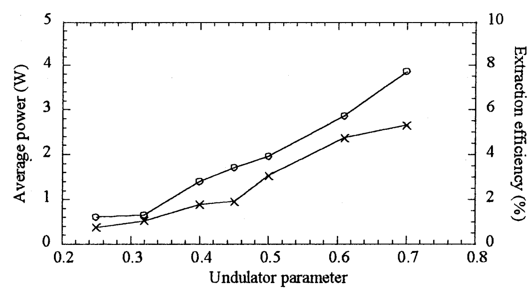

Figure 5: The efficiency and output power of JAER-FEL against the undulator parameter. The open circles and the crosses denote the measured extraction efficiency and the average power, respectively.

The extraction efficiency is estimated from energy loss of the electron beam due to the FEL interaction at the beam dump [13]. The efficiency and output power are shown in Fig. 5 as function of the undulator parameter. The average output power is measured at outside of the KRS5 window for 400 μs macropulse operation. The output power dependence on the wavelength differs slightly from the efficiency due to the variation of the output coupling efficiency of the center-hole output coupler [14].

Figure 6 shows measured and estimated relative rms width of the measured spectra against the undulator parameter. There is the so-called universal brightness because the efficiency is enhanced at the expense of a proportional specrum broadening [15]. The relative rms spectrum width is estimated by the universal brightness $0.86=\eta/(\sigma\lambda/\lambda)$, where η is the extraction efficiency and $\sigma\lambda/\lambda$ is the relative rms spectrum width. At the undulator parameter smaller than 0.5, the measured spectrum width is in good agreement with the estimated one. At the undulator parameter of 0.7, the measured spectrum width is narrower than the estimated one, but the measured efficiency consistents with the pulse width of the FEL radiation [16]. This difference is currently under investigation.

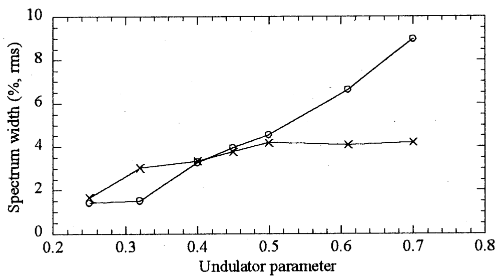

Figure 6: The measure and the estimated relative rms spectrum width against the undulator parameter. The crosses and the open circles denote measured and estimated spectrum width, respectively.

3 CONCULUSION

The wavelength of JAERI-FEL has been rapidly and continuously varied by adjustment of the undulator parameter without any readjustment of the electron beam. The wavelength range is between 23 μm and 17 μm against the undulator parameter of between 0.70 and 0.25. The measured wavelength is in good agreement with the wavelength estimated by the undulator parameter. For the larger undulator parameters, the extraction efficiency has been enhanced at the expence of a proportional spectrum broadening.

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