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FINE AND HYPERFINE STRUCTURE OF FEL EMISSION SPECTRA

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Abstract

This paper presents the results of experimental investigations of the fine and hyperfine spectral structures of the Novosibirsk free-electron laser (NovoFEL) and the compact free-electron laser of the Korea Atomic Energy Research Institute (KAERI FEL) by means of the optimal instruments, resonance Fabry-Perot interferometers. The very high coherence of the NovoFEL spectrum was measured in regimes with one pulse circulating inside its optical resonator (the coherence length is 7 km, and the relative width of the hyperfine structure lines is $2\cdot10^{-8}$) and with total absence of coherence between two circulating pulses, i.e. the fine structure.

Sixty pulses circulate simultaneously inside the KAERI FEL optical resonator, and the measured coherence length on average covers ten pulses (the coherence length is 1 m; the relative width of the fine structure lines is 10^{-4}).

INTRODUCTION

The spectrum of FEL radiation depends on its coherence. Practically all FELs radiate some sequence of short pulses, which are produced by pulse/pulses circulating inside the optical resonator and periodically fed by the electron beam. The spectral contour of the FEL radiation is determined by the intra-pulse coherence, which depends on fast radiation instabilities and their suppression. For example, two different types of fast side-band instabilities were observed in the terahertz NovoFEL. The instabilities, studied in works [1-3], can be fully suppressed due to detuning between the electron and light repetition frequencies. In such a stabilized regime, the contour of the NovoFEL laser line has a Gaussian form with a width equal to the Fourier-transform limit.

A fine structure of FEL radiation can appear in systems with many pulses inside an optical resonator due to certain coherence between the pulses, which is usually some technical feature of the FEL facility. It is clear that in common case, intra-cavity light pulses are physically independent because they neither overlap nor interfere with one another. However, on the other hand, the main feature of any laser is the tendency to generate coherent radiation. Such tendency can be realized if intra-cavity light pulses are linked with one another by means of electron beam, when the electron pulse density has a spike or front shorter than the radiation half wavelength. A fine structure of FEL radiation caused by coherency of intra-cavity pulses was observed earlier on the INEA [4], FELIX [5], and FLARE [6] FELs. In the paper we describe such effect on the KAERI FEL and its absence on the NovoFEL.

Finally, a hyperfine structure of FEL emission spectrum (optical resonator modes) is *a priory* present in all FELs with an optical resonator. In the simplest case of one radiation pulse inside an optical resonator, the output train of FEL light pulses is radiation of one and the same intra-cavity pulse, which is periodically partly outcoupled and coherently refreshed by the electron beam. It is clear that coherency of output pulses can be very high as coherency of radiation of any stationary laser. It depends on slow fluctuations in the active medium because the physical limit of quantum fluctuations, determined by the ratio of spontaneous and stimulated emissions (Schawlow-Townes limit), is very high. Thus, the subject of this investigation is the real value of hyperfine coherency or the average number of output coherent pulses. In the work, the value was exactly measured for the terahertz NovoFEL.

FEL FACILITIES

Compact KAERI FEL

A detailed description of the KAERI FEL is presented in papers [7-9]. The acceleration system of the installation includes the 6- to 7-MeV microtron with a current of 40 to 50 mA in a macropulse 5 to 6 μs long consisting of 2.8-GHz micropulses, as well as the electron-optical beam-line with bending magnets and quadrupole lenses. This beamline connects the acceleration system with the radiation-source one. The radiation-source system includes the 2-m 80-pole planar electromagnetic undulator with a magnetic field of 4.5 to 6.8 kG and the optical resonator. A detailed description of the optical resonator and its optimization is given in [9].

The laser generation by the KAERI FEL takes place in the wavelength range of 110 to 160 μm. The macropulse and micropulse radiation power is 50 to 100 W and ~ 0.5 to 1 kW, respectively. The micropulse duration is about of 30 ps. The repetition frequency of macropulses is 1 Hz in the typical operation regime. The contour spectrum of the laser radiation is the main fundamental mode with FWHM = 1-2 % and a moderate admixture of two side-band modes with a total spectrum base width of 2-3 % [8].

The optical resonator of the KAERI FEL is a hybrid resonator open in the horizontal x direction. It has a Gauss-beam field distribution, set by the horizontal curvature of its mirrors. In the transverse vertical y direction, it is a planar waveguide resonator with an operational TE_1 mode formed by the waveguide parallel metallic surfaces, slid apart to a distance of 2 mm. In the KAERI FEL, the repetition frequency of electron bunches is fixed equal to the magnetron frequency of the microtron RF system (2.8 GHz). The radiation of the optical resonator is output through a circular hole with a diameter 0.75 mm in one of

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its identical cylindrical mirrors (R_x = 3000 mm, $R_y = \infty$). The resonator length is L_0 = 2781 mm; the undulator length is 2000 mm; the horizontal size of the mirrors is 30 mm.

The KAERI FEL radiation is transported by the vacuum beam-line of open type to the user hall, where these experiments were carried out.

Terahertz NovoFEL

The Novosibirsk FEL facility is based on the multiturn energy recovery linac (ERL) [10,11]. The ERL can operate in three modes, providing electron beam for three different FELs. The whole facility can be treated as three different ERLs (one-turn, two-turn, and four-turn), which use the same injector and the same linac. The one-turn ERL is placed vertically. It works for the terahertz NovoFEL, the undulator of which is installed on the concrete floor.

Depending on the number of turns, the maximum final electron energy can be 12, 22, or 42 MeV. The electron energy in the terahertz NovoFEL is 12 MeV. The bunch length in the one-turn ERL is about 100 ps. The maximum average current achieved in the one-turn ERL is 30 mA, which is still the world's record for ERLs.

One essential difference of the Novosibirsk ERL as compared with other facilities is the use of low-frequency nonsuperconducting 180.4 MHz RF cavities. On the one hand, this makes the linac bigger, but on the other hand, this allows increasing the transverse and longitudinal acceptances, which in turn enables operation with longer electron bunches with large transversal and longitudinal emittances. Moreover, there are no beam break-up instabilities on the Novosibirsk ERL, and the average beam current is now limited by the electron gun power.

The first stage FEL includes two electromagnetic undulators 3.5 meter long with a period of 12 cm, a phase shifter, and an optical cavity. The chosen undulator pole shape provides equal electron beam focusing in the vertical and horizontal directions. The phase shifter is installed between the undulators; it is used for phasing of the radiation of the two undulators.

The optical cavity of the terahertz NovoFEL is of the open type; it is composed of two copper mirrors covered by gold [12,13]. The curvature radius of the mirrors is 15 m. The distance between the mirrors is 26.589 m, which corresponds to a round-trip frequency (and a resonance electron repetition rate) of 5.64 MHz. The radiation is outcoupled into the beam-line through the circular 8-mm hole in the mirror center. The open-type optical beam-line was filled with dry nitrogen at atmosphere pressure. A CVD-diamond window separated the optical beamline from the vacuum chamber of the optical resonator.

The laser system of the first stage FEL generates coherent radiation tunable in the range of 80-240 μm as a continuous train of 30-120 ps pulses with a repetition rate of 5.6, 11.2, and 22.4 MHz (the number of pulses inside the optical resonator is 1, 2, and 4). The maximum average output power is 0.5 kW; the peak power is more than 1 MW. The contour laser line in a stabilized regime has a 0.3%-width Gaussian form, which is equal to the Fourier-transform limit.

INSTRUMENTS AND METHODS

Resonance Fabry-Perot Interferometer (FPI). Two Operation Modes of FPI.

Optical setups for our spectral investigations are shown in Fig. 1. In both schemes, FEL radiation (I) is input into beam-forming system (II), after which the beam size decreases to the optimal value and the beam wavefront becomes plane. Then follows the main part of the devices: resonance Fabry-Perot interferometers (III). Radiation passed through the FPIs was measured by detector system (IV).

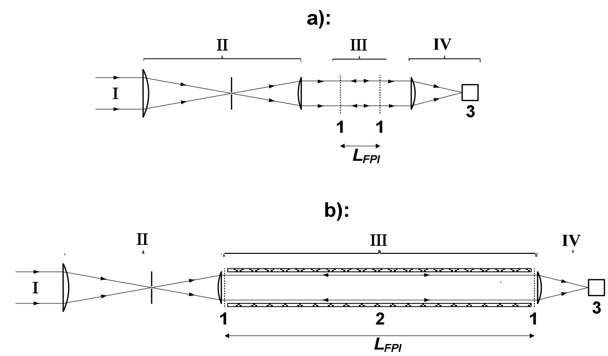

Figure 1: Optical schemes of devices used for measuring fine and hyperfine structures of KAERI FEL (a) and NovoFEL (b) spectra: I – radiated FEL beams, II – lens beam compressors and wavefront correctors, III – mesh resonance Fabry-Perot interferometers, IV – detector systems; 1 – electroformed metallic meshes, 2 – hollow dielectric waveguide (glass tube), 3 – different detectors. The length of Fabry-Perot interferometer L_{FPI} is the distance between the meshes.

An important feature of the FPIs is their resonance length L_{FPI} [14]. It should be noted that in the classical theory of FPI, continuous waves (CW radiation) circulating in a device always interfere with one another. With some simple modifications, this theory can be applied to pulse-periodical radiation of FEL only when $L_{FPI} = \Lambda/(2n)$ or $L_{FPI} = (\Lambda/2)\cdot m$, where Λ is the distance between pulses and n and m are integers. In the first case, it is necessary to take into account additional loss of radiation in the FPI; in the second case, only sets of pulses divided by the distance $\Lambda\cdot m$ are analysed. When an FPI has a non-resonance length, as in work [4], its efficiency fall dramatically (pulses inside the FPI do not overlap fully) and interpretation of the experimental results is practically impossible without special simulation.

The typical operation mode of FPI setups is the frequency-domain mode, when the transmitted radiation power is slowly measured as a function of ΔL_{FPI} (small variation of L_{FPI} near its resonance value). Sometimes the time-domain mode of FPI operation (the NovoFEL case) is

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very useful, when a rather fast detector measures the transmitted power as a function of time (3 on Fig. 1b) at a constant resonance length L_{FPI}.

In the fine mode of the KAERI FEL experiment, an FPI with $L_{FPI\text{-}1}$ = 53.6 mm (m=1) was used (Fig.1a). We also checked the measured data of the FPI using a device with the double length $L_{FPI\text{-}2}$ = 107.2 mm (m=2). In both FPIs, electroformed Ni meshes with square symmetry and 30-µm period were used as mirrors. A step-motor translation stage was changing the distance between the mirrors; a commercial pyroelectric detector was measuring the transmitted power.

For the hyperfine mode of the KAERI FEL experiment we prepared a high resolution FPI with $L_{FPI\text{-}3}$ = 536 mm (m=10) and Ni meshes with a 20-µm period. However, the transmittance of such device was small, and therefore we had to apply a liquid He-cooled detector. Unfortunately, the production of liquid He in the South Korea stopped, and this experiment was remitted for future.

Fine and hyperfine spectral experiments on the NovoFEL require FPIs with much higher resolution. Thus, an ultra-long vacuum waveguide FPI was created (Fig. 1b). Its length is equal to 2658.9 mm, which is ten times less than the NovoFEL optical resonator length. Actually, it is a modified (lengthened) optical resonator of our universal gas laser [15-17], which was used earlier in many technological experiment on the NovoFEL facility [3]. The EH_{11} waveguide operating mode of the FPI makes it possible to have a plane wave-front at a long distance, and the vacuum medium allows avoiding atmosphere absorption. The length of the FPI can be fixed or vary with the temperature of hollow invar rods, in which a thermo-stabilized liquid was circulating. A 10-period scanning of a NovoFEL fine structure takes about 10 minutes. In the slow frequency-domain working mode, a lock-in commercial pyroelectric detector system was applied. When the FPI worked in the fast time-domain mode, the FPI length was fixed near the resonance value due to the stable temperature of the invar rods. In this case, a self-made Schottky diode detector [18] was recording the transmitted power oscillograms.

EXPERIMENTAL RESULTS

Fine Structure of the KAERI FEL Spectrum

The fine mode structure of the KAERI FEL spectrum at a wavelength of 117 µm is shown in Fig. 2. We used two FPIs with the lengths $L_{FPI\text{-}1}$ = 53.6 mm (m=1) and $L_{FPI\text{-}2}$ = 107.2 mm (m=2). For the first device, $2L_{FPI\text{-}1} = \Lambda$, and for second, $2L_{FPI\text{-}2} = 2\Lambda$, where Λ is the distance between pulses. Thus, in the first FPI, all pulses will interfere. In the second one, two sets of pulses shifted by one pulse (for example, sets of conventional even and odd pulses) will interfere independently. We can see in Fig. 2 that the fine mode structures corresponded to the pulse frequencies. We used FPI-2 to confirm the experimental results of FPI-1 because the calculated instrumental function of FPI-1 was only two times narrower than the measured mode. In both experiments, we had the same result: the fine mode width of 0.29 GHz. It is easy to show [14] that the average number of coherent pulses N_c is equal to the fineness of the FPI interferogram ε multiplied by the number m. So, in our experiment we have $N_c = \varepsilon_1 \cdot 1 \approx 10$ or $N_c = \varepsilon_2 \cdot 2 \approx 10$. In the KAERI FEL optical resonator, 60 pulses circulate simultaneously, and thus the coherency covers only 1/6 part of all the pulses.

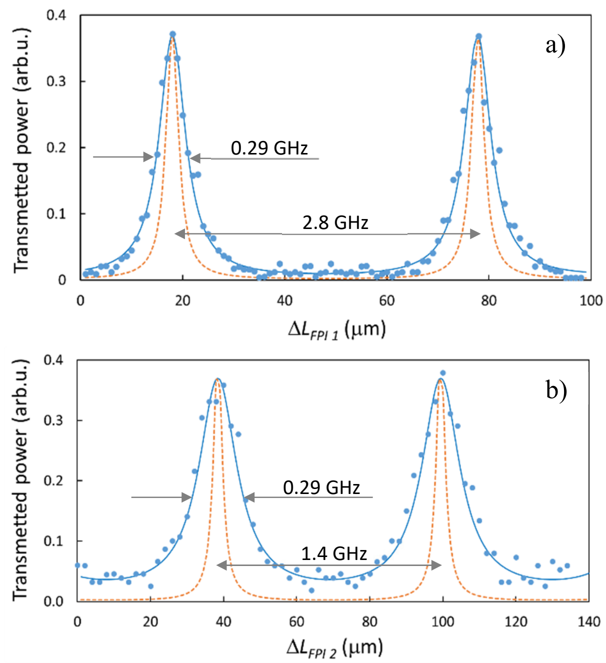

Figure 2: Fine structure of KAERI FEL radiation spectrum at central wavelength of 117 µm (2.6 THz) measured by Fabry-Perot interferometers with lengths $L_{FPI\text{-}1}$ = 53.6 mm (a) and $L_{FPI\text{-}2}$ = 107.2 mm (b). Dots: experimental points, blue solid lines: best fitting to experimental points. Dashed orange lines: instrumental functions of interferometers.

The obtained results can have the following explanation. The KAERI FEL definitely has a feature (spike or front) in electron pulses that are shorter than the radiation half-wavelength, which can synchronize all light pulses. Actually, only part of the light pulses are synchronized because of accumulation of phase shift caused by the electron pulse frequency jitter. In our case, the jitter for a time period of order of the laser generation rise time (0.2-0.5 µs) is substantial. We were not able to measure such jitter. But the experimental value of the parameter for a longer time period ($\delta f/f = \pm$ 250 kHz/2.8 GHz $\approx \pm 10^{-4}$) gives a calculated number of coherent pulses, which corresponds to the experimentally observed one $N_c \approx 10$.

We also measured the power of fine modes in a wider spectral range. Figure 3 presents the relative powers of 11 central fine modes, like those shown in Fig.2. We can see slow decrease in these modes relative to the maximum mode for $\Delta L_{FPI\ 1}$ = 117 µm; it corresponds to the contour laser line of the KAERI FEL. This classical behaviour of the fine structure differs from the results of the FLARE experiment [6], where a large unintelligible difference in the powers of close fine modes was observed.

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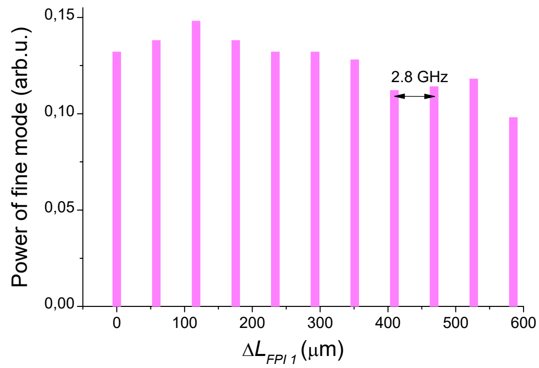

Figure 3: Relative powers of 11 central fine modes of the KAERI FEL.

Hyperfine Structure of the KAERI FEL Spectrum

Though no hyperfine structure of the KAERI FEL is measured in the experiment, it would be useful to make some remarks. The first is the *a priory* presence of a structure, because the KAERI FEL works in a quasi-stationary regime, which is formed by its optical resonator. Therefore the observed fine structure (Fig. 2) is actually only the averaged contour lines for the hyperfine structure with the period $\Delta\nu_{hf} = c/2L_0 = 54$ MHz, where c is the light velocity and L_0 is the optical resonator length. The fineness of the structure cannot be smaller than the passive quality factor of the optical resonator (≈ 10), but it can be much larger (the quality factor of the active laser resonator).

The second remark is about the technical possibility of increasing the fine coherency up to 60 pulses. In this case, the fine and hyperfine coherencies transform (degenerate) into a common coherency, which will be characterized by very narrow lines (like lines of hyperfine structure) and a high frequency of 2.8 GHz (like the frequency of fine structure). Such spectrum of the KAERI FEL radiation can be very useful for spectroscopy applications.

Fine Structure of the NovoFEL Spectrum

A low pulse frequency regime of the NovoFEL operation makes fine coherency impossible. Actually, the pulse frequency jitter would be $\delta f/f \leqslant \lambda/2\Lambda = \lambda m/2L_0 = 5\cdot10^{-6}$, where $\lambda = 0.15$ mm, $m = 2$, and $L_0 = 26589$ mm. The real jitter of the NovoFEL pulse frequency is probably an order of magnitude larger. Thus, two-pulse and four-pulse regimes of the NovoFEL will give the same hyperfine spectral structures as in a one-pulse regime because the pulses inside the optical resonator are practically independent and equivalent. This was confirmed in our experiments, in which absolutely the same normalized spectra were observed.

Hyperfine Structure of the NovoFEL Spectrum

For the study of hyperfine structure of the NovoFEL our special ultra-long resonance FPI (Fig.1b) was used. The main problem of such slow measurements in the frequency domain consisted in obtaining a very stable single-mode regime for a long time (~ 10-15 min for a 10-period interferogram). We should note that it was needed only for obtaining a good multi-period interferogram because the best time of the NovoFEL fine coherency was only 25 μs. One of the best examples of such interferogram is shown in Fig. 4. Unlike lower-resolution spectra of the KAERI FEL, here the FPI instrumental function is much wider than the hyperfine lines measured. Moreover, in such measurement we can obtain only the low estimate of the hyperfine coherency. For example, the measured spectrum in Fig. 4 practically coincides with the instrumental function. Nevertheless, when we take a line width of 10^{-7}, we have a visible difference in the contrast of the spectrum. Thus, the low estimate of the hyperfine monochromaticity here is $\delta\nu/\nu \leqslant 5\cdot10^{-8}$.

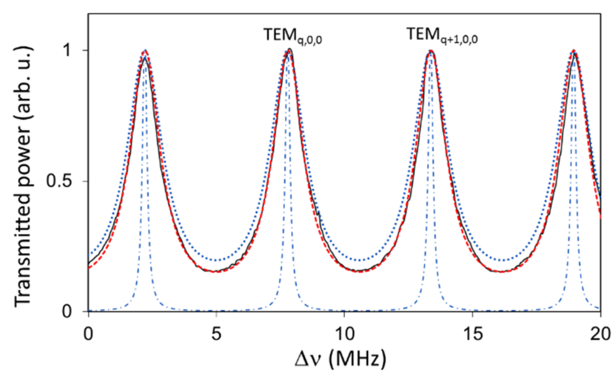

Figure 4: Hyperfine structure of THz NovoFEL radiation at central wavelength of 164 μm (1.83 THz). Solid black line: measured NovoFEL radiation, dashed red line: instrumental function of ultra-long waveguide vacuum FPI with 30-μm nickel meshes, blue dotted line: spectrum appreciably differing from experimental one as a result of convolution of laser line with relative spectral width of 10^{-7} (blue chain line) and instrumental function.

Replacement of the present 30-μm nickel FPI meshes with 12-μm gold meshes can provide four-fold narrowing of the instrumental function, but that is not sufficient. Therefore, we used a principally other time-domain method for exact measuring a NovoFEL hyperfine structure.

In the time-domain method, a two-pulse 11.2-MHz regime of the NovoFEL is used. The main idea of the method is going from the frequency domain to the time domain, where hard-to-measure narrow spectral lines transform into easy-to-measure long time intervals. It is also important that two phase-independent systems of pulses in the 11.2-MHz regime will effectively interfere inside the resonance FPI. Thus, in the output of the FPI we will have a beating signal. The signal maxima will be at the times when the radiation fields of the interfering pulses coincide; the minima will occur when the fields are opposite (Fig. 5b). The minimum beating period (T_{min} in Fig. 5b) will be observed for an opposite phase change in the two systems of pulses. Thus, this value T_{min} will also be the time of coherency (a 180-degree phase change) in each 5.6-MHz system of pulses or time of NovoFEL hyperfine coherency. We measured many oscillograms, like shown in Fig. 5b, to find

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the minimum value of the beating period. As a result, the following parameters were obtained: the hyperfine coherency time T_{min} = 25 µs, the average number of NovoFEL coherent output pulses in the one-pulse 5.6-MHz regime is 140, the coherency length is 7 km, and the monochromaticity of the hyperfine comb-structure of the NovoFEL radiation is $2.2\cdot10^{-8}$.

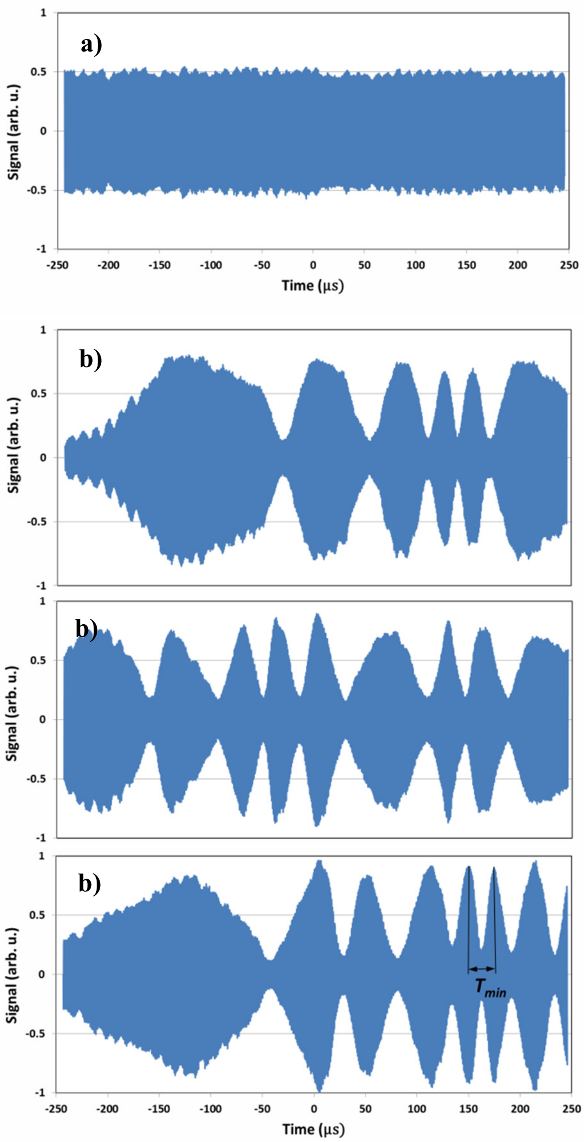

Figure 5: Power signals of Schottky diode detector (3 in Figure 1b, integration time of 100 ns) (a) for 5.6-MHz NovoFEL regime with single pulse in optical resonator and (b) for 11.2-MHz NovoFEL regime with two pulses in optical resonator. T_{min} is minimum modulation period. All signals were measured at the resonance FPI length, when its transmittance is maximal.

CONCLUSION

In the experimental investigation, the fine mode structure of the KAERI FEL radiation with a line monochromaticity of 10^{-4} was found. We are going to measure a hyperfine structure of the laser in the near future.

The hyperfine structure of the NovoFEL with a line monochromaticity of $2.2\cdot10^{-8}$ was measured. There is no fine mode structure or coherency between different pulses inside the optical resonator.

Knowing the real structure of FEL radiation is important for different user spectroscopic methods developed on the facilities.

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