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Modulation instability, three mode regimes and harmonic generation at the Novosibirsk terahertz free electron laser

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ABSTRACT

Different mode regimes vs. extent of stabilization of modulation instability were investigated with a complex diagnostics system. Slippage due to detuning of the frequencies of electron and light pulses turned out to be the main stabilization factor. Spectral and time parameters of the laser, especially radiation of high harmonics, have been shown to strongly depend on the stabilization.

1. Introduction

The Novosibirsk terahertz free-electron laser (NovoFEL) generates a CW sequence of rather long pulses (≈ 100 ps) [1,2]. As a result, we can have a sufficiently narrow laser line, which is important for many photochemical applications. High harmonic generation can strongly extend the NovoFEL spectral range and significantly increase the number of possible user experiments. Successful realization of the potentialities will be possible only if each light pulse has a good coherency. Unfortunately, free electron lasers are more subject to different instabilities than usual lasers, because of the absence of strong inner frequency selection. For example, it is well known that FEL pulses are unstable relative to perturbations with a period equal to the so-called slippage length $L_{sl}=N\lambda$, where N is the number of wiggler periods and λ is the wavelength. A light pulse can split up into a few incoherent parts, or sub-pulses, with length L_{sl}. Thus, in an unstable regime FEL spectrum will broaden strongly. It is obvious that the coherency break-up will influence especially the high harmonic radiation.

A universal method of stabilization of different instabilities is slippage of perturbations. We have realized such stabilization by detuning a little the repetition frequencies of electron and light pulses.

2. Diagnostic equipment

The NovoFEL has a set of equipment for complex investigation in the time and spectral domains. We used the Bruker vacuum Fourier spectrometer IFS-66vs for panoramic spectral measurement [3]. The output signal of the device (interferogram) is an

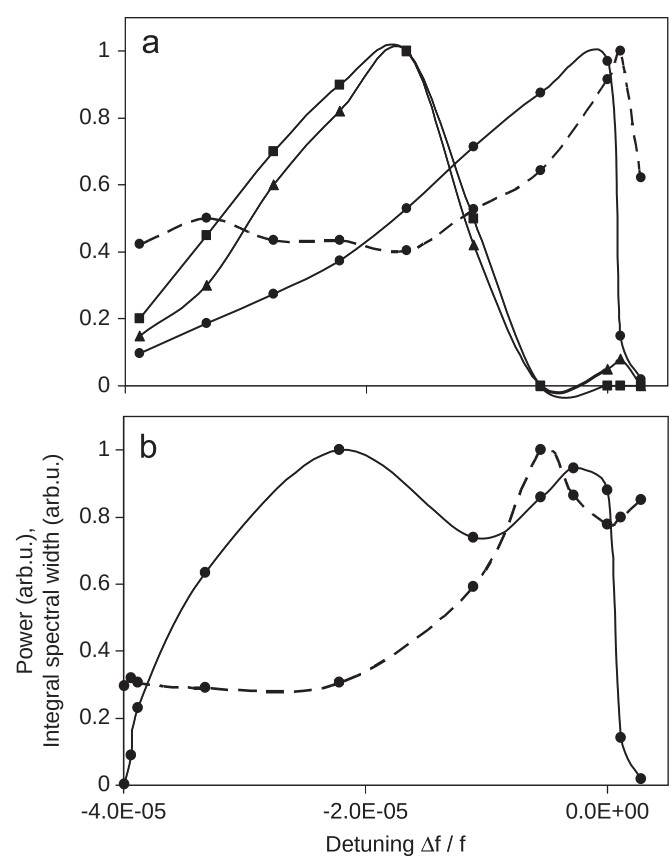

Fig. 1. Harmonic powers (solid lines and circles: the first harmonic, triangles: the second harmonic, squares: the third harmonic) and the integral spectral width of the first harmonic (dashed line) vs. relative detuning of the frequencies of electron and light pulses for a routine regime (a) and thoroughly tuned regime (b).

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autocorrelation function, which directly displays the very important coherence length. A grating monochromator was used for on-line spectral adjustment; for example, for optimization of high harmonic radiation or measurement of pulse-to-pulse spectral stability of the main first harmonic. This device allowed us to find out that all spectral peculiarities of the NovoFEL are linked with each light pulse rather than caused by power or spectral modulations during the measurement time of the Fourier spectrometer. For separation of real and artifact harmonics in the Fourier spectrometer and for measurement of harmonic parameters we used different film filters based on 2D periodical structures [4].

For fast time measurements we used detectors of two types based on submicron Schottky diodes. The first, high-sensitivity detector with a good antenna system was used in various experiments in which the integral linear response to a light pulse was enough [5]. The second type detector was less sensitive because it was specially constructed for ultra-fast operation. Its response time is shorter than 30 ps. It easily showed the form of our light pulses in the stable regime. Probably, this detector can also display sub-pulses in an unstable regime. However, we need an adequate direct oscilloscope for such an experiment. In the presented experiments, we used the Tektronix 50 GHz sampling oscilloscope, which could register light pulses in the stable

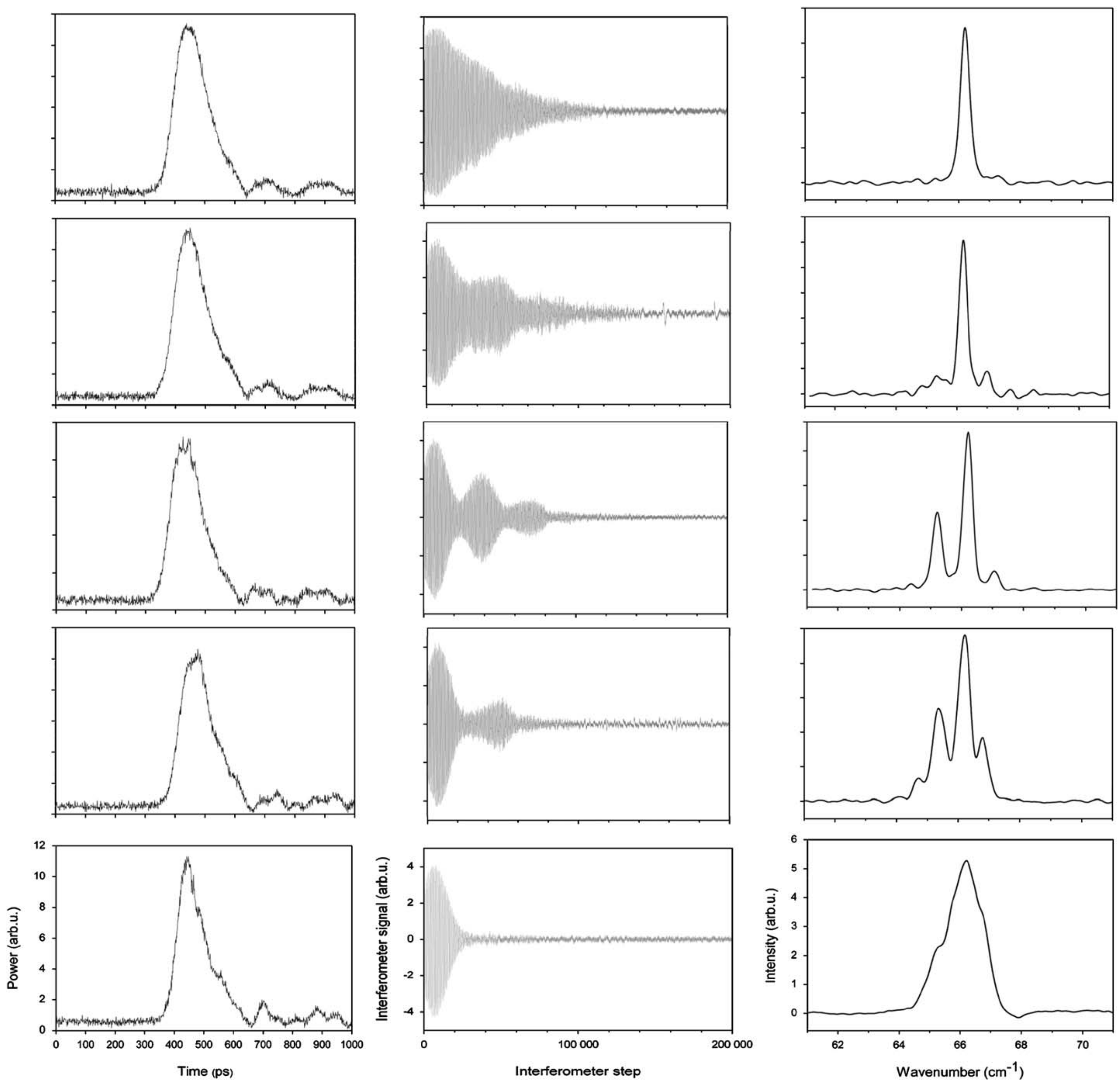

Fig. 2. Oscillograms of light pulses (left column), interferograms, or auto-correlation functions (middle column), and spectra (right column) for different relative detuning $\Delta f/f$ from the upper row to the lower one: -2.2×10^{-5}, -1.65×10^{-5}, -1.1×10^{-5}, -0.55×10^{-5}, 0. The full interferogram (2×10^{5} steps) corresponds to 6.328 cm (212 ps).

regime. Unfortunately, it cannot be reliably used in an unstable regime because of the jitter of sub-pulses.

3. NovoFEL mode regimes

As mentioned above, detuning of the repetition frequencies of electron and light pulses in the optical resonator is the main stabilization factor which influences the NovoFEL parameters in the frequency–time domain. In all our experiments we had a strongly broadened spectrum for zero detuning [3,6], which converged down to the Fourier-transform limit with increasing detuning (Fig. 1). In routine regimes, such detuning decreases the NovoFEL power due to the shortening of the radiating part of electron pulse (Fig. 1a). However, the light pulse is longer for a thoroughly aligned, high-current electron beam and therefore the NovoFEL gain is less sensitive to such additional stabilization slippage. Such regime is shown in Fig. 1b, where stabilization of instability was obtained without decreasing of the NovoFEL radiated power. The form of spectrum was different in different regimes. In some case the forms were very demonstrative. One of the regimes is shown in Fig. 2. We can see that ideal classical FEL radiation takes place for a certain detuning. At such detuning the light pulse is fully coherent and the spectral width is equal to the Fourier-transform limit. When stabilization detuning decreases, there appears rising modulation of side-band modes. In the beginning the modes are also coherent and we have a multi-mode, high-coherence regime. Then the modes begin to interact with each other and mode mixing takes place. As a result we have a quasi-single-mode (in fact, multi-mode) regime with a wide Gaussian-like spectrum and low coherency. The characteristic period of the observed instability can be measured from the Fourier interferograms, which, in contrast to the sampling oscilloscope, are not sensitive to the jitter of perturbations. It coincides well with the slippage length L_{sl}. Therefore, we assume that there is a modulation instability in the experiment. Let us conclude the section noting that the quasi-single-mode regime can be useful in some applications, for example, in spectroscopy [7].

4. Coherency and harmonic radiation

The high harmonic radiation was studied and optimized at the NovoFEL facility in 2006 [8]. We found out that high harmonics were much more sensitive to coherency than the first one. The relative part of the power of high harmonics (except the second harmonic) was less than 10^{-4} in the resonance case (zero detuning). As one can see in Fig. 1, high harmonics are effectively radiated only in a stable zone with good coherency. Thus, tuning of the high harmonic radiation is a more precise operation than tuning of the first harmonic and coherency is the main critical parameter of this tuning. As a result of such optimization we obtained a relative power of 0.6% for the third harmonic and 1.5% for the second harmonic. As is well known, there should be no second harmonic radiation in the symmetrical case. The required asymmetry appears in our experiment probably because the electron beam consists of two components. Some part of the electron beam can have a smaller energy and can pass through the wiggler with a certain tilt about its axis. Confirmation of such explanation can be seen in Fig. 3. Whereas the wavenumber of the third harmonic is exactly tripled wavenumber of the first one, the second harmonic wavenumber is the doubled wavenumber of the long-wave component of the first harmonic radiation.

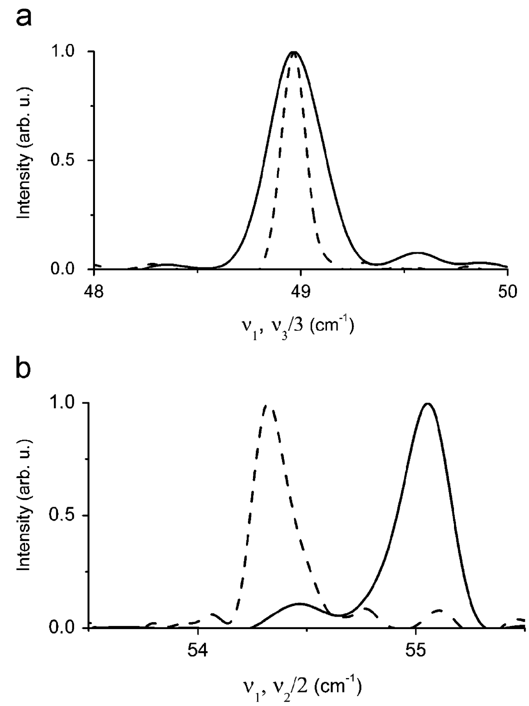

Fig. 3. Spectrum of the first, the second and the third harmonics: the first harmonic intensity vs. its wavenumber ν_1 (solid line, (a,b)), the third harmonic intensity vs. $\nu_3/3$ (dashed line, (a)), the second harmonic intensity vs. $\nu_2/2$ (dashed line, (b)).

Nevertheless, the main operation at the NovoFEL is optimization of the first harmonic. Now this harmonic has the following record parameters: the CW average power is 500 W, the maximum pulse power is 0.4 MW, the pulse duration (FWHM) is 100 ps, the frequency of light pulses is 5.6–22.4 MHz, the spectral width (FWHM, the Fourier-transform limit) is 2.5×10^{-3}.

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