SPONTANEOUS AND INDUCED INTERPULSE COHERENCE IN THE NIJMEGEN THz-FEL

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Abstract

Interpulse coherence allows creation of narrow band light, which is one of the key features of the Nijmegen THz-FEL. In the proposed set-up we expect strong coherent spontaneous emission. In combination with the high Q-factor of the RF LINAC, it will result in spontaneous phase-locking of all micropulses. The coherence can be further enhanced by implementing a Fox-Smith interferometer in the FEL cavity. In this paper, these two competing mechanisms are illustrated by means of a simple pulse evaluation model.

INTRODUCTION

The TeraHertz (THz) frequency range is highly relevant for biomolecular physics, solid state physics in high magnetic fields, and allegedly also in security applications. Unfortunately, this region of the spectrum still lacks both versatile and powerful sources. Since, in contrast to "traditional" lasers, the frequency of the light generated by a Free Electron Laser (FEL) is not limited by internal properties of an active medium but can be selected by proper choices of undulator and electron energy, FEL technology is well suited for the generation of THz radiation. A THz-FEL oscillator has been funded at the Institute of Molecules and Materials of the Radboud University Nijmegen (The Netherlands), and is scheduled to be in operation in the first half of 2011. This FEL is unique in that it will produce THz light in the 0.1 mm (3 THz)−1.5 mm (0.2 THz) spectral range and will deliver powerful picoseconds pulses suitable for time-resolved experiments as well as high resolution μs-macropulses with a narrow bandwidth of $\approx 10^{-5}$. Specifically for this FEL are the electron bunches, the length of which is similar to the wavelength of the generated light.

OPERATIONAL PRINCIPLE

A 3D design of the Nijmegen THz-FEL is shown in Fig. 1 and the most relevant FEL parameters are listed in Table 1. An RF LINAC will produce $\approx$3 ps long electron bunches at a rate of 3 GHz during 10-15 μs each 0.1 s. Since the bandwidth of a FEL gain function is $\Delta\nu/\nu \approx 1/2N$ (N is the number of undulator periods) the light will be produced in the form of μs-long macropulses consisting of sub-pulses (micropulses) of $\approx$25−400 ps duration, depending on the resonant wavelength. The synchronism condition, when the optical pulses perfectly overlap with the electron bunches at the undulator entrance, implies that the repetition rate of the electron bunches is a positive integer multiplied by the optical pulse round trip frequency. This means that at perfect synchronism 150 optical pulses will propagate simultaneously through the 7.5 m long optical cavity. If there is no fixed phase-relationship between pulses, the FEL will operate as 150 independent lasers. A typical spectrum of this laser in presented in Fig. 2. However, if the pulses are phase-locked, only longitudinal modes $150nc/2L$ (n is a positive integer) can exist in the

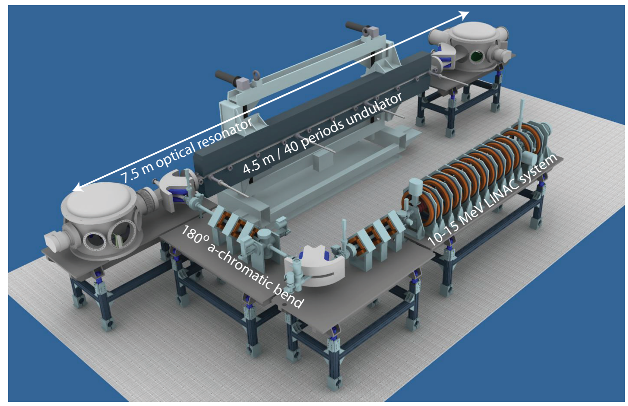

Figure 1: The Nijmegen THz-FEL.

Table 1: Nijmegen THz-FEL Parameters

RF frequency	3 GHz
Micropulse duration	3 ps
Length of macropulses	10−15 μs
Repetition rate of macropulses	10 Hz
Electron beam energy	10−15 MeV
Undulator period	110 mm
Number of undulator periods	40
Undulator parameter	0.7−3.3
Optical cavity length	7.5 m
Short pulse mode	
bandwidth	$\approx$1 %
max power in micropulses	300 kWatt
Narrow band, long pulse mode	
bandwidth after filtering	10^{-5}−10^{-6}
macropulse power after filtering	100 Watt

resonator. In this case, the optical pulses act as a single pulse propagating through a 150 times shorter cavity but still with the same number of undulator periods. Due to the sparse frequency spectrum of the totally coherent optical pulses, an external filter can be employed to reduce the bandwidth even further [1]. The spontaneous and induced

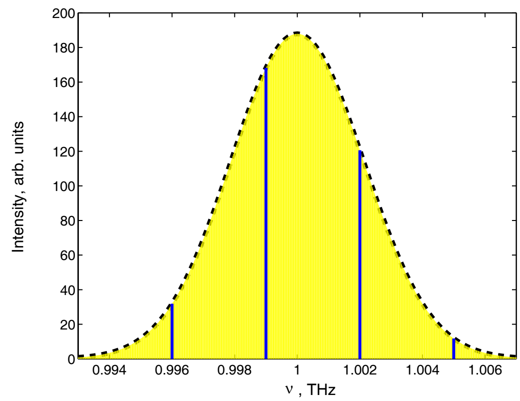

Figure 2: The frequency spectrum is presented by a Gaussian function (dashed black curve) at a resonant frequency of 1 THz with a bandwidth of 10 GHz. The longitudinal cavity modes are shown by the yellow and blue vertical lines when the phase of the optical pulses is uncorrelated and when there is a fixed phase-relationship, respectively. The modes are separated by 20 MHz (not visible) and 3 GHz, repsectively.

inter-pulse coherence will be discussed in the next section.

Since the RF LINAC will generate very short electron bunches, short-pulse effects will be significant for the FEL operation. One of these is slippage which is due the lag of the electron bunch relative to the optical pulse at the exit of the undulator by an amount of $N\lambda$. For instance, the pulse length is ≈1 mm while the slippage distance is ≈40 mm. It can result in a reduction of the single pass gain such that the macropulse length will not be sufficient to achieve saturation. This effect is known as "lethargy". In order to compensate for the reduced gain, the cavity can be desynchronized or, more efficiently, the RF LINAC repetition rate can be ramped [2]. Furthermore, the long wavelength of a THz FEL demands the use of a waveguide to suppress diffraction losses. It has been shown, that slippage effects can be reduced by tuning the waveguide gap [3].

SPONTANEOUS AND INDUCED INTERPULSE COHERENCE

The power spectrum of spontaneous (synchrotron) emission which is a seed for the FEL amplification can be presented as [4]

$$P(\lambda) = NP_1(\lambda) + N^2P_1(\lambda)f(\lambda), \qquad (1)$$

where P_1 is the power generated by a single electron at λ wavelength and $f(\lambda)$ is the form factor, being the Fourier Transform of the shape of the electron bunch. The first term represents the incoherent spontaneous emission (ISE), connected to the shot noise in the electron bunch, with a phase of emitted photons being uncorrelated. The second term represents coherent radiation with a fixed phase (CSE). Since for the Nijmegen THz-FEL the electron bunch length is comparable to the wavelength of the generated light, the spontaneous emission will be predominantly coherent. We note that already at a wavelength of 70 μm a considerable amount of CSE was detected in FELIX [5]. In order to get some insight into influence of the CSE on the long-range interpulse coherence, we employed the simple pulse evaluation model reported in Ref. [6]. This model is based on the following simplifications: 1) the electron bunches have identical shape; 2) FEL saturation is modelled by an analytical function; 3) the contribution of CSE is independent of the power in the cavity. The model allows to introduce jitter in the arrival time of the electron bunches, which will effect the interpulse coherence. The level of coherence between different optical pulses was calculated as a fringe visibility in an interferogram as it would be recorded with for example a Michelson interferometer. The fringe visibility will be periodic by 150 interpulse distances, since it corresponds to a total round trip length of the optical pulse. A time jitter in the arrival time of the electron bunches at the undulator entrance was assumed to be the white FM noise with a random walk of 5 and 10 % of the optical period. Results of the model presented in Fig. 3 obviously show that the level of the interpulse spontaneous coherence grows with the amount of CSE.

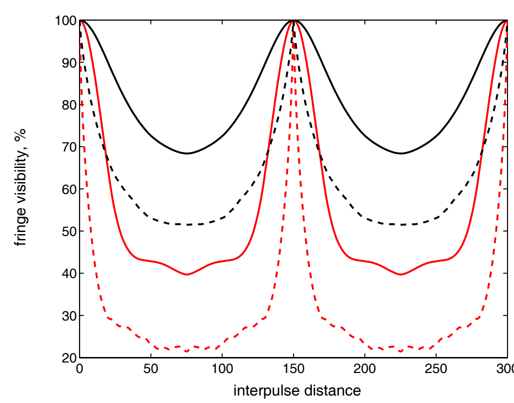

Figure 3: Simulation of the interpulse coherence at a resonant wavelength of 1.5 mm. The fringe visibility was determined at saturation and was averaged over 100 macropulses. The results obtained with a random walk in the arrival time of the electron bunches of 5 % and 10 % are shown by the black and red lines, respectively. The solid curves present the simulated data with a FSI coupled to the main cavity.

The interpulse coherence can be further affected by implementing a Fox-Smith interferometer (FSI) with a length of the half of the distance between the pulses coupled to the main laser cavity by means of the beam splitter [1]. In the FSI, two successive optical pulses will interfere and

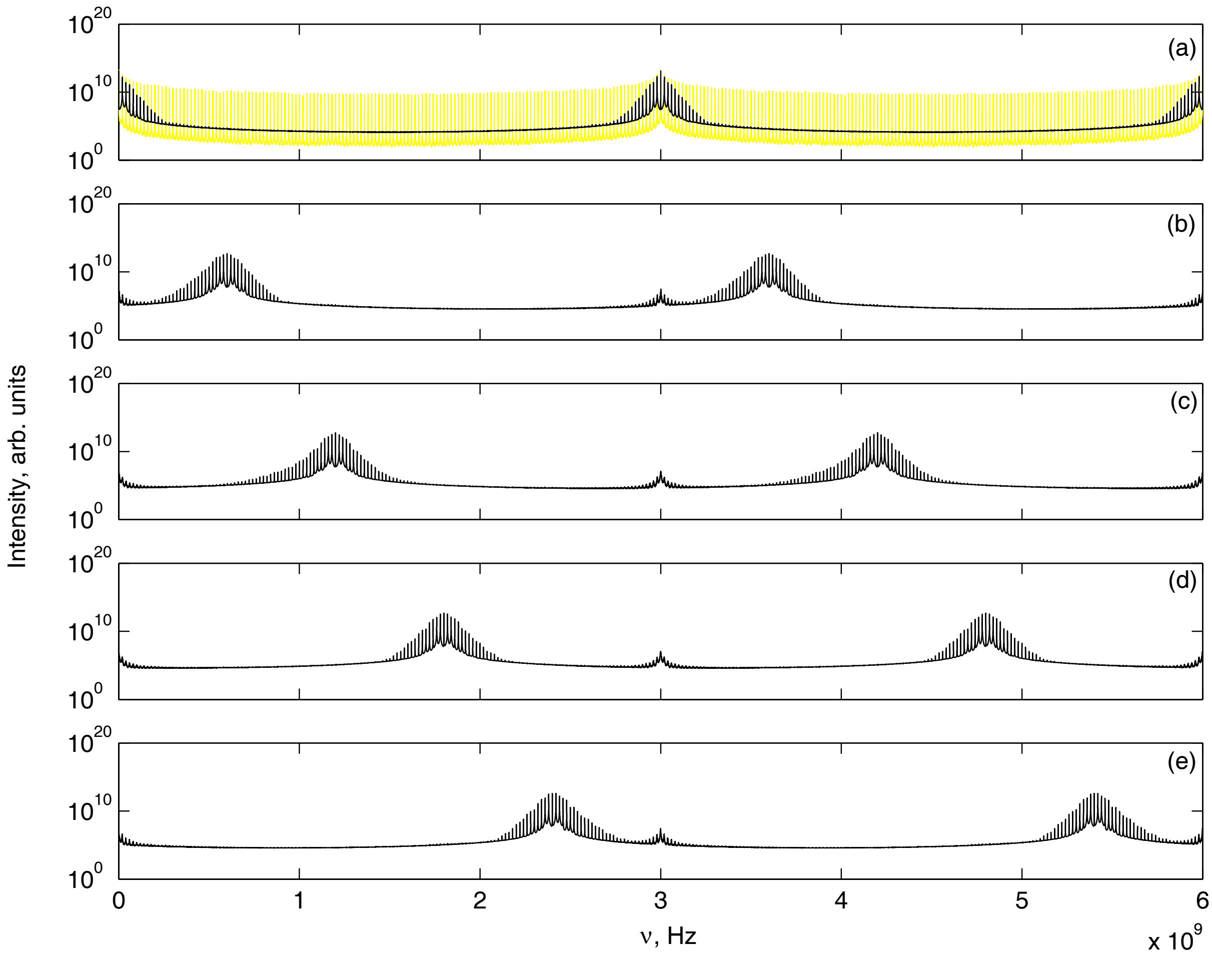

Figure 4: The yellow and black curves show simulated spectra obtained without and with FSI coupled to the main cavity, respectively. It is noted that this spectrum is repeated with 3 GHz, since in the model pulse shape is not considered. In (b), (c), (d), and (e) the FS cavity length was shortened by 0.1λ, 0.2λ, 0.3λ, and 0.4λ, respectively.

only longitudinal modes fulfilling resonant conditions of the FSI cavity, i.e., ν=150nc/2L, will interfere constructively, while others interfere destructively. The induced interpulse coherence was simulated with a similar model applied for development of spontaneous coherence. Simulation results show that the fringe visibility is increased significantly, although not to the 100 % level (Fig. 3). The corresponding frequency spectra are shown in Fig. 4 (a). The frequency spectra obtained with FSI coupled to the main cavity only contains modes located around 3 GHz, while that generated without FSI consists of all possible longitudinal modes of the FEL resonator. Similar results are presented in Fig. 4(b-d) which were simulated when the length of the FSI was reduced by 0.1λ, 0.2λ, 0.3λ , and 0.4λ, respectively. All these spectra still have contribution at 3 GHz which is due to the contribution from the spontaneous coherence. These results imply that by tuning the FSI length, the position of the frequency comb can be varied such that dominating frequencies are located at

$$\nu = \frac{2\delta L_{\rm FS}}{\lambda} n \times 3\ \text{GHz} \qquad (2)$$

and by applying an external filter, a tooth of the comb with a certain n number can be selected.

DISCUSSIONS AND FUTURE PLANS

Although the model applied here to simulate interpulse spontaneous and induced coherences is oversimplified, it provides important insight into these two competing mechanisms. In order to get more reliable results, other FEL parameters such as slippage, cavity desynchronization, and electron beam emittance must be taken into account as well. For instance, limit-cycle power oscillations were experimentally observed at FELIX and found to depend on the slippage distance and cavity desynchronization [7]. Such oscillations imply that the successive pulses are not identical and, thus, this effect is of relevance for the interpulse coherence. An improved description of the FEL physics involves models based on solutions of dynamical equations. Most of the models employ equations averaged over the ponderomotive potential or optical wavelength (see, e.g., Ref. [8]). In the present case, however, this approach is not valid since the electron bunch length is comparable in size to the wavelength and averaging will lead to loss of information about the electron bunch shape and, therefore, amount of the CSE will not be predicted correctly. In contrast, a macroparticle approach, i.e., when the electron bunch is cut into slices such that each slice is considered to behave as an individual particle, does not involve averaging. A model based on this approach was developed for coherent self-amplified spontaneous emission amplifiers [9]. Our intention is to extend this approach and to develop a 3D code for a waveguided Nijmegen THz-FEL.

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