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Free-electron laser: advancement into the X-ray region

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As far back as 1947, Ginzburg [1] considered the spontaneous radiation of electrons, as well as of electron 'bunches', moving at a relativistic velocity and executing an oscillatory motion in the plane perpendicular to this velocity – the radiation which has come to be known as undulator radiation. The undulator radiation was shown to offer two significant advantages over synchrotron radiation: the monochromaticity in a given direction and a higher power spectral density [1]. Somewhat later, in 1951, Motz [2] addressed the same problem.

Undulator radiation sources and free-electron lasers (FELs) developed on their basis have been of vital importance in many applications of modern physics. The fundamental difference between FELs and conventional lasers is that their frequency is not attributed to transitions between discrete energy levels in atoms, molecules, and ions or to interband transitions in crystals. The working medium of a short-wavelength FEL is the beam of relativistic electrons moving in a strong periodic magnetic field, while the FEL wavelength admits continuous tuning by changing the energy of the electron beam. The progress of accelerator technology has allowed the advancement of FELs from the initially mastered long-wave region to shorter wavelengths, first to the infrared and visible regions and later to the ultraviolet region. The order of the day is designing FELs in the vacuum ultraviolet (VUV) and soft X-ray regions (see, for instance, Refs [3 – 6]). The Deutsches Elektronen Synchrotron (DESY) laboratory in Hamburg and the Stanford Linear Acceleration Center (SLAC) in California have set for themselves the highly ambitious task of advancing to the short-wave spectral region: the goal pursued is to generate coherent X-ray radiation down to wavelengths $\lambda \sim 0.1 - 1$ nm in the form of femtosecond pulses. Recently, a review paper by Plönjes, Feldhaus, and Möller [7] was published as well as a paper by a research group from the Brookhaven National Laboratory [8], which outlines the results of experiments on the first harmonic-generation FEL operating in the ultraviolet region. Both papers are concerned with the advancement of FEL technology to the X-ray band.

[1] Every so often, the term *synchrotron radiation* is broadly interpreted to include undulator radiation as a kind of electron radiation in a magnetic field.

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In our brief article we outline the contents of Refs [7] and [8]. In Ref. [7], the primary emphasis is placed on the single-pass mode of self-amplified spontaneous emission (SASE) and the pioneering experiments on its realization in the VUV region at DESY. The point is that advancing to the soft X-ray region of the spectrum is basically possible with retention of the classical FEL scheme, i.e., with the undulator placed in a resonator. In the resonator, advantage can be taken of multilayer-coated mirrors down to wavelengths $\lambda \sim 10$ nm. For wavelengths on the order of a few nanometers and even more so for $\lambda \sim 0.1$ nm, there exist no mirrors with an efficiency high enough to form the resonator. Single-pass amplification and the formation of a coherent beam in the SASE mode are needed.

Plönjes et al. [7] give a qualitative explanation of the heart of the SASE technique: "While the synchrotron radiation emitted by the electrons moves through the undulator at the speed of light, the electrons themselves actually travel slightly slower. The electrons therefore lag a little behind their emitted radiation, which can catch up with — and interact with — earlier electrons. This interaction will either accelerate or decelerate the electrons depending on their exact position and the phase of the light wave with which they interact... The net result is that the light wave pushes the electrons into smaller so-called microbunches which are separated by a distance corresponding to the wavelength of the undulator's magnetic field. Several electrons now start to emit light in tandem, producing light of a higher intensity. This light then sorts the electrons into tighter and tighter bunches, and causes them to radiate in phase. As a result, the radiation power rises exponentially with distance along the undulator, until it finally saturates."

In other words, the SASE mode resides in that the function of the resonator should be fulfilled by the density pattern of the electron beam, which self-adjusts and phases itself owing to the retroaction exerted on the beam electrons by the photons emitted in the undulator. The energy exchange with the electromagnetic wave generated by the electrons has the effect that longitudinal density modulation of the electron beam emerges, which enhances as the beam travels through the undulator. At the output of the undulator, the electrons turn to be grouped into microbunches in the form of thin disks spaced at the wavelength of the generated light, with the result that the electrons radiate largely in phase. As a consequence, the radiation power increases exponentially with the distance traversed through the undulator — basically, up to saturation. The number of microbunches into which the initial electron bunch splits may range into the thousands.

According to Ref. [7], an experiment aimed to verify the SASE mode was carried out at DESY. The efficiency of the SASE mechanism was demonstrated on the TESLA test facility (TTF) at DESY, and an FEL was first implemented in the VUV spectral region in single-pass mode, without employing a resonator (February, 2000). Persistent improvement in the facility made it possible to obtain amplification up to saturation in the 80 – 120 nm range for the duration of the radiation pulses of about 50 fs. The peak power was ~ 1 GW, which corresponds to $\sim 2 \times 10^{13}$ photons per pulse. A traditional Young's double-slit experiment revealed a high degree of 'transverse' coherence of the laser beam. The fringe visibility with a contrast of 70% between the maxima and minima was observed in the interference pattern.

Implementing an FEL in the X-ray region imposes extremely heavy demands on acceleration techniques. For instance, the X-ray FEL at DESY will, according to Ref. [7], require electron beams in the form of bunches that are approximately 200 fs long and have a peak current of about 5000 A. In this case, the X-ray radiation pulses will last ~ 100 fs. It is projected to arrange the electron beams in pulse trains on the order of 4000 in number with a repetition rate of 10 Hz.

At present, work is underway to upgrade the FEL, with the first stage of the work to be completed at the end of 2004. This work involves extending the FEL length from 100 to 250 m, and the short-wavelength limit is expected to shorten to 6 nm in this case. Projected for the second stage is the construction of a superconducting 20-GeV accelerator in a 2-km long tunnel. It will take eight years to complete the construction. After completion of the second stage, the FEL wavelength tunability range will be $\lambda \sim 6 - 0.1$ nm.

The Linac Coherent Light Source (LCLS) FEL at SLAC will be put in operation in 2008. It is intended to produce radiation in the wavelength range from 0.15 to 1.5 nm.

An immanent feature of the SASE single-pass amplification mode is the element of randomness in the initial conditions of laser pulse formation, which is related to random variations in electron beam parameters. As a consequence, the intensity and spectrum of the laser pulse at the FEL output also experience chaotic variations for each realization of the experiment. This is the reason for interest in the modification of the SASE mode, implemented in experiments at the Brookhaven National Laboratory at the National Synchrotron Light Source (NSLS) facility [8].

The experiments involve the high-gain harmonic generation (HGHG) of seed laser radiation. The heart of this technique is as follows. The first undulator is tuned to the frequency ω of laser radiation. The interaction between the electron beam and the seed laser radiation in the undulator results in electron density modulation after transit through the dispersion magnet that follows the undulator. In the second (main) undulator, which is tuned to the harmonic frequency $n\omega$ of the seed laser pulse, the microstructured electron beam generates coherent radiation with a frequency $n\omega$ and its further amplification up to saturation.

The experiment at NSLS [8] demonstrated the production of third harmonic ($\lambda = 266$ nm) pulses of the seed radiation of a Ti:sapphire crystal laser ($\lambda = 800$ nm, 9 ps long pulses). The first undulator is 0.8 m long, and the second (main) undulator 10 m long. For a seed laser pulse power of 30 MW it was possible to obtain saturated amplified radiation of the 3rd harmonic with a pulse length of 1 ps and an energy of ~ 100 μJ. The parameters of the FEL are more stable than in the SASE mode; they are less dependent on the variations of electron beam characteristics. The latter was demonstrated by conducting experiments for different intensities of the seed laser radiation, down to its shut-off. These experiments also show that the HGHG technique realized in Ref. [8] permits the undulator length to be substantially reduced in comparison with the SASE mode. However, it is pertinent to note that it remains unclear how far into the X-ray region it will be possible to advance the HGHG technique. This is determined by the possibility of developing the requisite 'seed' laser. Furthermore, employing a 'seed' laser to an extent comes into conflict with the key fundamental feature of an FEL — the independence of FEL operation from any reference frequencies relevant to atomic transitions, resonators, and so forth.

This conflict is resolved when advantage is also taken of the radiation of an FEL, as is considered by Saldin et al. [9]. In principle, a cascade of several FELs is possible; the undulator of each succeeding FEL is tuned to a specific harmonic of the previous FEL. An example of this type is provided by Ref. [9], which discusses the $0.8 \to 0.4 \to 0.2 \to 0.1$ nm succession. It is not improbable that a pathway of this type holds the greatest promise for advancing FELs to the X-ray region. This judgement is supported by successful experiments on the generation of the 3rd harmonic (3ω) of the seed laser radiation, conducted at the NSLS facility at the Brookhaven National Laboratory [8].

The range of prospective applications of short-wavelength FELs is extremely broad. It comprises experiments on femtosecond photochemistry, investigations into the structure of complex biomolecules, cluster physics, superdense plasma physics, etc., many of which could not have been pursued before. This issue is discussed at length by Plönjes et al. [7].

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