X-ray free electron lasers in the course of physics of Technical University

E V Smirnov
Bauman Moscow State Technical University, 105005, Moscow, 2nd Baumanskaya, 5;
E-mail: seva09@rambler.ru

Abstract. The article provides an overview of the X-ray sources based on synchrotron radiation sources of the generation of the four – X-ray free electron lasers (XFEL). The multipolar system of magnetic fields – undulator – allowing receiving high intensity beams of X-rays is considered. Important properties of the radiation emitted by XFEL are noted: ultra-high brightness, ultra short pulses, the high spatial coherence of the beam. There is an urgent need to include this material in the course of general physics and in the courses of X-ray optics for Russian Technical Universities.

1. Introduction
Since the discovery of mysterious x-rays by Wilhelm Conrad Roentgen in 1895 and up to the present day, the use of X-rays has been at the forefront of scientific and technical progress. Recall at least the fact that the first in the history of the Nobel Prize in physics was awarded in 1901 namely Roentgen.

In recent decades, a very important role in the expansion of the use of X-rays in science and technology has been played by the emergence of synchrotron X-ray sources and their amazing opportunities for research in various fields – physics, chemistry, crystallography, biology, medicine, etc. [1,2].

Figure 1. Increasing the brightness of the x-ray sources [3]
Recently, the main attention of specialists has been paid to the creation of X-ray free electron lasers (XFEL), the brightness of which can significantly, by nine orders of magnitude, exceed the brightness of synchrotron X-ray sources of the previous third generation (figure 1). These lasers open new frontiers in many fields of science and technology. Currently, such lasers are built in the USA, Japan, Germany (European XFEL) (table 1).

These major achievements in the field of X-ray sources, of course, should be made available to the University audience. Just as the creation of lasers in the optical range once led to the inclusion of relevant sections on forced radiation in the General physics course, the creation of X-ray lasers on free electrons should be reflected in the physics course taught at Technical universities.

Table 1. Comparison of the properties of hard X-ray sources [3]

| Project               | LCLS, USA | SACLA, Japan | European XFEL |
|-----------------------|-----------|--------------|---------------|
| Max. electron energy (GeV) | 14.3      | 8.5          | 17.5          |
| Wavelength range (nm)  | 0.13–4.4  | 0.06–0.3     | 0.05–4.7      |
| Photons/pulse         | $10^{12}$ | $2 \times 10^{11}$ | $10^{12}$ |
| Peak brilliance        | $2 \times 10^{30}$ | $1 \times 10^{30}$ | $5 \times 10^{30}$ |
| Pulses/second         | 120       | 60           | 27,000        |
| Date of first beam    | 2009      | 2011         | 2017          |

2. Physics of XFEL

The physics of x-ray free electron lasers are based on the laws of motion of electrons in a magnetic field and the emission of X-rays by rapidly moving electrons, i.e. it is a natural extension and deepening of electrodynamics in the physics course of Technical universities. An important point in this issue is to take into account the interaction of electrons with the electromagnetic radiation emitted by them.

Unlike gas, liquid or solid-state optical lasers, in which electrons are excited in bound atomic or molecular states; the source of radiation in XFEL is a beam of electrons in vacuum passing through a system with periodically alternating in the transverse direction of the dipole magnetic fields series of magnets arranged in a special way – the so-called undulator (figure 2). The X-ray energy of the XFEL is derived from the kinetic energy of the relativistic electron beam when it moves in the undulator.

Figure 2. Motion of relativistic electron beam in undulator

In the diagram shown in figure 2: 1 – the source and the electron accelerator; 2 – the system of magnets (the undulator); 3 – a trap for electrons; 4 – a beam of x-rays.
2.1. Radiation emitted by a conventional undulator

Before describing the collective self-consistent radiation in the XFEL, we first consider the radiation emitted by electrons in the absence of any interaction of electrons with radiation in the XFEL, namely, – spontaneous radiation of undulator. When electrons fall from the accelerator into the undulator, their initial phase is random, which leads to the fact that the radiation emitted by individual electrons is incoherent (figure 3a).

![Figure 3a](image)

Figure 3a. The principle of operation of the XFEL [4]

To obtain a coherent contribution, the phases of electromagnetic waves emitted by electrons must be correlated, i.e. $\phi_{i} \approx \phi_{k}$ for all electrons. This means that the cluster of electrons propagating in the undulator, as sources of radiation, must be periodically divided into micro-clusters (subbanches), the position of which varies by the wavelength of radiation. This is exactly what happens when electrons interact with the electromagnetic field emitted by them in the XFEL, as schematically shown in figure 3b.

This is due to the interaction between electrons and the radiation emitted by them. If the current of the electron bunch is large enough, and the undulator is long enough, then the effect that was not taken into account earlier in the analysis of 3rd generation SR sources – the effect of the emitted radiation on electrons – becomes significant.

2.2. XFEL with a high gain

The interaction of electrons with the wave emitted by them leads to the breaking up of a bunch of electrons into separate micro bunches (subbanches), whose position differs by the wavelength (figure 3b). All these micro bunches emit coherently, therefore, the radiation intensity in the XFEL, as compared to the intensity of ordinary incoherent radiation from an undulator, can increase many times. Recall that in most conventional optical lasers, the path available for amplifying radiation is expanded by a resonator – an external optical cavity. This is not possible for X-rays since X-ray mirrors for normal incidence are extremely ineffective. Therefore, in this case, it is necessary to use “one pass”, but with a large gain and a very long undulator.

The mechanism of operation of a free-electron laser for X-rays is shown in figure 4. (a) Optical amplification is carried out by relativistic electrons in the accelerator and is triggered by a periodic array of magnets (undulator). (b) The first waves emitted by electrons include the formation of micro bunches (subbanches). Electrons in micro bunches (d) are correlated so that they are separated from one another by wavelength. This means that all electrons belonging to the same subbunch oscillate in the phase. (e) It can be shown that this leads to an exponential increase in intensity with distance, which continues
until saturation is reached. In the saturation state, energy is transferred from the electrons to the wave and back.

**Figure 4.** The mechanism of a free-electron laser for X-rays [5]

3. Properties of X-ray radiation emitted by XFEL

The wavelength of the radiation emitted by the XFEL, taking into account the reduction of the Lorentz and the longitudinal Doppler effect has the form

\[
\lambda = \frac{L}{2\gamma^2}
\]

Here \(L\) is the period of the undulator and the Lorentz factor \(\gamma = \frac{1}{\sqrt{1-(v/c)^2}}\). At electron energy \(E=1\div14\) GeV, the undulator 120 m long with a period \(L=15\) mm, the wavelength \(\lambda\) of the x-ray emitted by the laser is 0.1-4.5 nm, and the pulse duration \(\sim 10\) fs.

The radiation emitted by LSE has the following very important properties:

1. Very high brightness, which is about \(10^9\) times the brightness of third-generation SR sources (see figure 1).
2. Ultra short pulses of up to several femtoseconds duration \((10^{-15})\) s).
3. High spatial coherence of the emitted beam.

Ultrashort XFEL pulses make it possible to conduct a dynamic study of physical and chemical processes, i.e. make the transition from time-and-space-averaged images of nanoobjects to “movie frames”, with which you can make films about physical processes and molecular reactions at the atomic level.

Due to the high brightness, coherence and short pulse duration using XFEL it is possible to study in detail the nanostructures and structures of biomolecules at the atomic level. Especially important is the short duration of XFEL pulses, since it allows one to obtain information about the structure of an object before the object is destroyed by the same laser pulse. For researchers, the high spatial resolution provided by the XFEL is very important – down to the fractions of a nanometer.

4. First applications of XFEL

One of the first works in the field of application of X-ray lasers in the study of the structure of biological objects should be noted on the study of mimivirus performed at Stanford in 2015. Considering the diffraction of X-rays on single mimivirus specimens introduced into the XFRL ray (figure 5) and investigating a series of images of diffraction patterns, scientists from Stanford University have compiled a precise three-dimensional model of the internal structure of this virus [6].
The researchers managed to create an algorithm for correct alignment of 198 diffraction patterns obtained. This is not a trivial task since each particle falls under the laser beam in an arbitrary orientation.

Figure 6a presents a 3d-reconstruction of the mimivirus, which demonstrates the asymmetry of its internal parts. In figure 6b – the projection of the obtained electron density, in Fig. 6c – a cut through the center of the projection. In this experiment, asymmetry of the internal structure of the virus was found.

**Figure 6.** The results of the study of the structure of a mimivirus using femtosecond crystallography using XFEL

5. **Conclusion. XFEL in the course of physics of Technical University**

As follows from the presented material the physics of x-ray lasers on free electrons do not contain anything fundamentally new in comparison with those sections of electromagnetism that are studied in the modern course of physics at Technical Universities of Russia. Since the opportunities offered by these lasers in science and technology, in the creation and development of new technologies, are extremely important, the section on X-ray lasers on free electrons, must be included in the physics course and studied by students of Technical Universities.

**References**

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