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Laser sources in the soft X-ray spectral region

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Abstract. The launch of the soft X-ray (6 – 30 nm) free-electron laser at the DESY research center in Hamburg is reported, and other new coherent soft X-ray laser sources are discussed.

The September issue of the *Physics World* journal presented a brief report [1] announcing that the first free-electron laser (FEL) operating at vacuum ultraviolet (VUV) and soft X-ray wavelengths had come online at the DESY research center in Hamburg, Germany. The laser, which was given the name VUV-FEL, generates radiation at wavelengths between 6 and 30 nm in the form of 10 – 50-fs long pulses. Thereby, it is the world's first operating laser which combines such most important characteristics as a short radiation wavelength (6 – 30 nm) and a short output pulse duration to provide an unparalleled high radiation intensity for this spectral region. A qualitative intensity estimate was given: the peak brilliance is 10 million times higher than that of the majority of synchrotron radiation sources.

The construction cost of the VUV-FEL (a linear accelerator, a 260-m long undulator, etc.) amounted to 117 million euros.

It is planned that some 200 scientists from 11 countries in the near future will start experimentation in cluster physics, solid state physics, surface physics, plasma physics, molecular biology, and some other branches of science.

The VUV-FEL operates in the self-amplified spontaneous emission (SASE) mode. The gist of the SASE mode was qualitatively explained by Plönjes et al. [2]: "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." The SASE mode is also discussed by Ragozin and Sobel'man [3]. The SASE mode ideology was approved by carrying out an experiment on the TESLA Test Facility (TTF) at DESY in February 2000, which implemented an FEL in single-pass mode and demonstrated 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 ($\sim 2 \times 10^{13}$ photons per pulse) [3].

By conducting a successful test of the VUV-FEL, the DESY center has made a major step forward from the TTF laser towards development of high-efficiency short-wavelength radiation sources. The demonstration of the SASE mode in the 6 – 30 nm spectral region is of fundamental importance for advancement to the domain of even shorter wavelengths. The point is that with shortening wavelength there emerge difficulties in realizing the customary FEL configuration with the undulator inside a resonator, as is the case, for instance, in the visible and infrared ranges. As the wavelength becomes shorter, the task of making an efficient resonator becomes difficult, if not impossible. The essence of the SASE mode lies in the fact 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. Therefore, a single-pass saturated amplification mode becomes possible without the use of an external resonator.

We emphasize that 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. The stochastic nature of the radiation can be overcome if the frequency-stabilized seeding radiation of sufficient intensity is injected into an FEL amplifier. This is precisely the intention in the second step of laser development [4]. It is intended to install a laser system of two undulators separated by a narrow-band monochromator. The first undulator operating in the SASE mode should generate the initial pulse. Next, the radiation pulse is transmitted through a high-resolution diffraction monochromator which fulfils the function of a narrow-band filter, thus producing the coherent seed which is amplified to saturation in the second undulator stage. The electron beam by-passes the monochromator and travels through a magnetic chicane that is employed to remove the partial beam density prebunching induced in the first undulator. The employment of stabilized seeding radiation should increase the output spectral brilliance by about a factor of 100. It is hypothesized that the output power of the seeded FEL will be concentrated in a single spectral line estimated to be about a hundred times

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narrower than the spectrum of the 'conventional' SASE-unseeded FEL. In addition to its short wavelength and tunability, the new FEL version will exhibit spatio-temporal coherence, similar to classical lasers of the 'optical' range.

Apart from the scientific program, the DESY center intends to employ the VUV-FEL as a pilot scheme for elaborating the design of the next laser called XFEL (X-ray free-electron laser) that is expected to start up at DESY in 2013. This laser with an overall length of 3.4 km (a superconducting 20-GeV accelerator in a 2-km long tunnel) will provide coherent radiation at even shorter wavelengths (0.1 – 6 nm) than the VUV-FEL and will have a better time resolution [2, 3].

It is planned that the VUV-FEL and the XFEL will run concurrently for a certain period in the effort of covering different types of experiments [1].

The XFEL designers are of the opinion that the construction and commissioning of the laser facility will substantially broaden the scope of applications of coherent short-wavelength radiation sources in physics, chemistry, and biology. In particular, the XFEL will enable studying the process of chemical bonding in time and determining the structure of proteins without having to crystallize them first, which is required in experiments involving existing synchrotron radiation sources.

According to designers' estimates, the construction cost of the XFEL will amount to some 900 million euros [1].

The DESY center is not the only research center that is working to advance an FEL to the far UV and X-ray spectral regions. The Stanford Linear Accelerator Center (SLAC) plans to build by 2009 an FEL called the Linac Coherent Light Source (LCLS) for the 0.15 – 6 nm spectral region, whose cost is estimated at $380 million [1 – 3, 5]. Highly promising work on modifying the SASE mode for short-wavelength FELs is being pursued at the National Synchrotron Light Source (NSLS) facility at the Brookhaven National Laboratory [3, 6]. The approach taken in this laboratory makes use of the seeding laser radiation of a picosecond laser. In the first undulator (modulator) tuned to the laser frequency, the seeding laser radiation introduces into the electron beam a small modulation in energy, which is subsequently transformed into longitudinal density modulation in the dispersion magnet that follows the undulator. The density-microstructured electron bunch next traverses the second undulator tuned to the frequency of a higher harmonic. As a result, 1-ps long harmonic pulses are generated at the output.

The impressive success of short-wavelength FELs has taken a half a century of development of acceleration and undulator technologies since the first publications on undulator radiation to come about [7, 8].

Side by side with FEL development, efforts are underway to make other laser radiation sources in the soft X-ray and vacuum ultraviolet (VUV) spectral regions. These include lasers utilizing radiative transitions of multiply charged ions of the Ne, Ni, etc. isoelectronic sequences in plasmas pumped by a high-power solid-state or iodine photodissociation laser, as well as a fast electric capillary discharge (see, for instance, Ref. [9]). The laser on the transition of the Ne-like Y ion ($\lambda = 15.5$ nm, pulse energy ~ 5 mJ, pulse duration ~ 80 ps, and divergence ~ 10 mrad) realized at the Lawrence National Livermore Laboratory (USA) [10] supposedly remains among the brightest sources of this kind. J J Rocca and his collaborators at Colorado State University, USA managed to create a laser system of relatively moderate size harnessing a fast electric capillary discharge in an Ar atmosphere [11]. Use was made of the $3p\,^1S_0 \to 3s\,^1P_1$ transition in Ne-like Ar ion ($\lambda = 46.9$ nm); the average output laser power amounted to 3.5 mW for a pulse length of 1.5 ns, an average pulse energy of 0.88 J, and a pulse repetition rate of 4 Hz. More recently, they succeeded in developing a compact version of the capillary discharge laser [12] that fits on top of a small desk measuring 0.4 by 0.4 m (or 0.4 by 0.8 m with the inclusion of the vacuum pump); the average pulse energy is 13 μJ for a pulse repetition rate of 12 Hz. By using pulse-periodic laser excitation (~ 1 J, 8 ps, 5 Hz) of solid targets with a prepulse, Rocca and his collaborators demonstrated gain-saturated laser action on the $3p\,^1S_0 \to 3s\,^1P_1$ transition in Ne-like Ti (32.6 nm), V (30.4 nm), and Cr (28.6 nm) ions, as well as on the $4d\,^1S_0 \to 4p\,^1P_1$ transition in Ni-like Mo (18.9 nm), Ru (16.5 nm), Pd (14.7 nm), Ag (13.9 nm), and Cd (13.2 nm) ions. The average pulse energy was equal to 300 nJ in V, and 530 nJ in Ti ions for an average output power of 1.5 and 2.6 μW, respectively [13].

One more source of coherent VUV radiation is furnished by the generation of high-order harmonics of femtosecond solid-state laser radiation in a gas jet or a gas-filled capillary. Although the pulse energies in the 10 – 20 nm range are measured in nanojoules (for a pulse repetition rate of about 1 kHz), on this way it has been possible to advance into the subfemtosecond (attosecond) duration range [14, 15].

The strong points of alternative approaches to FELs — compactness, moderate cost, and simplicity, as well as the capacity to master the attosecond duration range — open them up to their own application areas.

When comparing the above approaches to the generation of coherent radiation in the far VUV and soft X-ray spectral regions, it is pertinent to note that FELs are unrivaled leaders as regards the collection of parameters and the outstanding possibilities for application. Their strong points are, first of all, their high average power, wavelength tunability, and the possibility in principle to attain the ~ 0.1 nm frontier.

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