1 Introduction

This Technical Design Report of the European X-Ray Free-Electron Laser (XFEL) Facility has been prepared by a large community of scientists and engineers and was edited at Deutsches Elektronen-Synchrotron (DESY) laboratory under the supervision of the European XFEL Project Team.

In September 2004, at the initiative of the German Federal Ministry for Education and Research, a Memorandum of Understanding (MoU) on the preparatory phase of the European XFEL Facility was drafted, and has so far been signed by 13 countries. Under the MoU, an International Steering Committee was created, with the task of overseeing all activities of the preparatory phase of the new European Facility. The International Steering Committee, as foreseen by the MoU, appointed two Working Groups of experts, one on Scientific and Technical Issues (STI), the other on Administrative and Financial Issues (AFI); it also appointed a European Project Team, to be hosted by DESY, with the specific task of preparing all documents necessary for the interested countries to decide to proceed to the Foundation of the European XFEL Facility.

The present report is one of these documents. The following chapters provide a description of the scientific motivations, the background provided by the Tera-Electronvolt Superconducting Linear Accelerator (TESLA) collaboration and the Free-electron LASer in Hamburg (FLASH) facility at DESY (previously known as the VUV-FEL), the physical and technical layout of the new facility, the technical description of the accelerator and of the undulator systems, an indication of the priorities and a technical description of the components of the photon beamlines and the experimental stations.

1.1 Accelerator-based light sources

It is evident that light is perhaps the most important tool by which we know the world around us. This is true not only for our everyday experience, but also for the scientific pursuit of an understanding of nature. Experiments using electromagnetic waves, in a range of wavelengths going well beyond the relatively small range of visible light, have played an important role in the development of modern science. Atomic and molecular spectroscopy, i.e. the study of the characteristic wavelengths emitted by matter in the gas phase, has been fundamental in establishing the laws of quantum mechanics and has given us important information on the composition of stars and planets. Röntgen's discovery of x-rays in 1895, and the subsequent demonstration, by von Laue and others in 1911, of x-ray diffraction by crystals laid the foundations of crystallography, by which we can unravel the atomic structure of crystals. Every secondary school student is familiar with Watson and Crick's exploit of 1953, which identified the double helix structure of DNA from the x-ray diffraction work of Franklin and Wilkins, probably the most famous piece of crystallographic work ever.

It is, therefore, hardly surprising that scientists have been eager to obtain the brightest light sources, in order to understand the atomic and electronic structure of matter even more. In parts of the infrared, in the visible and in the near UV, the invention of the laser has provided an extraordinary tool, which has led to many exciting discoveries and applications. Over a much broader range, encompassing not only the infrared and the visible, but also the whole of the UV and the x-rays to wavelengths well below 0.05 nm, the tool of choice for many scientists is synchrotron radiation (or synchrotron light), i.e. the bright emission of highly collimated electromagnetic waves from electrons (or positrons) orbiting at ultrarelativistic energies in storage rings with diameters of tens to several hundreds of meters (generally called, slightly improperly, “synchrotrons”). In spite of their large dimensions and associated cost, there are some 50 or so storage rings around the world built and operated solely for the purpose of producing light, and more are under construction.

The driving force behind the development of light sources is the optimisation of their brilliance (or spectral brightness), which is the figure of merit of many experiments. Brilliance is defined as a function of frequency given by the number of photons emitted by the source in unit time in a unit solid angle, per unit surface of the source, and in a unit bandwidth of frequencies around the given one. The units in which it is usually expressed are photons/s/mm^2/mrad^2/0.1% BW, where 0.1% BW denotes a bandwidth of $10^{-3}\ \omega$ centred around the frequency ω. As one can appreciate from the definition, brilliance puts a premium not only on the photon flux (photons per second in a given bandwidth), but also on the high phase-space density of the photons, i.e. on being radiated out of a small area and with high directional collimation.

The brilliance of available synchrotron sources has been growing at a formidable pace in the last decades, since the first attempts at a systematic exploitation of storage rings as sources of photons for scientific experiments in the 1960s. At that time, some electron storage rings designed and built for nuclear and sub-nuclear physics started to be used parasitically, for some fraction of the time, as sources of photons for experiments in atomic, molecular and solid state physics. These machines are nowadays referred to as “first generation light sources”. The experimental results were so interesting that they stimulated the construction of dedicated rings, designed and optimised to serve exclusively as light sources. Examples of these “second generation” machines are the BESSY I ring in Berlin, the two National Synchrotron Light Source rings in Brookhaven, NY (USA), the SuperACO ring in Orsay, near Paris, and the Photon Factory in Tsukuba (Japan). In the 1990s a new generation of rings started operation. These “third generation” synchrotron sources are characterised by a reduced emittance (i.e. reduced phase-space volume) of the circulating particle beam, and by the extensive use of undulators as radiation sources, with a further increase of the brilliance by several orders of magnitude. Undulators are arrays of magnets, typically 2 to 5 m long, inserted in a straight section of the ring, which produce magnetic force on the drifting electrons and modify their straight trajectory into a zig-zag one, producing a large number of bends with intense radiation emission. Examples of this generation of sources are the European Synchrotron Radiation Facility (ESRF) in Grenoble, the Advanced Light Source in Berkeley, California, Elettra in Trieste, BESSY II in Berlin, Max-II in Lund, Sweden, the Advanced Photon Source, in Argonne, Illinois, Spring 8 in Japan, and the Swiss Light Source in Villigen (CH).

One feature of the storage ring as a light source is that the same electrons turn for hours and hours, going hundreds of thousands and even millions of time per second through the same undulators and dipole magnets. The radiofrequency cavities in the ring give back the radiated energy to the electrons (they typically radiate about 0.1% of their energy at each turn) so that they keep turning and turning. Every times an electron emits a photon, a non-deterministic quantum process, recoil effects perturb its momentum and position. These millions and millions of “random” perturbations per second determine a lower limit to the emittance that the magnetic lattice of the ring can impose on the electrons, i.e. they prevent the phase-space volume of the electrons from being too small. A careful and thorough quantitative analysis shows that it is not possible to substantially lower the emittance of a storage ring below the values achieved in third generation machines. This is the reason why the pursuit for the fourth generation has oriented itself to “single-pass” or “few-passes” machines, where a given electron goes only very few times through an undulator.

1.2 Free-electron lasers

At the start of the 21st century, we are witnessing a revolution in synchrotron source intensities, with fourth-generation sources emerging in the form of free-electron lasers (FEL), made possible by recent progress in accelerator technologies, developed in connection with high-energy linear colliders. X-ray FELs (XFELs) have made a new regime of intensities accessible, thus opening up a fundamentally new physical domain.

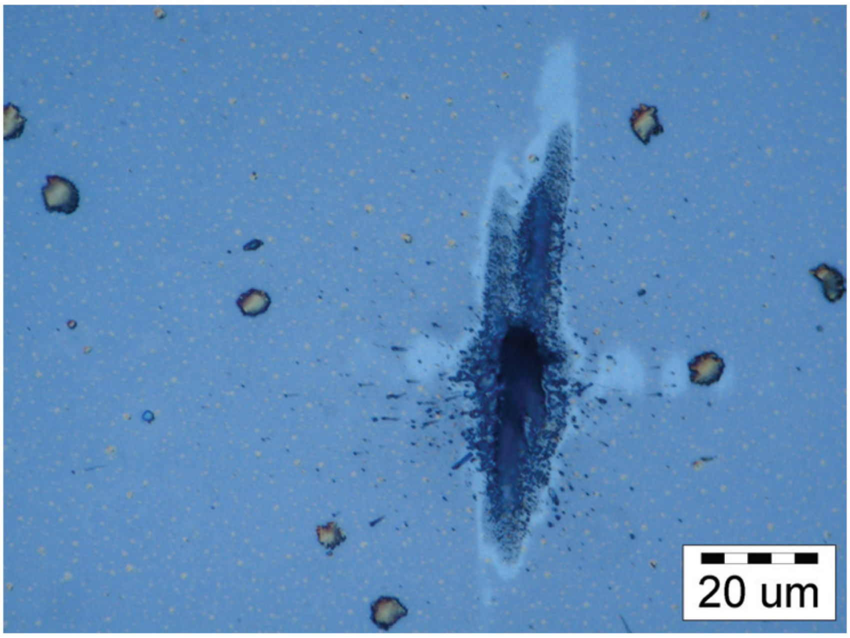

Figure 1.2.1 *Interaction of powerful Vacuum Ultraviolet (VUV) radiation with solids* **[1-1]**. *Ablation of Gold target after one pulse of the VUV Self-Amplified Spontaneous Emission (SASE) FEL at the TESLA Test Facility (TTF) at DESY. Radiation wavelength is 98 nm, pulse duration is 40 fs, peak power density is about 100 TW/cm*^{2}.

Introduction

A new era of synchrotron radiation research has begun with the first user experiments on a VUV FEL based on SASE. Radiation pulses of 98 nm wavelength, with 40 fs pulse duration and a peak power of 1.5 GW, were obtained by the TTF at DESY. Wabnitz et al. reported the first scientific results from this device in **[1-2]**. They illuminated Xenon clusters with high-intensity (10^{14} W/cm^2) pulses and observed unexpectedly strong absorption of the VUV radiation. Such a highly nonlinear interaction between light and matter at VUV wavelength range has never been seen before and these fascinating results show the potential of this new class of light sources for scientific research. Further work on FLASH at DESY has been focused on the wavelength range around 80 nm at the request of the second user group. These users studied the ablation of various materials with intense VUV radiation (see Figure1.2.1). FLASH at DESY is currently operating at a wavelength down to 26 nm, and is being extended to cover the soft x-ray spectral range down to wavelengths of 6 nm. Regular user operation started in spring 2005 **[1-3]**.

Compared to present day synchrotron radiation sources, its peak brilliance is more than 100 million times higher (see Figure 1.2.2), the radiation has a high degree of transverse coherence and the pulse duration is reduced from the ~ 100 picoseconds (ps) down to the ~ 10 fs time domain. While modern third generation synchrotron light sources are reaching their fundamental performance limit, recent success in the development of FLASH at DESY has paved the way for the construction of the novel type of light source which will combine most of the positive aspects of both lasers and synchrotrons.

In the following, a slightly more technical description of the physics of FELs is given. The FEL is not, strictly speaking, a laser, i.e. a device based on quantum-mechanical stimulated emission, and its operation is completely described within the framework of classical physics. The FEL is a system consisting of a relativistic electron beam and a radiation field interacting with each other while propagating through an undulator. The FEL is most closely related to vacuum-tube devices. As with vacuum-tube devices, FEL devices can be divided in two classes: amplifiers and oscillators (see Figure 1.2.3). The FEL amplifier is seeded by external radiation, and there is no feedback between the output and input. The FEL oscillator can be considered as an FEL amplifier with a feedback. For an FEL oscillator in the optical wavelength range the feedback is carried out by means of an optical resonator. FELs based on the oscillator principle are limited, on the short-wavelength side, to ultraviolet wavelengths, primarily because of mirror limitations. Free-electron lasing at wavelengths shorter than ultraviolet can be achieved with a single-pass, high-gain FEL amplifier only.

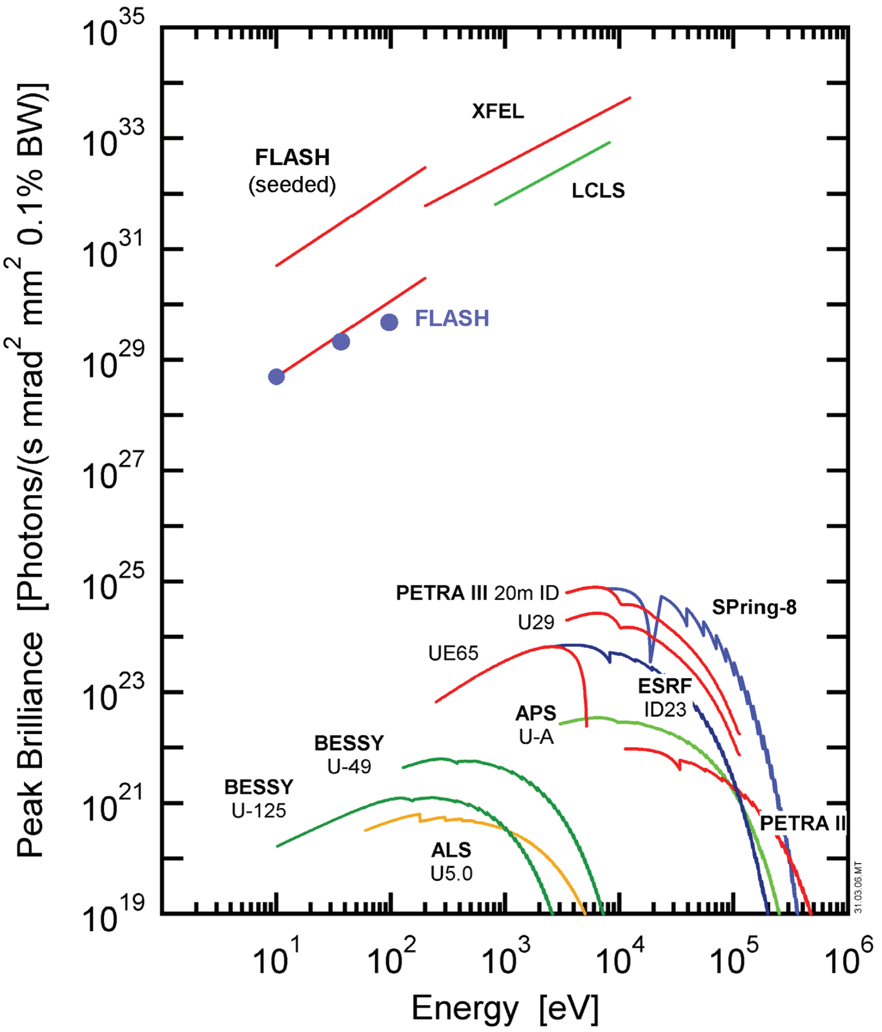

Figure 1.2.2 *Peak brilliance of XFELs versus third generation SR light sources. Blue spots show experimental performance of the FLASH at the DESY.*

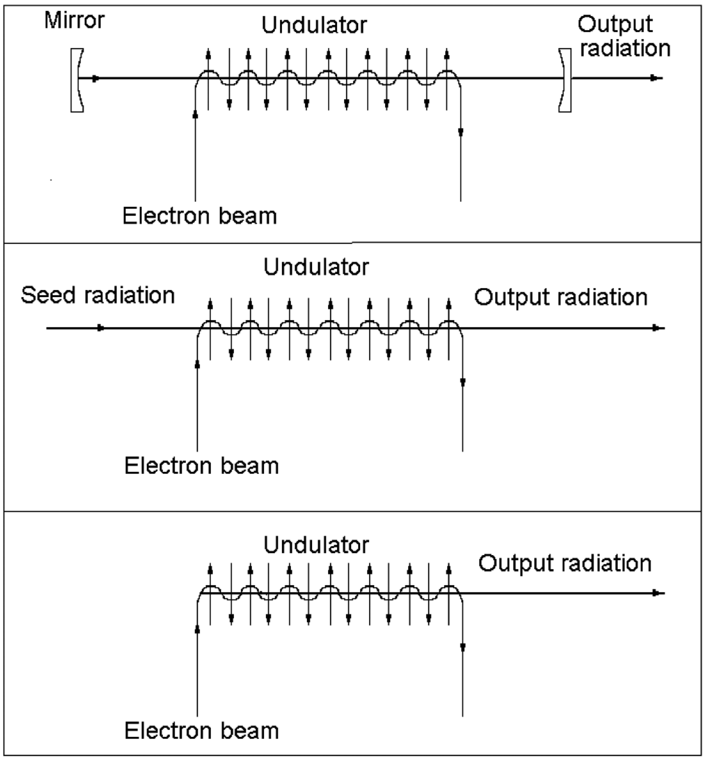

Figure 1.2.3 *Free-electron laser configurations: oscillator (top), seeded amplifier (middle), and SASE FEL (bottom).*

The high gain FEL amplifier is an attractively simple device (see Figure 1.2.3). It is a system consisting of a relativistic electron beam and an undulator. At a first glance, this is essentially the setup of a third generation synchrotron radiation source familiar to all users. However, the FEL process is considerably more complicated than the spontaneous emission from relativistic electrons travelling down an undulator. It is essentially a phenomenon that can be described as a radiation-induced collective instability. The basic principle of radiation-induced instability can be described within the standard picture for the generation of synchrotron radiation. Electrons propagate along a sinusoidal path and emit synchrotron radiation in a narrow cone in the forward direction. When an electron beam goes through an undulator, it emits radiation at the resonance wavelength $\lambda = (\lambda_w / 2\gamma^2)(1+K^2)$. Here λ_w is the undulator period, $mc^2\gamma$ is the electron beam energy, $K = eH_w \lambda_w / (2\sqrt{2}\,\pi\, mc)$.

The electromagnetic wave is always faster than the electrons, and a resonant condition occurs when the radiation is ahead of the electrons by a distance λ after one undulator period. The fields produced by the moving charges in one part of the electron bunch react on moving charges in another part of the bunch. Thus, we deal with some tail-head instability leading to a growing concentration of particles wherever a small perturbation started to occur.

The FEL collective instability in the electron beam produces an exponential growth (along the undulator) of the modulation of the electron density on the scale of undulator radiation wavelength (micro-bunching). Several conditions must be satisfied for the collective FEL instability to occur. A parameter of crucial importance is the electron beam density in the six-dimensional phase-space. In practice, a (intensity) gain in excess of 10^7 - 10^8 can be obtained in the short wavelength regime. At this level of gain, the shot noise of the electron beam is amplified up to complete micro-bunching. In the beginning – without micro-bunching – all the N electrons can be treated as individually radiating charges, and the resulting spontaneous emission power is proportional to N. With complete micro-bunching, all electrons radiate almost in phase. This leads to a radiation power growth as N^2, and thus, to an amplification of many orders of magnitude with respect to spontaneous emission of the undulator.

Fluctuations of the electron beam current play the role of an input signal to the XFEL. The shot noise corresponds to the fact that photoelectron emission from a cathode is a random process. The emission of electrons from the cathode is believed to be a Poisson process, and from this assumption alone the total fluctuations in current can be deduced. Such random fluctuations in the beam current correspond to an intensity modulation of the beam current at all frequencies simultaneously – including, of course, the frequency to which the undulator is tuned. When the electron beam enters the undulator, the presence of the beam modulation at frequencies close to the resonance frequency initiates the process of radiation.

The actual physical picture of start-up from noise should take into account that the fluctuations of current density in the electron beam are uncorrelated, not only in time, but in space as well. Thus, a large number of transverse radiation modes are excited when the electron beam enters the undulator. These radiation modes have different gain. Obviously, as they progress down the undulator, the high gain modes will increasingly dominate and we can regard the XFEL as a filter, in the sense that it filters the components corresponding to the high gain modes from an arbitrary radiation field. If we consider the undulator radiation from the point of view of paraxial optics, then we immediately see that the high gain modes are associated with radiation propagating along the axis of the undulator, as opposed to radiation propagating at an angle to the axis, which has a low gain. Hence, for a sufficiently long undulator, the emission will emerge in a single (fundamental) transverse mode and the degree of transverse coherence of the output radiation will approach unity.

The amplification bandwidth of a high gain FEL amplifier is determined by the number of undulator periods N_w within one gain length. The gain length is the distance over which the power increases by a factor of e (e=2.718…). Since we study the start-up from shot noise, we assume the input current to have an homogeneous spectral distribution. The spectrum of the transversely coherent fraction of radiation is concentrated within the narrow band, $\Delta\lambda / \lambda = 1/(2\pi N_w)$. The typical amplification bandwidth of the XFEL is of the order of 0.1%. The electron beam in XFEL transfers enormous peak power. For instance, for typical XFEL parameters (energy of electrons 17.5 GeV and peak current 5 kA), it is about 100 TW. The conversion efficiency of the kinetic energy of electrons into light is in the order of the amplification bandwidth, therefore, the peak power of X-ray radiation is in the multi-GW range.

1.3 Historical development of the XFEL

The origin of the FEL history can be traced to the paper by Pantell, Soncini, and Puthoff **[1-4]**, which contains the first complete set of distinctive features of the FEL: stimulated scattering of the radiation on relativistic electrons moving in the undulator. After the pioneering work of Madey and co-authors **[1-5]** on the first FEL oscillator, and subsequent theoretical work by Kroll and Mc Mullin on the possibility of single-pass gain **[1-6]** the XFEL, which was proposed in 1982, has had more than 20 years of development. The first proposal to use the FEL collective instability to produce optical radiation using a single-pass amplifier starting from shot noise, was published by Kondratenko and Saldin in 1979 **[1-7]**. Single-pass amplification with start-up from noise was also investigated by Bonifacio, Pellegrini, and Narducci **[1-8]**. Following the terminology of quantum lasers (amplified spontaneous emission, ASE), Bonifacio et al. **[1-9]** used the term "self amplified spontaneous emission (SASE)" in connection with an FEL amplifier starting from shot noise. This terminology does not completely correspond to the actual FEL physics (in fact, it is just a vacuum-tube device), but the abbreviation "SASE FEL" has been widely accepted by the physics community.

The first proposal to use the instability in a single-pass amplifier starting from shot noise for a soft (5 nm) XFEL was published by Derbenev, Kondratenko, and Saldin in 1982 **[1-10]**. This proposal envisaged the use of a storage ring to provide the electron beam. At that time, an electron storage ring was the accelerator delivering the highest electron beam quality. Later on, a similar proposal was discussed by Murphy and Pellegrini in 1985 **[1-11]**. However, the limitations on emittance, peak current and energy spread limited the shortest FEL wavelength to about 10 nm.

The next important step was the proposal by Pellegrini, in 1992, of using a recently developed radio frequency (RF) photocathode electron gun coupled to the two-mile Stanford linear accelerator (linac), to produce lasing in the hard x-ray region **[1-12]**. A study group coordinated by Winick developed this concept, calling it the Linac Coherent Light Source (LCLS). This work led many groups to start development of SASE FELs in the infrared to VUV spectral ranges, to demonstrate the concept and develop the technologies necessary to build a linac-based XFEL. First experimental results were obtained in 1997. The SASE FEL theory received some experimental support when the high-gain linear regime of the SASE FEL operation in the infrared range was achieved by Pellegrini and co-workers **[1-13]**. This was the first unambiguous demonstration of the SASE FEL mechanism.

After many years of development, efforts to produce saturated lasing using a SASE FEL started to come to fruition at the start of this century. In September 2000, a group at Argonne National Laboratory (ANL) demonstrated saturation in a visible (390 nm) SASE FEL **[1-14]**. In March 2001, the VISA collaboration, between Brookhaven National Laboratory (BNL), UCLA and the Stanford Linear Accelerator Centre (SLAC), demonstrated lasing to saturation at 830 nm **[1-15]**.

In September 2001, the VUV-FEL at DESY demonstrated lasing to saturation at 98 nm **[1-16]**. In January 2002, saturation was achieved at 82 nm **[1-17]**, and in November 2005 the lasing at 26 nm, the shortest wavelength at which any FEL works, was demonstrated. Recently, the German government, encouraged by these results, launched the proposal of a European collaboration to establish a hard X-ray SASE FEL user facility – the European X-ray Free-Electron Laser Facility at DESY. The US Department of Energy (DOE) has given SLAC the go ahead for the LCLS to be constructed at SLAC. These devices will produce 100 fs x-ray pulses with over 10 GW of peak power **[1-18, 1-19]**, and will be able to produce intensities in the order of 10^{18} W/cm^2. The main difference between the two projects is the linac: the LCLS will be based on the existing room temperature SLAC Linac; the European XFEL, on the other hand, is foreseeing the construction of a superconducting Linac based on the TESLA technology.

The XFEL based on superconducting accelerator technology will make possible not only a jump in peak brilliance by ten orders of magnitude, but also an increase by five orders of magnitude in average brilliance. The LCLS and European XFEL projects are scheduled to start operation in 2009 and 2013, respectively.

References

[1-1] L. Juha et al., *Ablation of various materials with intense XUV radiation,* Nucl. Instrum. and Methods A 507 (2003) 577.

[1-2] H. Wabnitz et al., *Multiple Ionization of Atom Clusters by Intense Soft X-rays from a Free-Electron Laser,* Nature 420 (2002) 482.

[1-3] V. Ayvazyan et al., *First operation of a free-electron laser generating GW power radiation at 32 nm wavelength*, Eur. Phys. J. D37 (2006) 297.

[1-4] R.H. Pantell, Y. Soncini, and H.E. Puthoff*, Stimulated Photon-Electron Scattering*, IEEE Quantum Electronics 4 (1968) 905.

[1-5] D.A.G. Deacon et al., *First Operation of a Free-Electron Laser,* Phys. Rev. Lett. 38 (1977) 892.

[1-6] N.M. Kroll and W.A. McMullin, *Stimulated emission from relativistic electrons passing through a spatially periodic transverse magnetic field,* Phys. Rev. A 17 (1978) 300.

[1-7] A.M. Kondratenko, E.L. Saldin, *Generation of Coherent Radiation by a Relativistic Electron Beam in an Undulator,* Sov. Phys. Dokl. vol. 24, No. 12 (1979) 986; Part. Accelerators 10 (1980) 207.

[1-8] R. Bonifacio, C. Pellegrini and L.M. Narducci, *Collective Instabilities and High-Gain Regime in a Free-Electron Laser,* Opt. Commun. 50 (1984) 373.

[1-9] R. Bonifacio, F. Casagrande and L. De Salvo Souza, *Collective Variable Description of a Free-Electron Laser,* Phys. Rev. A 33 (1986) 2836.

[1-10] Ya.S. Derbenev, A.M. Kondratenko, and E.L. Saldin, *On the Possibility of Using a Free-Electron Laser for Polarization of Electrons in Storage Rings,* Nucl. Instrum. and Methods 193 (1982) 415.

[1-11] J.B. Murphy and C. Pellegrini, *Free electron lasers for the XUV spectral region*, Nucl. Instrum. and Methods A 237 (1985) 159.

[1-12] C. Pellegrini, *A 4 to 0.1 nm FEL Based on the SLAC Linac,* Proceedings of the Workshop on Fourth Generation Light Sources, SSRL-SLAC report 92/0.2, (1992), p. 364.

[1-13] M. Hogan et al., *Measurements of Gain Larger than 105 at 12 µm in a Self-Amplified Spontaneous-Emission Free-Electron Laser,* Phys. Rev. Lett. 81 (1998) 4867.

[1-14] S.V. Milton et al., *Exponential Gain and Saturation of a Self-Amplified Spontaneous Emission Free-Electron Laser*, Science, 292 (2001) 2037.

[1-15] A. Tremaine et al., *Characterization of a 800 nm SASE FEL at saturation,* Nucl. Instrum. and Methods A483 (2002) 24.

[1-16] V. Ayvazyan et al., *Generation of GW Radiation Pulses from a VUV Free-Electron Laser Operating in the Femtosecond Regime*, Phys. Rev. Lett. 88 (2002) 104802.

[1-17] V. Ayvazyan et al., *A new powerful source for coherent VUV radiation: Demonstration of exponential growth and saturation at the TTF free-electron laser,* Eur. Phys. J. D20 (2002) 149.

[1-18] P. Audebert et al., *TESLA XFEL: First stage of the X-ray laser laboratory – Technical design report* (R. Brinkmann et al., Eds.), Preprint DESY 2002-167 (see also http://xfel.desy.de).

[1-19] The LCLS Design Study Group, *LCLS Design Study Report*, SLAC reports SLAC-R521, Stanford, 1998 (see also http://www-ssrl.slacstanford.edu/lcls/CDR).