The European X-ray Free-Electron Laser Project

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C 8 The European X-ray Free-Electron Laser Project [1]

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[1] Lecture Notes of the $43^{\rm rd}$ IFF Spring School "Scattering Methods for Condensed Matter Research: Towards Novel Applications at Future Sources" (Forschungszentrum Jülich, 2012).

1 Introduction

Synchrotron radiation sources have revolutionized UV and x-ray experiments in many fields of science. The driving force behind the development of light sources is the optimization of their brilliance (or spectral brightness), which is the figure of merit for 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.

In the most modern synchrotron sources (the so-called "third-generation light sources", such as the ESRF, Elettra, Diamond, Swiss Light Source, etc.) the average brilliance of undulator radiation reaches values up to $10^{19} - 10^{20} photons/s/mrad^2/mm^2/0.1\%BW$ [1]. Taking into account the pulsed nature of the sources, i.e. the filling patterns and revolution times of storage rings, this corresponds to peak brilliance values of $10^{24} photons/s/mrad^2/mm^2/0.1\%BW$. In order to achieve such values, two ingredients are essential. The first ingredient is the extensive use of undulators as radiation sources. An undulator is a set of two arrays of magnets, located in a straight section of the ring above and below the vacuum chamber where electrons run, and subjecting the electrons to a vertical magnetic field varying with position in a sinusoidal manner. The corresponding Lorentz force on the electrons results in an oscillating trajectory, with many bending points from which emission of synchrotron radiation occurs. In undulators, the broadband radiated power of bending magnet radiation, due to the interference of the different emission points along the trajectory, is concentrated in a spectrum of narrow lines, centered about the wavelengths:

$$n\lambda = (\lambda_u/2\gamma^2)(1 + K^2/2) \tag{1}$$

Here $n = 1, 2, 3 \ldots$ is the order of the harmonic, λ_u is the period of the undulator magnetic structure, γ is the electron energy, expressed in units of the electron rest energy, and K is the undulator parameter, a number of order 1 given by $K = \gamma\theta$, where θ is the maximum angular deviation of the electrons from their unperturbed trajectory, induced by the undulator magnetic field. It can be shown that Eq. (1) identifies the wavelength of the fundamental harmonic λ as the distance by which one electron lags behind the emitted photons after traveling over the distance λ_u from the emission point.

The second ingredient is the reduction in the phase-space volume of the circulating electrons in the two transverse directions (the horizontal and vertical directions perpendicular to the average orbit). These quantities are called horizontal (vertical) emittances and are roughly speaking a measure of the horizontal (vertical) size of the electron bunch times the angular divergences of the corresponding velocity vectors projections. Progress in accelerator physics has allowed reduction of the horizontal emittance to values of order $1\,nm\,rad$, as presently achieved by the $6\,GeV$ Petra III ring at DESY [2]. It is intuitive that the properties of small dimension and high collimation of the electron beam translate into corresponding attributes of the radiated photons, and therefore in higher brilliance. A substantial further reduction of emittance values towards the fundamental limits is presently the subject of extensive research on the so called "ultimate" storage ring source [3]. Rings under construction, such as the $3\,GeV$ NSLS II in Brookhaven [4] and Max IV in Lund, Sweden [5], aim at emittances of a few $0.1\,nm$, and machines on the drawing board, such as the $4.5\,GeV$ PEP-X project at SLAC in Stanford [6] aim at the $0.1\,nm$ and below range. In general, the achievement of very low emittances involves the use of long rings (both Petra III and PEP exceed $2\,km$ in circumference), special devices such as damping

wigglers, and daring innovations in lattice design, with compromises on maximum current, lifetime and ease of injection.
The light source becomes diffraction limited for radiation at wavelength λ when the emittance is reduced towards and beyond $\lambda/4\pi$. This means that there is a high degree of transverse coherence in the radiation at that wavelength.
Another fundamental limitation of storage rings concerns the bunch length, i.e. the duration of the light pulses. Typically, pulse duration in storage rings is limited to some $30\,ps$; if the bunch length is compressed below such a length, the bunch will anyway return to the original length after a certain number of turns, because of the intense emission processes in the insertion devices and in the bending magnets; the equilibrium length results from a balance between quantum excitations and radiation damping [3]. Substantially shorter pulses can only be achieved at the expense of dramatic reductions of the radiated intensity. This poses a limitation to the time scales which can be explored by time-resolved experiments with synchrotron sources: at full power they are limited to the $\simeq 50\,ps$ time scale; access to the scale of atomic motions and rearrangements (typically, sub-ps), is only possible by techniques such as "bunch slicing", which produce pulses of $100\,fs$, but with intensities limited to $\simeq 10^3$ photons per pulse, and a few kHz pulse repetition rate [7]. On the other hand, there is a high demand for ultrafast experiments capable to explore atomic motions and configuration changes on a sub-ps time scale. The development of fs lasers in the infrared, the visible and near UV has shown a variety of interesting phenomena essential for the understanding of chemical reactions, phase transitions, etc.; only shorter wavelengths, however, can resolve smaller and smaller distances, and ultimately only x-rays can provide us with atomic position information.
In the following sections we shall review progress in the realization of x-ray FEL (free-electron laser) sources, based on linear accelerators, which allow generation of transversely coherent ultrashort (typically $10 - 100\,fs$) pulses, with a spectacular increase of some nine orders of magnitude in peak brilliance with respect to third-generation synchrotron sources (see Fig. 1). The linear accelerator allows indeed to obtain very low emittances, and, in addition, is a single-pass machine, in which the electron bunches run only once through the undulator, keeping the original bunch length.

2 The SASE process and single-pass Free-Electron Lasers

In the undulators of a synchrotron source, electrons are forced to follow a zigzag trajectory by the device magnetic field. There is a definite phase relationship between the radiation emitted by the same electron at different points of the trajectory, and, since the fields overlap (the angle θ of maximum deviation, entering the undulator parameter K of Eq. (1), is of order $1/\gamma$, i.e. of the aperture of the radiation cone) there is an interference, which is constructive only for the wavelengths described by Eq. (1). Notice, however, that under such circumstances all interference between the fields radiated by different electrons is averaged out, as no definite phase relationship occurs between them. The reason is that electrons are randomly distributed inside the bunch, with no correlation between positions of different electrons. In order to have such interference, electrons should be spatially ordered; considering for simplicity two electrons, if the longitudinal coordinate (projection on the undulator axis of the position) of the second lags behind that of the first by an integer number of wavelengths, the corresponding radiation fields will superpose in phase after the electrons have run through an integer number of undulator periods: remember that the light radiated by the second will "catch up" with the first, getting

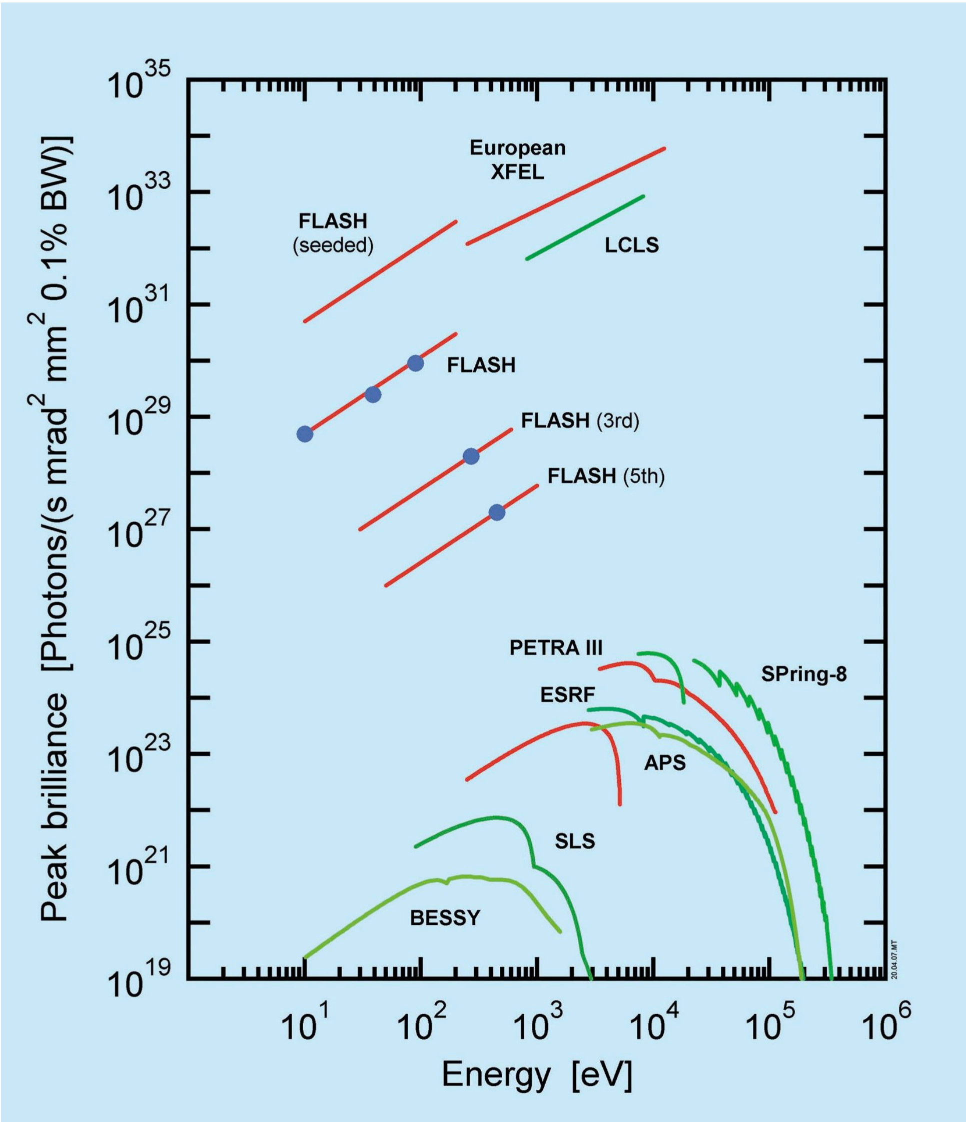

Fig. 1: *Peak brilliance as a function of photon energy of FLASH, the LCLS in Stanford and the future European XFEL in Hamburg (an upgraded version of FLASH based on "seeding", see Section 5, is also shown). For comparison, some 3rd generation synchrotron radiation facilities are shown. Dots denote measured values at FLASH. The third and fifth harmonics of the FLASH undulator, on which lasing was observed, but not saturation, are also shown.*

closer to it at the rate of one wavelength λ per undulator period λ_u. The intensity radiated from the two electrons will be four times larger than that of one single electron. From these simple considerations one can understand how coherence effects between different electrons can arise when the density in the bunch (integrated over the transverse directions) has a Fourier component at the wavelength of the radiation, i.e. when this density shows a modulation at the radiation wavelength. The intensity of the radiation in such cases becomes proportional to the square of the number of electrons involved in the modulation.

For short wavelengths, in the nm range or below, controlling the electron density on that scale may appear extremely difficult. However, in a certain sense, the radiation does it for us. This microbunching phenomenon occurs because the electric field of the radiation has a small component parallel (or antiparallel) to the electron velocity (see Fig. 1), which tends to accelerate some electrons and decelerate those which are positioned one half radiation wavelength ahead or behind, leading to bunching on the radiation wavelength scale. Whenever shot-noise fluctuations in the electron bunch introduce a Fourier component of the appropriate wavelength in the electron density, the coherence effect between electrons described above increases the radiated intensity; it turns out that, for a sufficiently low-emittance and high peak-current electron beam, in a sufficiently long undulator, the stronger radiation field, via the microbunching process, reinforces the density fluctuation, and so on, in a runaway process that leads to exponential amplification of the radiated intensity. The amplification proceeds until saturation, which occurs when the intense radiation and subsequent recoil effects lead to a degradation of the electron beam quality that prevents further amplification. This single-pass process, known as Self-Amplified Spontaneous Emission (SASE) was theoretically identified many years ago, long before electron beams of sufficient density and quality were technologically feasible [8], [9], [10].

The first experimental demonstration was in the visible range, at the LEUTL facility at Argonne National Laboratory [11], and later pushed to lower and lower wavelengths (down to $4.2\,nm$) at the $1.2\,GeV$ FLASH facility at DESY, in Hamburg [12], [13]; the 2009 results [14] at the $14\,GeV$ Linac Coherent Light Source (LCLS) at SLAC in Stanford, California, demonstrated SASE lasing at $0.15\,nm$, opening the era of hard x-ray FELs. In spring 2011, SASE amplification at $0.12\,nm$ was also observed at the $8\,GeV$SACLA facility at SPring-8 in Japan [15], and more recently down to $0.08\,nm$.

The linear accelerator (linac) geometry is essential in allowing the low emittance and the high peak current required to trigger the SASE process. During acceleration in a linac, the normalized emittance $\epsilon_n = \gamma\epsilon$ is approximately constant, and this implies that the emittance decreases as the energy γ grows. So, if a sufficiently low emittance is available already at the start, i.e. at the electron gun of the injector system, emittances well below the $0.1\,nm$ range are achievable. Today's state of the art injector systems achieve normalized emittances of order or below $1\,\mu m\,rad$ for bunch charges of order $1\,nC$, and even lower for reduced bunch charges. Since $\gamma \simeq 20,000$ at an energy of $10\,GeV$, emittances below $\epsilon \simeq 0.05\,nm\,rad$ are achievable. Furthermore, the required high peak currents can be achieved by compressing the bunches in one or several suitable magnetic chicanes, down to bunch lengths of order $\simeq 10\mu m$, corresponding to pulse durations of $30\,fs$. With lower bunch charges, few fs pulses were demonstrated at LCLS [16].

It is important to underline that, whereas in a synchrotron source the limitation on attainable wavelengths is only related to the tunability of undulators (i.e. to the possibility of modifying the K parameter by using a mechanical movement of the magnet support structure to change the magnetic field in the device), in a SASE FEL the achievement of saturation requires a sufficient

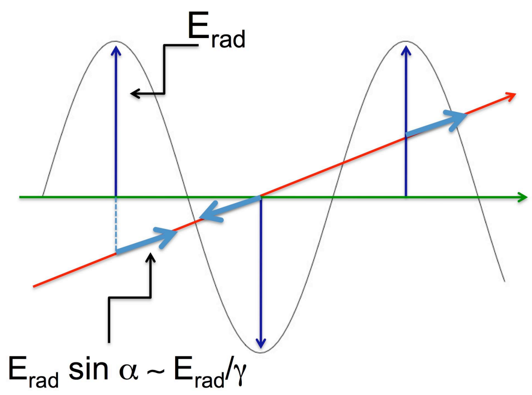

Fig. 2: *Schematics of the microbunching process. The radiated electromagnetic wave (black wavy line) propagates along the undulator axis (green line), and the electron trajectory (red line) is at an angle $\alpha \sim 1/\gamma$ to this axis. Therefore the radiation electric field E_{rad} has a small component (blue arrows) parallel or antiparallel to the electron velocity, $E_{rad} sin \alpha$, which can perform work on the electrons and therefore accelerate or decelerate them.*

length of the undulator. The characteristic length of the exponential intensity growth is the gain length, L_g, which is roughly proportional [17] to ${\epsilon_n}^{5/6}/I^{1/2}$; here the normalized emittance and the peak current of the bunch are the crucial quantities. A good estimate for the saturation length is a factor 9 or 10 times the gain length. Therefore, for SASE lasing at a given wavelength it is not only necessary to tune the undulator at that wavelength; the emittance must be small enough and the peak current high enough to ensure that the saturation length is shorter than the undulator length.

3 Scientific case for hard X-ray Free-Electron Lasers

The most important features of the x-ray pulses of Free-Electron Lasers (FEL's) are the short duration, typically on a few $10\,fs$ time scale, the high peak brilliance, translating into a number of photons per pulse in the $10^{11} - 10^{12}$ range; the very high degree of transverse coherence [18]; and a typical bandwidth of the pulses in the $\Delta\lambda/\lambda \simeq 10^{-3}$ range. This means that the number of photons, that typically reach the sample in one second in an experiment on the best synchrotron beamlines, can be delivered on some $\simeq 30\,fs$ in an FEL experiment.

The very short duration of pulses and the high degree of coherence are beginning to deliver a big scientific payoff in x-ray structural experiments. In traditional crystallography, x-ray diffraction is used to unveil the electron density, for example in a molecule, by analyzing the intensity distribution of the Bragg peaks in the diffraction pattern of a crystal of the molecule in question. This is done because the signal is enhanced by the coherent superposition process at the origin of Bragg reflections (scattering power growing with $\simeq N^2$ rather than N = number of molecules) and also because the large number of photons needed to acquire the signal is distributed between many molecules, limiting the effects of radiation damage. On the other hand, the spatial periodicity of the crystal is not an indispensable route to the acquisition of sufficient information to reconstruct the electronic density of a system; theoretical [19] and experimental [20] evidence show that collection of data with a spatially coherent soure, on a fine grid of scattering vectors (more precisely, "oversampling" on a grid finer than the Nyquist spacing, i.e. the inverse of the size of the diffracting specimen) can allow the solution of the phase problem by iterative algorithms. This applies to both general non-periodic objects and to very small crystals, smaller than the illuminated volume, in which periodicity is broken by the sample surfaces. In principle, delivering some $10^{11} - 10^{12}$ photons to such a sample, reconstruction is possible. However the problem of radiation damage imposes very tight constraints, especially for biological samples. Photoelectron and Auger electron emission induces a high number of defects, charging of the target and raising of its effective temperature, with a large number of atoms displaced from their original positions. Here the short duration of the FEL pulse, however, brings a decisive advantage: data collection takes place on a time scale too fast for the atoms to move, the observed structure is therefore the unperturbed one, even if the sample is deeply distorted, or even completely destroyed in the process.

The first experimental demonstration of this principle was the single-pulse coherent diffraction imaging by Chapman *et al.* [21], in which a diffraction pattern sufficient to reconstruct an image by standard iterative algorithms was acquired using a single FLASH pulse of $25\,fs$ duration. As a result of the high number of photons in the pulse, photoelectric absorption deposits sufficient energy in the sample (a microstruture milled through a silicon nitride membrane) to bring it up to a temperature of 60,000 K and to destroy it completely. Nonetheless, the extremely short duration of the pulse allows collection of the relevant data before the sample is blown apart.

Although the use of 32 nm radiation limits the resolution to a few tens of nm, which could be obtained easily by other, non-destructive, methods, the interest of this experimental breakthrough lies in the proof-of-principle of single-shot imaging of non-periodic objects. One of the chapters of the scientific case for hard x-ray FEL's is the hope to be able to image non-periodic biological objects (from individual cells down to large macromolecules), with resolution approaching the atomic scale, without the need for crystallization - which is a major hurdle in structural biology studies. Very significant steps towards this goal were achieved at the LCLS, where images of single large viruses were acquired and reconstructed [22], and sub-nm resolution structures of biomolecules were obtained from nanocrystalline samples, dispersed in aqueous solution [23].

One can imagine other fields in which the possibility to acquire images on an ultra-fast time scale can be important. For example, in the study of liquids with x-rays (and even more so with neutrons) so far, the acquisition time has always been much larger than that of the disordered translational and rotational molecular motions that permanently rearrange the configuration: only average quantities such as radial distributions are measurable. With an FEL source one can take snapshots of instantaneous configurations and think of questions such as the statistics of configurations in a liquid versus that in the amorphous solid; or a real time observation of nucleation phenomena at the liquid-solid boundary.

The possibility of single-shot structural information, as confirmed by these novel experiments, opens naturally the door to the study of time-dependent phenomena on the atomic scale. If one can get structural information on a system in a very short time, one could dream of following the evolution of chemical reactions in time, e.g. biochemical processes, catalytic mechanisms, and so on. However, the sample destruction by a single shot manifestly interrupts the time evolution one would like to investigate. There is a way out, though, as long as the object of investigation (the molecules of the reagents, for example) is available in many indistinguishable copies, and there is a possibility of fast "triggering" of the process; for example, if we consider a photochemical reaction triggered by an IR laser flash, the "pump and probe" experimental strategy can be put to work: we repeat the experiment on many copies of the system, each time enforcing a different time delay between the start of the process and the interrogation by an FEL pulse. Each acquisition is like one snapshot of a movie, and when they are put together, they deliver the time evolution of the phenomenon. There are limits to the precision of determining the time delay of an IR laser pulse and an FEL pulse: but the experience so far acquired at FLASH and LCLS shows that this is possible with an accuracy of the order of one or a few hundreds of fs (see for example [24]). This is still one order of magnitude longer than the duration of either pulse, but it is an interesting time scale for a variety of photochemical processes.

So far only measurements of structural quantities such as the charge density were discussed. We know, on the other hand, that other important observables and order parameters, such as magnetic moments, and other electronic order parameters such as orbital ordering are also accessible to x-ray investigations, especially in the resonant scattering regime. Recent experiments demonstrated the possibility of pump-probe studies of these order parameters (see [24]). Measurement of a single-shot resonant magnetic scattering pattern at the Co M edge of a Co-Pt multilayer system was reported in [25]).

In addition, the remarkable transverse coherence can be used to probe fluctuation dynamics by X-ray Photon Correlation Spectroscopy, with much increased possibilities with respect to those achievable in a synchrotron source.

Other uses of powerful FEL pulses are envisaged in plasma physics and more generally in the

Table 1: *Basic parameters of the three hard x-rays FEL projects (see text); brilliances are expressed in* $photons/s/mrad^2/mm^2/0.1\%BW$.

Project	LCLS	SACLA	European XFEL (SASE1)
Max. Electron Energy (GeV)	14.3	8.0	17.5
Min. Photon Wavelength (nm)	0.15	0.08	0.05
Photons/pulse	$\sim 10^{12}$	2×10^{11}	$\sim 10^{12}$
Peak Brilliance	1.5×10^{33}	1×10^{33}	5×10^{33}
Average Brilliance	4.5×10^{22}	1.5×10^{23}	1.6×10^{25}
Pulses/second	120	60 X N	27 000
Date of first beam	2009	2011	2015

study of high energy-density states of matter. The creation of plasma-like or other highly excited states of matter by FEL pulses has been mentioned before, essentially as a drawback for imaging experiments. However, to achieve in the laboratory conditions usually found only in astrophysical environments, and to investigate portions of the temperature/density phase diagram of materials usually not encountered at the surface of the earth, is very appealing. A vigorous activity in this field already exists, using powerful (up to petawatt) IR or visible lasers to generate the corresponding conditions. X-ray pulses have the definite advantage of a much larger penetration depth, resulting in a more uniform excitation profile in the sample part accessible to the probe (e.g. a subsequent x-ray pulse).

4 The European XFEL and the international competition for hard x-ray FEL's

The remarkable results obtained at the FLASH facility have allowed considerable progress in the understanding of the SASE process itself, and demonstrated the revolutionary potential of FEL experiments for a variety of disciplines. This has provided further stimulation to projects for the realization of hard x-ray FEL's. There are at present three major projects worldwide, one in the USA (the Linac Coherent Light Source, LCLS, in Stanford, California [26]) which obtained the first beam at 0.15 nm in April 2009; one in Japan (the SACLA, SPring-8 Angstrom Compact Laser, at SPring-8 [27]), currently completing its commissioning and expecting the first users soon; and one in Europe (the European XFEL in Hamburg, currently under construction [28]); all of them target wavelengths of the order or smaller than $0.1\,nm$ suitable for experiments determining structural properties with atomic resolution. The main features of the three projects are summarized in Table I.

More recently projects in Switzerland [29] and in South Korea [30] were started.

The LCLS project in Stanford has been welcoming users for experiments since late 2009. It uses the pre-existing SLAC high energy linear accelerator, or, more precisely, one third of its length, to accelerate electrons and feed them into an undulator with fixed gap, $112\,m$ long, to produce coherent x-rays with photon energies between 0.8 and 8 keV, i.e. with wavelengths between 1.5 and $0.15\,nm$. Tuning of the photon energy occurs by tuning of the electron energy

Fig. 3: *Layout of the European XFEL, showing the trace of the underground tunnels running under the northwest districts of Hamburg and the neighbouring town of Schenefeld*

between 4.5 GeV and the maximum energy 14.3 GeV. The linear accelerator has been modified to accept the bunches produced by a RF photocathode gun and preserve the low-emittance beams required for the SASE process; and also to include two stages of bunch compression. The repetition rate is 120 pulses per second. Remarkably, the low emittance values obtained by lowering the charge of individual bunches allowed achievement of robust SASE lasing [14] at $0.15\,nm$, with attainment of saturation intensity requiring only about one half of the available undulator length. These very exciting results provide strong confirmation to the validity of the SASE principle and to the reliability of computational simulations of the process.

The Japanese SACLA project is characterized by the attempt to reduce the size and the cost of large FEL installations by daring innovations, such as the use of a thermionic cathode gun to produce very low emittance bunches, the use of C-band accelerator technology to generate very high acceleration gradients, a very high compression ratio for the bunch length (4,000) and the use of a tunable in-vacuum undulator, with a $4\,mm$ gap in the standard operation for generation of $0.1\,nm$ radiation with an electron energy of $8GeV$, considerably lower than in the competing projects. The design value for the number of pulses per second varies, as there are 60 RF pulses per second, and each of them can be filled with more than one bunch. There are five undulators foreseen in the ultimate configuration of the facility. So far the commissioning is making good progress with lasing down to $0.8\,nm$ reported.

The European X-ray Free-Electron Laser Facility (European XFEL), which started construction in January 2009 in Hamburg, is deriving its basic technical choices from the successful FLASH experience. The photoinjector and the gun are directly derived from the corresponding FLASH components and so is the basic superconducting accelerator technology, first developed in the context of the international TESLA collaboration, coordinated by DESY. The 1.7 km long accelerator, located in an underground tunnel (see Fig. 3), can provide electrons up to $17.5\,GeV$

energy, and feed them into two beamlines according to the scheme displayed in Fig. 4 [28]. The first beamline contains a hard x-ray undulator (SASE1), for $\leq 0.1\,nm$ coherent photons and a soft x-ray one (SASE3), which can sometimes make use of the "spent" beam resulting from saturation of SASE1 to generate soft X-rays in the 0.4 to 1.6 nm range (at 17.5 GeV electron energy: softer x-ray radiation is of course obtained if the electron energy is reduced). The second beamline contains a second hard x-ray undulator (SASE2), identical to SASE1, and two tunnels downstream in which two further undulators can be located. In the baseline design for the initial phase of the facility, each of the three SASE undulators will feed into two instruments. The six instruments foreseen to become available in 2015 are:
Hard x-ray instruments: 1. Materials Imaging and Dynamics (MID); its purpose is to use the coherence of the beams to explore dynamic fluctuations in matter, accessing unprecedented length and time scales.
2. X-ray Femtosecond Experiments (FXE) the purpose of this instrument is to explore ultrafast phenomena in the physics and chemistry of solids, liquids and soft-matter systems.
3. Single Particle, Cluster and Biomolecular Imaging (SPB); this instrument is devoted to the pursuit of structural studies in non-periodic systems, especially in structural biology.
4. High Energy-Density Science (HED); here the idea is to use the FEL pulses to bring a target to extremely high values of temperature and then to interrogate it in order to access regions of the phase diagram not easily accessible in the laboratory (e.g. warm dense matter, in which ordinary densities of solid materials are present at temperatures such that $k_B T \simeq 1 - 10eV$).

The soft x-rays instruments are:
1. Small Quantum Systems (SQS); this instrument should continue and extend to higher photon energy the innovative experiments pioneered at FLASH on ions, atoms and molecules.
2. Soft X-ray Coherent Scattering and Spectroscopy (SCS); this is a multi-purpose instrument, on which different end-stations should be mounted for a variety of techniques in the soft x-ray analysis of materials, such as RIXS, absorption, photoemission, etc.

The use of the superconducting technology is a formidable advantage of the European facility: it allows a very wide flexibility in the operating conditions; in particular, it allows to fill each RF pulse with a very large number of electron bunches. In the European XFEL it is foreseen to have a train of up to 2,700 bunches in each of the 10 RF pulses (of 600 μs duration) per second. It will be possible to switch the electrons from one beamline to the other during each bunch train. The possibility to use such a large number of bunches, with a spacing of 220 ns, implies considerable development work in the field of detectors, as well as in the lasers for pump-probe experiments, which should be able to follow the time structure of the XFEL pulses. This is already in progress. The average brilliance, corresponding to this large number of X-ray pulses per unit time, could prove very important in experiments such as coherent diffraction of non-periodic objects, where hits of the FEL pulses with a molecule are expected to be very rare, but a large number of them needs to be accumulated in order to achieve a satisfactory signal-to-noise ratio.
The civil construction started in January 2009, with advance funding from the German government. At present, a Convention concerning the Construction and Operation of a European X-ray Free-Electron Laser Facility was signed by representatives of twelve countries (Denmark, France, Germany, Greece, Hungary, Italy, Poland, Russia, Slovakia, Spain, Sweden, Switzerland), The largest contributors to the construction costs are Germany and Russia. The Convention foresees the creation of a limited liability company under German law, which exists, under

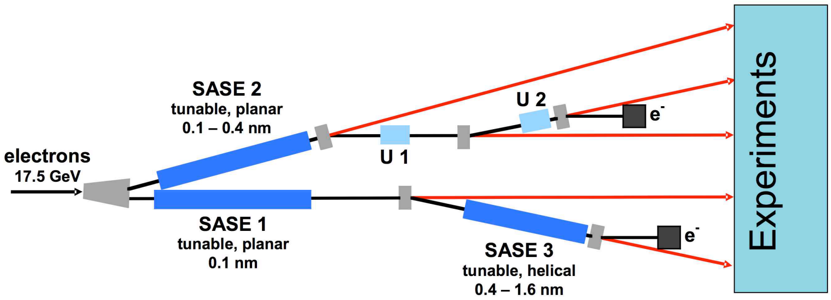

Fig. 4: *Schematic layout of the arrangement of undulators at the European XFEL. The initial configuration of the facility does not include the spontaneous emission undulators U1 and U2, nor the helical version of SASE3, which is going to be initially built in the planar version.*

the name European X-ray Free-Electron Laser Facility GmbH, since September 2009, and is in charge of the project.

5 Future perspectives: self-seeding of hard x-ray FEL's

We have so far mentioned the transverse coherence properties of SASE FEL radiation, but did not address the issue of its longitudinal (or temporal) coherence. In point of fact, longitudinal coherence is very poor, and a SASE x-ray pulse is composed of a very large number of incoherent spikes (see Fig. 5). The reason can be understood as follows. In order to achieve full longitudinal or temporal coherence the microbunching described in Section 2 should uniformly encompass the whole bunch length: a density modulation should extend from the tail to the head of the bunch without interruption or phase variation. This cannot happen in most cases because the microbunching is imprinted by the emitted radiation as it catches up with the electrons that were ahead of the emission point. But the resonance condition for the undulator (Eq. (1) with $n = 1$) ensures that the radiation gains a wavelength λ over the electrons in a distance λ_u (a magnetic period). This implies that in an undulator with N magnetic periods, the maximum length of a coherent microbunching pattern is $N\lambda$. If this is shorter than the bunch length, one can expect different parts of the bunch to display unrelated (phase incoherent) microbunching, each producing a SASE spike with no phase relationship to the others. A coarse estimate of the number of spikes is, according to the previous argument $N_s = L_b/N\lambda$, where L_b denotes the bunch length. For typical parameters for the European XFEL, where $\simeq 4000$ undulator periods of $40\,mm$ constitute the SASE1 or SASE2 undulators, and a bunch length of $30\,\mu m$, corresponding to $100\,fs$ duration, at $0.1\,nm$ one can estimate $N_s \simeq 70$. On the same basis the duration of a spike is of order of $1\,fs$ and this the basic estimate of the coherence time of the source, which is very small.

In order to improve the longitudinal coherence, that is to obtain a smooth single-mode lineshape instead of the ragged pattern of Fig. 5 , various *seeding* schemes are possible. The idea behind seeding is to start the amplification process not by random shot noise fluctuations in the bunch electron density distribution, but by an external better controlled radiation pulse, with a pulse energy exceeding that of random fluctuations. In longer wavelength FEL's the external pulse is provided by an IR or visible laser, that is used to generate suitable harmonics, either in a non-linear medium, or in an additional undulator. This is the principle of seeding schemes, as tested in Japan [31] and adopted in soft x-ray facilities such as FERMI@Elettra in Trieste [32].

In hard x-ray facilities, generation of laser harmonics is not going to work, as the order of the harmonic would be too high. Therefore various versions of *self-seeding* are being thought of, in which the seeding radiation is produced in a short undulator with the same parameters as the long SASE one that follows. The radiation from the first undulator is monochromatized and superposed again to the electron bunch in the SASE undulator. The most promising *self-seeding* scheme was proposed in [33] and should be tested at LCLS. A self-seeded x-ray FEL could have a $\Delta\lambda/\lambda$ between 10^{-4} and 10^{-5} , with an enhancement of the peak power in the $\simeq 100GW$ range and would be a remarkable progress in the field.

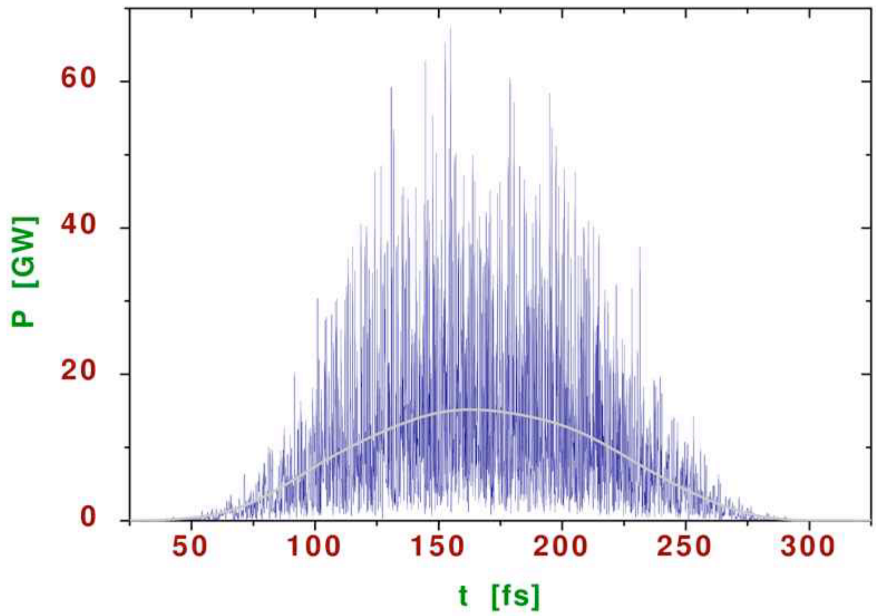

Fig. 5: *Simulation of the temporal profile of a 12.4 keV European XFEL pulse from SASE1 (Courtesy of M.V. Yurkov)*

6 Conclusions

As we tried to illustrate briefly, this is a very exciting time in the development of accelerator-based light sources, as many new and revolutionary facilities are starting operation. Their promise is great, and the scientific user community should accordingly prepare for them. The scientific pay-off of the new facilities, in fact, will to a large extent be determined by the progress of instrumentation for experiments. The new extremely bright and ultrafast sources require, for their full exploitation, corresponding progress in optics, diagnostics, and above all detectors and data acquisition strategies. They might also imply a change in the size and composition of the experimental teams. The early attention to instrumental issues and a close relationship with potential users from the very beginning may turn out to be a factor of importance for the success of the new generation of light sources.

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