The TESLA X-ray Free Electron Laser Project at DESY

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Abstract

This paper presents the basic features and the schematic layout of the X-ray Free Electron Laser (XFEL) facility which is planned at DESY/Hamburg in combination with the TeV Superconducting Linear Accelerator (TESLA) for high energy physics collider experiments. This 4th generation X-ray source will continue the tremendous developments of synchrotron radiation sources and its scientific applications over the past three decades. In comparison to third generation sources the photon peak brilliance increases by about ten orders of magnitude, the time resolution decreases into the fs regime and a spatially fully coherent beam will be available.

1 Introduction

Since their discovery in 1895 X-rays have played a crucial role in basic science and medical diagnostics, as well as in industrial research and development. In spite of the efforts made for building more powerful X-ray tubes, progress has been limited, certainly if seen in the light of the tremendous progress made with synchrotron radiation sources (Figure 1). The development of storage ring designs with special magnet components, called wigglers and undulators, over the past twenty years has led to third generation machines specially designed for synchrotron radiation research, which are surpassing by far their design goals. This illustrates impressively how predictable accelerator physics has become today. Most recent successes in accelerator development concerning linear accelerators have opened the route for a new jump in photon source quality. Very long undulators coupled to linear accelerators can provide coherent X-rays with true laser properties. Although such a source of coherent laser-like X-rays would find many applications and the search for such an X-ray laser has occupied many scientists, a practical solution to this problem has not yet been realized. To be an efficient research tool, such a source has to provide stable intensities with short pulses and repetition frequencies similar to what is found in optical lasers. Exactly this can become possible by using the so-called self amplified spontaneous emission process SASE [1], [2].

First discussions on machine related issues started in the workshop 'Prospects of a

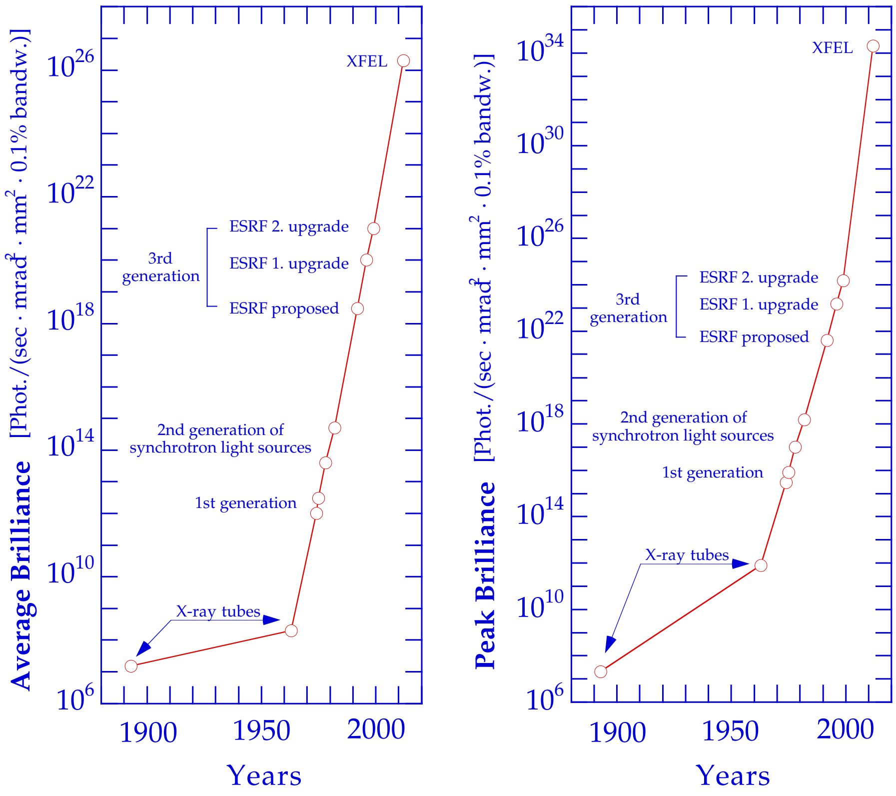

Figure 1: Brightness development of X-ray sources since the discovery of X-rays

1Å Free-Electron Laser' held at BNL in 1990 [3]. They were continued discussing fourth-generation X-ray sources at three further workshops held at SLAC in 1992 [4], at the ESRF 1996 [5] and at APS in 1999 [6]. In parallel to this several workshops were held to specify the scientific case for such a new laser source [7, 8, 9, 10].

Finally two design studies were presented [11, 12]. These proposed linac based XFELs should provide X-rays at wavelength down to 1 Å in pulses of 100 fs length with intervals between pulses ranging from ns to ten ms. This source is fundamentally different from a spontaneous undulator in that the emitted radiation causes electron density modulation at the wavelength within each electron bunch and thus leads to true coherent emission. This is clearly seen in the spectral shape displayed in Figure 2.

The coherently emitted XFEL lines appear in addition to the spontaneously emitted undulator spectrum which can extend into the MeV regime. The time average spectral brilliance of the XFEL, as seen in Figure 3, would exceed by 10^3 to 10^4 those of undulators at the new third generation synchrotron radiation sources ESRF, APS, and SPring-8. In fact the spectral brilliance of *each pulse* would exceed the spectral brilliance per second

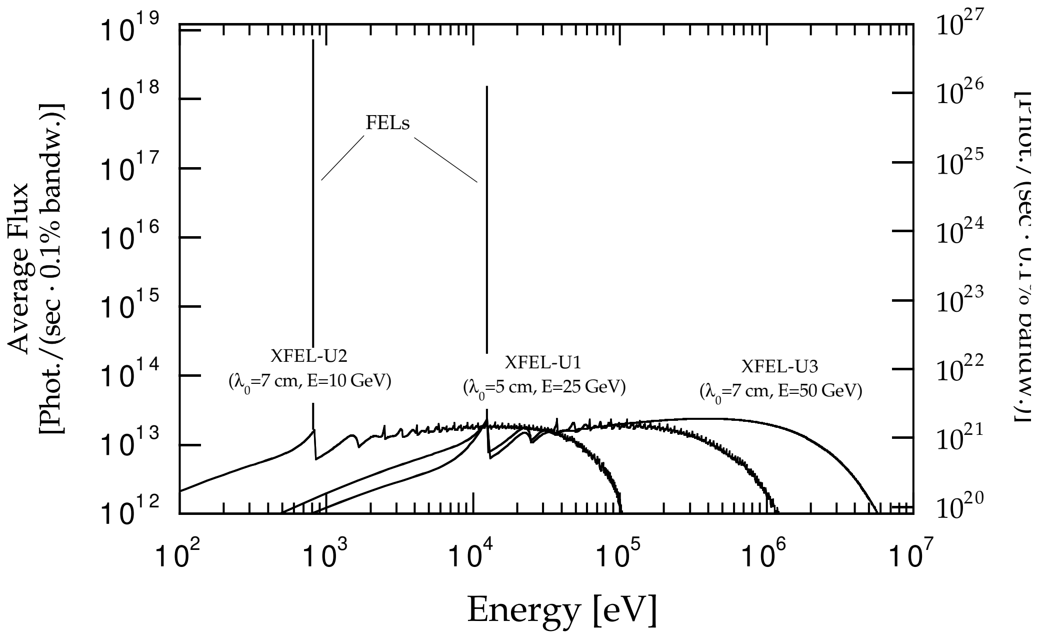

Figure 2: Average and peak flux for undulators U1, U2, and U3 with fundamental FEL line (parameters see tables 2, 3 and 4)

at the new sources. In addition, the peak brilliance, as displayed in Figure 4, within each hundred fs pulse would be greater by more than 10 orders of magnitude than in third generation synchrotron radiation pulses of more than 30 ps duration.

This proposed radiation source with a circular focal shape would have a diameter as small as 20 μm with an opening angle as little as 1 μrad. At third generation sources the corresponding values from undulators are typically $100 \times 100\,\mu\mathrm{m}^2$ with a divergence larger than $30 \times 30\,\mu\mathrm{rad}^2$. For an XFEL this means that even at 100 m distance the beam will have opened up to only 0.1 mm. This is a characteristic which relates to the fact that the XFEL beam is spatially fully coherent. The number of photons per coherence volume as displayed in Figure 5 is above the 10^{10} regime and thus comparable to optical lasers.

2 The coherent X-ray source

The progress of the various Linear Collider R&D projects over the last years not only forms the basis for the construction of a Linear Collider, but it also contributes significant knowledge on how to build a Free Electron Laser (FEL) at wavelengths much shorter than the visible. The reason is that for both devices it is crucial to generate and accelerate electron beams of unprecedented quality. Taking into account the progress in other fields of accelerator technology (such as the development of photoinjectors and advanced undulators), it now seems possible to construct such a laser (called XFEL for short in this report) providing coherent X-ray radiation at spectacular brilliance. A LINAC is the proper choice of an electron accelerator of particle energy E since the emittance decreases as E^{-1} while it increases as E^2 in a storage ring.

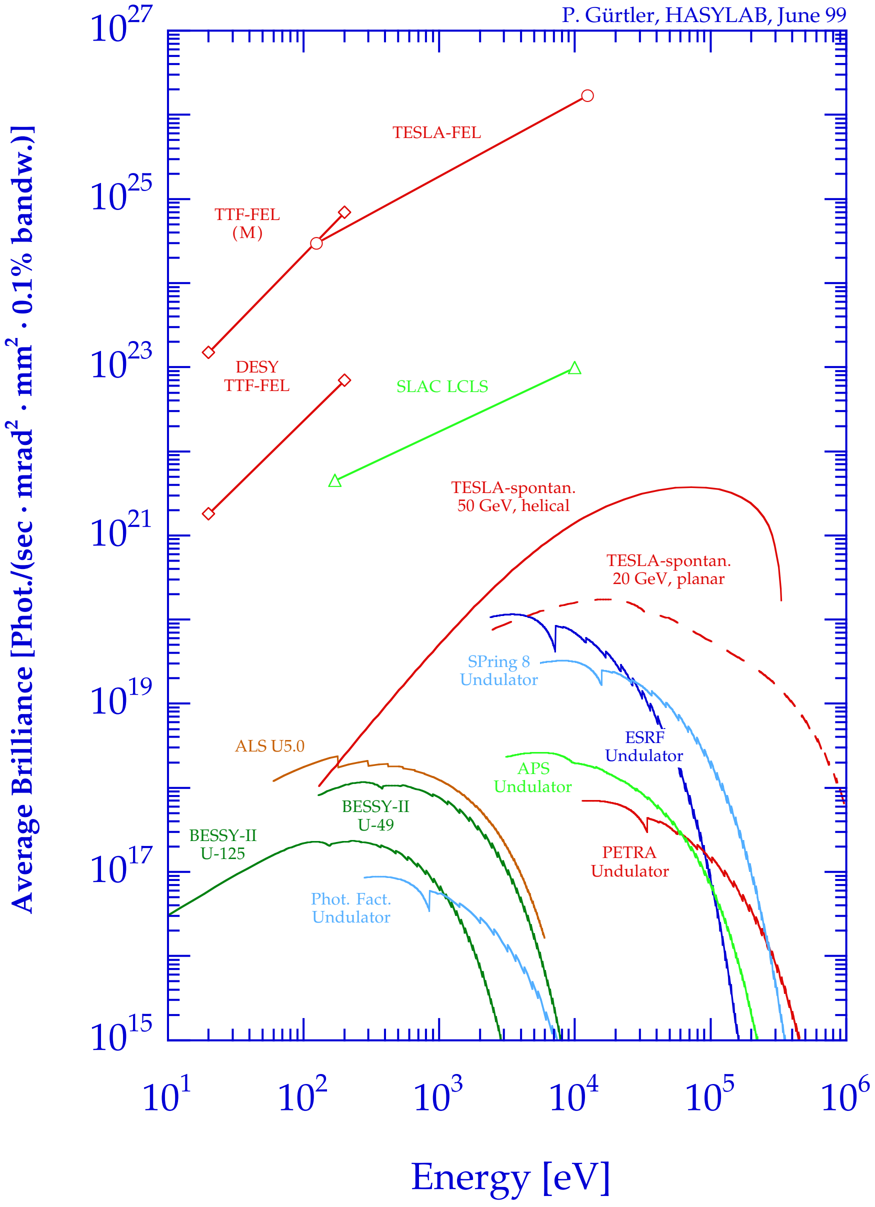

Figure 3: Average spectral brilliance of XFELs based on the TESLA linear collider, together with that of third generation synchrotron radiation sources and the LCLS Free Electron Laser project discussed at SLAC, Stanford, USA. The three orders of magnitude between LCLS and TESLA is mainly due to the fact that the LCLS is proposed as a single-bunch machine while TESLA will operate with long bunchtrains. Note also that the TESLA values will be reduced accordingly, if the bunchtrain is distributed to many undulators. For comparison, also the spontaneous spectra of two XFEL undulators are shown.

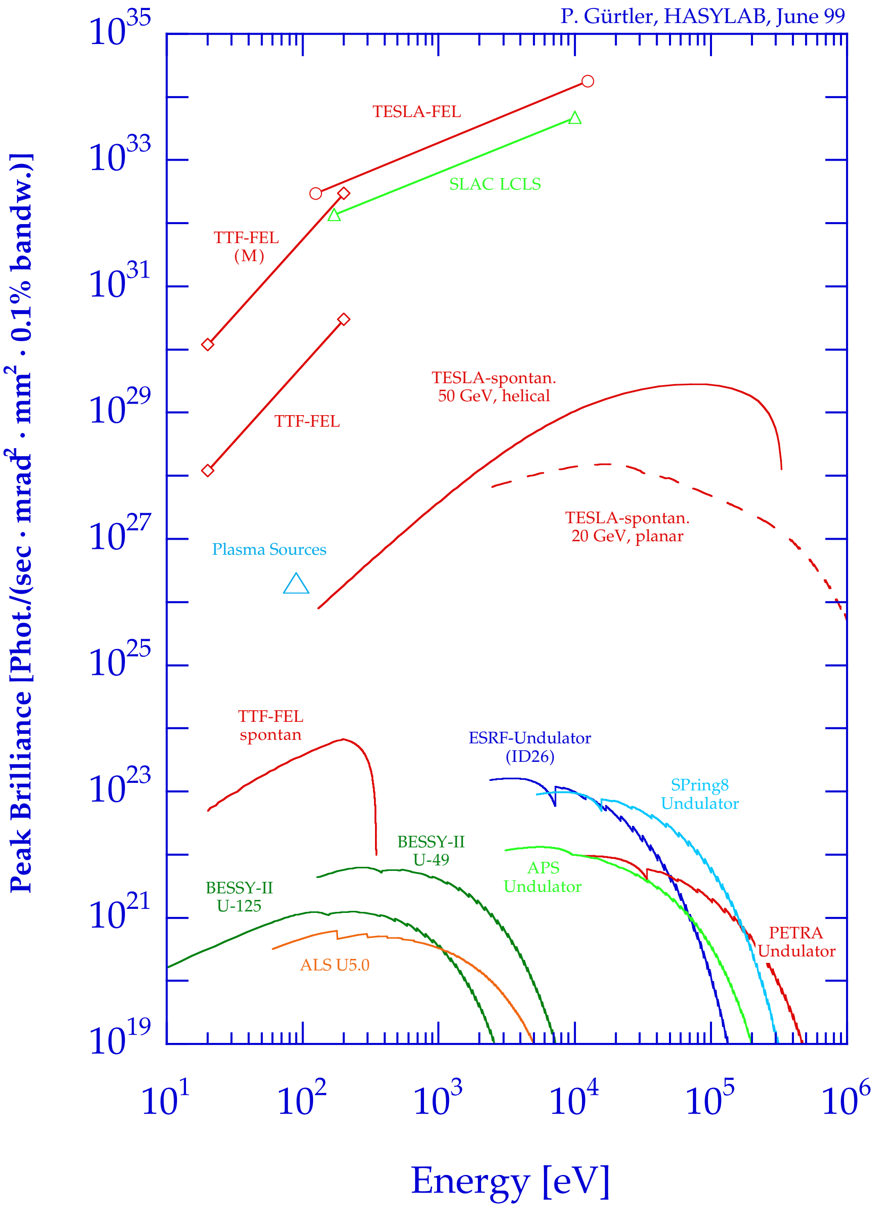

Figure 4: Peak spectral brilliance of XFELs based on the TESLA linear collider, together with that of third generation synchrotron radiation sources and the LCLS Free Electron Laser project discussed at SLAC, Stanford, USA. For comparison, also the spontaneous spectra of two XFEL undulators are shown. The peak brilliance of state-of-the-art plasma lasers is also noted.

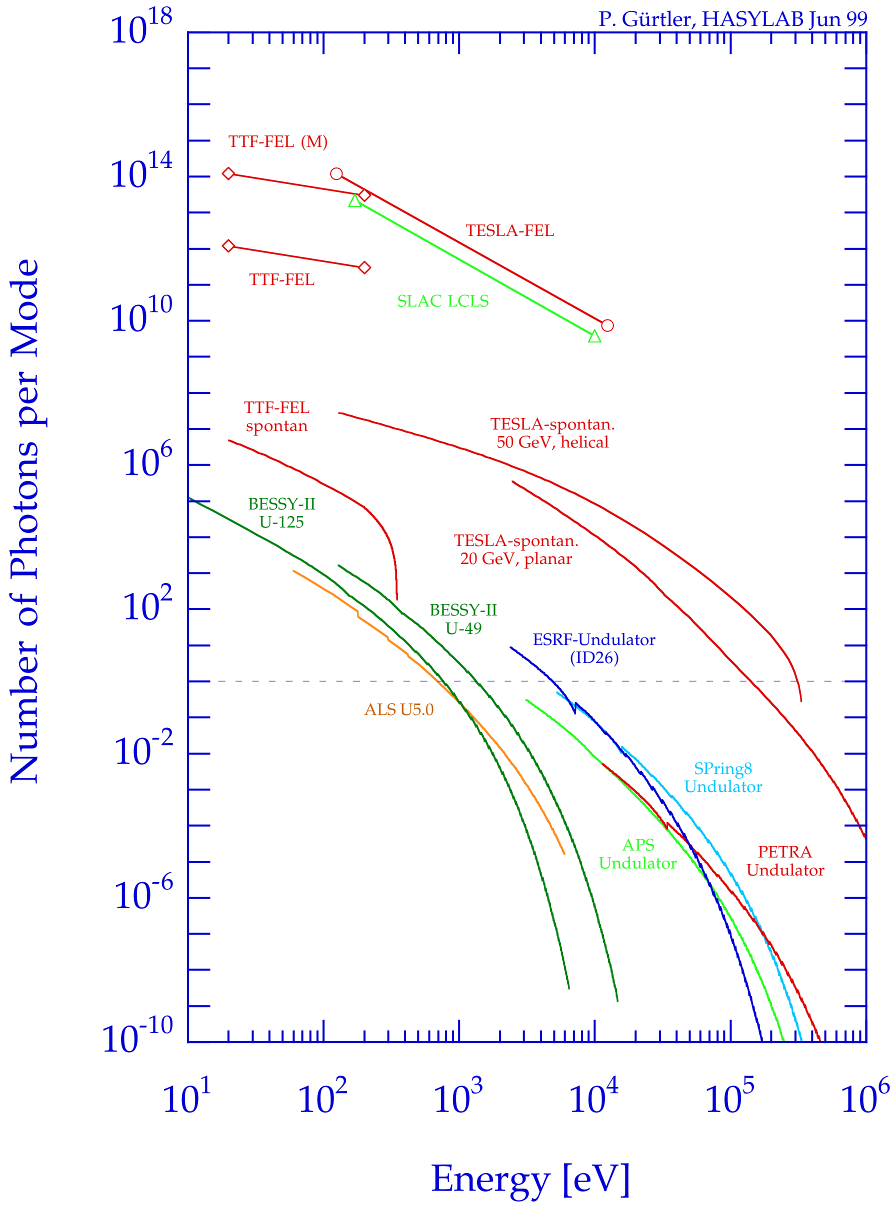

Figure 5: Number of photons per coherence volume of XFELs for TESLA, together with that of third generation synchrotron radiation sources and the LCLS Free Electron Laser project discussed at SLAC, Stanford, USA. This number of photons N is calculated from the peak brilliance PB and the photon wavelength λ_{ph} according to $N = \frac{PB \cdot {\lambda_{ph}}^3}{4 \cdot c}$.

Linac Parameters	
optimized gradient for XFEL operation	22 MV/m
linac repetition rate f_{rep} for XFEL	5 Hz
bunch length (rms)	80 fs
bunch spacing	93 ns
number of bunches per train	11315
bunch train length	1050μs
bunch charge	1 nC
normalized emittance	1 π mrad mm
longitudinal emittance	27 keV mm
RF duty cycle	0.5 %
average electron beam power (of both 25 GeV and 50 GeV branches)	2.1 MW
over-all power efficiency AC to electron beam	28 %
FEL Parameters	
typical saturation length	50 - 100 m
photon energy range	$\approx$ 12 keV
photon beam power range	60 - 280 GW
number of photons per bunch	1 - 100 10^{12}
typical photon beam divergence (rms)	1μrad
typical photon beam diameter (rms) at source	20 μm

Table 1: Key parameters for XFEL operation.

The basic principle [1, 2, 13] makes use of the fact that an electron beam of sufficient quality, passing a long undulator magnet, exponentially amplifies an initially existing radiation field, if the photon wavelength λ_{ph} matches the resonance condition determined by undulator parameters and beam energy. The amplified wavelength λ_{ph} is:

$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}(1 + K^2) \tag{1}$$

Here, γ is the electron energy in units of its rest mass, λ_u is the undulator period, K is the undulator parameter. Coherent emission is achieved because a bunch density modulation of the electron beam at the optical wavelength builds up during the passage of the bunch through the undulator.

Because the E-vector of the electromagnetic wave is always parallel to the transverse velocity of the electron, energy is transmitted from the radiation field to the electron or vice verse. Depending on their precise longitudinal position some electrons get accelerated while others get decelerated. This effect leads to the formation of equidistant microbunches. One can consider these electrons in one microbunch concentrated within a length smaller than the wavelength of the emitted radiation. Therefore, they radiate as one point charge. The radiated power from a point charge is fully coherent and proportional to the square of this charge. The radiated power from a microbunch is, therefore, proportional to the square of the number of electrons in this microbunch.

Fig. 6 illustrates schematically the longitudinal density modulation of the electron bunch. The distance between the microbunches is related to the wavelength of the emitted photons (properly Lorentz transformed and Doppler shifted into the laboratory frame)

	Units	E_{min}	E_{max}
Electron beam			
Energy	GeV	10	25
Peak current	kA	5	
rms bunch length	μm	23	
Undulator			
Period	cm	5	
Peak magnetic field	T	0.887	
Undulator parameter		4.14	
Coherent radiation			
Wavelength	Å	6.25	1
Saturation length	m	33	95
Peak power	GW	74	65
Average power	kW	0.9	0.8
rms spot size at undulator exit	μm	27	25
rms angular divergence	μrad	3.6	0.75
Bandwidth	%	0.2	0.2
Peak flux of photons	sec^{-1}	$2.3 * 10^{26}$	$3.3 * 10^{26}$
Average flux of photons	sec^{-1}	$2.8 * 10^{18}$	$4 * 10^{17}$
Peak spectral brilliance	B^*	$1.2 * 10^{33}$	$6.6 * 10^{33}$
Average spectral brilliance	B^*	$1.4 * 10^{25}$	$8 * 10^{25}$

$^*photons/sec/mrad^2/mm^2/(0.1\%bandwidth)$

Table 2: Parameters for XFEL Undulator U1.

	Units	E_{min}	E_{max}
Electron beam			
Energy	GeV	10	25
Peak current	kA	5	
rms bunch length	μm	23	
Undulator			
Period	cm	7	
Magnetic field	T	0.85	
Undulator parameter		5.55	
Coherent radiation			
Wavelength	Å	15	2.4
Saturation length	m	35	87
Peak power	GW	85	85
Average power	kW	1	1
rms spot size at undulator exit	μm	28	28
rms angular divergence	μrad	6	1.4
Bandwidth	%	0.2	0.2
Peak flux of photons	sec^{-1}	$6.4 * 10^{26}$	10^{26}
Average flux of photons	sec^{-1}	$7.7 * 10^{18}$	$1.2 * 10^{18}$
Peak spectral brilliance	B^*	$5.7 * 10^{32}$	$3.5 * 10^{33}$
Average spectral brilliance	B^*	$6.8 * 10^{25}$	$4.2 * 10^{25}$

$^*photons/sec/mrad^2/mm^2/(0.1\%bandwidth)$

Table 3: Parameters for XFEL Undulator U2.

leading to a coherent superposition of the radiation from all microbunches. Coherence also develops in the lateral direction. Figs. 7 and 8 show how the power density changes as the electrons traverse an undulator [14]. Starting from noise only the central mode grows exponentially while the other modes die out.

Figure 6: Development of coherence in a FEL starting from noise. The 3D distribution of the photon field is shown at the beginning (left), middle (center) and exit of the undulator. (Courtesy of Sven Reiche)

This principle of Self-Amplified-Spontaneous-Emission (SASE) [1], [2] does not require the optical cavity resonator used in multi-pass, longer wavelength FELs and can hence in principle deliver light with wavelengths in the Angstrom regime. Mirrors for these wavelengths only work under grazing incidence so that no X-ray cavities can be built. Crystals need to keep the exact Bragg condition so that heat load will be a problem when the radiated power is increasing.

Compared to state-of-the-art synchrotron radiation sources, one expects a transversely fully coherent beam, larger average brilliance, and, in particular, a pulse length of about 200 fs FWHM with ten or more orders of magnitude larger peak brilliance [1] , see Figs. 4 and 3. The peak power is of the order of 100 GW. Possible parameters for typical undulators are given in tables 2, 3 and 4 [11]. As the SASE FEL is completely independent of atomic excitation levels, it can be tuned over a wide range of wavelengths by changing the electron beam energy or the undulator gap.

3 Spontaneous Spectra

Like any normal undulator, the long FEL undulator will also emit a spontaneous spectrum. Although the brilliance and flux of the spontaneous emission is several orders of magnitude smaller than the laser values, the spectrum has the advantage that it is nearly a continuum.

[1]For partially coherent light sources (wigglers and undulators) the brilliance is calculated from the spectral flux divided by the photon beam sizes and divergences, convoluted with the electron beam sizes and divergences:

$$spectral\,brilliance = \frac{spectral\;flux}{4\pi^2 \cdot \sum_x \cdot \sum_x' \cdot \sum_z \cdot \sum_z'}; \quad \sum = \sqrt{\sigma_e^2 + \sigma_p^2},\; \sum{}' = \sqrt{\sigma'^2_e + \sigma'^2_p}$$

And for fully coherent sources (FELs) it is the spectral flux divided by the transverse photon phase space volume:

$$spectral\,brilliance = \frac{spectral\;flux}{(\lambda/2)^2}$$

	Units	E_{min}	E_{max}
Electron beam			
Energy	GeV	25	50
Peak current	kA	5	
rms bunch length	μm	23	
Undulator			
Period	cm	7	
Magnetic field	T	0.785	
Undulator parameter		5.13	
Coherent radiation			
Wavelength	Å	4	1
Saturation length	m	45	95
Peak power	GW	280	200
Average power	kW	3.4	2.4
rms spot size at undulator exit	μm	21	17
rms angular divergence	μrad	3.2	0.8
Bandwidth	%	0.2	0.2
Peak flux of photons	sec^{-1}	$5.6 * 10^{26}$	10^{26}
Average flux of photons	sec^{-1}	$6.8 * 10^{18}$	$1.2 * 10^{18}$
Peak spectral brilliance	B^*	$7 * 10^{33}$	$3 * 10^{34}$
Average spectral brilliance	B^*	$8.5 * 10^{25}$	$2.4 * 10^{26}$

$^*photons/sec/mrad^2/mm^2/(0.1\%bandwidth)$

Table 4: Parameters for XFEL Undulator U3.

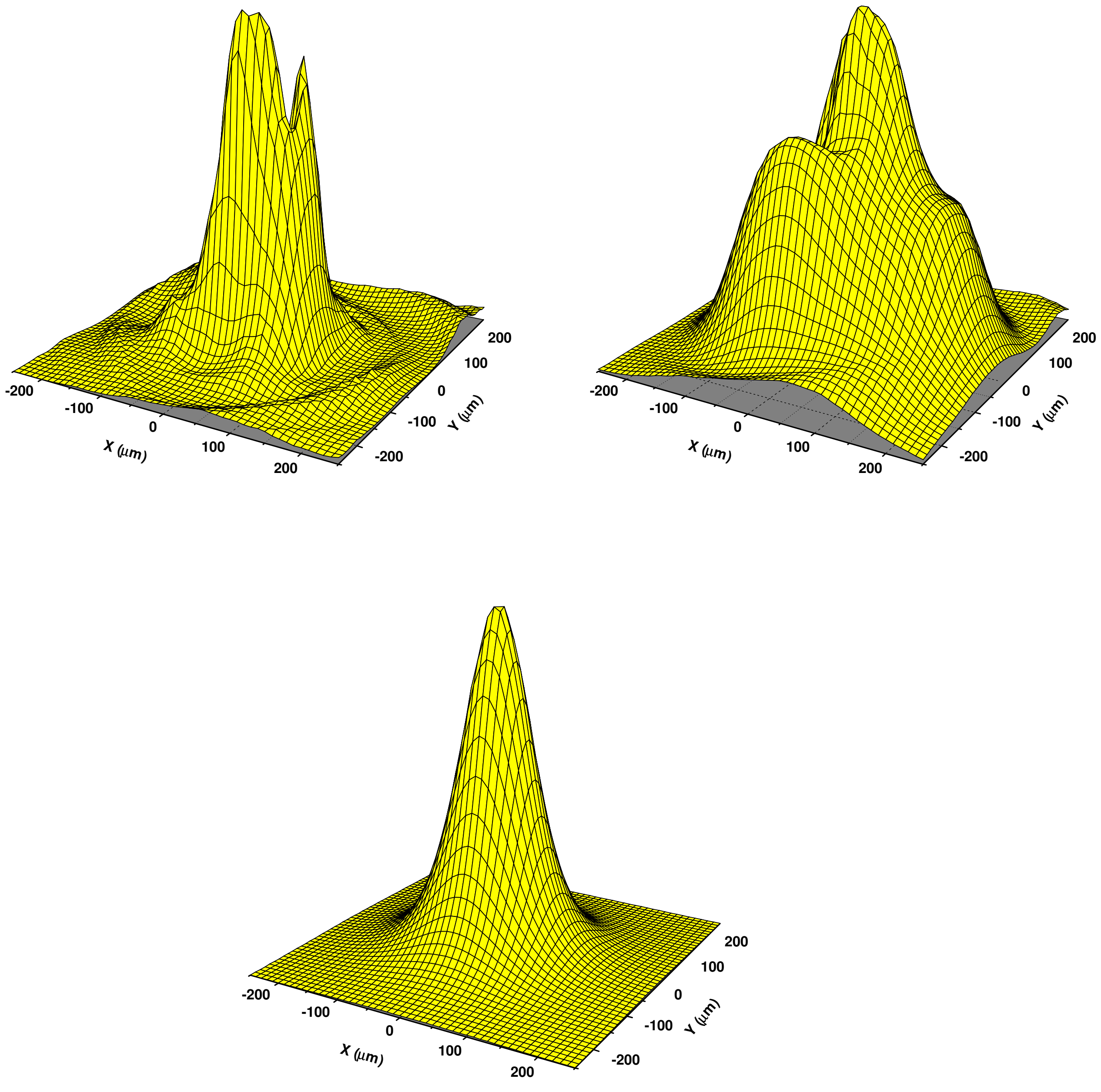

Figure 7: Distribution of the instantaneous power flux density in the near zone at the undulator length of 2 m, 4.5 m and 8 m (upper, middle and lower plot, respectively).[14]

Combining three undulator designs with the possibility of varying the electron energy between 10 and 50 GeV, one is able to cover the spectral range from 100 eV up to about 4 MeV with nearly constant spectral flux of about 10^{13} Phot./sec/0.1%. The spectral flux is 5 orders of magnitude below that of the FEL spectral line, but the total flux integrated over the whole spectrum is comparable. Correspondingly this is also true for the power emitted by the spontaneous radiation, which is for certain designs even higher than the power emitted into the laser line.

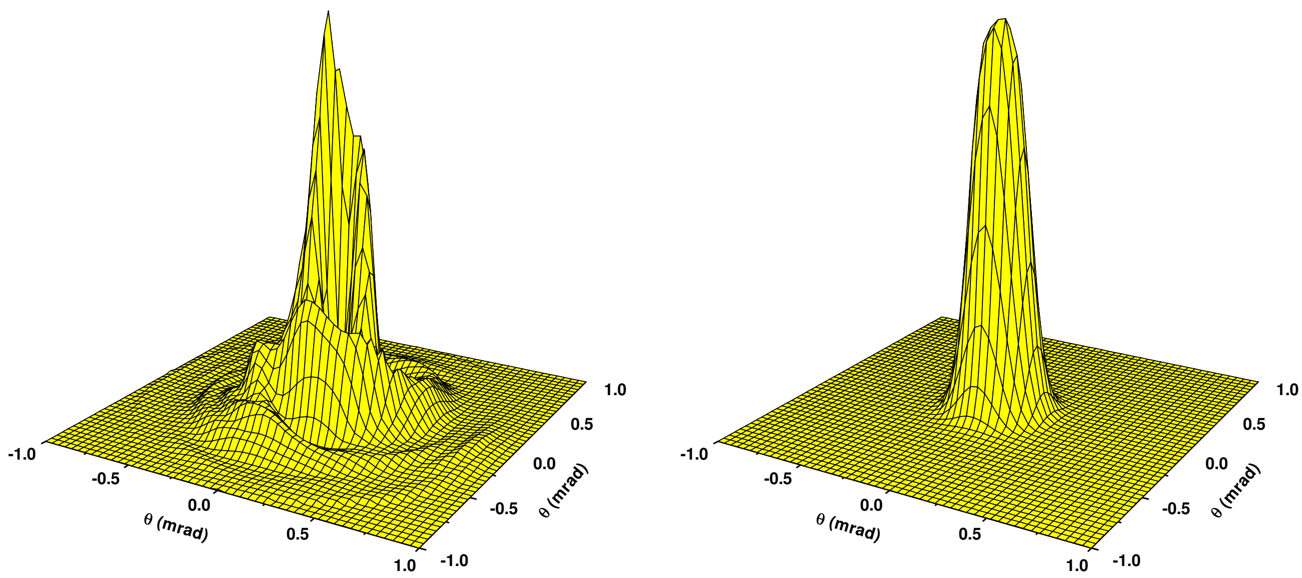

Figure 8: Directivity of the instantaneous radiation intensity in far zone at the undulator length of 2 m and 8 m (upper and lower plot, respectively).[14]

Another important difference between FEL and spontaneous radiation is the angular divergence. Whereas the laser line and the undulator fundamental line are extremely well collimated with an angular divergence of some μrad, the angular divergence of the power of the total spontaneous radiation is about 100 μrad (see Fig. 9). Therefore it is easily possible to isolate the laser beam by passing it through an aperture of some μrad acceptance. Especially for a helical FEL, this is a very efficient method because the total spontaneous radiation of such a device has a minimum on axis.

Behind the undulator, the quality of the electron beam may no longer be good enough for laser action, but still good enough to produce a nearly diffraction-limited spontaneous undulator beam. Such undulators installed behind the FEL will emit photon beams with a quality comparable to today's third generation storage rings but with a much superior time resolution. Like undulators in storage rings, these devices can be optimized for a certain photon energy.

To give typical examples, Table 5 compiles parameters of undulators optimized for spontaneous radiation at three different photon energies. Device 4 needs to be tapered in order not to degrade flux and brilliance by the loss of electron energy during undulator passage. The spectra of the peak brilliance are included in Fig. 10, together with the spectra of the three FELs and some undulators from BESSY, ESRF and PETRA for comparison. The peak brilliance of the undulators is of course much lower than that of the FEL devices, but it is far above common undulators in storage rings. Fig. 11 shows the respective average brilliance plots.

Another useful property of spontaneous undulator radiation is the coherent flux emitted by these devices. In Fig. 12 the peak coherent flux and the peak total flux emitted from undulator 1 is shown in comparison to an undulator at the ESRF. For both devices the coherent flux is lower than the total flux by some orders of magnitude, but the linac undulator U1 radiates at a much higher intensity level, so that its *coherent* flux is much higher than the *total* flux from the ESRF device.

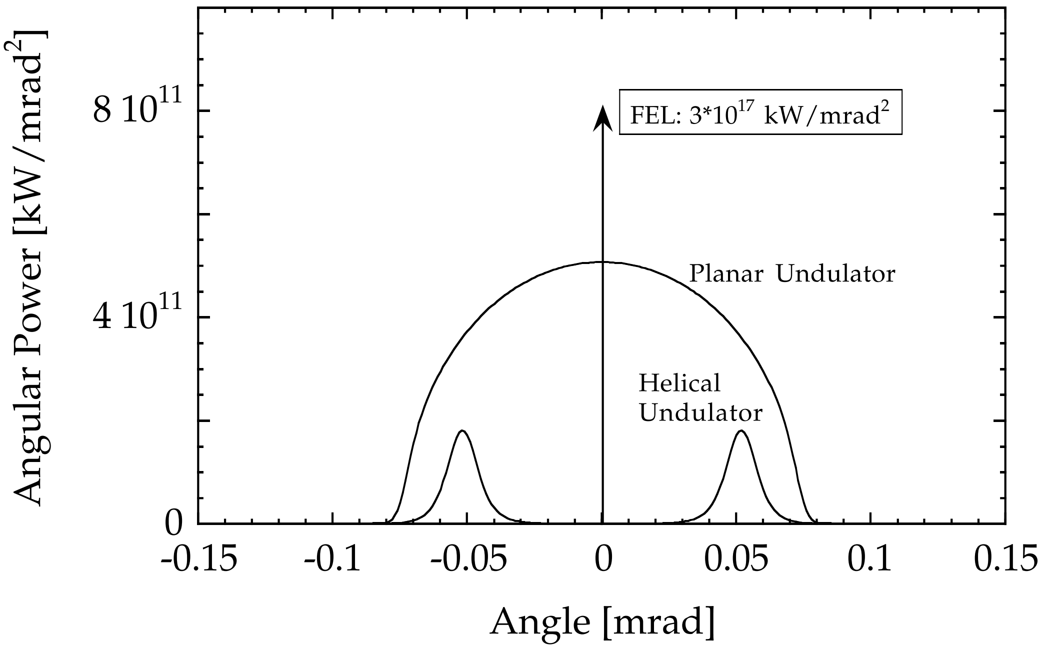

Figure 9: The angular distribution of the power emitted by the FEL-line and by the spontaneous radiation from a helical or a planar undulator.

4 A multi user facility

In a LINAC in contrast to a storage ring each electron bunch will pass the accelerator only once. Therefore it is possible to extract individual bunches from the linear accelerator and guide them alternatively to various undulators. For the TESLA-XFEL project the long 250 GeV TESLA-LINAC will be available. Extraction lines can be built in parallel, for various electron energies which can be used for producing different X-ray energies in the X-FEL laboratory in a quasi-simultaneous manner. At present two such extraction lines for electron energies between 10-25 GeV and 20-50 GeV, respectively, were studied as test cases . These electron beams are feeding FEL undulators which in turn will be of different types either changing polarization or photon energy range.

At the end of the extraction tunnel, a beam switchyard is foreseen distributing the beams to different undulators, see Figure 13. Having left the FEL, the quality of the electron beam may still be attractive enough for other FEL undulators or can be passed through further undulators generating spontaneous radiation. The over-all length of the X-FEL area is determined by the length of the electron beam switchyard, the length of the FEL undulators and by several hundred meters of drift lines for the intense photon beams. This long radiation drift assures that the radiation safety requirements in the experimental hall will be similar to those in present day synchrotron X-radiation laboratories. This means that the electron beam is separated early enough from the photon beam so that the required photon collimation shields enough of the unwanted background radiation. In addition, it lets the SASE beams grow by the natural divergence until the first optical elements can handle the heat loads. Finally, it also makes a large demagnification ratio of

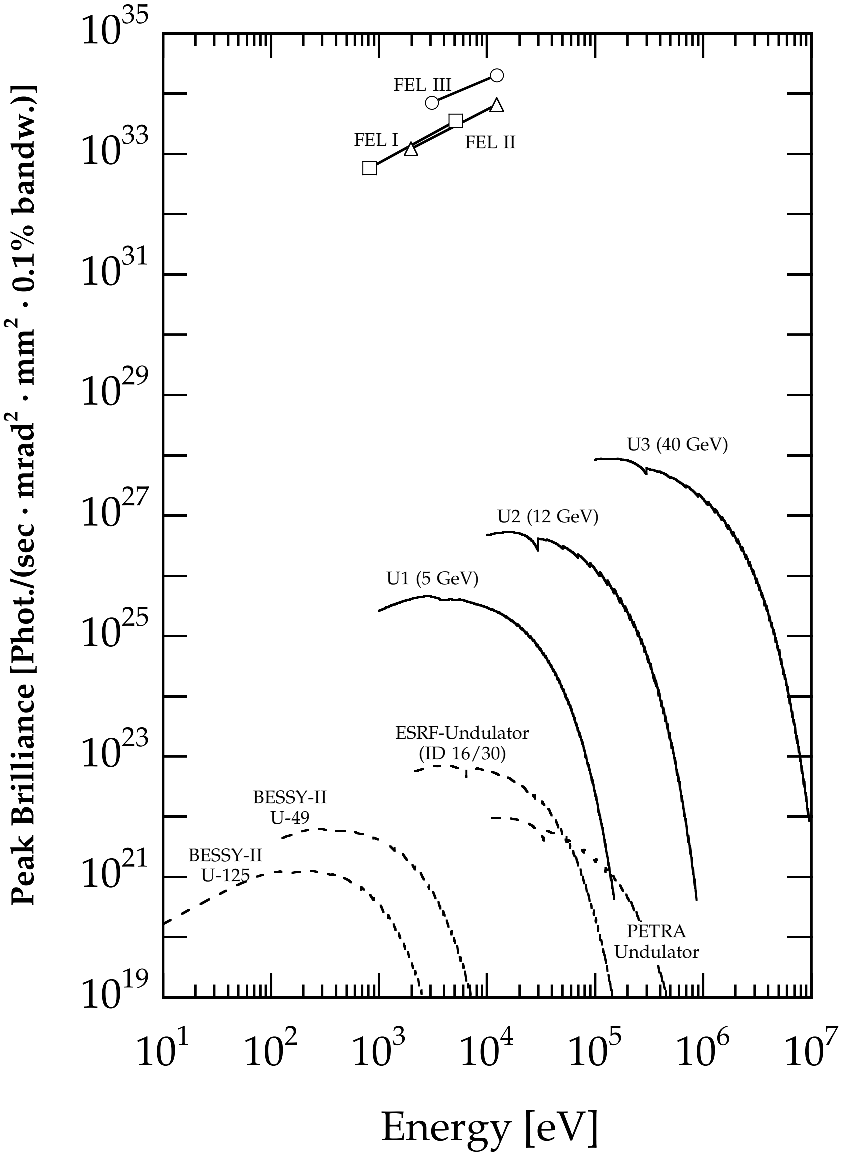

Figure 10: Peak brilliance of the three FELs and three possible undulators emitting spontaneous radiation, in comparison with some conventional storage ring undulators.

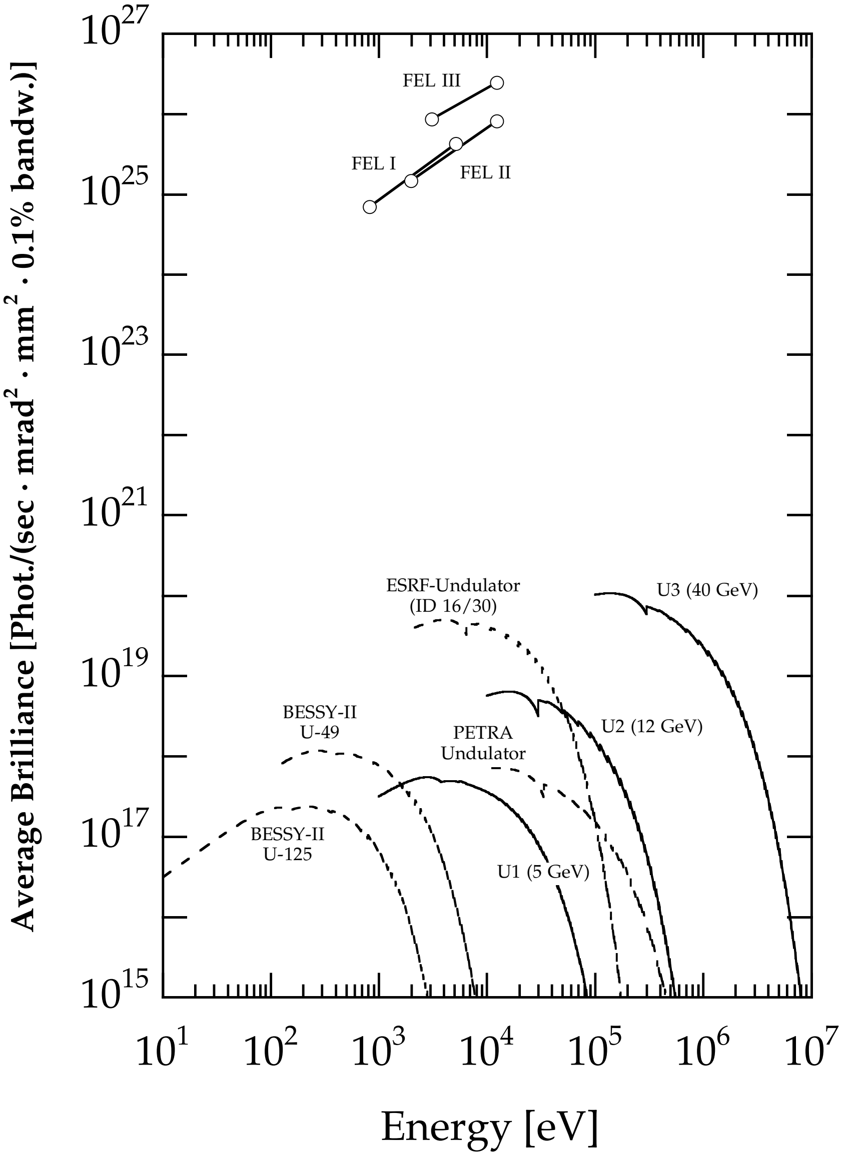

Figure 11: Average brilliance of the three FELs and three possible undulators emitting spontaneous radiation, in comparison with some conventional storage ring undulators.

Table 5: Undulators for spontaneous radiation

Parameters	**Device 1**	**Device 2**	**Device 3**	**Device 4**
Photon energy [keV]	1	10	100	1000
Electron energy [GeV]	5	12	40	100
Electron beam divergence [μrad]	2.6	1.7	0.9	0.59
Electron beam size [μm]	39	25	14	8.9
Total Length [m]	30	30	30	30
Periodic length [cm]	4.3	3.81	3.90	3.50
Number of periods	697	787	769	857
Magnetic field [Tesla]	0.75	0.65	0.66	0.57
Undulator Parameter	3.01	2.28	2.41	1.85
Total average Power emitted [Watt]	16	68	806	60812
Peak-Flux of 1. Harmonic*	$4.69 * 10^{20}$	$5.05 * 10^{20}$	$5.02 * 10^{20}$	$5.19 * 10^{20}$
Peak-Brilliance of 1. Harmonic**	$2.58 * 10^{25}$	$4.66 * 10^{26}$	$8.42 * 10^{27}$	$4.86 * 10^{29}$

* [Phot./(sec$\cdot$ 0.1%)]
** [Phot./(sec $\cdot$ mrad^2$\cdot$ mm^2$\cdot$ 0.1%)]

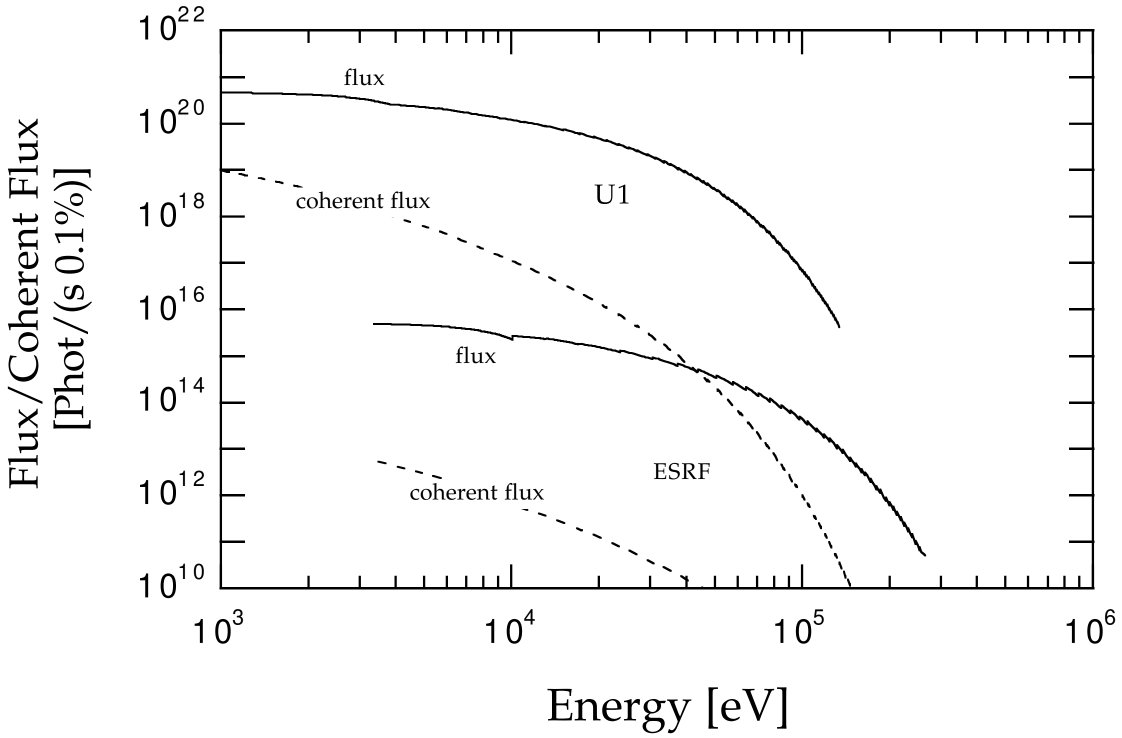

Figure 12: Flux and coherent flux of one of the undulators for spontaneous radiation (device 1) compared with a device at the ESRF.

the X-ray beams possible. Including the actual experimental area, this leads to an overall length requirement of about 800 m.

5 Applications

The unique outstanding properties of the X-FEL beams have stimulated a whole sequence of international workshops discussing the scientific case and is potential applications. This started 1994 [7] and was followed by several international workshops [8, 9, 10] which finally found the first summary in Chapter 5 of [11].

In a scientific case for such new sources of radiation there are always the so called "trivial" extensions of what we can already do now but could then do very much better and there are the unexpected surprises and completely new experiments. In the first category, the X-FEL will continue the path from the X-ray tube versus first and second generation sources of synchrotron radiation using the bending magnets through the third generation machines which introduced special magnet devices and undulator radiation (Fig. 1). The later one have made the pioneering experiments on systems with low scattering power (surfaces, interfaces, small sample areas, magnetic scattering etc.) and kinetic studies, which were already performed on first and second generation sources, to routine measurements. On the other hand it has already become evident that certain experiments conceivable today are far beyond the possibilities of present day sources.

Nuclear resonant scattering for example requires a very narrow energy band as well as short pulses with relatively long intervals. This technique will therefore greatly profit from the peak brilliance and the versatile time structure of an X-FEL.

The investigation of ultra dilute samples with spectroscopic methods and highly sensitive spectromicroscopy will become possible. Ultra-high time resolution can be achieved which will be specially useful in pump-probe experiments. Novel methods like Raman X-ray absorption spectroscopy will find much broader applications. Beyond this, multiphoton processes in the X-ray regime will become observable in atoms, molecules, clusters, solids and plasmas.

Inelastic scattering is a link between spectroscopy and structure analysis, in the sense that it probes the dynamics of the structure. The X-FEL will allow the study of linear and non-linear optical properties on microscopic and even atomic length scale and on a femto second time scale.

An outstanding quality of the X-FEL is its full spatial and partial temporal coherence. With current sources, coherence can only be achieved at the cost of intensity by using monochromators/pinhole optics. Therefore, X-ray time fluctuation spectroscopy has only been developed recently at third generation sources. To make this technique a widely applicable spectroscopy more intense coherent sources are needed.

Because of the coherence phase sensitive experiments (holography, phase contrast imaging, interferometry etc.) will become routinely applicable in the X-ray regime. In addition, the fact that the X-FEL is a diffraction limited source will allow extreme focusing. Although atomic resolution does not require the long transverse coherence length the time resolution will allow holographic atomic scale imaging with extreme time resolution.

The unprecedented coherent power in combination with a high Bose degeneracy factor should allow the observation of quantum optical effects in the X-ray regime.

Applications of the above mentioned techniques cover such a wide variety of fields in fundamental, applied and industrial research that we cannot discuss them within this paper and refer to [11].

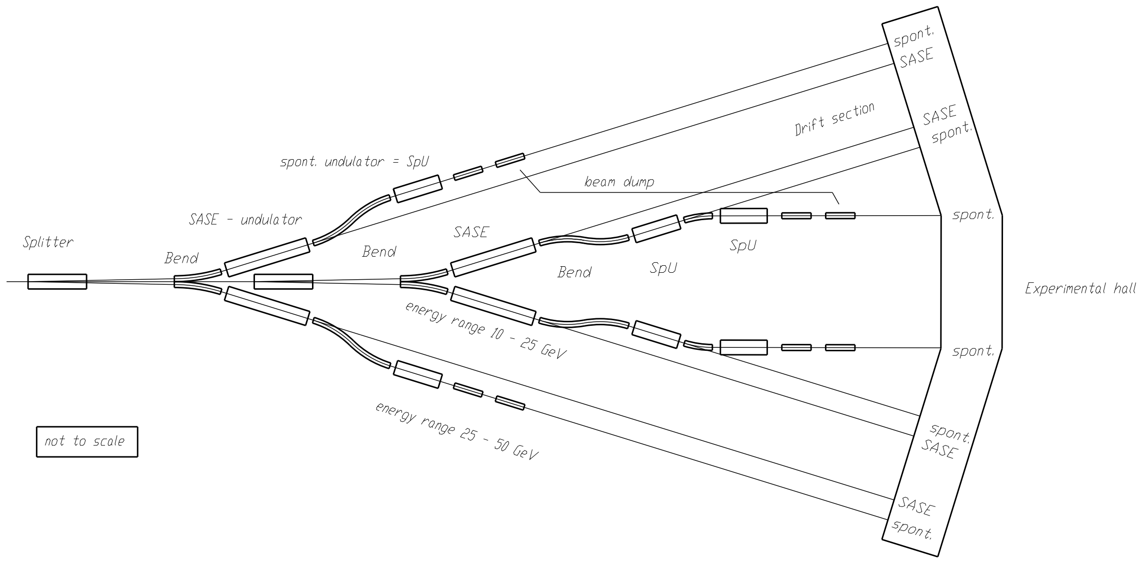

Figure 13: Sketch of a coherent X-ray source laboratory based on a linear collider installation. The beam can be extracted at any energy between 2 and 250 GeV and is transferred inside the linac tunnel to the X-ray lab located close to the interaction points (I.P.). Multiple extraction lines could be utilized in parallel, so that various beam energies are available in the X-ray lab quasi-simultaneously. The XFEL electron beam is provided by an RF gun followed by a sequence of bunch compressors.

6 Conclusion

It is inevitable that these developments will also lead to corresponding applications at other photon sources in turn. The variety of new and exciting experimental possibilities in physics, chemistry, materials science, biology, and industrial applications should in fact lead to the same sort of revolutionary developments in X-ray studies of matter that was produced in optical studies by introduction of the visible/UV lasers.

7 Acknowledgement

The work reported here is based on contributions of many scientist and engineers listed in chapter 5 of ref.[11].

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