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The free-electron laser project at DESY: concept and applications

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Abstract

This paper gives an overview of the layout and the present status of the Free Electron Laser (FEL) project at DESY. A single pass FEL for the vacuum ultraviolet (VUV) spectral range based on self-amplification of spontaneous emission (SASE) is currently under construction. The project will proceed in two phases. In Phase I a 390 MeV superconducting accelerator will be used to drive a FEL operating up to 30 eV. This facility is intended to test various hardware components and to prove the SASE principle for the first time at short wavelengths. After successful completion of the tests the linear accelerator will be upgraded to 1 GeV and the FEL will deliver photons up to 200 eV. An experimental hall will be added and the facility will be available for external users (Phase II). Based on the theory of SASE it is expected that the VUV FEL will produce extremely intense sub-ps pulses which will open up new areas of research.

Keywords: Free-electron laser; fs pulses; Synchrotron radiation; VUV spectral range

1. Introduction

Since the discovery of X-rays in the last century the use of high energetic electromagnetic radiation has developed into a very powerful tool in many different fields of basic and applied research. In this context synchrotron radiation has played an important role because of its broad spectral range, high flux and strong collimation. In the last three decades there have been tremendous achievements in producing beams with increasing brightness. From the first use of synchrotron radiation up to the present the brilliance has increased by more than 10 orders of magnitude. One dream, however, to extend the properties of lasers to the soft and hard X-rays, is still unfulfilled. Several approaches have been proposed in the past, but only now does this aim seem to be in reach by constructing free-electron lasers (FEL) based on the principle of self-amplification of spontaneous radiation (SASE) [1]. The recent advances in linear accelerators and low-emittance electron guns developed for the needs of particle physics and the construction of very precise undulators for advanced synchrotron radiation sources make these developments possible [2,3]. A serious obstacle in constructing lasers for the vacuum ultraviolet (VUV) and soft X-rays is the lack of mirrors for resonators. FELs based on the SASE principle operate without resonators and are therefore expected to allow the production of high energy radiation with short wavelength [3,4]. The performance expected from these sources, especially their high peak and average brilliance, extremely short pulse length and lateral coherence will open new and exciting areas of research and technological applications. FELs using optical cavities operating in the visible and infrared (IR) have already been in operation for several years [1]. The properties of these devices are well understood on the basis of FEL theory developed in the last 20 years [5–7]. VUV FEL projects based on the SASE principle have recently been started at the APS (Argonne) [8], NSLS (Brookhaven) [9], DESY (Hamburg, for a detailed description see the facility report by Feldhaus and Sonntag [10], and the proposal by Rossbach [11]) and SPRING8 (Kamigori) [12]. Very recently, a large gain of 10^5 has been measured at the 12 μm SASE-FEL at Los Alamos [13]. The experimental results are in excellent agreement with recent numerical simulations [14]. On the basis of these promising results it is expected that VUV FELs will provide photon beams which exceed the flux and brilliance of all other existing VUV sources by several orders of magnitude. On the other hand, the requirements for the properties of the electron beam, the undulator and the alignment of all elements are close to the limit of present technology. This has so far prevented the extension of FELs to the VUV spectral range.

2. Concept and principle of the SASE process

Electrons in a storage ring usually emit incoherent synchrotron radiation (SR). As a result the photon flux is

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proportional to the number N of electrons in the bunch. The key idea of a FEL is based on the emission of coherent light providing a photon flux which can be, at least in principle, proportional to the squared number N of the emitting electrons. As a result the flux and brilliance can exceed that of a conventional SR source by a factor N. In practice, the gain will be lower because only a small percentage of electrons inside the so-called ''cooperatation length'' will contribute. Typically, a gain of 10^5 compared to conventional SR sources can be expected in the VUV spectral range. The key issue is how to force the electrons to emit coherently. The principle of operation of a coherently emitting FEL based on self-amplified spontaneous emission (SASE) is outlined in Fig. 1. Relativistic electron bunches move through a long undulator creating in the usual way an intense photon beam at wavelength λ_n. As in a conventional synchrotron radiation source the wavelength of this spontaneous radiation is determined by the energy of the electrons, the undulator period and the strength of the magnetic field. The interaction of the radiation field with the electron beam along the undulator leads to an electron density modulation with a period which is exactly equal to the wavelength of the radiation. As a result the individual parts of the bunch can emit coherently, provided the waves are in phase, which increases the power. Since the phases are randomly distributed at the beginning of the self-amplification process, the whole process starts from noise at the entrance of the undulator. Only the odd harmonics emitting on axis are amplified in a planar undulator. Three different regimes in the undulator can be distinguished. In the first part the power increases linearly with the distance. After the microbunching has started the power increases exponentially and the emission becomes coherent. Finally, after a saturation length the maximum radiation power is reached. The saturation length L_{sat} is given by $4\pi L_{gain}$, where L_{gain} is the length it takes the power to growth by a factor e.

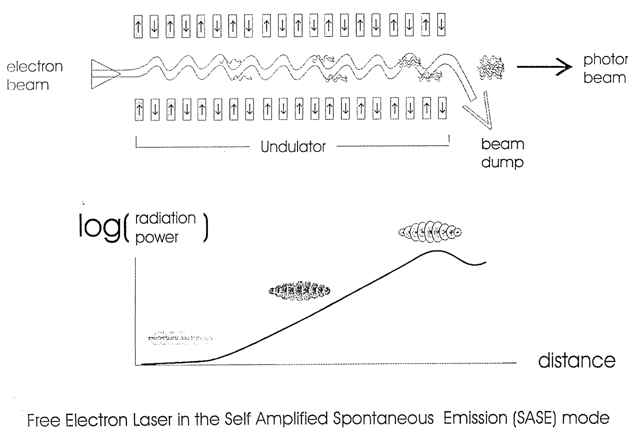

Fig. 1. The principle of self-amplified spontaneous emission (SASE). The interaction of the spontaneous radiation with the electrons in a long undulator modulates the electron density within the bunch. As a result a strong amplification can be obtained.

Further increasing the length of the undulator decreases the power because the electrons emit lower energy photons out of phase with the formed radiation field due to large radiation losses. In order to achieve a high amplification along the undulator and in order to reach saturation, electron beams with extremely high charge, small energy width and low emittance at GeV energies are required. This prevents the implementation of a FEL for VUV operation into a storage ring.

3. Free-electron lasers at DESY

DESY has a longstanding fruitful tradition of combing high energy physics and synchrotron radiation. The superconducting linear accelerator which is currently under construction on the DESY site as part of the TESLA Test Facility (TESLA stands for Terra Electronvolt Superconducting Linear Accelerator) is ideally suited to drive a short wavelength FEL based on the SASE principle [15]. This project was started in 1995 as a large cooperation with scientists from many different countries and institutions. The project will proceed in two phases. In Phase I, a 390 MeV superconducting linear accelerator will be used to drive a FEL in the wavelength range 70–120 nm. The main goal of Phase I is to test various hardware components and to prove the SASE principle at short wavelengths. So far it has been demonstrated only in the infrared regime. After successful tests the linear accelerator will be upgraded to higher energies and FEL radiation will be produced with photon energies up to at least 200 eV in the first harmonic. While Phase I is mainly a test facility, Phase II is planed as a user facility with a large experimental hall for three different beamlines.

3.1. Proof of principle in the VUV

The Phase I FEL is presently under construction. The first of three superconducting accelerator modules has already been successfully tested in 1997. After the installation of the undulator in the beginning of 1999 the SASE experiments in the VUV will be started. The layout of the Phase I VUV FEL is shown schematically in Fig. 2. The properties of the electron and the photon beam are summarised in Table 1. Along the undulator a nearly perfect overlap between the electron and the photon beam is required. Therefore, a small electron beam diameter and divergence is needed. Furthermore, a small energy spread and a very short pulse length are essential in order to obtain a large gain and saturation. The main components needed in order to achieve these requirements are a low emittance electron gun, several bunch compressor stages, superconducting accelerator modules with an extremely low damping factor and a long, precise undulator.

The low emittance electron beam is produced by a radio frequency (RF) gun which consists of a laser driven

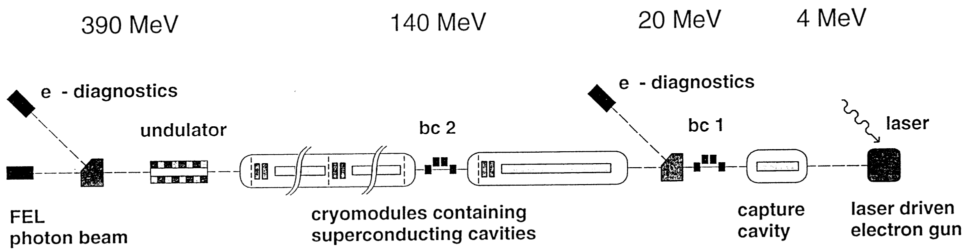

Fig. 2. Schematic layout of the Phase I VUV FEL. The bunch compression stages are indicated by bc1 and bc2.

cathode placed inside a RF cavity. The fast acceleration of the electrons allows for a small size of the electron cloud because space charges have no time to act on the electrons. The cathode will be driven by 2–20 ps pulse trains at 262 nm from a Nd:YLF laser system developed at the Max-Born Institute in Berlin. The pulse structure of the FEL is presented in Fig. 3. It consists of bunch trains with up to 7200 pulses followed by a 99 ms pause.

The superconducting linear accelerator consists of three 12.2 m long cryomodules, which contain eight niobium cavities operated at 1.3 GHz. The maximum acceleration energy depends on the field gradient achieved. With 15–25 MV/m field gradient a total energy of 360 to 600 MeV can be achieved. Superconducting linear accelerators are ideally suited for driving a FEL since they provide high power efficiency, large duty cycle and, most important, minimal perturbations of small emittance beams during the acceleration process. Rather narrow profiles of the electron beam have already been obtained during a test at 125 MeV in 1997.

Table 1
Parameters expected for the VUV SASE-FEL at 300 MeV (Phase I) and 1 GeV (Phase II) electron energy

	Phase I	Phase II
Electron beam properties at the beginning of the undulator		
Energy	300 MeV	1000 MeV
Peak current	500 A	2500 A
Bunch charge	1 nC	1 nC
Bunch length (rms)	250 μm (830 fs)	50 μm (170 fs)
Bunch width (rms)	58 μm	57 μm
Normalized emittance (rms)	2π mm mrad	2π mm mrad
Energy spread (rms)	0.17%	0.1%
Number of bunches per train	1–7200	1–7200
Bunch separation	111 ns	111 ns
Repetition rate	10 Hz	10 Hz
Properties of the planar hybrid undulator		
Period length	2.73 cm	2.73 cm
Magnetic gap	12 mm	12 mm
Peak magnetic field	0.497 T	0.497 T
Length of undulator module	4.5 m	4.5 m
Number of modules	3	6
Photon beam properties at the end of the undulator		
Wavelength	70 nm	6.4 nm
Bandwidth (FWHM)	1%	0.6%
Angular divergence (rms)	130 μrad	15 μrad
Beam width (rms)	110 μm	90 μm
Pulse length (rms)	500 fs	100 fs
Autocorrelation time	15 fs	2 fs
Number of photons per pulse	$1.3\cdot10^{14}$	$4\cdot10^{13}$
Pulse energy	0.36 mJ	1.2 mJ
Peak power	300 MW	5 GW
Maximum average power	25 W	90 W

In order to achieve a high instantaneous beam current the bunches are longitudinally compressed in two different magnetic chicanes. This works in the following way. Electrons in the beginning of the bunch have higher speed than those at the end. In a magnetic chicane (see Fig. 2) the fast electrons have a longer path. If the parameters are chosen properly the length of the bunch is reduced from 2 mm at the entrance of the first stage to 0.25 mm at the exit of the second stage.

The undulator for the VUV FEL differs considerably from undulators installed in storage rings. First of all the undulators are very long, for Phase I a total length of 13.5 m is required, for Phase II 27 m is needed. The undulators are built from three and six modules, respectively, each of which are 4.5 m long planar magnetic structures with a fixed gap using permanent magnet technology. Since the gap is fixed the photon energy can only be varied by changing the energy of the linear accelerator. It is expected that this can be done routinely on a very fast time scale. In order to guarantee a large overlap between the photon and the electron beam along the undulator the electron beam must be focussed, otherwise the natural divergence would reduce the overlap. This is accomplished by adding a FODO lattice [16], i.e. a sequence of focusing and defocusing quadrupoles, to the sinusoidal field of the undulator. Furthermore, beam position monitors, diagnostic tools and steering coils are incorporated in the undulator.

Before the photon beam enters a small experimental area

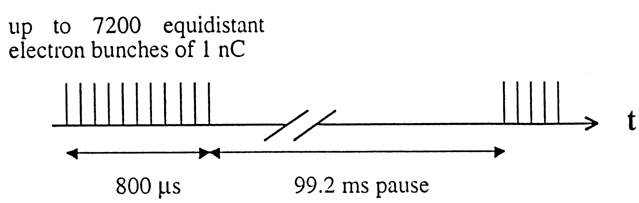

Fig. 3. The time structure of the VUV FEL.

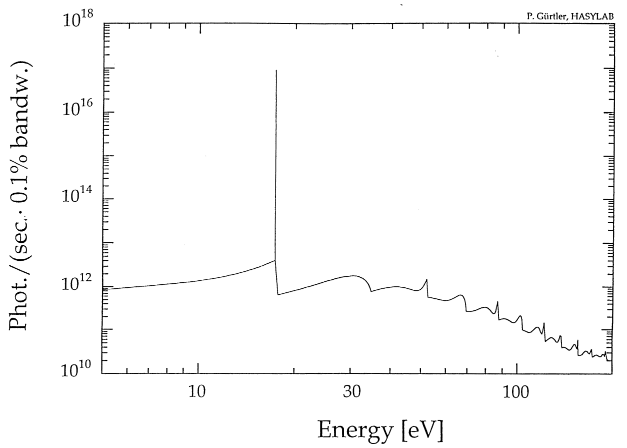

Fig. 4. Time-averaged flux of the first harmonic of the Phase I VUV FEL superimposed on the angle integrated spontaneous undulator emission.

the intense electron beam has to be separated by a magnetic sector field. Some important parameters of the photon beam are summarised in Table 1. At saturation, approximately 10^{14} photons will be delivered at 10 eV energy in a pulse of 500 fs rms length. The average flux in the sharp FEL line will exceed that of the spontaneous undulator emission by approximately four orders of magnitude. Fig. 4 presents the average photon flux of the Phase I FEL superimposed on the angle integrated spontaneous undulator radiation.

An extensive characterisation of the photon beam will be performed by a group of scientists from various European institutions (HASYLAB, Universität Jena, LURE Paris, Lund Laser Centre, MAX-LAB, FZ Jülich, INFN Milano, Dublin City University, Sincrotrone Trieste, Universität Hamburg, Daresbury Laboratory, Polish Academy of Sciences). Four different tasks will be tackled:

1. measurement of the total intensity and its angular distribution for each pulse,
2. measurement of the spectral distribution of individual pulses,
3. direct measurement of the duration and the temporal structure of the individual pulses,
4. determination of radiation damage thresholds of optical elements.

These measurements are crucial for starting and optimising the operation of the FEL and testing theoretical predictions. Fig. 5 shows a schematic outline of the experimental area. Due to the start up from noise the radiation emitted from a SASE-FEL exhibits a characteristic spiking both in the temporal and spectral domain. Typical frequency and time spectra are presented in Figs. 6 and 7 [17]. While the instantaneous radiation power distribution will change statistically from pulse to pulse the integrated power over each pulse is expected to be quite stable, at least if saturation is reached. The statistics of the radiation contain important information on the SASE process and will therefore be investigated in great detail. For scientific applications the spiking makes quantitative data analysis more difficult, especially for pump-and-probe experiments.

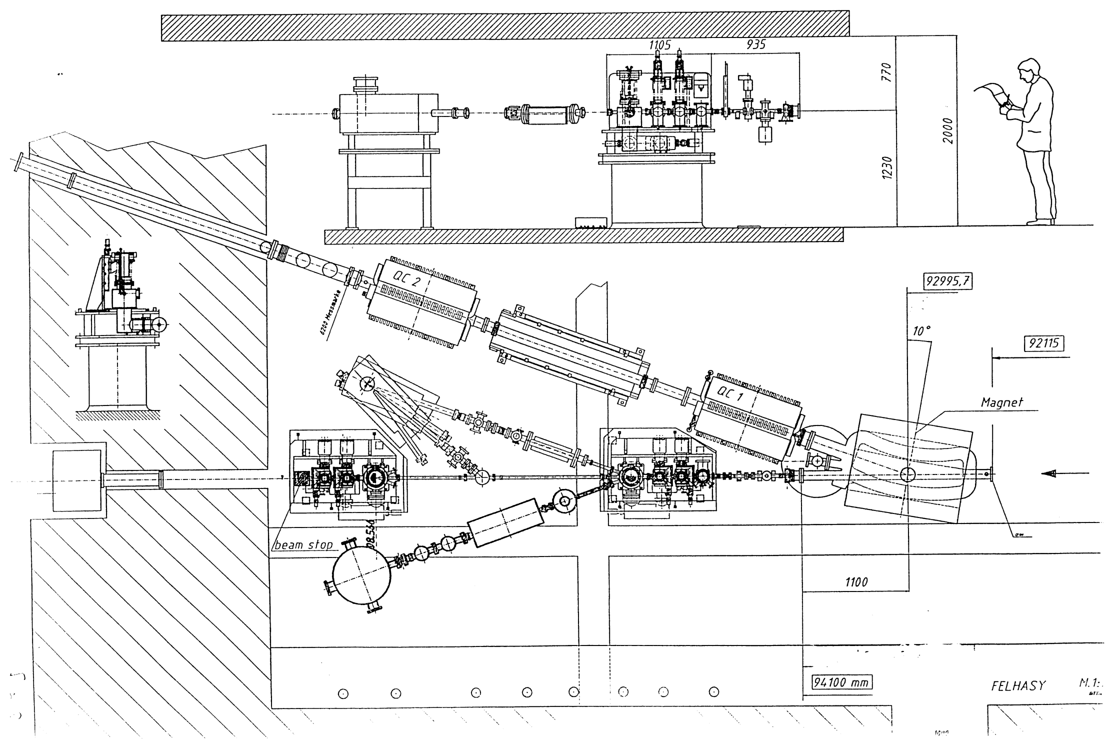

Fig. 5. The experimental area for the characterisation and test experiments of the Phase I VUV FEL.

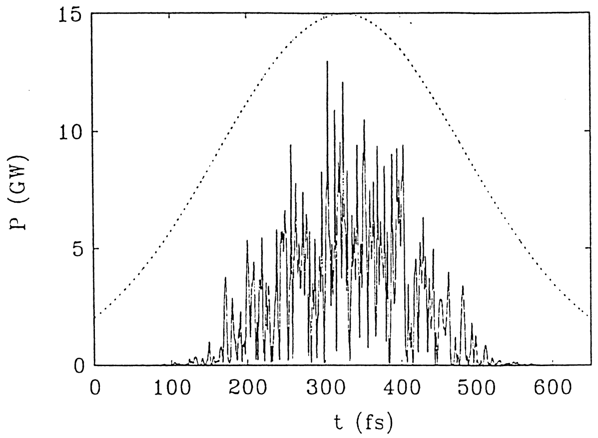

Fig. 6. Temporal structure of the radiation pulse at the saturation point of the Phase II VUV FEL. The dashed line represents the temporal structure of the electron beam current (from Ref. [17]).

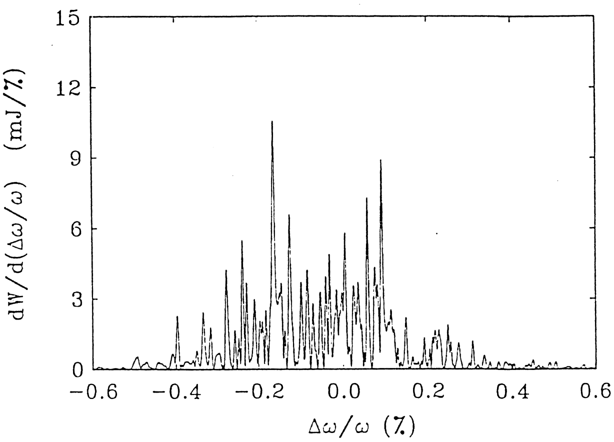

Fig. 7. Spectral distribution of the radiation pulse at the saturation point of the Phase II VUV FEL (from Ref. [17]).

Presently, new approaches are proposed to avoid these problems. They will be outlined in the last part of this paper.

3.2. User facility for wavelengths down to 6 nm (Phase II)

In parallel to the tests and characterisation of the photon beam at around 100 nm a user facility for wavelengths down to 6 nm or even shorter will be constructed. In order to achieve short wavelengths the linear accelerator has to be upgraded to 1.5 GeV by installing additional cryomodules. Another bunch compressor will be added which reduces the length of the bunch to 0.05 mm. Furthermore, three additional undulator modules will be installed resulting in a total undulator length of 27 m. Fig. 8 shows the layout of Phase II. The experimental hall will be located outside the DESY ground outside the PETRA storage ring. This hall will first be used as an exhibition hall for the EXPO 2000 world exhibition. It is expected that operation of Phase II will start in 2002. Some characteristic parameters of the photon beam are given in Table 1. In the first harmonic the wavelength can be varied from approximately 30 to 6 nm, corresponding to 30–200 eV. The spectral brilliance is four orders of magnitude higher than the values reached by the new third generation synchrotron radiation sources operating at low emittance storage rings. The expected peak brilliance of the VUV FEL is compared with other advanced light sources including the proposed X-ray facilities at DESY [18] and at SLAC [19] in Fig. 9. The gain in peak brilliance of FELs amounts to eight orders of magnitude or even more. However, it is not only the high intensity which makes this laser a unique research tool in the VUV and soft X-ray

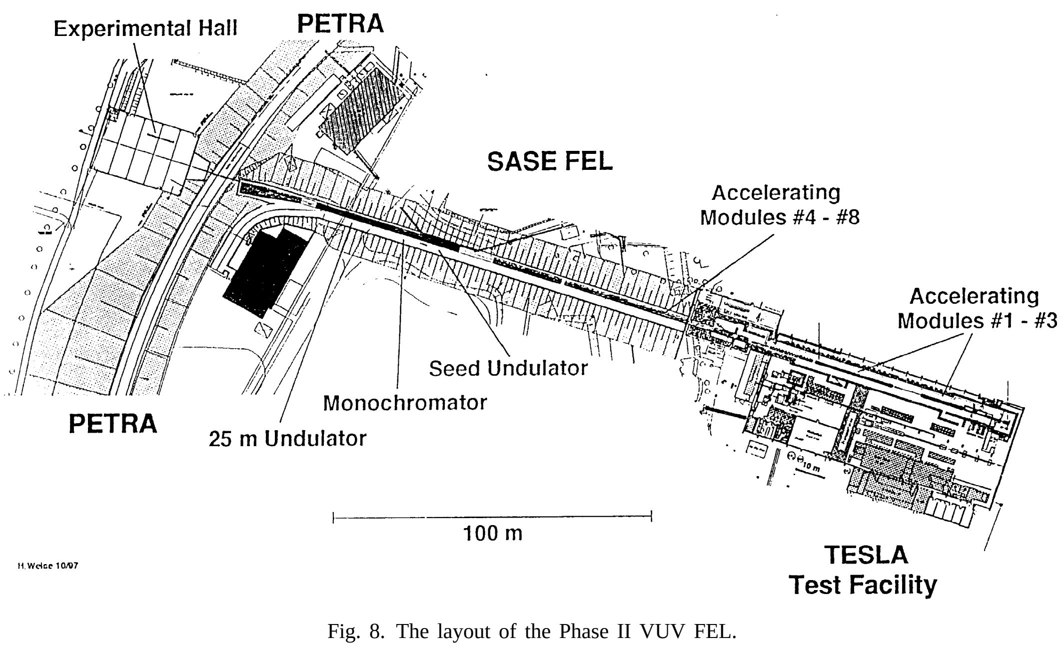

Fig. 8. The layout of the Phase II VUV FEL.

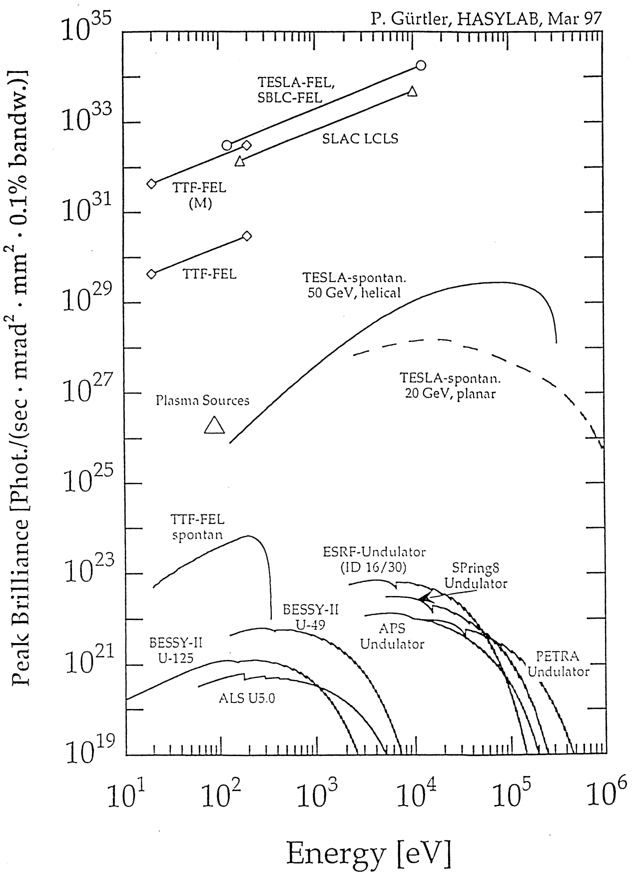

Fig. 9. Expected peak brilliance of the FELs at DESY (TTF-FEL, TESLA-FEL, M stands for the seeding scheme with a monochromator described in Section 4) in comparison with other advanced light sources.

regime. The radiation is fully coherent in the transverse beam direction. This opens new possibilities at short wavelength. Another key feature is the very short length of the pulses. The envelope of the light pulse exhibits a length of 150 fs. This has to be compared with typical pulse lengths of 20–200 ps for storage ring based synchrotron radiation sources.

3.3. Scientific applications

Two workshops were held at DESY in 1994 and 1995 in order to define the scientific case. More than 100 participants from universities, Max-Planck institutes and research groups from Germany and abroad worked out a detailed proposal [15]. The unique properties of the VUV FEL radiation will open new and exciting areas of basic and applied research in biology, chemistry and physics. For example, the high peak power will be used to induce non-linear processes, to diagnose short-lived events in dilute media and provide microscopic snapshots of temporally unstable targets. The first series of test experiments, especially on dilute gaseous samples, can use the photon beam as emitted from the VUV FEL. On the other hand, many experiments will require monochromatic and/or focused radiation which can be provided in Phase II. There are already plans to incorporate advanced optical schemes into the FEL beamlines (see Section 4). The development of optical elements capable of withstanding the high power FEL radiation is a great challenge and will stimulate the VUV optics technology. Pump-and-probe techniques will be ideal methods to investigate dynamics in condensed matter on the time scale of the motion of atoms and molecules. Fields expected to benefit greatly from the VUV FEL radiation are atomic and molecular physics, spectroscopy of ion beams, plasmas and clusters. Furthermore, the VUV FEL will allow the investigation of new aspects, e.g. dynamics, of solids and biological structures, surfaces and thin films and of photochemical processes. By focusing or defocusing the photon beam the power density at the sample can be varied according to the experimental requirements. It is expected that power densities exceeding 10^{16} W/cm^2 can be obtained. At such power levels every sample will immediately be converted into a hot plasma and one enters a rather unexplored area of research.

Experiments on dilute samples will particularly benefit from the high power of the VUV FEL. As an example, an experiment on clusters is illustrated in Fig. 10. The low density in cluster beams has so far prevented the investigation of single sized clusters with VUV radiation or X-rays. VUV FEL radiation will allow the detailed and direct investigation of the geometric and electronic structure by well-established methods such as EXAFS (extended X-ray absorption fine structure) or XPS (X-ray photoelectron spectroscopy). Furthermore, by combining the

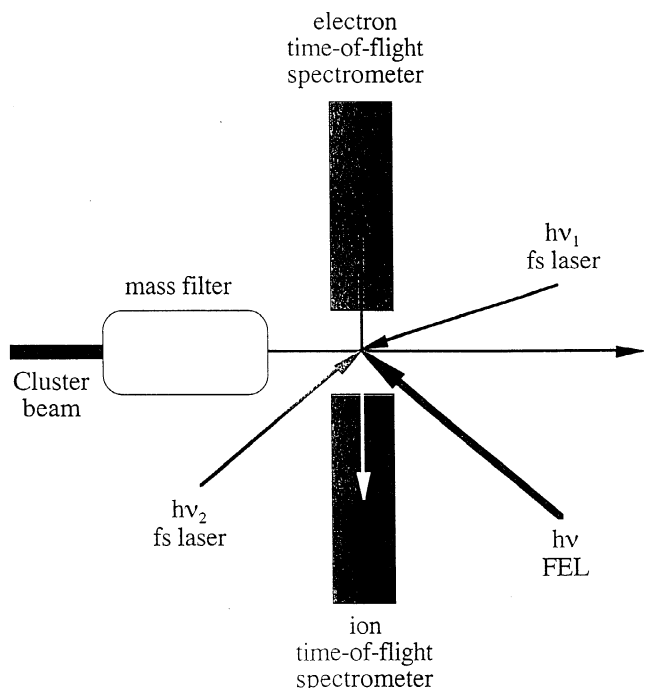

Fig. 10. Schematic illustration of an experiment on single sized cluster ions making use of the VUV FEL. Pulsed optical lasers can be used in order to study the dynamics using pump-and-probe techniques.

VUV FEL with optical fs lasers pump-and-probe techniques can be applied. As a result the dynamics of different elements inside a cluster can be explored by tuning the VUV FEL to the characteristic absorption bands of the different elements.

4. Outlook

At present, SASE seems to be the most promising concept for the generation of extremely intense radiation at short wavelengths. The short pulse length, which is one of the requirements to make SASE work, opens up new areas for research in the VUV since the dynamics can be probed in the sub-ps regime. In order to overcome the inconvenient statistical fluctuations in time and energy one goal is to develop a true VUV laser which is fully coherent in space and time. One idea is to divide the undulator into two parts with a narrow band width monochromator in between [17]. A schematic layout is shown in Fig. 11. The monochromator selects a narrow band of radiation emitted by the first undulator, seeding the second undulator which amplifies it to saturation. When the bandwidth of the monochromator approaches the characteristic line width of 5×10^{-5} the output radiation will be fully coherent with one very narrow single line and a smooth pulse structure. Under these conditions the photon pulse length will be nearly the same as the electron pulse length, i.e. 400 fs (FWHM). In order to obtain well defined and even shorter pulses for pump-and-probe experiments there are ideas to seed the second undulator by two lines with narrow bandwidth but slightly different wavelengths. As a result there will be a beating in the time domain as illustrated in Fig. 12. The beating frequency and the separation of the pulses can be varied by changing the energy separation of the two seeding pulses.

For the future an important goal is the realisation of an X-ray laser facility (XFEL) for photon energies up to 12 keV as part of a 500 GeV linear collider. The layout and scientific applications are described in the recently published conceptual design report [18].

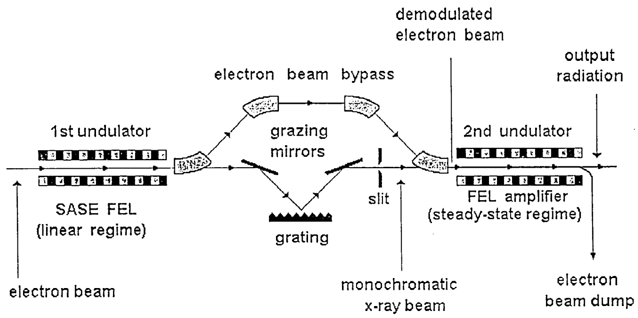

Fig. 11. Schematic layout of a seeding scheme proposed for the Phase II facility.

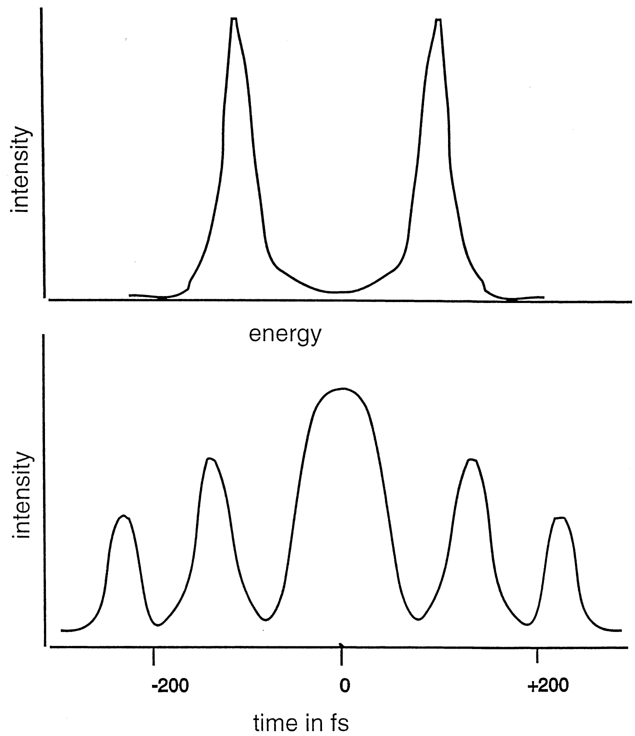

Fig. 12. Schematic illustration of the spectral distribution of a seeding scheme with two slightly different wavelengths (energies) and the resulting temporal structure of the amplified photon beam.

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