The Potential for the Development of the X-Ray Free Electron Laser

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Abstract

X-ray photon beam from a SASE FEL undulator is in principle a single user tool, just like an optical laser. Therefore, the operation and amortization cost cannot be easily spread over many simultaneous experiments. To avoid prohibitive cost for each experiment, a new XFEL laboratory scheme is proposed. The wavelength range 0.1-1.6 nm at fixed electron energy of 15 GeV can be covered by operating the SASE FEL with three undulators which have different period and tunable gap. All electrons will be guided into only one electron beamline and dump. Using 0.1% electron (photon) energy shifter in a SASE undulator it is possible to rapidly switch the FEL photon beam from one SASE undulator beamline to the other, providing simultaneous multi-undulator capability. A photon beam distribution system based on movable multilayer X-ray mirrors can provide an efficient way to generate a multi-user facility. Distribution of photons is achieved on the basis of pulse trains and it is possible to partition the photon beam among a few tens independent beamlines thereby obtaining many users working in parallel. The second way to increase the number of simultaneous experiments is based on the working with a series of perfect crystals in transmission (Laue) geometry. The later concept is the basic idea of the Troika beamline at ESRF. In principle, a hundred of photon beamlines with different experiments can be served by a single XFEL source. It is a great advantage that the accelerator and electron beam transport line in the proposed scheme of multi-user facility operate at fixed parameters, thus an "electron switchyard" is not required. The proposed XFEL scheme is applicable for the Linac Coherent Light Source (LCLS) and European XFEL.

Contents

1 Introduction

The preferred layout of a SASE FEL is a linear arrangement in which the injector, accelerator, bunch compressors and undulators are nearly collinear, and in which the electron beam does not change the direction between accelerator and undulators. On the other hand, a X-ray FEL laboratory should serve several tens, may be up to a hundred experimental stations which should operate independently according to the needs of the user community. The present paper describes a beam distribution system which allows to switch the FEL beam quickly between many experiments in order to make efficient use of the source. Many applications require only very high peak brilliance. Such experiments for which average brilliance and wavelength are not critical, could operate simultaneously at the same radiation wavelength.

Baseline design of present XFEL projects [1–4] assumes only standard (SASE FEL) mode for production of radiation. Recent developments in the field of FEL physics and technology form a reliable basis for perspective extensions of the XFEL facilities. Relevant study for possible perspective developments of LCLS within next ten years since its commissioning has been presented in [5]. In this paper we propose a concept of XFEL laboratory which will allow to implement all perspective features from the very beginning of operation. These extra features are high-power (sub-TW level) option, attosecond option, and two-color option.

Special attention is devoted to the strategy for tuning the SASE process. It is evident that tuning of SASE operating at 0.1 nm wavelength is a challenging problem. The problem is that standard electron beam diagnostic tools are not able to provide sufficient information about parameters relevant to the SASE amplification process. For effective tuning of the SASE process it is necessary to know slice beam parameters: current, emittance, and energy spread. The most sensitive probe of the beam quality is the FEL process itself. In this paper we propose to use long-wavelength SASE undulators for the purpose of beam diagnostics. Installation of three undulators with overlapping wavelength ranges in one beamline will provide an effective tool for reliable tuning of the short-wavelength SASE undulator.

2 Generation of SASE radiation

For the design of the XFEL laboratory and the undulators the requirements with respect to photon energy range and tunability are important. The FEL laboratory will provide intense photon beams in the X-ray regime. Within the upper limit for generation of XFEL radiation at about 15 keV (0.08 nm) a wide range of photon energies has to be provided [1–3]. The lower energy cutoff is practically determined by the availability of the other sources, in particular the DESY TTF soft X-ray FEL facility which is foreseen to deliver FEL radiation with wavelength down to 2 nm in its third harmonic [6].

The superconducting linac is capable of supplying the pulse rate needed to support a farm of X-ray undulators. The proposed XFEL source will consist of three FEL beam lines. All together we expect that up to a hundred experimental stations can be distributed

among the three undulator beam lines according to the needs of the user community.

2.1 Layout of XFEL

The accelerator will be operated at 10 Hz repetition rate providing bunch trains of up to 4000 electron bunches within one bunch train. All electron bunch trains will be guided into one electron beamline and dump. The electron beam transport line takes every bunch train and delivers it to the 1st SASE undulator (see Fig. 1). The performance of the FEL depends critically on the parameters of the electron beam. The optics between the undulators is especially designed to ensure the desired beam quality. The two bending
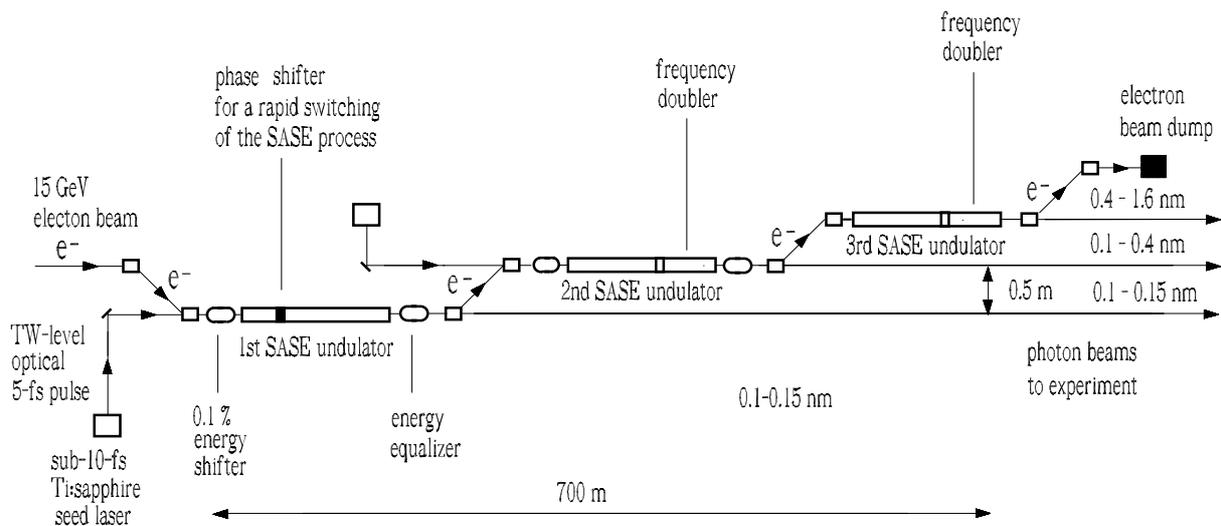
Fig. 1. Sketch of a X-ray SASE FEL source
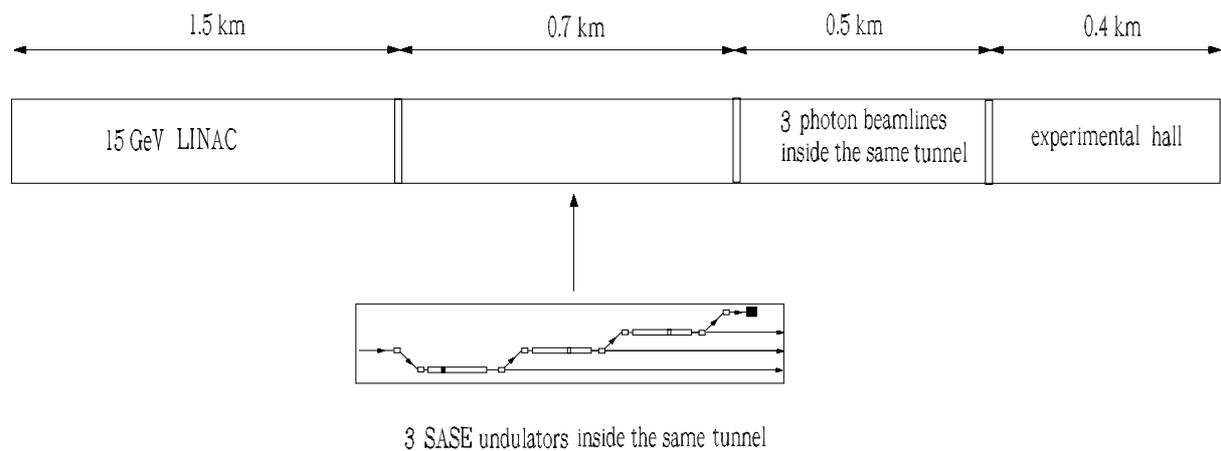
Fig. 2. The schematic layout of the XFEL

Table 1
Specification of undulators

| | λ_r^* | λ_u | gap | B_w | K_{rms} | β_f | L_w |
	nm	mm	mm	T		m	m
SASE1	0.1-0.15	36.5	10-12	0.8-1	1.9-2.5	10-50	150
SASE2	0.1-0.4	44.8	10-19	0.6-1.3	1.7-3.8	10-50	150
SASE3	0.4-1.6	60.6	10-20	0.8-1.7	3.2-6.7	10-50	110

*For nominal electron energy of 15 GeV.

Table 2
Specification of photon beam properties*

	Units	SASE1	SASE2	SASE3
Wavelength range	nm	0.1-0.15	0.1-0.4	0.4-1.6
Photon energy range	keV	12.4-8.3	12.4-3.1	3.1-0.8
Peak power	GW	10	20	20
Average power	W	40	80	80
Photon beam size (FWHM)	μm	90	60	60
Photon beam divergence (FWHM)	μrad	1.1	2.2	6.6
Coherence time	fs	0.22	0.25	0.5
Spectrum bandwidth (FWHM)	%	0.08	0.14	0.3
Pulse duration (FWHM)	fs	100	100	100
Number of photons per pulse	#	5×10^{11}	2×10^{12}	4×10^{12}
Average flux of photons	#/sec	2×10^{16}	8×10^{16}	2×10^{17}
Peak brilliance	B	2.5×10^{33}	1.4×10^{33}	8×10^{31}
Average brilliance	B	1×10^{25}	6×10^{24}	3×10^{23}

*Parameters are calculated for nominal electron energy of 15 GeV and middle of tunability range (see section 4 for more details). Average characteristics are calculated for 10 Hz repetition rate, and 4000 pulses per one train. Brilliance is calculated in units of photons/sec/mrad^2/mm^2/(0.1% bandwidth).

magnets with a 10 mrad bending angle provide the parallel shift of the beam axis by a distance of 0.5 m, then the electron beam reaches the entrance of the 2nd SASE undulator. To bend the beam into the undulator, magnets operate in a DC mode with improved field stability. The photon beams of the 1st and 2nd SASE undulators have to be separated by a distance of 2 m in the experimental hall, which is realized by a deflection angle of about a one mrad. After passing all three undulators, the electrons are stopped in the beam dump. All three photon beamlines can be operated in parallel.

At a fixed electron energy the magnet gap of the FEL undulator can be varied mechanically for wavelength tuning. The wavelength range 0.1-1.6 nm at a fixed electron energy of 15 GeV can be covered by operating the XFEL with three undulators which have different periods. These SASE undulators can be placed behind each other assuming that the subsequent undulator radiates at longer wavelength. It is a great advantage that accelerator and electron beam transport line in new scheme of multi-user facility operate at fixed parameters and that a fast "electron switchyard" is not required. In order to avoid the need for a costly additional tunnels and shafts, the XFEL source is designed such that accelerator, all three SASE undulators, electron beamline, and three photon transport beamlines are installed inside the same (5 m diameter) tunnel (see Fig. 2).

2.2 Control of the amplification process with SASE switchers

Although the electron beam leaving the 1st SASE undulator has acquired some additional energy spread, it is still a good "active medium" for the 3rd SASE undulator at the end. In this scheme it will be possible to provide in parallel hard (around 0.1 nm) and soft (around 1 nm) X-rays for two photon beamlines (after-burner mode of operation). Normally if a SASE FEL operates in saturation, the quality of the electron beam is too bad for the generation of SASE radiation in a subsequent undulator which is resonant at a few times longer wavelength. On the other hand, to operate XFEL at the requested radiation wavelengths, three undulators are needed. The new method of SASE undulator-switching based on a rapid switching of the SASE process proposed in this paper is an attempt to get around this obstacle (see Fig. 3). This approach could be a very interesting alternative to the SASE undulator-switching based on "electron beam switchyard". The same goal, rapid switching between different SASE undulators, can be achieved in a more technically reliable way at less expenses.

There are two approaches to solving the problem of rapidly switched FEL. The first one focuses on the development of electromagnetic phase shifter embedded in the other components needed inside the undulator insertion. Second, electron energy shifter, can also be used. The technique of using a phase shifter as a switch relies on the fact that dependence of the FEL gain on the phase between the electron beam modulation and the radiation field, acting on the electrons is very strong. It is apparent that the electron's relative position within a radiation wavelength will determine whether it consistently gains or loses energy as it travels through the undulator. Optimal suppression is obtained when phase shift is such that most of electrons fall into accelerating phase and after passing through the phase shifter the electrons start to absorb power from electromagnetic wave. For the purpose of phase switching, electron beam has to be slightly delayed (about of Angstrom) as compared to the radiation beam. This is done by a suitably designed magnetic chicane called a phase shifter [7] (see Fig. 4). It consists of three horizontal
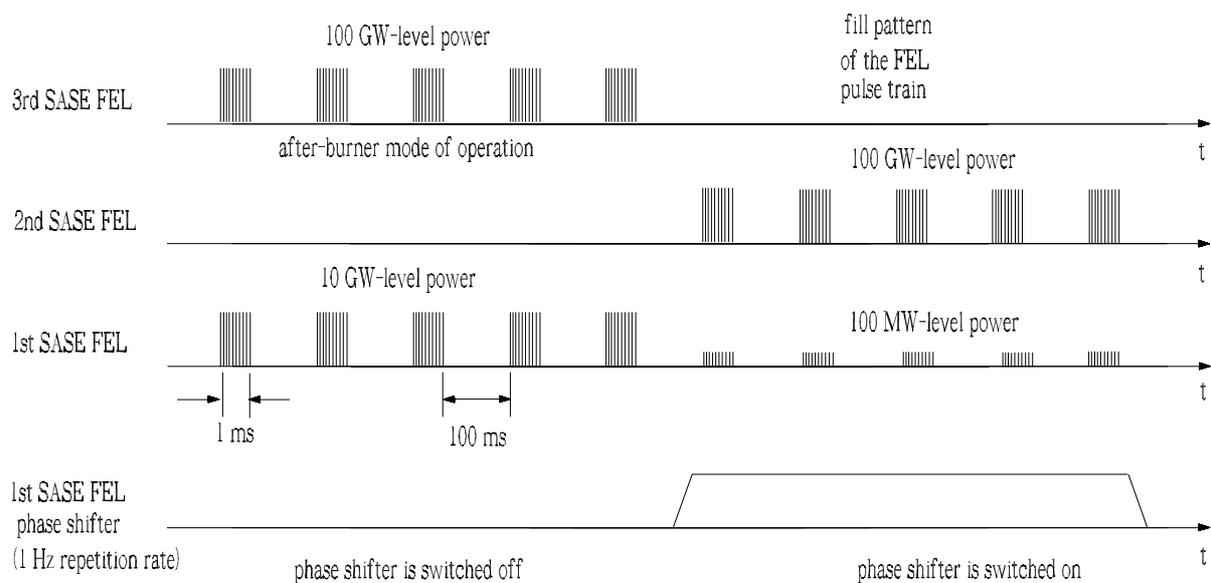
Fig. 3. Possible photon pulse train patterns for the X-ray SASE FEL

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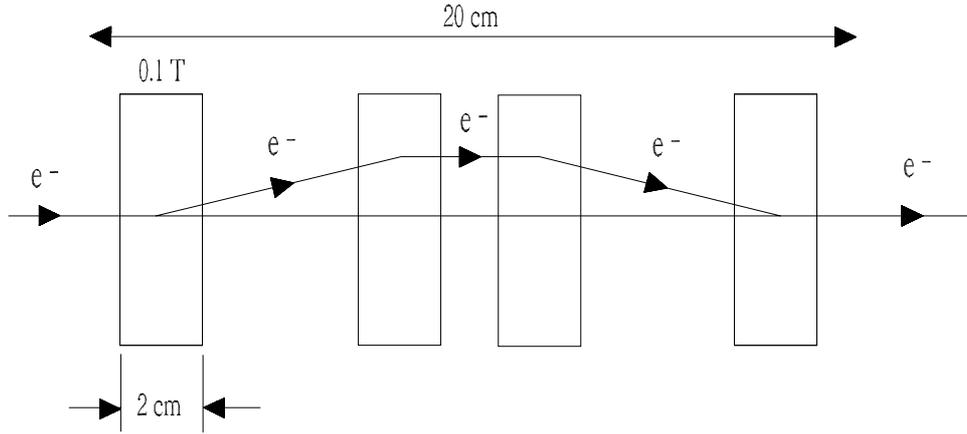
Fig. 4. Electromagnetic phase shifter for a rapid switching of the SASE process in the 0.1 nm undulator
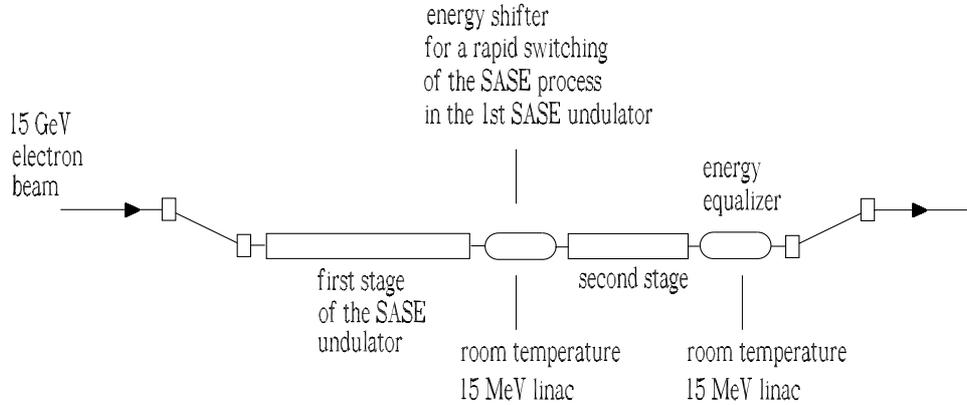
Fig. 5. The second way to a rapid switching of the SASE process in the 0.1 nm undulator. Conceptual layout of the electron (photon) energy shifter

magnets. The length of the center one is doubled because it needs twice the strength. The total length of phase shifter is about 20 cm. It uses electromagnets at an excitation level which is low enough, so that water cooling is not needed. For trapezoidal mode a frequency of 1 Hz is specified with a switching time of less than 10 ms. This kind of insertion device can be embedded between two neighboring undulator segments.

Another interesting approach is that of photon (electron) energy shifter. This method of beamline switching is based on the accelerator technique. In this case the SASE undulator beamline consists of an input undulator, and an output undulator separated by an accelerator module (see Fig. 5). The typical FEL amplification bandwidth in the X-ray wavelength range is of the order of 0.1%. The offset photon energy 0.2% corresponds to electron energy shift of 15 MeV. By shifting the energy of the electron beam, one can effectively switch output undulator off. So the effective length of the undulator system can be rapidly varied (see Fig. 6). The RF switch consists of RF accelerator module with total voltage $V_0 \simeq 15$ MeV. We select 1.3 GHz structure based on standing-wave room temperature cavities with gradient of 8 MV/m. The quadrupole separation of an undulator
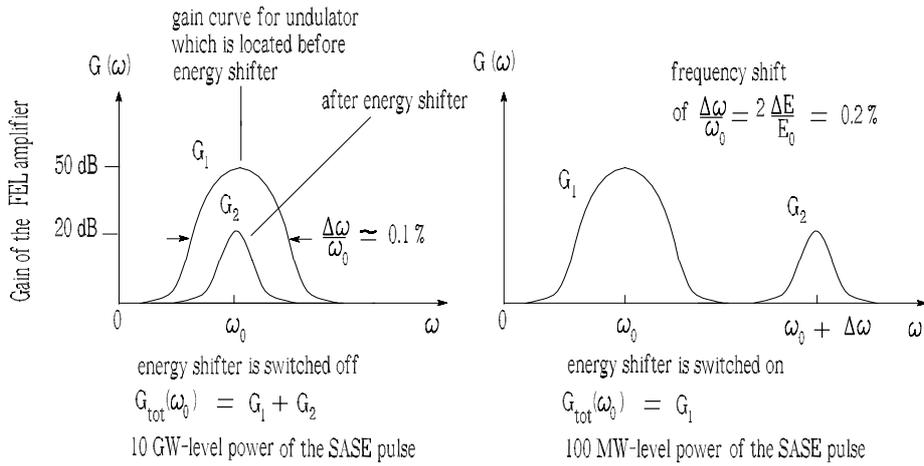
Fig. 6. Basic principle of the SASE switching system based on the energy shifter
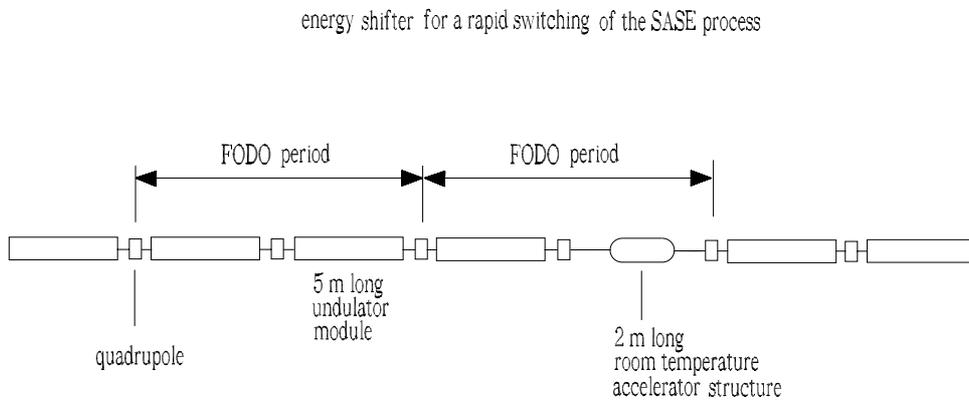
Fig. 7. Installation of an energy shifter for a rapid switching of the SASE process. The quadrupole separation of a FODO lattice is large enough so that an accelerator structure of length 2 m can be installed.

FODO lattice is large enough so that relatively short (2 m) accelerator structure can be installed (see Fig. 7). Each RF switch would require one klystron TH 2104. This klystron is used for the TTF RF gun. The RF switch is operated with full beam loading and with design beam parameters. The average heat load of the accelerator cavity amounts to 20 kW which has to be removed by the cooling water. DESY is now developing similar room temperature accelerator structure for research unit PITZ at DESY Zeuthen [8].

2.3 Extended possibilities beyond standard (SASE) mode of operation

The developments discussed in this paper concern also the increased FEL output radiation power. The most promising way to achieve the goal is the method of tapering the magnetic field of the undulator. Tapering consists in slowly reducing the field strength of the undulator field to preserve the resonance wavelength as the kinetic energy of the electrons changes. Figure 8 shows the design principle of a high-power undulator. The first stage is a conventional X-ray SASE FEL. The gain of the first stage is controlled

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2nd SASE undulator with tunable gap

0.2 nm option with maximum efficiency

tapered undulator

switched on

0.1 nm option with maximum efficiency

frequency doubler with tapered undulator

switched on

0.2 nm option with maximum gain

switched off

untapered undulator

dispersion section
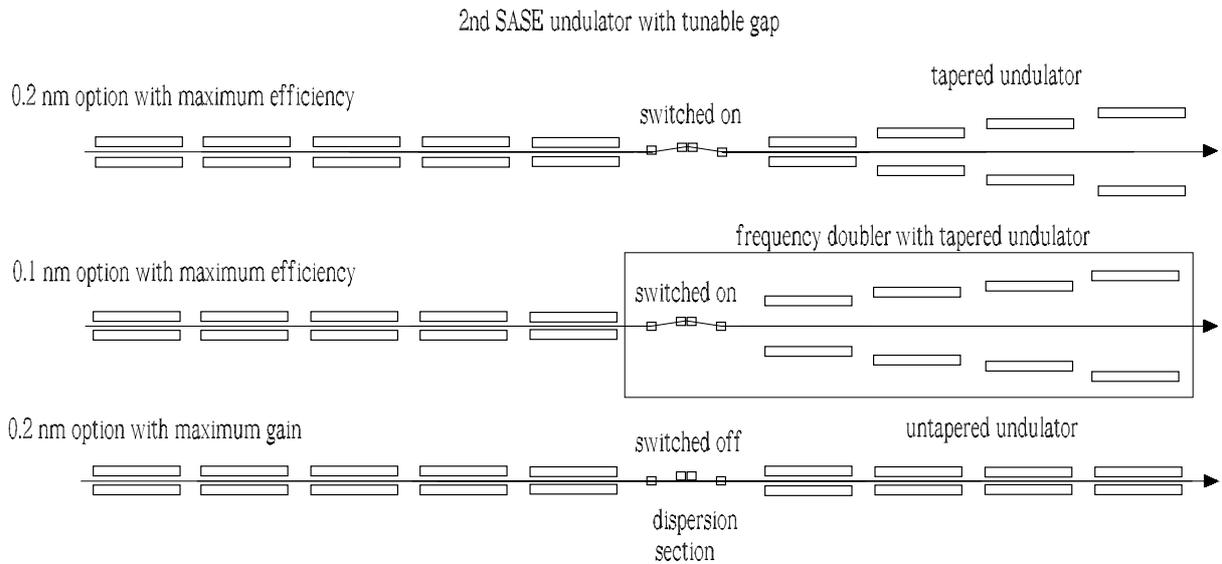
Fig. 8. Three schemes for 2nd SASE undulator. Only one type of undulator magnet structure is needed. The radiation wavelength will be tuned by changing the gap. The total magnetic length is 150 m

2nd SASE undulator

FODO period

FODO period

5 m long undulator module

4 m long dispersion section with electron beam offset 1 mm
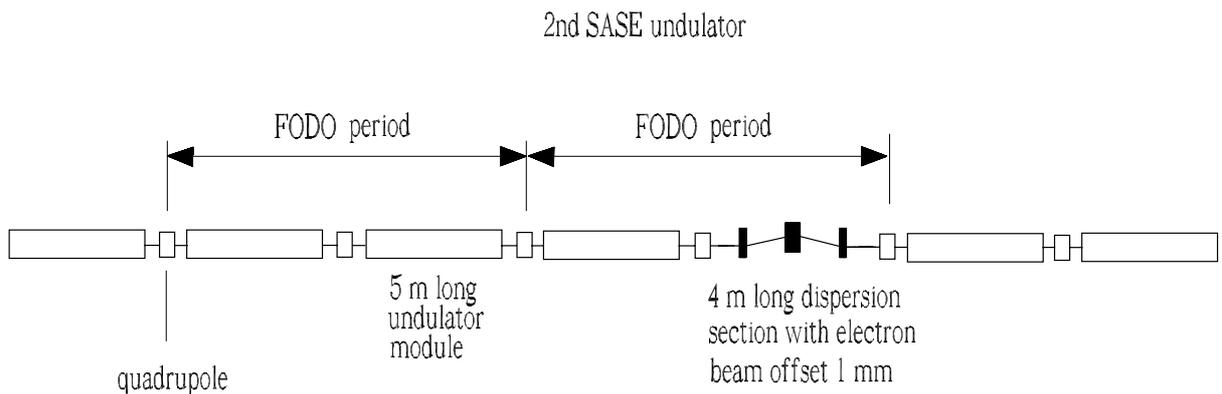
quadrupole

Fig. 9. Installation of a dispersion section in the 2nd SASE undulator. The quadrupole separation of a FODO lattice is large enough so that magnetic chicane of length 4 m can be installed

in such a way that the maximum energy modulation of the electron beam at the FEL exit is about equal to the local energy spread, but still far away from saturation. When the electron bunch passes through the dispersion section this energy modulation leads to effective compression of the particles. Then the bunched electron beam enters the tapered undulator, and from the very beginning produces strong radiation because of the large spatial bunching. Radiation field produces a ponderomotive well which is deep enough to trap the particles, since the original beam is relatively cold. The radiation produced by these captured particles increases the depth of the ponderomotive well, and they are effectively decelerated. As a result, much higher power can be achieved than for the case

of a uniform undulator. At the total undulator length of 150 m, the FEL output at 0.2 nm is enhanced by a factor of 8, from 20 GW to 150 GW. With the proposed variable gap undulator design this option would require only installation of a dispersion section. Our study has shown that the required net compaction factor of the dispersion section is about a fraction of μm. The quadrupole separation of an undulator FODO lattice is large enough so that relatively short (4 m) dispersion section can be installed (see Fig. 9). An undulator taper could be simply implemented as a step taper from one undulator segment to the next.

The specification of the 2nd SASE undulator in uniform mode of operation gives a range of wavelengths between 0.2 and 0.4 nm. It was concluded that most experiments which are not interested in particular resonance effects will benefit from using photon energies close to 0.1 nm. A design was conceived that enables to obtain XFEL radiation at a close to 0.1 nm wavelength at two of the three SASE undulators simultaneously. The problem to be solved is how to extend the higher photon energy cutoff of the 2nd SASE undulator up to 12 keV. In this paper we propose to use an efficient frequency doubler for the 2nd and 3rd SASE FELs [9]. In its simplest configuration the frequency doubler consists of an input undulator, and an output undulator separated by a dispersion section. After passing through the dispersion section the bunched beam has not only a fundamental radiation frequency component, but also has considerable intensity in its harmonics. It is possible to have an input undulator operating at one frequency, and an output undulator operating at double of this frequency (see Fig. 8). The radiation in the output undulator will then be excited by the harmonic component in the electron beam, and the FEL will operate as a combination of frequency multiplier and amplifier.

Another perspective development is an attosecond mode of operation. A technique for the production of attosecond X-ray pulses is based on the use of X-ray SASE FEL combined with a femtosecond laser system [10]. It is important that this attosecond scheme is based on the nominal XFEL parameters, and operates in a "parasitic" mode not interfering with the main mode of the XFEL operation. It can be realized with minimum additional efforts. The machine design should foresee the space for installation of modulator undulator and a viewport for input optical system. Many of the components of the required laser system can be achieved with technology which is currently being developed for applications other than the attosecond X-ray source.

2.4   Strategy for reliable tuning of the SASE process

Tuning of the accelerator for the 0.1 nm SASE FEL operation is very difficult task without information about relevant beam parameters. This underlines the urgent necessity to develop electron beam diagnostics tools which are crucial for the proper operation of XFEL. Electron bunches with very small transverse emittance and high peak current are needed for the operation of XFEL. The bunch length for XFEL applications is of order of 100 fs. The femtosecond time scale is beyond the range of standard electronic display instrumentation and the development of nondestructive methods for the measurement of such short bunches is undoubtedly a challenging problem. Reliable methods for measuring bunch shape, slice emittance and energy spread on a femtosecond time scale should be

developed. A new principle of diagnostic techniques described here offers a way around this difficulty. The principle of global optimization of the proposed XFEL source is essentially based on the measurement of the long wavelength SASE radiation properties. Actually, radiation measurements are very reliable and accurate, and in combination with FEL theory we can infer a lot about the properties of the part of electron bunch that produces the SASE radiation. In particular, a method of the peak current, slice emittance and energy spread reconstruction, based on detection of 1.6 nm SASE radiation from the 3rd SASE undulator, would perfectly fit this purpose. It is important to note that even at a normalized emittance of 6 mm-mrad and peak current of 3 kA the SASE process in the 3rd SASE undulator develops successfully because of the long radiation wavelengths (see Appendix A).

3 Multi-user distribution system for a X-ray SASE FEL laboratory

We should note that each FEL source emits only one photon beam. Therefore, the operation and amortization costs cannot be easily spread over many simultaneous experiments. To avoid prohibitive cost for each experiment, new photon beam distribution scheme is proposed. It would specifically partition the photon beam among a few tens independent beamlines thereby obtaining many users working in parallel.

3.1 Multi-user distribution system based on multilayers

The technical approach adopted in this variant of XFEL laboratory design makes use of movable multilayer X-ray mirrors. Layered synthetic materials – multilayers – are layered structures with usually two alternating materials: a low and high density materials. They play an important role in synchrotron X-ray optics [11–14]. They provide less energy resolution but correspondingly more flux and keep the angular beam divergence constant (in the ideal case). Typical multilayers used as optical elements at third generation synchrotrons provide a spectral bandwidth of 1 to 5%. Typical glancing angles are of the order of a degree and thus lie between the mrad wide angles of X-ray mirrors and the much bigger 10 degree wide Bragg angles of single crystals. The angular acceptance of X-ray multilayer mirror is of the order of one mrad (for a bandwidth 1%). As a rule, from 100 to 400 periods participate in effective reflection in such mirrors. About 90% peak reflectivity was achieved for wavelengths around 0.1 nm. Computer simulations are in very good agreement with experimental results in all cases so that efficiencies can be safely predicted.

The concept of photon beam distribution system is very simple. Figure 10 shows rele-
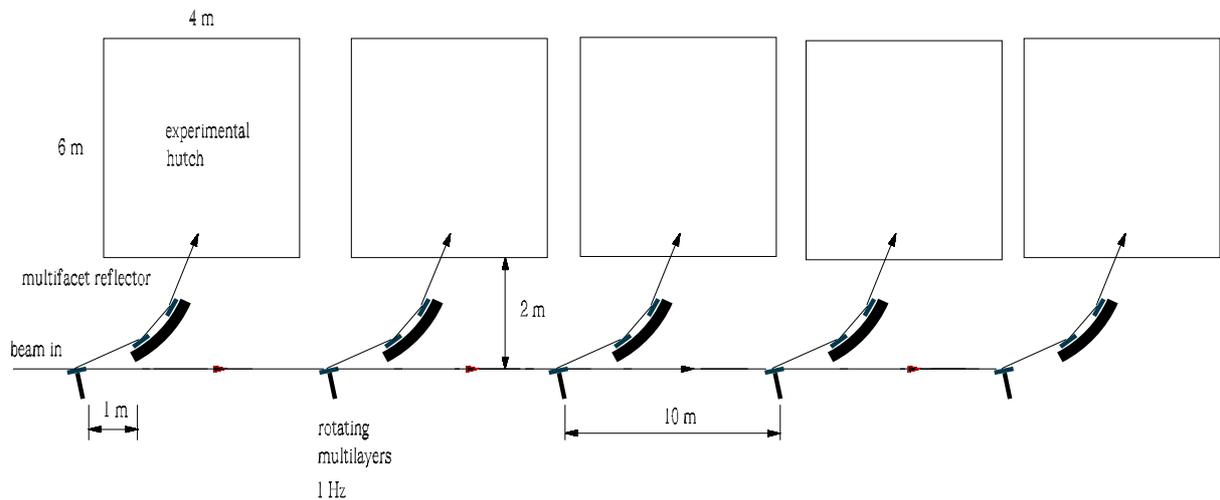
Fig. 10. Proposed SASE undulator beamline for studies with maximum X-ray flux. The distribution of photons is achieved on the basis of pulse trains and it is possible to serve 5 user stations with repetition rate 1 Hz
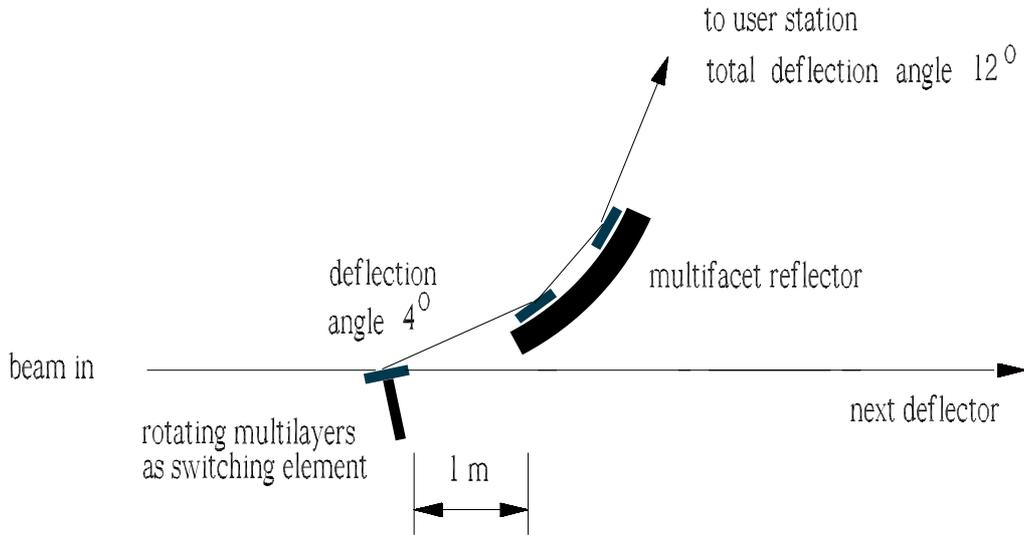
Fig. 11. Concept of the photon beam deflector based on multilayer X-ray mirror. Using rotating multilayer mirrors as switching elements between the multifacet reflectors makes it possible to provide X-ray radiation for many user stations
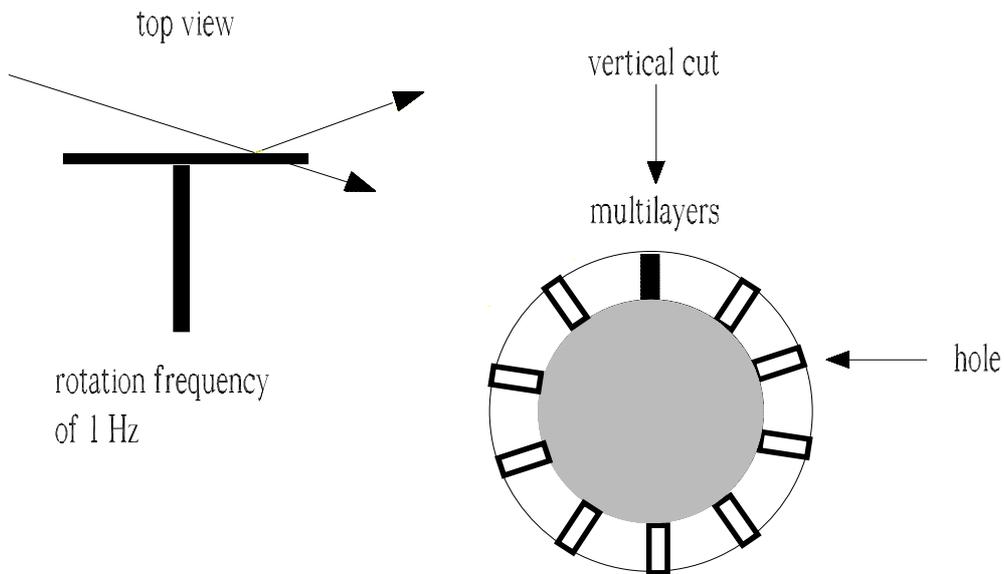
Fig. 12. Different views of a switching multilayer mirror

vant photon beamline configuration. The distribution of pulse trains among the different user stations can be done by movable deflectors. A schematic diagram of a movable deflector is shown in Fig. 12. Its key components include rotating multilayers and multifacet reflector. The advantages of multilayer as movable photon beam deflector are based on two factors: the larger deflection angle compared to X-ray mirrors; and the larger angular acceptance compared to crystals. The multilayer mirror angular acceptance is of the order of one mrad, and is well matched to the natural opening angle, (from one to a few μrad), of an XFEL source. In order to achieve stable photon beam deflection the alignment accuracy of multilayer deflectors must be less than 0.1 mrad. It is believed that technology,

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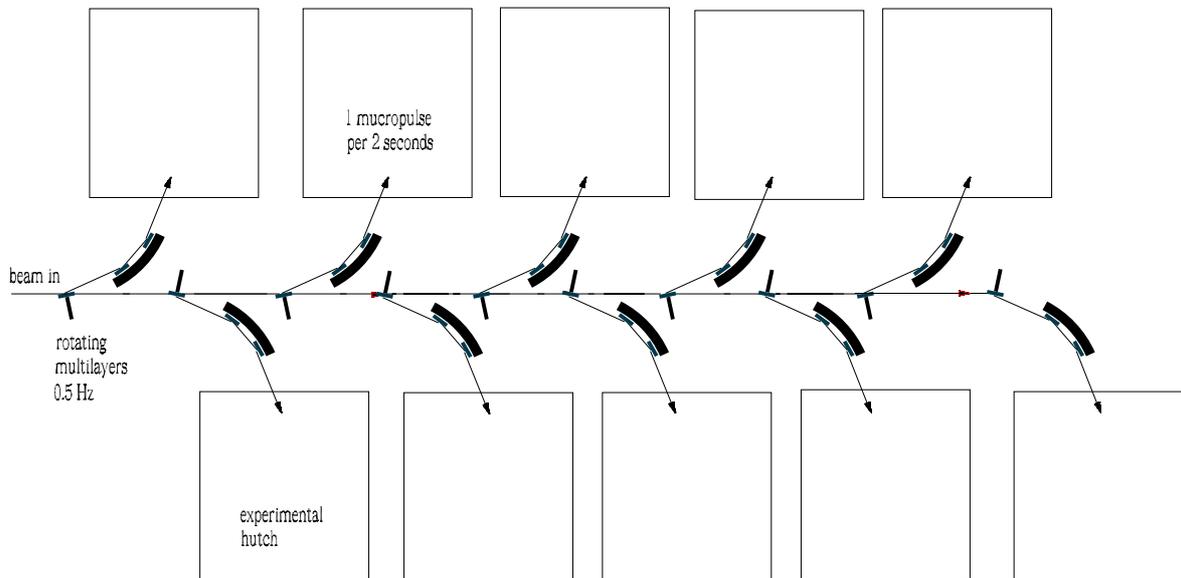
Fig. 13. Second beamline scheme for studies with maximum X-ray flux. It is possible to serve 10 user stations with repetition rate 0.5 Hz

presently in advanced development for applications other than XFEL, will enable rotating multilayers to satisfy these requirements. The initial photon beam is transformed into 5 beams. The switching mirrors need to rotate at a frequency of 1 Hz such that each user actually receives one train of pulses with a full duration of 1 ms per second. Note that even if the photon beam is distributed among many users, the peak flux per user remains untouched (apart from the losses in the deflector system). Such a scheme, which adopts multilayer deflector concept, allows one to increase the total number of user stations by using standardized X-ray optical components. The extended version of SASE undulator beamline scheme for studies with maximum X-ray flux is depicted in Fig. 13. Ten deflectors enable us to perform 10 different experiments simultaneously. In this case the switching mirrors need to rotate at a frequency of 0.5 Hz such that each user receives one pulse train per 2 seconds.

An attractive feature of the distribution system based on movable multilayers is the absence of no apparent limitations which would prevent operation at even hundred user stations (per SASE undulator) simultaneously. All users will receive the photon beam of identical (and high) quality. Every time deflection process happens only once during one pass of the photon beam through the deflector unit with only three multilayers, and the problem of the absorption of the radiation in the distribution system does not exist at all. Another advantage comes from small (one to a few μmrad) angular divergence of the FEL radiation. As a result, in an extended sequence of deflectors (say, a few tens of meters), photon beam properties (spot size) remain unchanged. The larger number of beamlines, the smaller is the macropulse repetition rate per user station. Note also that even if the beam is distributed among 50 users, the macropulse repetition rate per user will still be 0.1 Hz. It is important to note that for many experiments this may not be a difficulty and the macropulse (4000 pulses) per 10 seconds is more than sufficient. Photon intensity integrated over macropulse is equivalent to an intensity integrated per an hour at synchrotron radiation sources today. Another attractive feature of the proposed photon

system is a high degree of flexibility: if some user will request a full photon flux for a while, this can be done simply by means of "freezing" motion of the multilayers for a while such that full photon flux is directed to dedicated user station.

3.2 Multi-user distribution system based on crystal deflectors

Photon beam distribution system based on movable multilayers is one of the alternatives under consideration to extend the XFEL capability to a few tens users working in parallel. The second potential candidate for the XFEL laboratory to progress into multi-user facility class is that distribution system based on (fixed) crystal deflectors. Figures 14 and 15 show a schematic layout of the second variant of the XFEL laboratory. This is a farm of multi-station SASE undulator beamlines, working with a series of transmission crystal deflectors (see Fig. 17). Advantage of this scheme is the possibility of using not only the diffracted photon beam, but also the transmitted "broadband" SASE beam for downstream experimental stations operating at different photon energies (see Fig. 18). The latter concept is the basic idea of the Troika beamline at ESRF [15–17]. Note that even if the photon beam is distributed among a few tens of users, the peak brilliance per user remains untouched (apart from the losses in the deflector system). In the case of end stations the direct photon beam is used.

The relative spectral bandwidth for Laue reflection is independent of the wavelength or glancing angle of X-rays and is given merely by properties of the crystal and the reflecting atomic planes. In particular, it implies that the choice of a crystal and reflecting atomic planes determines the spectral resolution. For example, one can consider Si(111) crystals, which have FWHM bandwidth of $\Delta\lambda/\lambda \simeq 1.2 \times 10^{-4}$ in Laue transmission geometry (see Fig. 16). Deflectors at photon beam lines are fabricated from silicon. The main advantage of the silicon is the availability of almost perfect synthetic monocrystals,
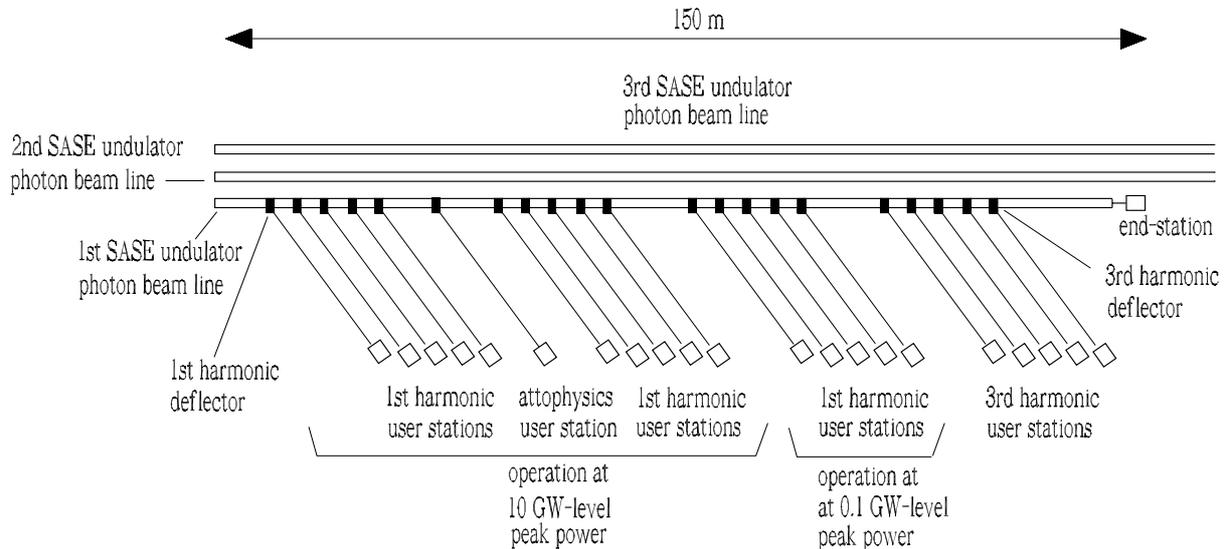
Fig. 14. 1st SASE undulator beamline. The photon beam distribution system, described in the paper, can provide 1st SASE undulator radiation for 21 user experiments in a simultaneous mode
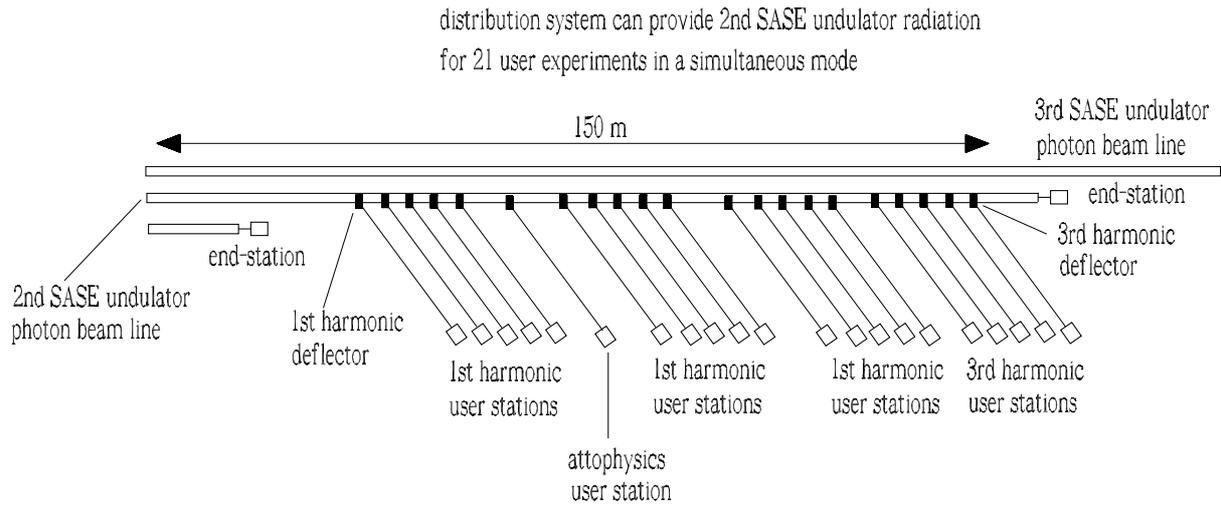
Fig. 15. 2nd SASE undulator beam line
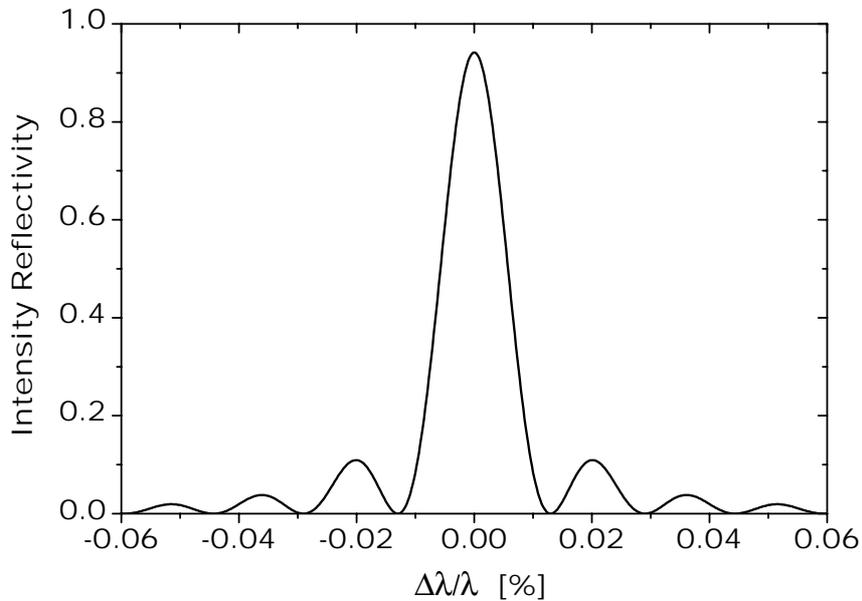
Fig. 16. Reflectivity curve for a Si(111) crystal in the Laue case. Crystal thickness is 15μm, radiation wavelength is 0.1 nm

with high transparency. The reason is that semiconductor industry has created a huge demand for defect-free, perfect single crystal. In order to maintain a high transmission through the deflectors for the downstream stations, it is necessary to limit the absorption in the 10 deflectors to about 50% at 0.1 nm. The thickness of the one crystal must therefore not exceed 15 μm (see Fig. 19). The angular acceptance of silicon deflector is of the order of 20 μrad for a wavelength of 0.1 nm, and is well matched to the natural opening angle, (one μrad), of an XFEL source.

The use of a Laue deflector can be extremely advantageous in the case of high thermal

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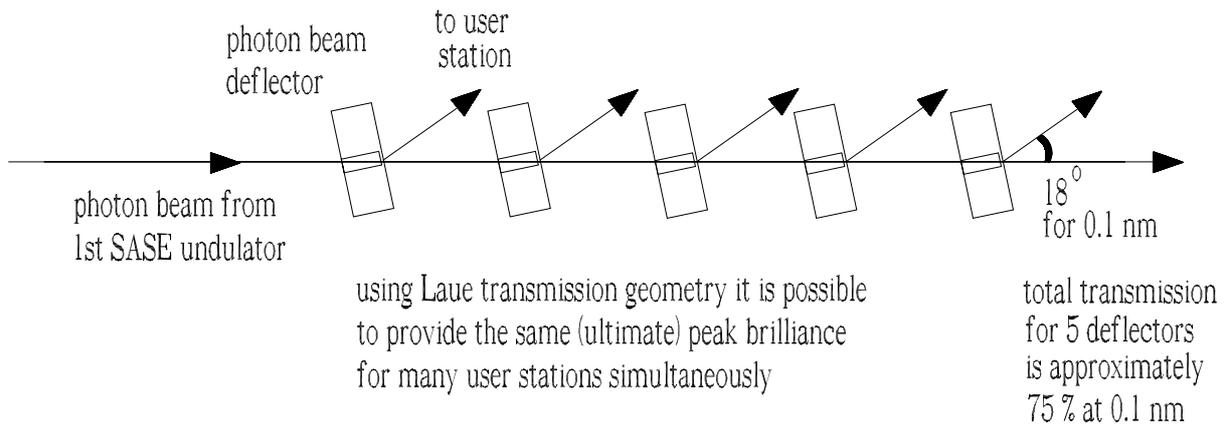
Fig. 17. Photon beam distribution system setup for simultaneous multi-user mode of operation at 0.1 nm
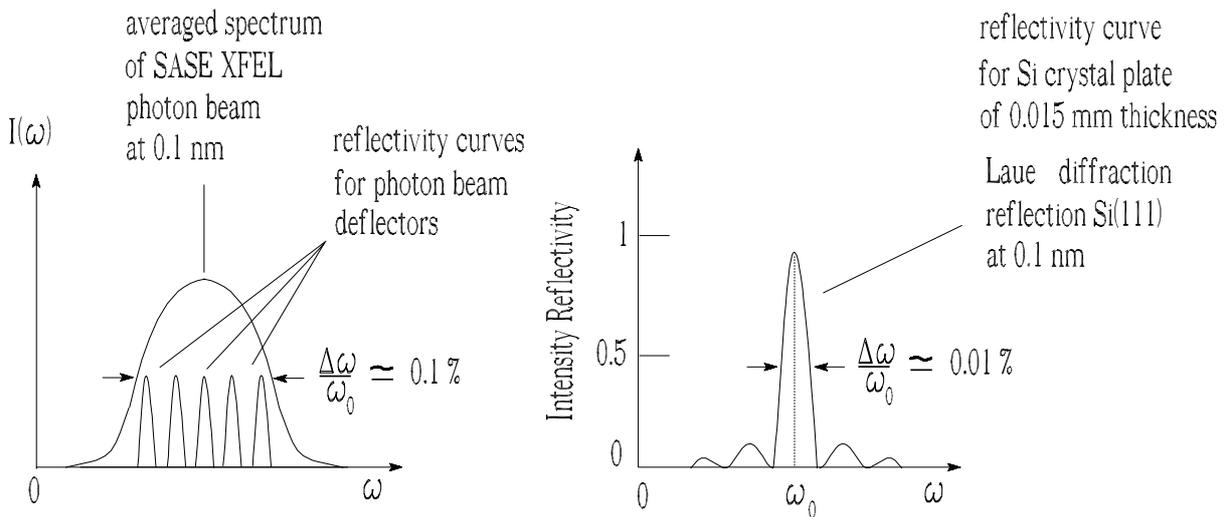
Fig. 18. Basic principle of the XFEL multi-user distribution system. Using Laue diffraction in Si crystals as a method of photon beam deflection it is possible to provide X-ray radiation for many user-station simultaneously

loads, because the beam is almost entirely transmitted, and only a small part is absorbed. At 0.1 nm an average power of 40 W (2 mJ× 5 trains/s × 4000 pulse/train) at the 1st SASE undulator exit corresponds to a normal incidence power density of 50 W/mm^2 at the distance of 1000 m from the undulator for a beamsize (FWHM) of 1 mm. The absorbed power per one deflector is about 2 W.

Silicon has the advantage of a high heat conductivity and high damage threshold, thus achieving good performance at high power load. It is well known that when crystal plate is cooled, the thermal deformation results in a slope error composed of a bending and bump
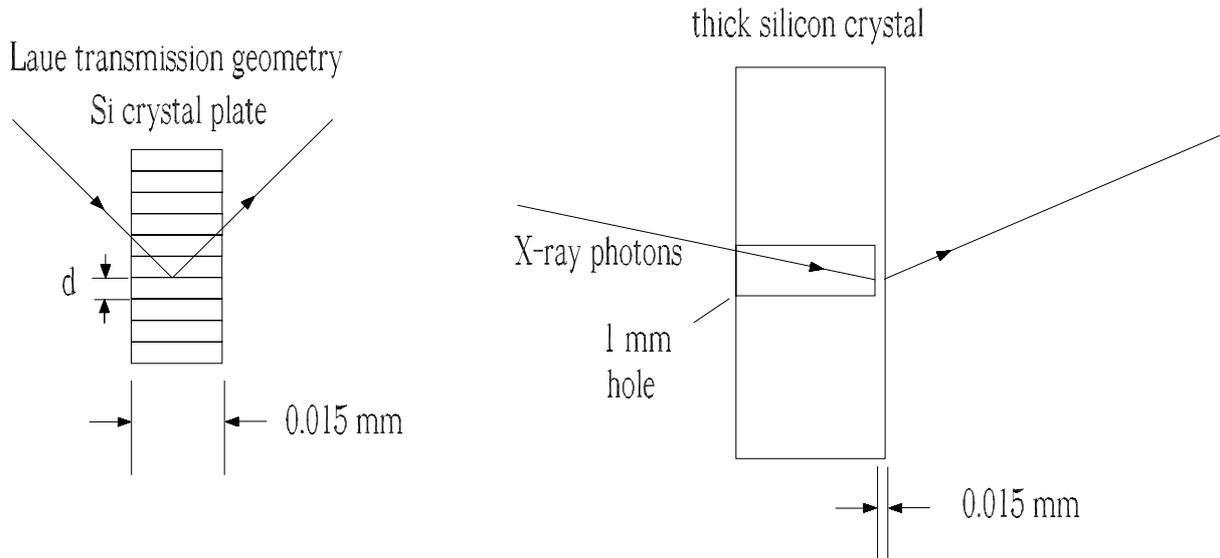
Fig. 19. Concept of the photon beam deflector

component. Briefly, the thermal deformation of the crystal induced by heat load depends on the ratio α/k, where α and k are the thermal expansion coefficient and the thermal conductivity of the crystal, respectively. This ratio is strongly temperature dependent for silicon. The ratio α/k is zero at 125 K, and about 50 times smaller at liquid-nitrogen temperature (77 K) than at room temperature.

The time-averaged power and power density at large distance from the SASE undulator are comparable to those of the third generation synchrotron radiation sources. For example, the brightest X-ray beams at ESRF facility are produced by in-vacuum undulators. These undulators emit about 0.5 kW of X-ray power in the central cone and the power density, at the position of the silicon monochromator 30 m from the source, is about 200 W/mm^2. Cooling techniques such as cryogenic cooling of Si have become standard at the third generation sources. The thermal deformation of the silicon crystal, which is indirectly cooled by liquid nitrogen, was studied experimentally and by finite-element analysis. Excellent agreement between the experimental measurements and theoretical results was observed. There is the best high-power working point for the crystal, when the power is raised to the point where the maximum temperature reaches 125 K. At this temperature the ratio between the thermal expansion and the thermal conductivity is zero [18].

The advantage of operating single-crystal-silicon deflector at cryogenic temperatures is obvious. Lowering the temperature of silicon from room temperature to liquid-nitrogen temperatures improves the so-called figure of merit, k/α, by 50-fold. A thin crystal is desired so that a large fraction of the incident beam would be transmitted, hence reducing the absorbed power in the deflector that has to be removed by the liquid nitrogen.

Although XFEL sources are designed primarily to generate brilliant X-rays with moderate energy 5-15 keV, high-energy X-rays are of great usefulness. In particular, high-energy focused beam is quite attractive for structural studies of amorphous solids and liquids and for diffraction studies of crystalline materials because of its extinction-free na-

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averaged spectrum
of 3rd harmonic
at 0.03 nm

$I(\omega)$

reflectivity curves
for photon beam
deflectors

$\dfrac{\Delta\omega}{\omega_0} \simeq 0.06\,\%$

0

ω

reflectivity curve
for Si crystal plate
of 0.1 mm thickness

Laue diffraction
reflection Si(111)
at 0.03 nm

Intensity Reflectivity

1

0.5

0

$\dfrac{\Delta\omega}{\omega_0} \simeq 0.01\,\%$

0

ω_0

ω
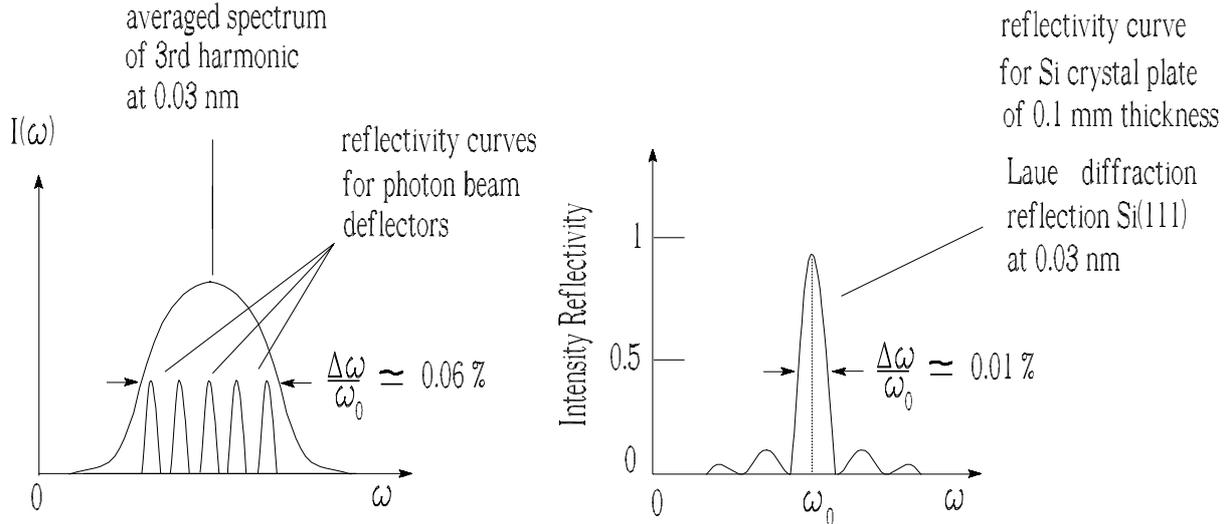
Fig. 20. Basic principle of the 3rd (undulator) harmonic multi-user distribution system

ture. The analysis shows that strong harmonic growth can be expected in SASE XFELs. When a beam is strongly bunched in the sinusoidal ponderomotive potential formed by the undulator field and the radiation field of fundamental frequency, the electron beam density spectrum develops rich harmonic contents. Coherent radiation at the odd harmonics can be generated in a planar undulator and significant power levels for the third harmonic can be reached before the FEL is saturated. Explicit calculations show that the power of the transversely coherent third-harmonic radiation can approach a fraction of a per cent of the fundamental power level.

In this paper we propose to utilize the third harmonic radiation from the XFEL. Four upstream transparent deflectors, which adopt so-called "Laue transmission geometry" concept, enable us to perform five different experiments simultaneously (see Fig. 20). High-energy X-rays are associated with a large penetration power, which makes it possible to use relatively "thick" silicon deflectors. The thickness of one crystal is 0.1 mm. The other main difference between diffraction at high energies and at conventional energies is the smaller Bragg angles. In particular for the 1st order Si(111) reflection at 0.03 nm the deflection angle is about 0.1 rad (see Fig. 21).

The distribution of pulse trains among the different beamline clusters can be done by a photon (electron) energy shifter pulsed at 5 Hz (see Fig. 22). It directs every other photon pulse train into a second cluster of photon beamlines. This method of pulse train distribution is based on the accelerator technique. In this case the SASE undulator beamline consists of an input energy shifter, SASE undulator, and output energy equalizer (see Fig. 23). Using photon energy shifter as switching element between 3 clusters of photon beamlines makes it possible to provide simultaneously X-ray radiation for $5 \times 3 = 15$ user station. Distribution of photons is achieved on the basis of pulse trains. Each user station actually receives one, two, or three pulse trains of full length at 1 Hz repetition rate (see Fig. 24 and 25).

The experiments are housed in experimental hutches as shown in Fig. 26. The adopted

the peak brilliance is 7 orders of magnitude higher
than that of modern 3rd generation synchrotron light sources

total transmission
is approximately
70 % for 3rd
harmonic

to user
station

total transmission
for 5 deflectors
is approximately
85 % at 0.03 nm

photon beam after
first harmonic
distribution system

photon beam
deflector

$6°$
for 1st order reflection
at 0.03 nm

Fig. 21. Setup for simultaneous multi-user mode of operation at the 3rd undulator harmonic

$I(\omega)$

averaged spectrum
of SASE XFEL
photon beam

reflectivity curves
for 1st cluster
of photon beam
deflectors

$\frac{\Delta\omega}{\omega_0} \simeq 0.1\,\%$

0

ω

energy shifter
is switched on

energy shifter
is switched off

energy shifter
is switched on

frequency shift
of $\frac{\Delta\omega}{\omega_0} = -0.2\,\%$

frequency shift
of $\frac{\Delta\omega}{\omega_0} = 0.2\,\%$
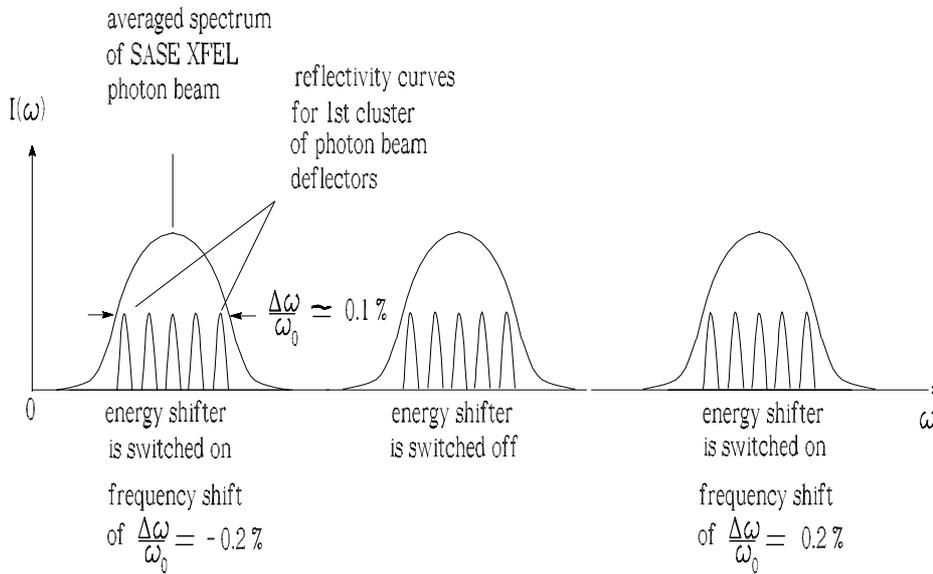
Fig. 22. Principle of photon pulse train distribution system

concept allows a completely modular design. The deflector is configured as a double-crystal monochromator in nondispersive, horizontal scattering geometry. If silicon is chosen as the second crystal, one achieves intrinsically a fixed exit geometry and the monochromatic beam remains parallel to the SASE beam independent of the selected energy. As shown in Fig. 27, the deflectors have a 2 m horizontal offset distance in order to keep a sufficient working space in the corresponding experimental hutches. A goniometer of the 1st crystal is mounted on a high precise translation stage being movable upstream of the second crystal. Since Bragg angle can be changed, the photon energy range of 8-15 keV is selectable. Silicon crystals are mounted on a liquid-nitrogen-cooled holder taking Laue case arrangement.

It should be noted that crystal deflector performances are complementary to those

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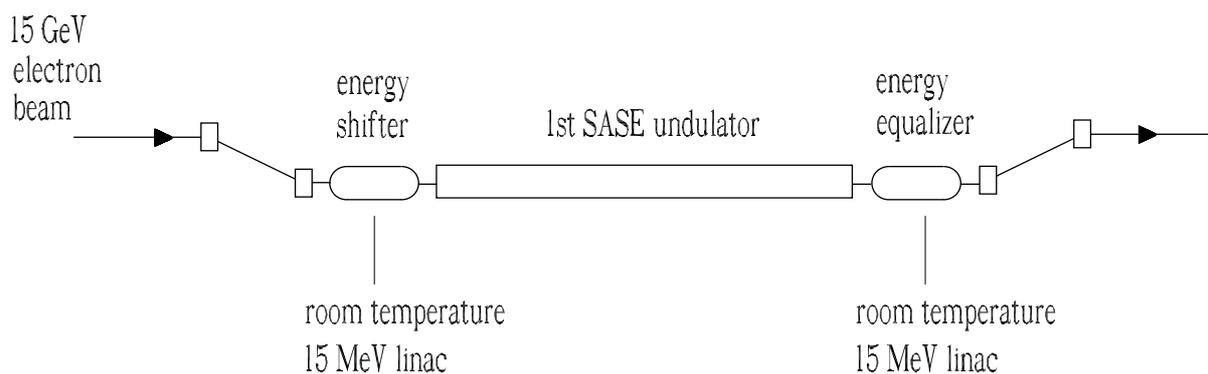
Fig. 23. Electron (photon) energy shifter as a switching element between 3 beamline clusters. Conceptual layout
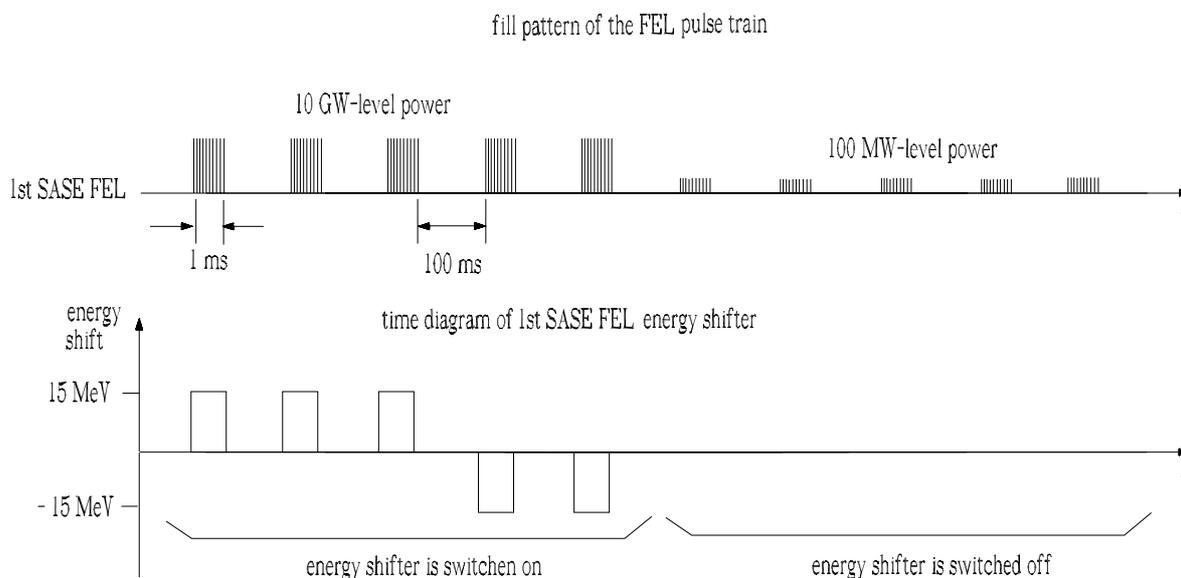
Fig. 24. Energy shifter pulse structure needed for 1st SASE undulator operation with 3 photon beamline clusters

of multilayer deflectors, whose bandwidth is much wider but whose photon flux is much higher. Crystal deflectors have a band-pass of the order of 10^{-4}, which is unnecessary narrow in many experiments. On the other hand, the fundamental SASE radiation has an energy peak-width of 10^{-3} and thus, using the whole SASE radiation peak, the flux is more than 10 times higher than that obtained with crystal deflector.

Both types of deflectors are important, their roles are complementary, and one type cannot replace the other. Figure 28 shows the optimal beamline configuration. The first 20 beamlines are planned to be multi-purpose beamlines for experiments with maximum X-ray flux. In this case 21nd ... end-stations use the photon beam distribution system

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fill pattern of the FEL pulse train

100 GW-level power

2nd SASE FEL

t

1 ms

100 ms

energy shift

time diagram of 2nd SASE FEL energy shifter

15 MeV

- 15 MeV

t

energy shifter is switched off

energy shifter is switched on
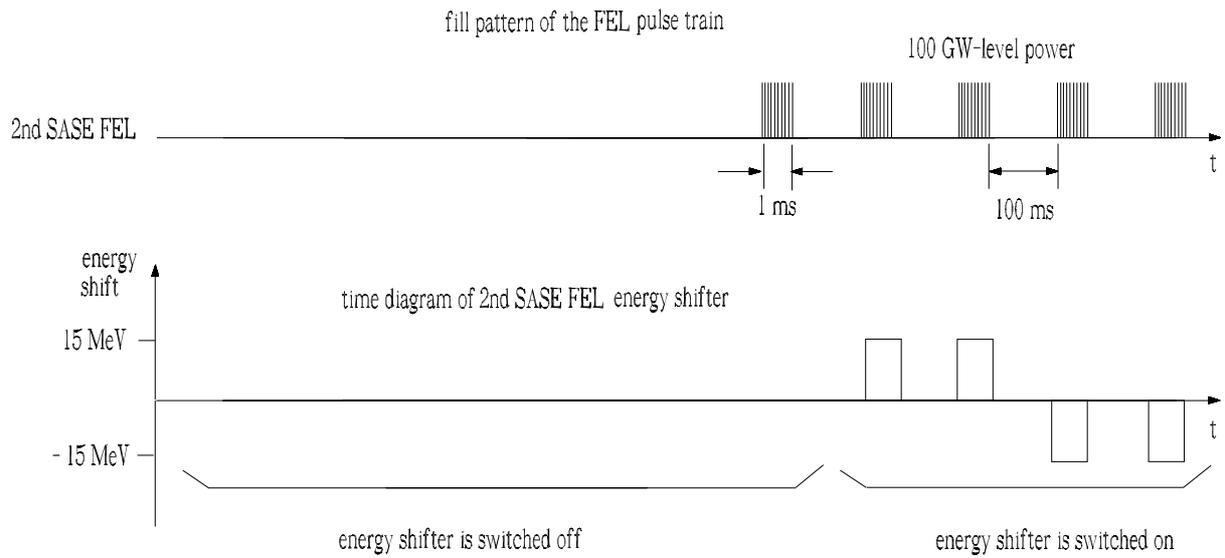
Fig. 25. Energy shifter pulse structure needed for 2nd SASE undulator operation with 3 photon beamline clusters

4 m

experimental hutch

6 m

1000 m from the 1st SASE undulator exit

2 m

6 m

2 m
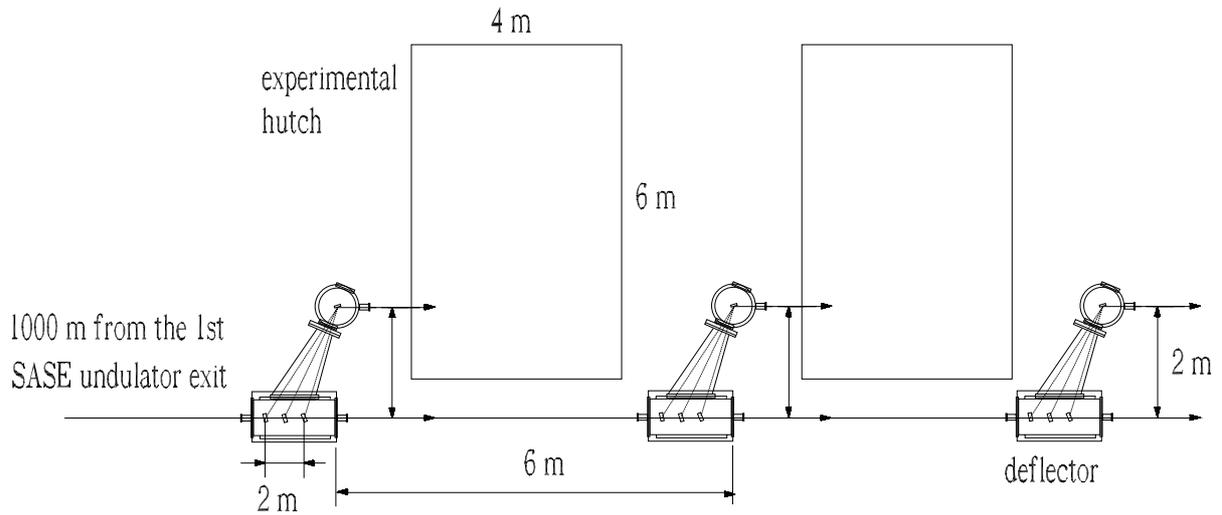
deflector

Fig. 26. Optical layout of the 1st SASE undulator beamline working with transmission crystal deflectors.
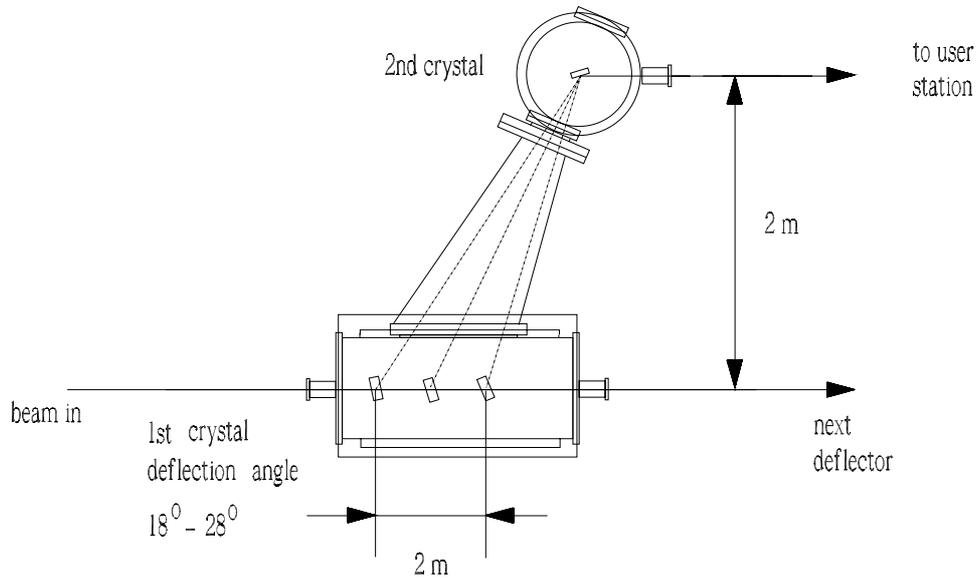
Fig. 27. Plan view of deflector unit
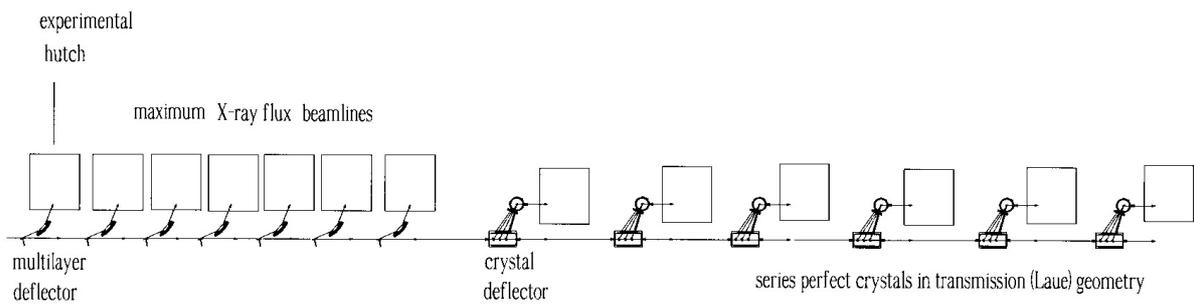
Fig. 28. 1st SASE undulator beamline. A photon beam distribution system based on combination movable multilayers and crystals in transmission (Laue) geometry can provide efficient way to generate a multi-user facility

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4 Operation of FEL source

Present concept of an XFEL facility assumes to cover continuously wavelength range from 0.1 to 1.6 nm at a fixed energy of the electron beam. This is achieved with three undulators installed in a series in one beamline as illustrated in Fig. 1. Optimization of undulator parameters (see Table 1) has been performed for the electron beam parameters presented in the Supplement to TESLA XFEL Technical Design Report: peak current 5 kA, rms normalized emittance 1.4 mm-mrad, and initial energy spread of 1 MeV. All undulators are planar, variable-gap devices with an identical mechanical design. Magnetic properties of the undulators are accepted to be the same as in TESLA XFEL TDR (the on-axis maximum field of hybrid NdFeB undulator is given by: $B_{\max}[\text{T}] = 3.694 \exp[-5.068(g/\lambda_{\mathrm{w}}) + 1.52(g/\lambda_{\mathrm{w}})^2]$, where g is the undulator gap).

Operation of SASE FEL at minimum wavelength (0.1 nm) is the most critical one. Previous design of XFEL user facility (Supplement to TESLA XFEL TDR) assumed only one short-wavelength SASE FEL in each beamline. User demands for a wide wavelength tunability range (by a factor of four) forced to use a concept of a wide tunability of the undulator gap. This means that minimum wavelength of 0.1 nm was achieved at an open undulator gap which corresponds to the worst conditions for SASE FEL operation resulting in a longer undulator. As a compromise, it was assumed to build SASE2 fixed-gap undulator optimized for operation at 0.1 nm.

Present concept of XFEL source fits well to conflicting requirements of a wide wavelength tunability and optimal operation of SASE FEL. This is achieved by means of installation of three undulators with moderate gap tunability and extensive use of frequency doublers. Our study shows that such an approach allows to cover large wavelength range (0.1-1.6 nm) at fixed energy of the electron beam (15 GeV). Combination of this FEL scheme with "pine-like" photon beam distribution system allows to increase number of user's stations by an order of magnitude comparing to previous design.

FEL beamline accommodates three undulators (SASE1-3) installed one after another. The first undulator, SASE1, is optimized for operation at the wavelength range 1-1.5 nm. Our study shows that such tunability range almost does not affect operation at the shortest wavelength of 0.1 nm. Operation of two other FELs (SASE2 and SASE3) is not so critical, and nominal tunability range is chosen to be by a factor of two (2-4 nm, and 8-16 nm, respectively). The length of the undulators is chosen such that continuous wavelength tunability can be provided by means of extra opening the undulator gaps, or by tuning to the frequency doubler mode of operation.

It should be noted that wide wavelength tunability range of the proposed XFEL concept is not the only important feature. Changing of undulator gaps in different parts of SASE2 and SASE3 undulators allows one to tune the modes with high output power (sub-TW level), or for effective generation of the second harmonic. The latter feature might be important for future pump-probe experiments. Also, recently proposed attosecond SASE FEL scheme is foreseen for implementation.

Three different undulators installed in one beamline provide a reliable way for commissioning the XFEL source (or, for effective tuning after a failure or shutdown). Indeed,

tuning of SASE1 for operation at 0.1 nm is undoubtedly a challenging problem. An absence of relevant diagnostics of slice beam parameters is a serious problem for tuning an isolated undulator. In our concept the whole chain can be easily and effectively tuned starting from SASE3, then going over to SASE2, and final tuning SASE1, the most critical piece of the equipment. This becomes possible due to gradual increase of the SASE performance with the increase of the operating wavelength. The experience obtained at TTF1 gives us a reliable basis for such a statement: SASE3 driven by TTF1 bunch (see Appendix A) is able to generate radiation down to wavelengths of about 1 nm.

4.1 Operation at the fundamental harmonic

In this section we present main characteristics of XFEL source operating in a standard mode, i.e. conventional SASE mode. Figures 29, 30, and 31 show main characteristics: average radiation power versus undulator length, profiles of the radiation intensity at the undulator exit, and angular distribution of the radiation intensity in the far zone. Figures 32-40 present detailed illustration of SASE1 operating at 0.1 nm wavelength. Saturation of SASE FEL is achieved at the undulator length of about 120 m. Figures 32 and 33 shows temporal and spectral structure of the radiation pulse at saturation. Figure 34 shows temporal structure of the radiation pulse reflected by thin Si (111) crystal (see Fig. 16).
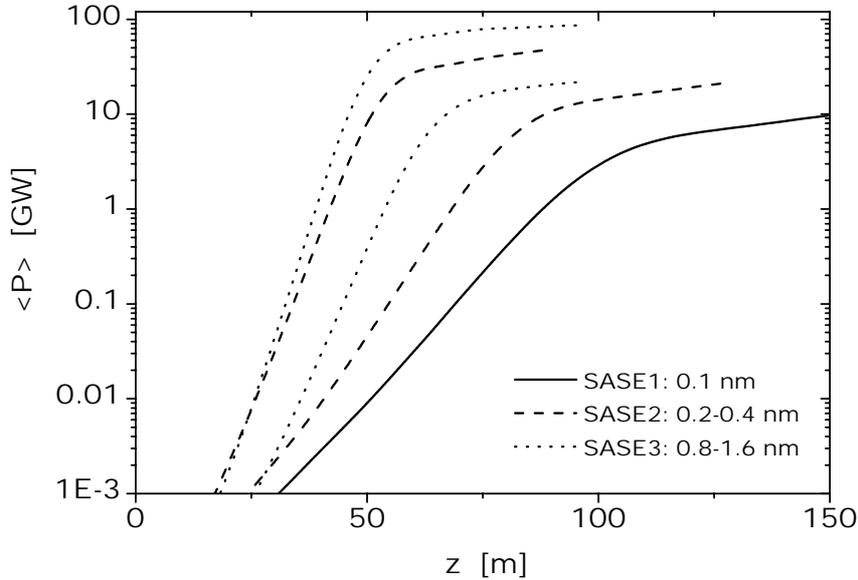
Fig. 29. Average radiation power versus undulator length. SASE FELs are tuned for operation on the fundamental harmonic
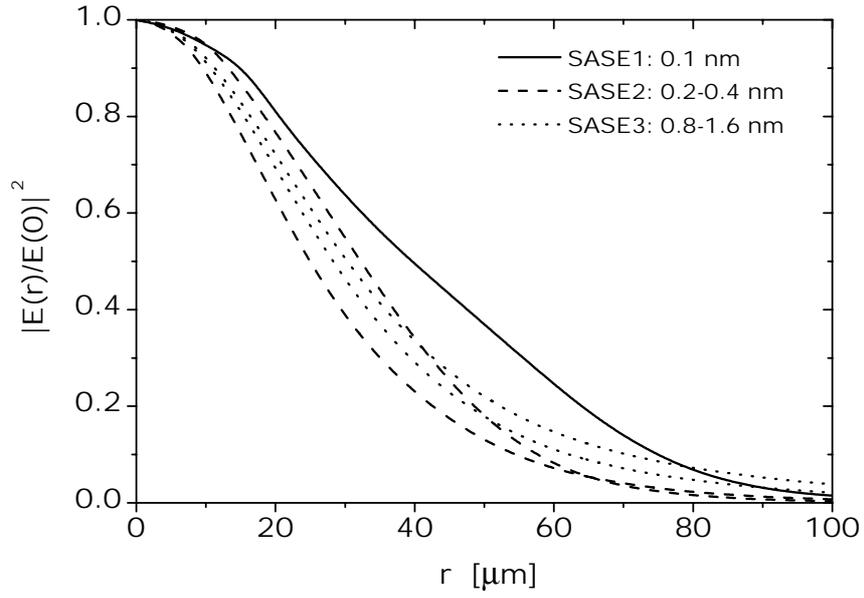
Fig. 30. Profile of the radiation intensity at the undulator exit. SASE FELs operate at saturation
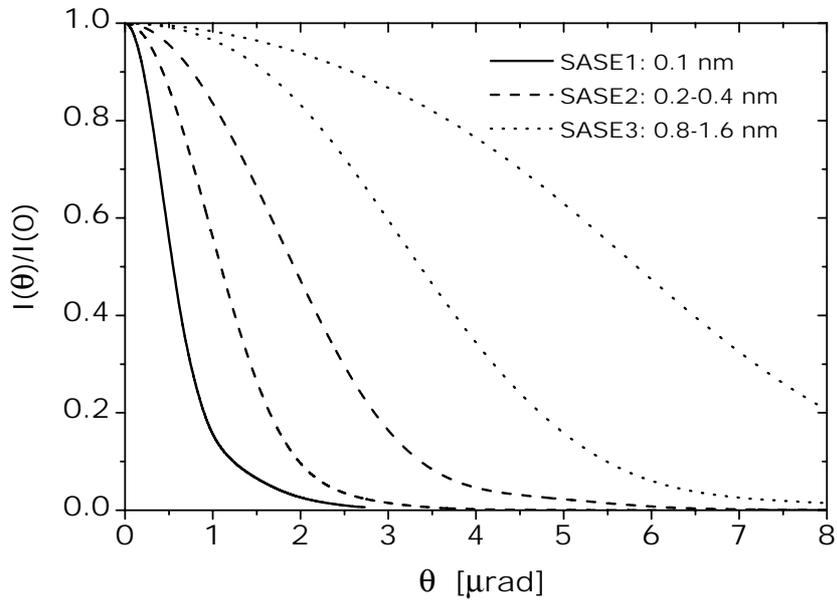
Fig. 31. Angular distribution of the radiation intensity in the far zone. SASE FELs operate at saturation
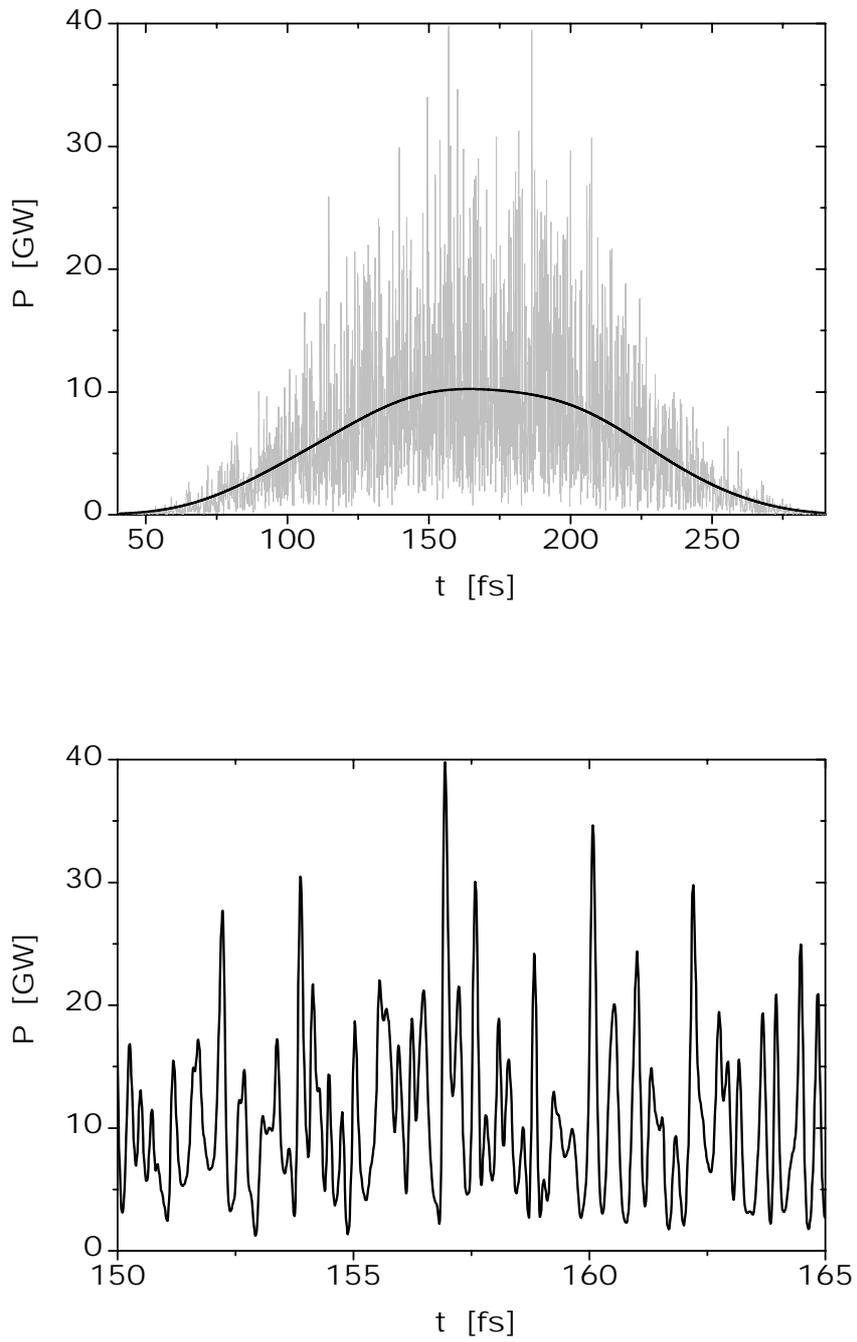
Fig. 32. Temporal structure of the radiation pulse. Lower plot shows enlarged view of the upper plot. SASE1, radiation wavelength is 0.1 nm, undulator length is 120 m
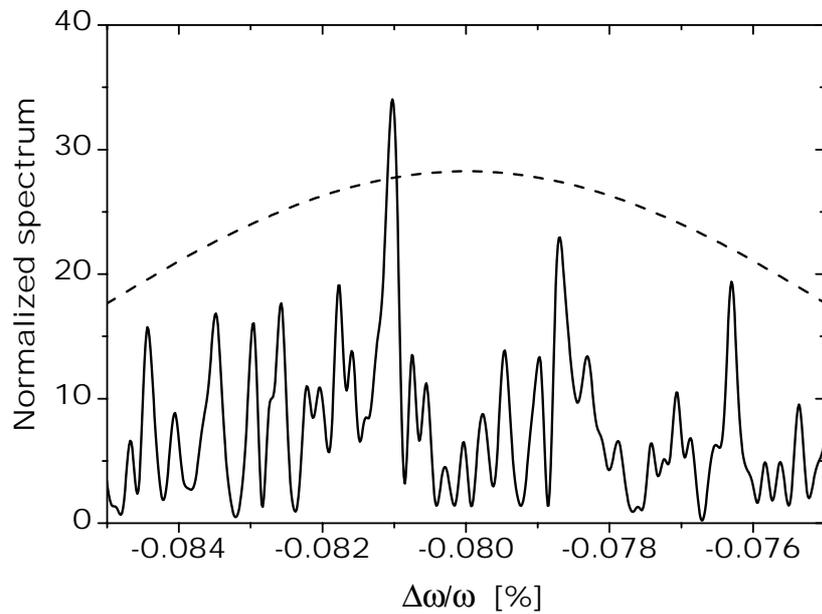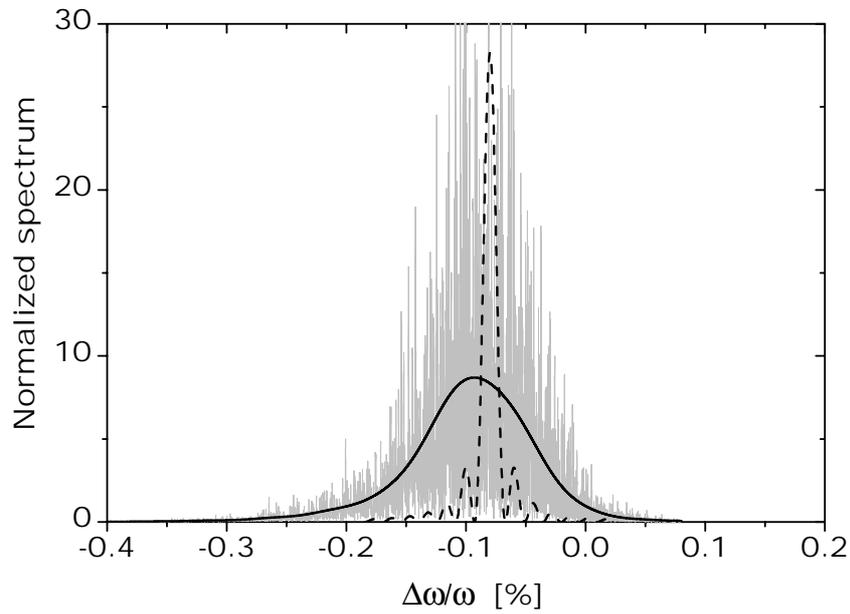
Fig. 33. Spectral structure of the radiation pulse. Lower plot shows enlarged view of the upper plot. Solid line shows averaged spectrum. Dashed line shows reflectivity curve of crystal monochromator (see Fig. 16). SASE1, radiation wavelength is 0.1 nm, undulator length is 120 m
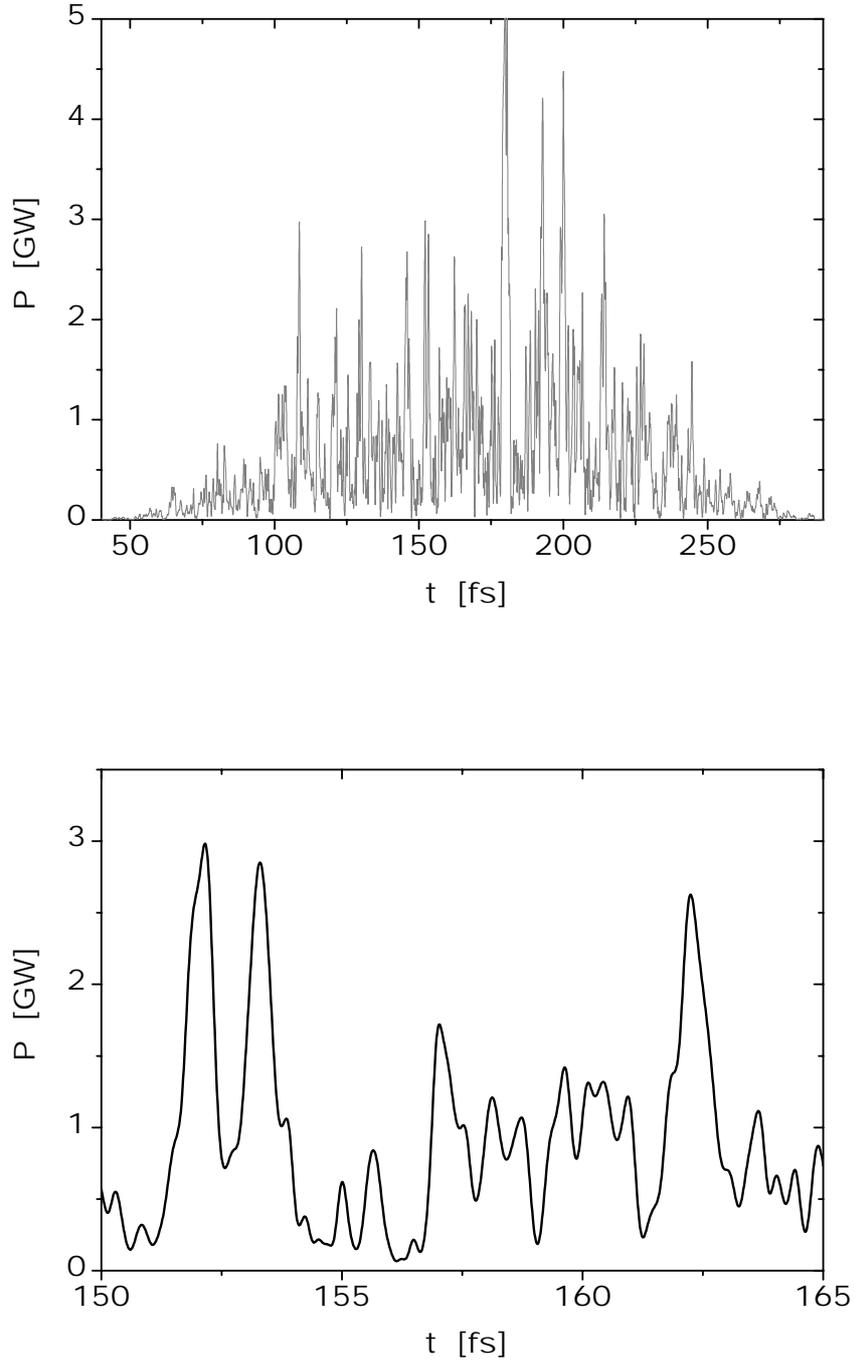
Fig. 34. Temporal structure of the radiation pulse (see Fig. 32) reflected by thin Si (111) crystal (see Fig. 16). Central frequency corresponds to $\Delta\omega/\omega = -0.08\%$ (see Fig. 33). Lower plot shows enlarged view of the upper plot. SASE1, radiation wavelength is 0.1 nm, undulator length is 120 m

4.2 Efficient frequency doubler (two-color mode of operation)

Present concept of XFEL laboratory assumes to minimize number of different undulators while extending available radiation wavelength to maximum. This is achieved by means of application of frequency doubler scheme [9] illustrated in Fig. 8. The frequency doubler scheme operates as follows. The electron bunch enters the first part of the undulator and produces SASE radiation at the fundamental harmonic. During the amplification process the radiation power grows exponentially with the undulator length. Simultaneously, the energy and density modulation of the beam are growing. At the end of the undulator the beam energy modulation is comparable with the local energy spread.
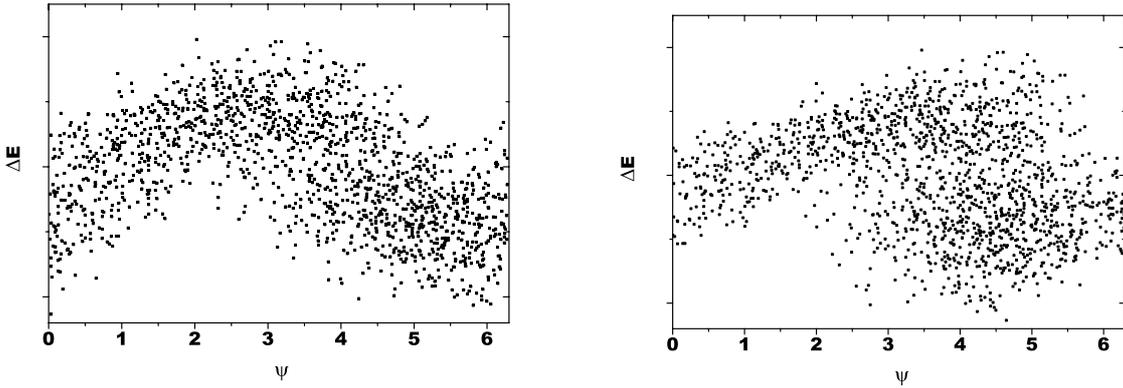
Fig. 35. Phase space distribution of the particles in a slice before (left plot) and after (right plot) the dispersion section
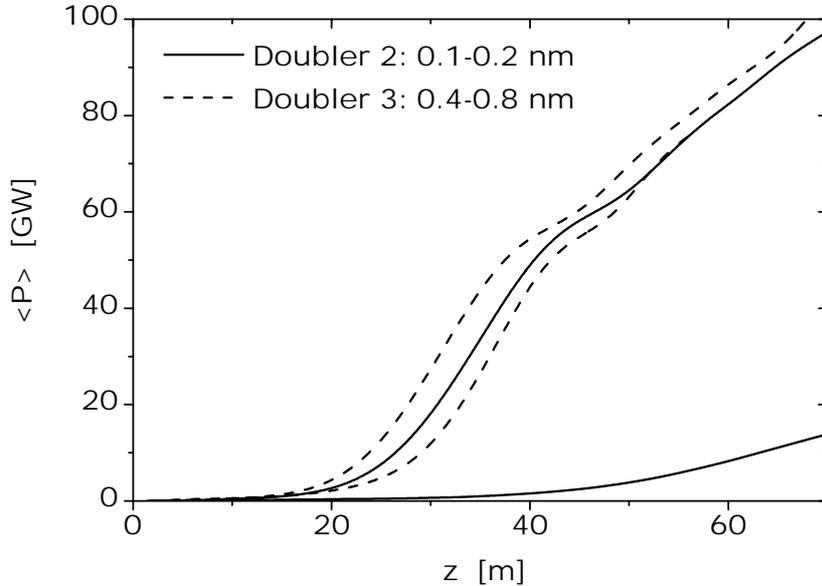
Fig. 36. Average radiation power versus length of the frequency doubler. SASE FELs are tuned for operation at the second harmonic

The left plot in Fig. 35 shows the phase space distribution of particles in a slice of the bunch. Such a picture is typical for every spike. The modulation amplitude at the second harmonic is small, but there is visible energy modulation with an amplitude of about the value of the local energy spread. When the electron bunch passes through the dispersion section this energy modulation leads to effective compression of the particles as it is illustrated with plots in the right plot in Fig. 35. When the bunched beam enters the second part of the undulator tuned to the second harmonic, it immediately starts to produce powerful radiation at the second harmonic. Effective amplification of the radiation at the second harmonic is achieved at an appropriate tapering of the undulator parameters. Figure 36 shows the evolution of the energy in the radiation pulse for the doublers SASE2 and SASE3. Despite of the original spiking seeding the process of the second harmonic, we effectively trap a significant fraction of the particles, and can achieve a high power. As a result, application of frequency doubler scheme allows to extend operating wavelength of the SASE FEL by a factor of two.

4.3   High power mode of operation

Application of dispersion section in combination with undulator tapering is an effective tool for achieving extremely high output power of XFEL. Relevant arrangement of undulator is shown in Fig. 8. The first part of the undulator the gap is fixed, and amplification process is developed as in usual SASE FEL. When energy modulation of the electron beam becomes to be comparable with local energy spread, the electron bunch passes via dispersion section resulting in an effective compression of the electron bunch (see Fig.35). Then bunched electron beam enters the second half of the undulator where the gap is tapered for effective extraction of the energy from the electron bunch. Our studies shows that output radiation power can reach a sub-TW level.
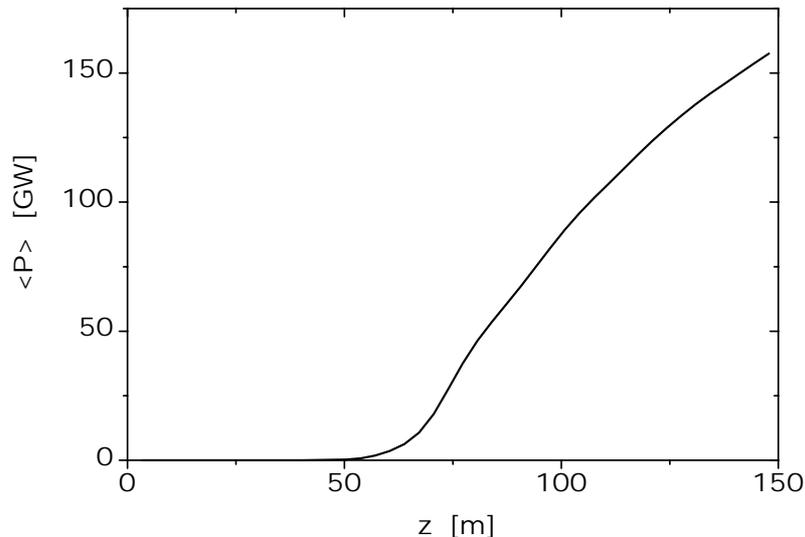
Fig. 37. Average radiation power versus undulator length for SASE2 tuned for high power mode of operation. Radiation wavelength is 0.2 nm

29
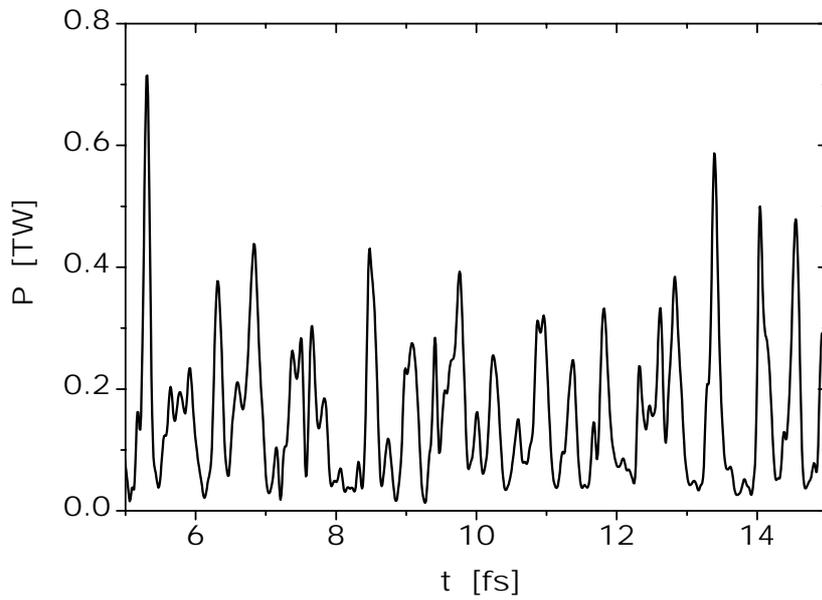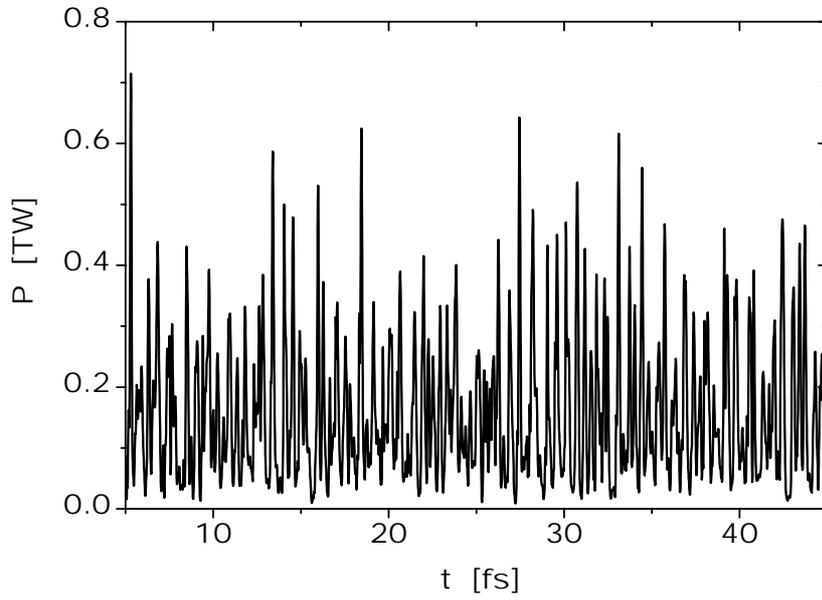
Fig. 38. Temporal structure of the radiation pulse for SASE2 tuned for high power mode of operation. Lower plot shows enlarged view of the upper plot. Radiation wavelength is 0.2 nm, undulator length is 150 m

30
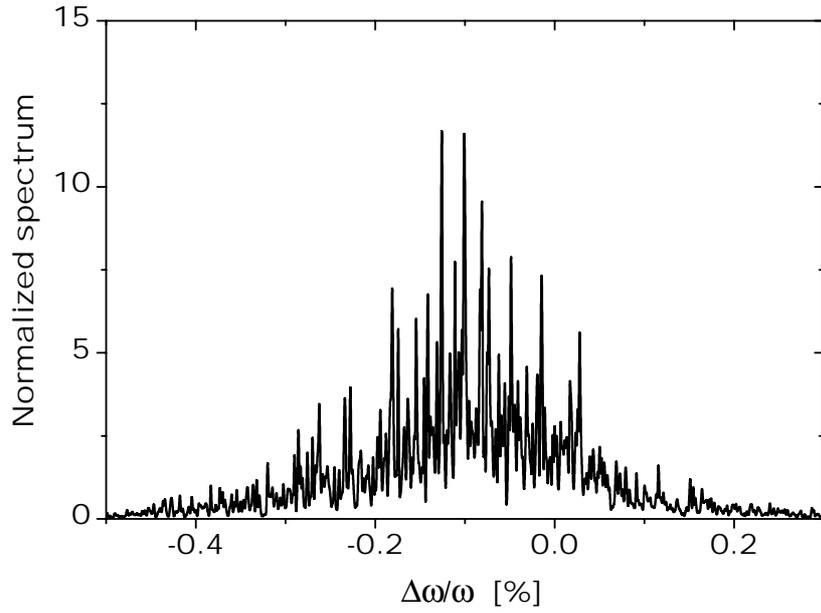
Fig. 39. Spectral structure of the radiation pulse for SASE2 tuned for high power mode of operation. Radiation wavelength is 0.2 nm, undulator length is 150 m
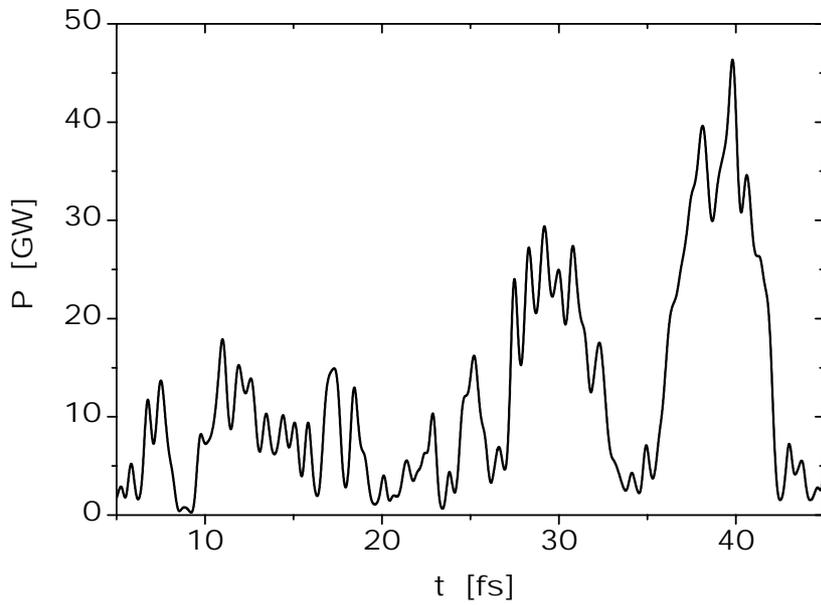
Fig. 40. Temporal structure of the radiation pulse (see Fig. 38) reflected by thin Si (111) crystal (see Fig. 16). Central frequency corresponds to $\Delta\omega/\omega = -0.1\%$ (see Fig. 39). SASE2 tuned for high power mode of operation Radiation wavelength is 0.2 nm, undulator length is 150 m

Proposed layout of XFEL laboratory also accommodates a technique for the production of attosecond X-ray pulses which is based on the use of X-ray SASE FEL combined with a femtosecond laser system [10]. A few-cycle optical pulse from a Ti:sapphire laser interacts with the electron beam in a two-period undulator resonant to 800 nm wavelength and produces energy modulation within a slice of the electron bunch. Following the energy modulator the electron beam enters the X-ray undulator and produces SASE radiation. Due to energy modulation the frequency is correlated to the longitudinal position within the few-cycle-driven slice of SASE radiation pulse. The largest frequency offset corresponds to a single-spike pulse in the time domain which is confined to one half-oscillation period near the central peak electron energy. The selection of single-spike pulses is achieved by using a crystal monochromator after the X-ray undulator. This technique is capable to produce 300 attoseconds long single pulses with GW-level output power in the 0.1 nm wavelength range.

A basic scheme of the attosecond X-ray source is shown in Fig. 41. An ultrashort laser pulse is used to modulate the energy of electrons within the femtosecond slice of the electron bunch at the seed laser frequency. The seed laser pulse will be timed to overlap with the central area of the electron bunch. It serves as a seed for a modulator which consists of a short (a few periods) undulator. Following the energy modulator the beam enters the X-ray undulator. The process of amplification of radiation in this undulator develops in the same way as in a conventional X-ray SASE FEL: fluctuations of the electron beam current serve as the input signal. The proposed scheme for the generation of attosecond pulses is based on frequency-chirping the SASE radiation pulse. When an electron beam traverses an undulator, it emits radiation at the resonance wavelength $\lambda = \lambda_{\mathrm{w}}(1 + K^2/2)/(2\gamma^2)$. Here λ_{w} is the undulator period, $mc^2\gamma$ is the electron beam energy, and K is the undulator parameter. The laser-driven sinusoidal energy chirp produces a correlated frequency chirp of the resonant radiation $\delta\omega/\omega \simeq 2\delta\gamma/\gamma$. After the undulator, the radiation is passed through a crystal monochromator which reflects a narrow bandwidth. Since the radiation frequency is correlated to the longitudinal position within the beam, a short temporal radiation pulse is transmitted through the monochromator as it is illustrated in Fig. 44.
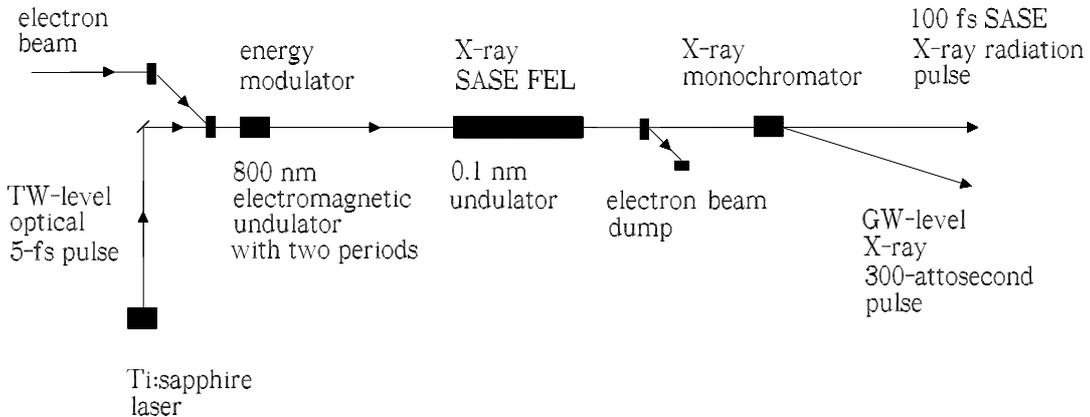
Fig. 41. Schematic diagram of attosecond X-ray source
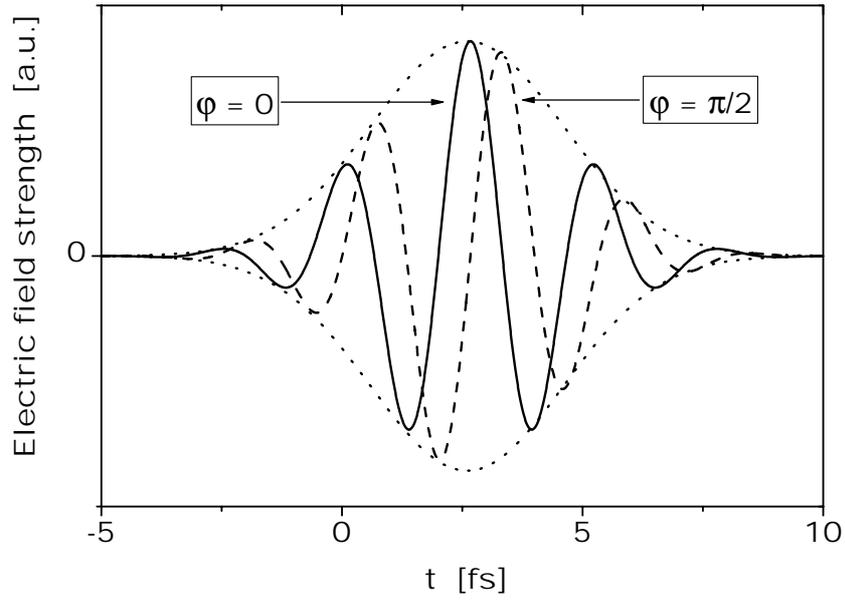
Fig. 42. Possible evolutions of the electric field in the 5-fs pulse. carried at a wavelength 800 nm for two different pulse phases ($\phi = 0, \pi/2$)
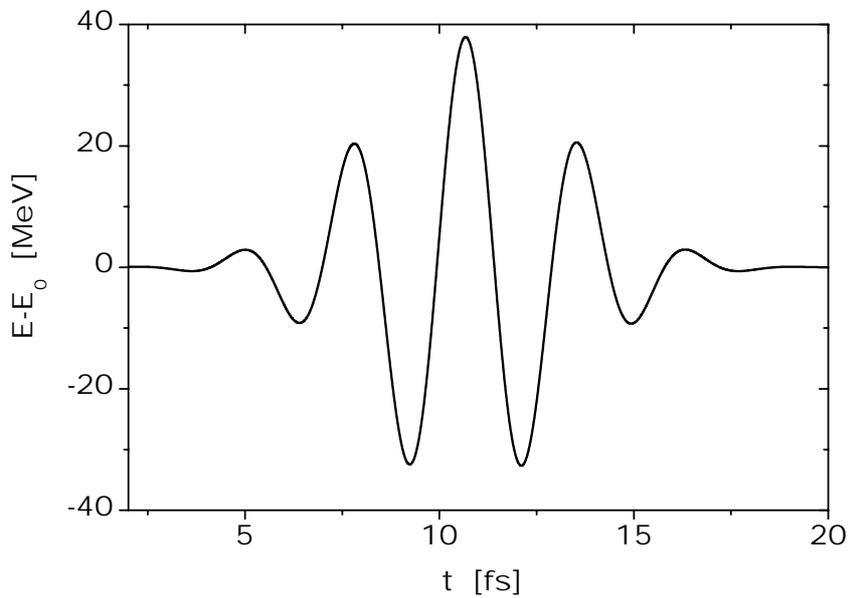
Fig. 43. Energy modulation of the electron beam at the exit of the modulator undulator. The laser parameters are $\lambda = 800$ nm, $W_{\text{peak}} = 800$ GW, and FWHM pulse duration of $\tau_{\text{p}} = 5$ fs
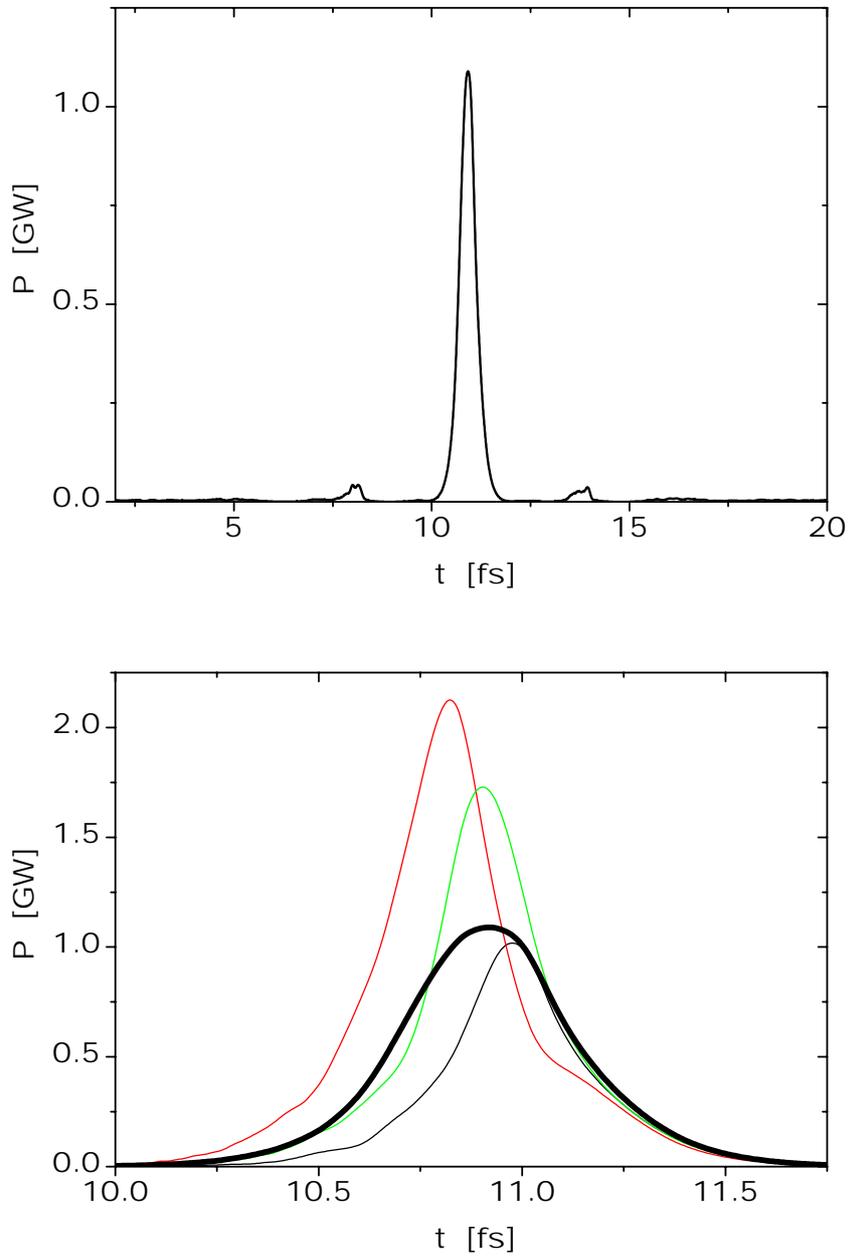
Fig. 44. Attosecond mode of operation. Temporal structure of the radiation pulse behind monochromator tuned to single spike selection Upper plot shows average over many pulses, and lower plot shows details of single pulses. Bold curve is average over many pulses

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A   XFEL driven by TTF1 bunch

The VUV FEL at the TESLA Test Facility has successfully demonstrated saturation from 82 nm to 125 nm with GW peak power and pulse duration about 40 fs. TTF FEL, Phase I fulfilled its ultimate goal – integrated test of all components for future XFELs: production and acceleration of high-current, low-emittance electron beams, generation of powerful coherent radiation in SASE undulator, and test of user's interface. Experimentally realized value of the peak bunch current of 3 kA is close to the target value for the XFEL. In particular, we demonstrate here that SASE3 driven by TTF1 bunch [19]is able to generate FEL radiation with the wavelength down to 1 nm. Reconstruction of the electron beam parameters from FEL measurements have been already demonstrated experimentally during operation of TTF FEL Phase I [20,21].
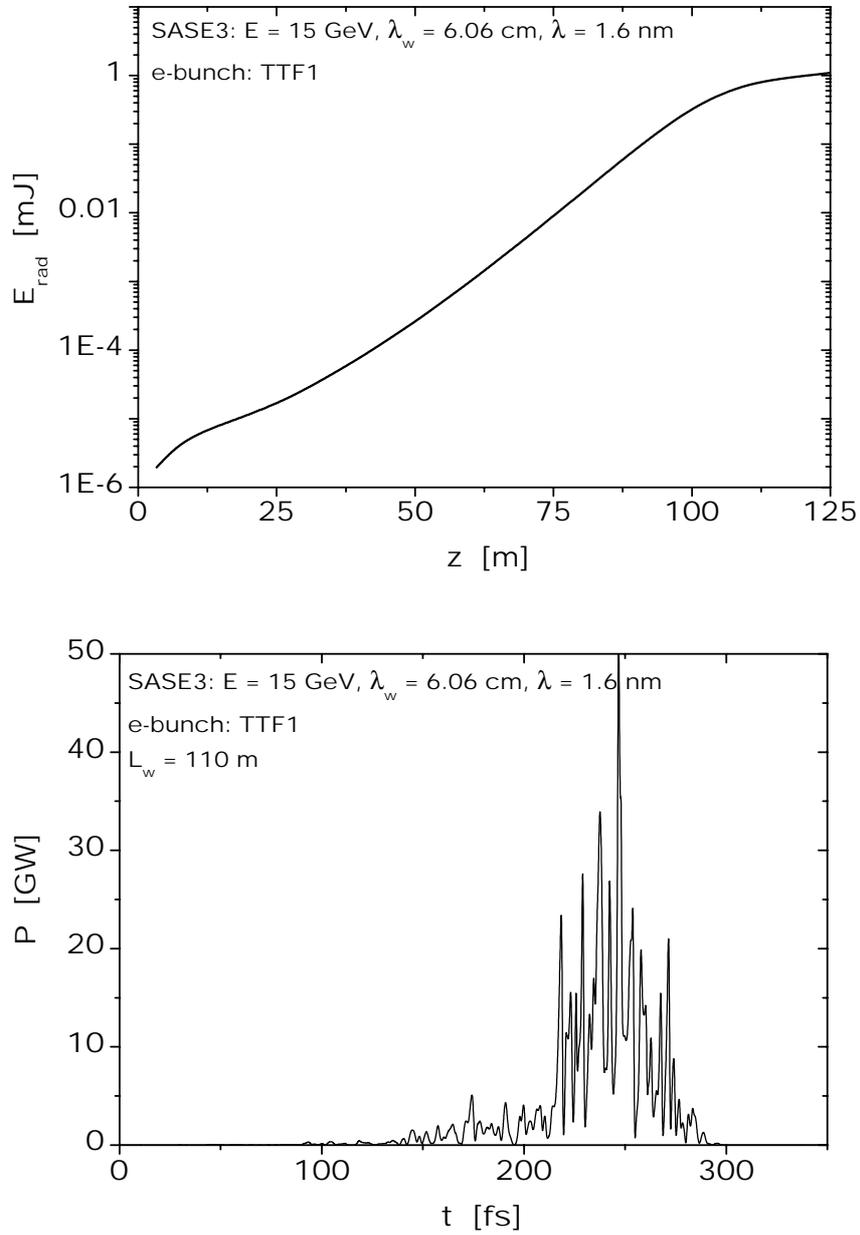
Fig. A.1. SASE3 driven by TTF1 bunch. Top: energy in the radiation pulse versus undulator length. Bottom: time structure of the radiation pulse at the undulator length of 110 m

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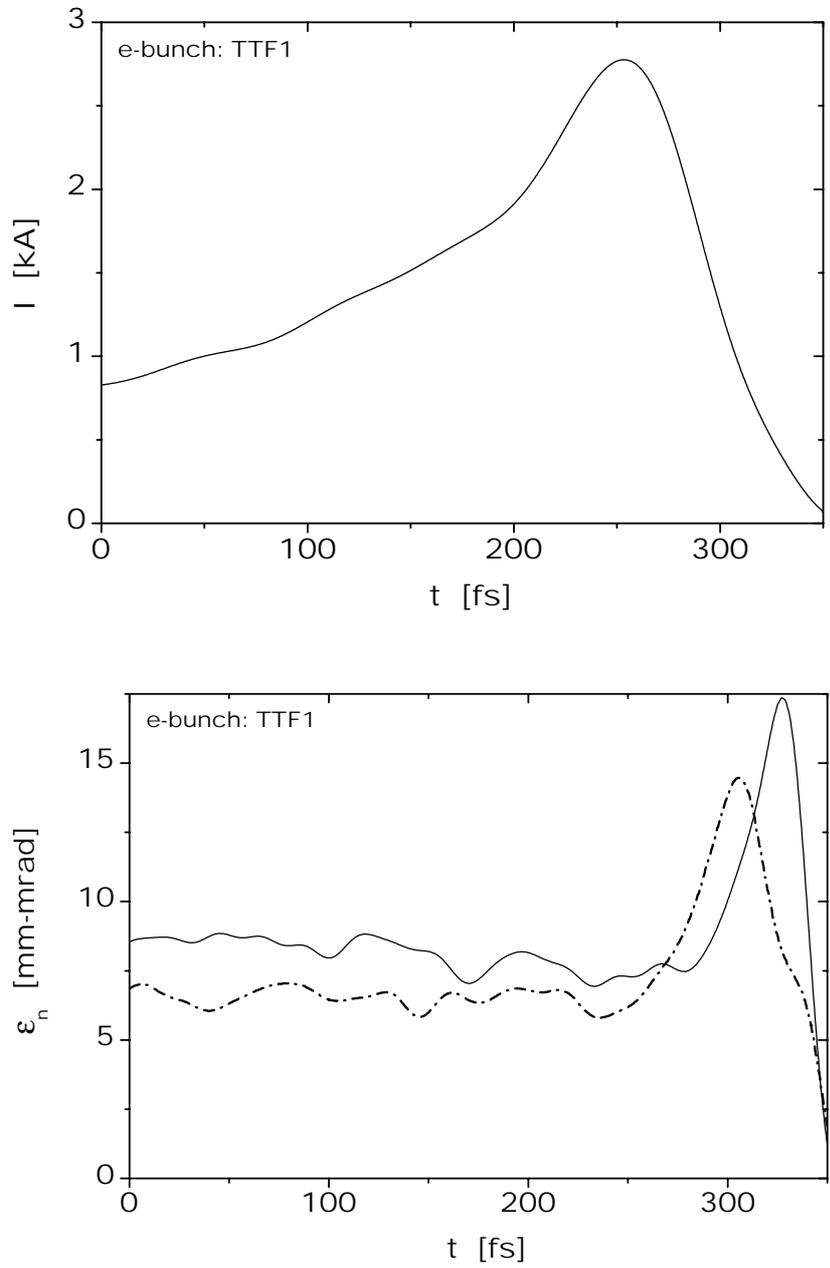
Fig. A.2. Parameters of TTF1 bunch. Top: current along the bunch. Bottom: rms normalized emittance (x,y)

Acknowledgments

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