THE POTENTIAL FOR THE DEVELOPMENT OF THE X-RAY FREE ELECTRON LASER: GENERATION OF SASE RADIATION

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Abstract

We present a concept of a universal FEL beamline covering continuously wavelength range from 0.1 to 1.6 nm at a fixed energy of the electron beam. FEL beamline accommodates three undulators (SASE1-3) installed one after another. The first undulator, SASE1, is optimized for operation at the wavelength range 0.1-0.15 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. 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.

INTRODUCTION

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, 2, 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 [4].

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.

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 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 17.5 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.

Table 1: Specification of undulators

	λ_{r} nm	λ_{u} mm	gap mm	B_{w} T	L_{w} m
SASE1	0.1-0.15	39	10-12	0.8-1	150
SASE2	0.1-0.4	47.9	10-19	0.6-1.3	150
SASE3	0.4-1.6	64.8	10-20	0.8-1.7	110

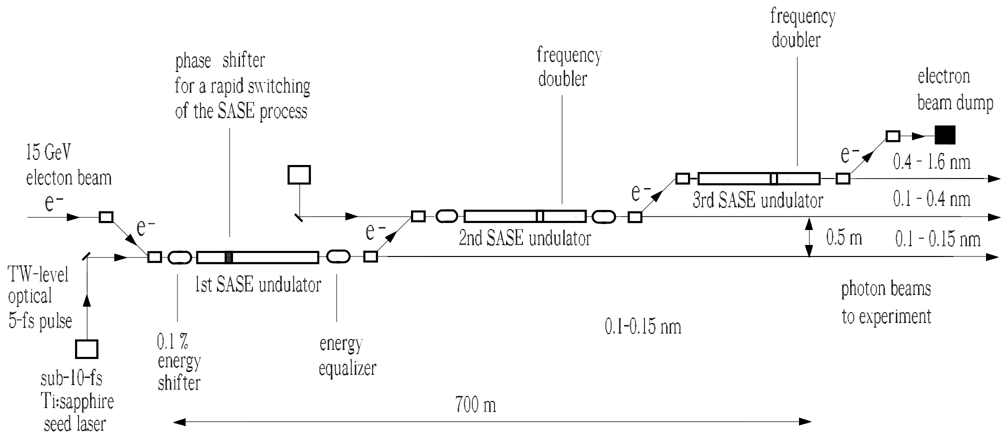

Figure 1: Sketch of a X-ray SASE FEL source.

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 17.5 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).

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. 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 trav-

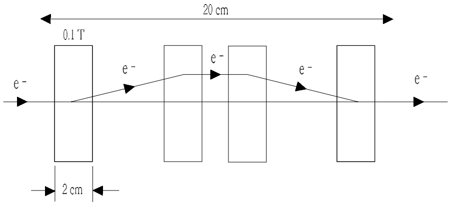

Figure 2: Electromagnetic phase shifter for a rapid switching of the SASE process in the 0.1 nm undulator.

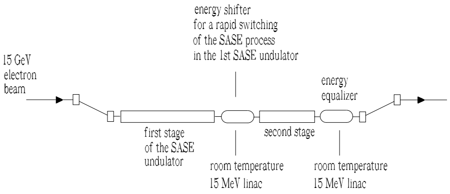

Figure 3: The second way to a rapid switching of the SASE process in the 0.1 nm undulator. Conceptual layout of the electron (photon) energy shifter.

els 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 [5] (see Fig. 2). It consists of three horizontal 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. 3). 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. 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 FODO lattice is large enough so that relatively short (2 m) accelerator structure can be installed (see Fig. 4). 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 [6].

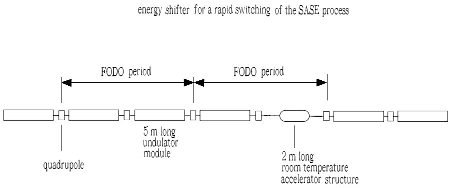

Figure 4: Installation of an energy shifter for a rapid switching of the SASE process. The quadrupole separation of a FODO lattice is large enough so that an accelerator structure of length 2 m can be installed.

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 5 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 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

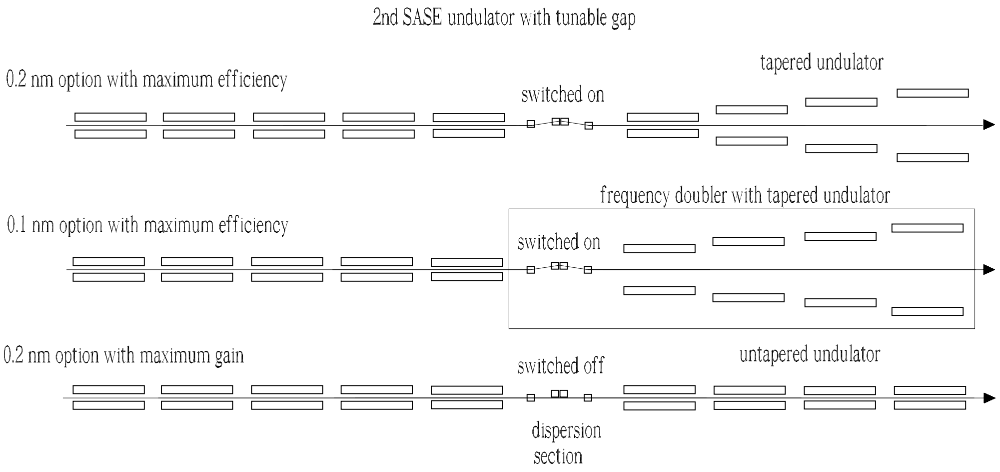

Figure 5: Three schemes for 2nd SASE undulator. Only one type of undulator magnet structure is needed. The radiation wavelength will be tuned by changing the gap. The total magnetic length is 150 m

of μm. The quadrupole separation of an undulator FODO lattice is large enough so that relatively short (4 m) dispersion section can be installed. 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 [7]. 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. 5). 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 [8]. 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.

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