SUB-TERAWATT MODE OF OPERATION OF X-RAY SASE FEL

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Abstract

Application of dispersion section in combination with undulator tapering is an effective tool for achieving extremely high output power of XFEL. In 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. 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 show that output radiation power can reach a sub-TW level in Angstrom wavelength range.

INTRODUCTION

Baseline design of present XFEL projects [1, 2, 3, 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].

The first stage of the European XFEL facility assumes installation of five radiators, and three of them are SASE undulators. 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 (SASE1-SASE3) [6]. A VUV option (SASE4) is under consideration, too [7]. 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. 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 (see Fig. 1). The latter feature might be important for future pump-probe experiments. Also, recently proposed attosecond SASE FEL scheme is foreseen for implementation [8, 9].

The developments discussed in this paper concern the increased FEL output radiation power.

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
VUV	1.6-6.4	110	19-37	0.7-1.6	80

STANDARD SASE MODE OF OPERATION

In this section we present main characteristics of XFEL source operating in a standard mode, i.e. conventional SASE mode. Figure 2 shows evolution of the averaged radiation power along undulator length. Saturation occurs at the undulator length of about 100 m. Figures 3 shows temporal and spectral structure of the radiation pulse at saturation. Increase of the undulator length results in moderate growth of the radiation power, but this happens mainly due to the growth of the sidebands. As a result, radiation spectrum spreads, and brilliance drops down.

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 and avoiding problems of sideband growth in the nonlinear regime. 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 1 shows a concept of a universal undulator allowing implementing different modes of XFEL operation: standard SASE, frequency doubler, and high power. 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

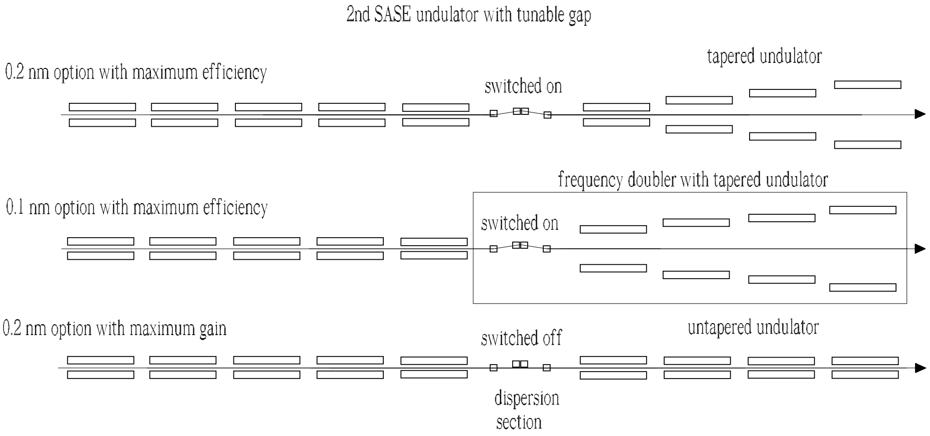

Figure 1: Three schemes for 2nd SASE undulator. Only one type of undulator magnet structure is needed. The radiation wavelength will be tuned by changing the gap. The total magnetic length is 150 m.

energy spread, but still far away from saturation. The left plot in Fig. 4 shows the phase space distribution of particles in a slice of the bunch. Such a picture is typical for every spike. The modulation amplitude 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 the right plot in Fig. 4. 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

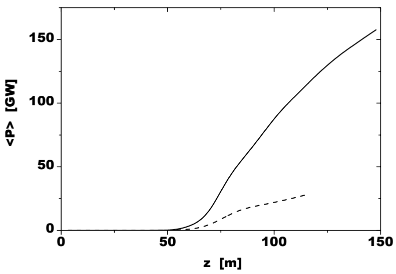

Figure 2: Average radiation power versus undulator length. Solid line: high power mode of operation. Dashed line: standard SASE mode. Radiation wavelength is 0.2 nm.

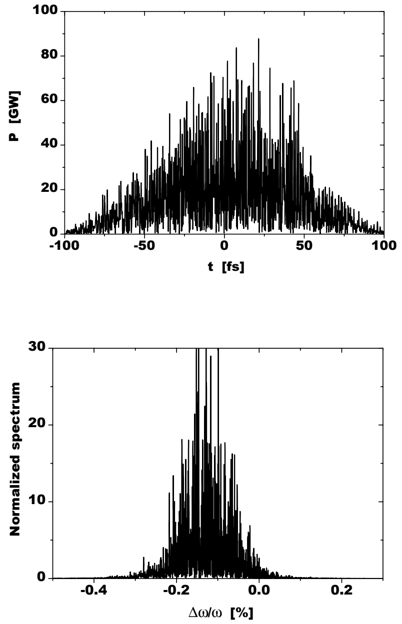

Figure 3: Temporal and spectral structure of the radiation pulse at saturation. Undulator length is 100 m. SASE FEL operates in a standard SASE mode.

at 0.2 nm is enhanced by a factor of 8, from 20 GW to 150 GW (see Fig. 2). Figure 5 shows time structure of the radiation pulse at the undulator exit. It is seen that tapering procedure provides extremely high power of individual spikes, up to sub-TW level. Such features of the radiation may be useful for applications studying nonlinear processes. Figure 6 shows spectral structure of the radiation pulse. One can see that it does not contain a signature of

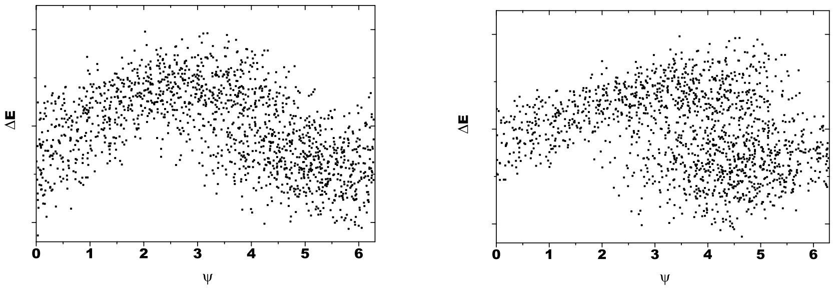

Figure 4: Phase space distribution of the particles in a slice before (left plot) and after (right plot) the dispersion section.

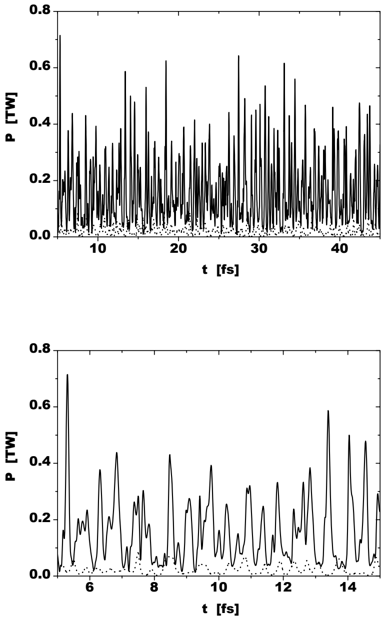

Figure 5: Temporal structure of the radiation pulse for SASE2 tuned for high power mode of operation. Lower plot shows enlarged view of the upper plot. Radiation wavelength is 0.2 nm, undulator length is 150 m. Dashed line shows power level of standard SASE FEL at saturation.

sidebands, and the spectrum width does not differ from that of conventional SASE, while peak radiation power is much higher. The radiation filtered through a crystal (Si (111)) monochromator (see Fig: 7) has high peak power comparable with standard SASE level, but with much less spectrum width.

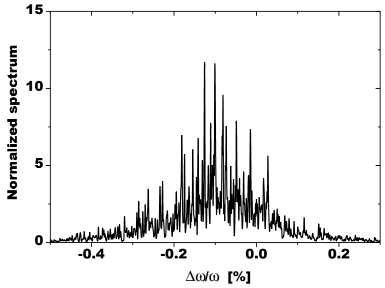

Figure 6: Spectral structure of the radiation pulse for SASE2 tuned for high power mode of operation. Radiation wavelength is 0.2 nm, undulator length is 150 m.

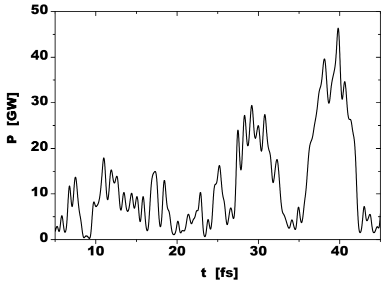

Figure 7: Temporal structure of the radiation pulse (see Fig. 5) reflected by thin Si (111) crystal. Central frequency corresponds to $\Delta\omega/\omega = -0.1\%$ (see Fig. 6). SASE2 tuned for high power mode of operation. Radiation wavelength is 0.2 nm, undulator length is 150 m.

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