SASE CHARACTERISTICS FROM BASELINE EUROPEAN XFEL UNDULATORS IN THE TAPERING REGIME

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Abstract

The output SASE characteristics of the baseline European XFEL, recently used in the TDRs of scientific instruments and X-ray optics, have been previously optimized assuming uniform undulators without considering the potential of undulator tapering in the SASE regime. Here we demonstrate that the performance of European XFEL sources can be significantly improved without additional hardware. The procedure consists in the optimization of the undulator gap configuration for each X-ray beamline. Here we provide a comprehensive description of the X-ray photon beam properties as a function of wavelength and bunch charge. Based on nominal parameters for the electron beam, we demonstrate that undulator tapering allows one to achieve up to a tenfold increase in peak power and photon spectral density in the conventional SASE regime.

INTRODUCTION

The output SASE characteristics of the baseline European XFEL have been previously optimized assuming uniform undulator settings and used in the design of scientific instruments [2–4]. In order to enable experiments over a continuous photon energy range, European XFEL undulators have adjustable gap [1]. The availability of very long tunable gap undulators provides a unique opportunity for an up to tenfold increase in spectral density and peak output power (up to the TW-level) for nominal electron beam parameter sets. [5] provides an overview of the design considerations and the general layout of the X-ray instrumentation of the European XFEL sources, beam transport systems and instruments. Baseline parameters for the electron beam have been defined and presented in [6, 7]. These parameters have been used for simulating FEL radiation characteristics and saturation lengths relevant to the European XFEL SASE undulators [8]. A well-known way to enhance the SASE efficiency is to properly configure undulators with variable gap [9–12]. In [13] it has been studied on an example of a particular working point how a tapering procedure, i.e. a slow reduction of the field strength of the undulator in order to preserve the resonance wavelength, while the kinetic energy of the electrons decreases due to the FEL process, can be used to significantly improve performance of the European XFEL sources without additional hardware. In present article we demonstrate that tapering allows one to achieve up to a tenfold increase in output for all achievable photon energies and all nominal electron bunch charges. A new set of baseline parameters of the electron beam for the European XFEL has been recently updated [6, 7] and was used in present work.

In the following we assume that SASE1 operates at the photon energy of 12 keV, and the FEL process is switched off for dedicated SASE3 operation with the help of a betatron switcher [14]. The energy spread due to spontateous radiation emission in SASE1 is accounted for. We highlight operation of SASE3 for the electron energy of 14 GeV as the most probable working energy. Optimal tapering is found by numerical optimization using a piecewise-quadratic law. The Genesis 1.3 code [15] has been used for our FEL studies. Benchmarks have been performed with another FEL code ALICE [13, 16]. More details on the simulation procedure can be found in [17] and up-to-date parameters will be maintained on the XFEL.EU photon beam parameter web page [18].

PHOTON BEAM PROPERTIES

At the European XFEL facility three photon beamlines will be delivering X-ray pulses to six experimental stations. For fixed electron and photon energy, five working points are foreseen, corresponding to bunch charges of 0.02 nC, 0.1 nC, 0.25 nC, 0.5 nC, 1 nC, and resulting in pulse durations of roughly 2 fs, 8 fs, 20 fs, 40 fs and 80 fs. The hard X-ray undulators SASE1/2 are 250m long producing 4keV-25keV photons, and the soft X-ray undulator SASE3 is 120 m with photon energy range of 0.25-3 keV. We will focus on a more comprehensive description of SASE3 parameters, with the performance of SASE1 discussed more shortly. The improvement in SASE1 performance is comparable to that of SASE3. Moreover, a self-seeding setup [19] is foreseen for SASE1 from the beginning, which makes the high power extraction in the SASE mode more attractive in the soft X-ray range.

The source properties: size, divergence, radiation pulse energy, and maximum photon spectral density depend on photon energy, bunch charge, and electron energy. The pulse energies and the number of photons per pulse are shown in Fig. 1 for the tapered mode and in Fig. 2 for the saturation mode as functions of photon energy and bunch charge. In the tapered mode, pulse energy (or, equivalently, number of photons) increases by up to ten times compared to saturation, depending on the bunch charge and radiation wavelength. For short bunches (e.g. corresponding to 0.02 nC) the tapering efficiency drops since the radiation slips forward relative to the electron bunch and stops being amplified.

Figures 3 and 4 show comparisons of peak power and photon spectral density produced in the standard SASE mode

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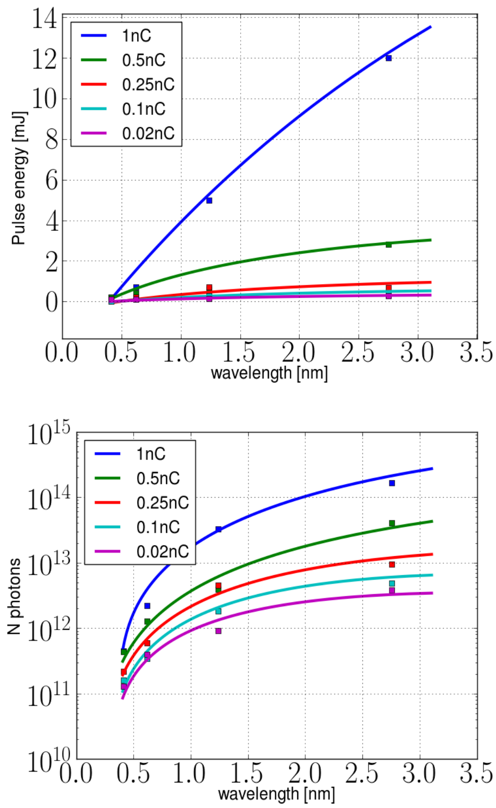

Figure 1: SASE3 baseline for 14 GeV electron energy: (top) pulse energy and (bottom) number of photons per pulse as a function of photon energy and bunch charge in the SASE saturation mode of operation.

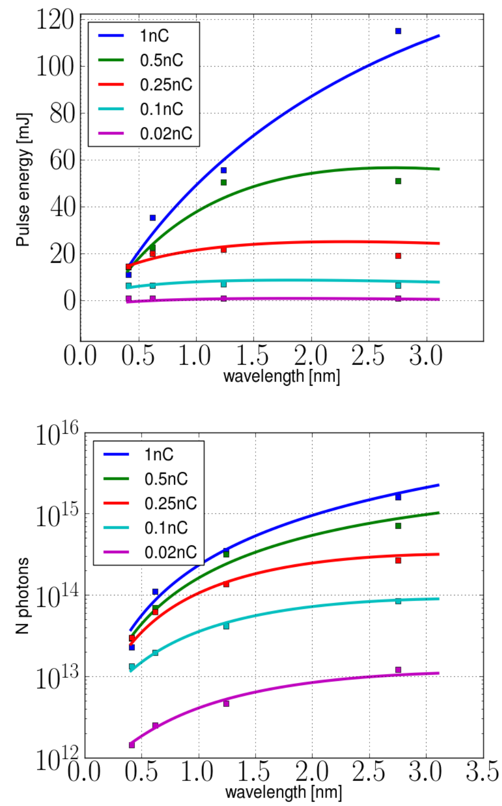

Figure 2: SASE3 baseline for 14 GeV electron energy: (top) pulse energy and (bottom) number of photons per pulse as a function of photon energy and bunch charge in the SASE tapering mode of operation.

at saturation and in the tapered mode. Also in this case, up to tenfold increase in these parameters is observed.

For soft X-rays produced at SASE3 a grating monochromator will be used in order to reduce the bandwidth of FEL radiation for spectroscopy applications. This monochromator provides resolution better than 10^{-4} and is able to accept the high power level of the XFEL radiation [5]. Since the monochromator bandwidth is much narrower than the SASE FEL bandwidth, in order to predict the monochromator output in terms of number of photon per pulse it is convenient to describe the calculated spectral distribution by the maximum photon spectral density of the source.

The source divergence is the most important parameter for the layout of the X-ray beam transport system. Figure 5 shows X-ray pulse divergence in terms of the FWHM of the angular distribution of X-ray pulse energy as a function of photon energy and bunch charge, for saturation and tapered modes respectively. The source divergence is largest for the smallest photon energies and the lowest bunch charges. Since one needs to minimize diffraction from the optics aperture and preserve the radiation wavefront, any optical elements should ideally have an aperture size large enough to accept at least 4σ tails. The (horizontal) offset mirrors of the SASE3 beamline are placed about 300 m behind the undulator exit. This mirror system can be adjusted between 6 mrad and 20 mrad incidence angle. The X-ray optics and transport group is planning to implement offset mirrors with clear aperture of 800 mm [4]. With these parameters, using Fig. 5, one obtains that the transverse clear aperture of the offset mirrors is in principle enough to fulfill the 4σ requirement for the SASE tapering mode of operation.

Figure 6 shows the evolution of the output energy in the photon pulse and of the variance of the energy fluctuation as a function of the distance inside the undulator, including tapering. Figures 7 and 8 show a comparison of power and spectrum produced in the standard SASE mode at saturation and power and spectrum produced in the SASE mode including post-saturation tapering.

Similar results can be obtained for the hard X-ray undulator SASE1 (see Fig. 9). Moreover, here, due to the shorter radiation wavelength, the radiation slippage does not cause the decrease in tapering efficiency for shorter pulses.

The photon beam quality in the saturation and tapered regime need not be the same. It is best to study such quality by propagation of the photon pulse through the X-ray optics and looking at the distribution of the photon field at the experiment. Simulations with SRW [20] show that for the SPB line [4], the beamline for coherent imaging where smallest

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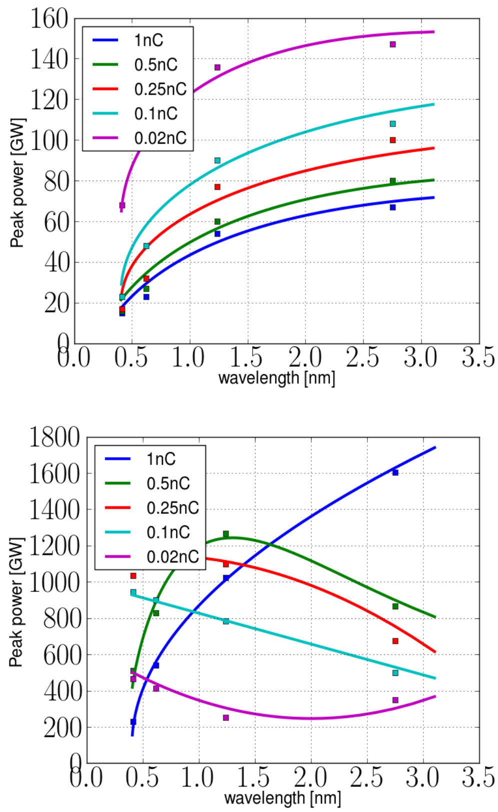

Figure 3: SASE3 baseline for 14 GeV electron energy: peak power in saturation (top) and tapering (bottom) mode.

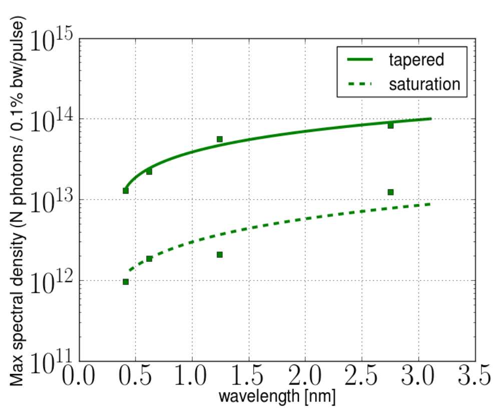

Figure 4: SASE3 baseline for 14 GeV electron energy: Maximum of average spectral density, for 0.5 nC electron beam.

spot size is possible, 100nm focusing can be achieved both with the saturation and tapered parameters (see Fig. 10), which demonstrates that the photon beam quality does not deteriorate. A more detailed analysis of the photon been quality will be done elsewhere.

CONCLUSION

In this article we demonstrated that the potential of the European XFEL in the standard SASE mode has been underestimated up to the present day. The output X-ray pulse

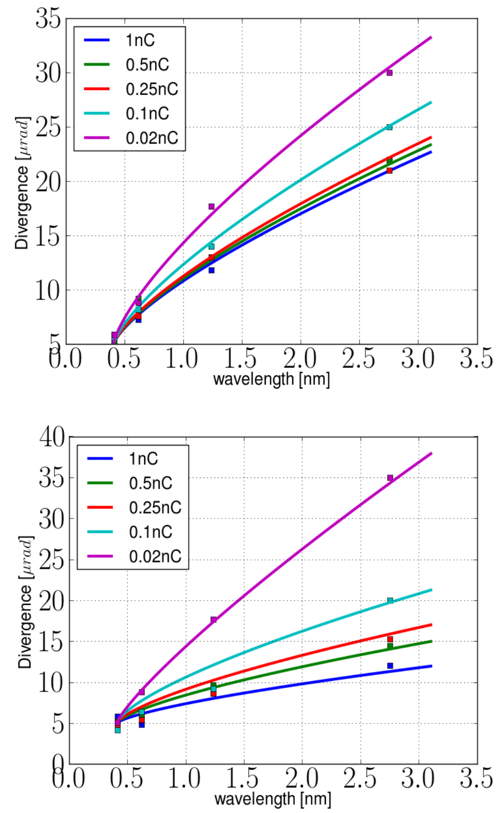

Figure 5: SASE3 baseline for 14 GeV electron energy: FWHM of angular distribution of X-ray pulse energy as a function of photon energy and bunch charge in SASE saturation mode (top) and in tapered mode (bottom).

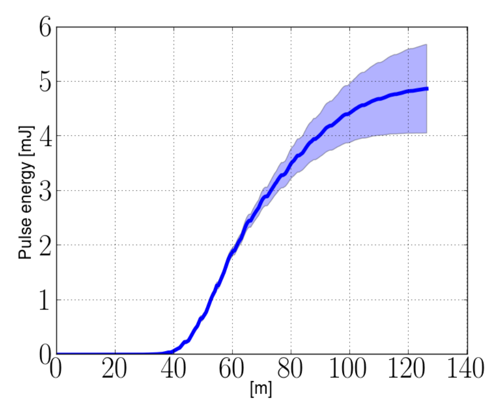

Figure 6: SASE3 baseline for 14 GeV electron energy, 0.1nC bunch charge, 1keV photon energy: Pulse energy evolution

parameters indicated in the design reports of scientific instruments and X-ray beam transport system are far from the optimum found in this paper. Based on start-to-end simulations it has been shown that tapering of baseline undulators for both hard and soft X-rays provides an additional factor of ten increase in spectral density and output power (up to TW-level) for a baseline electron beam parameter set.

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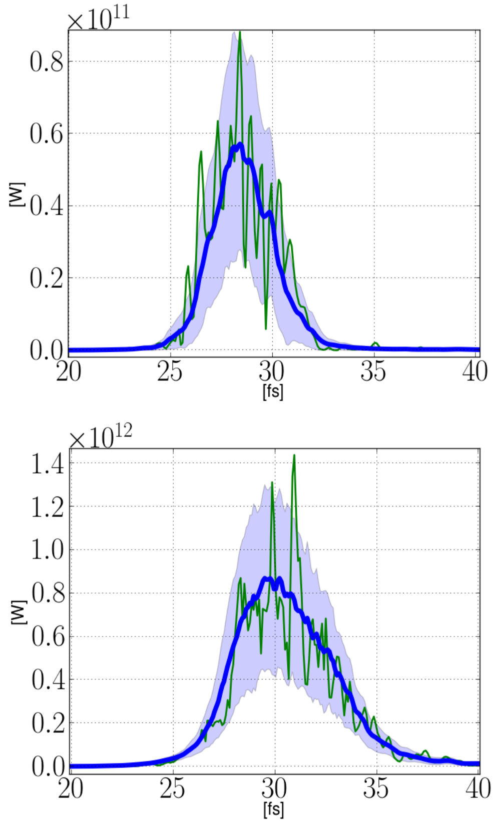

Figure 7: SASE3 baseline for 14 GeV electron energy, 0.1nC bunch charge, 1keV photon energy. Pulse shape: mean (blue), rms (shaded), and median (green). Saturation (top) and tapered (bottom).

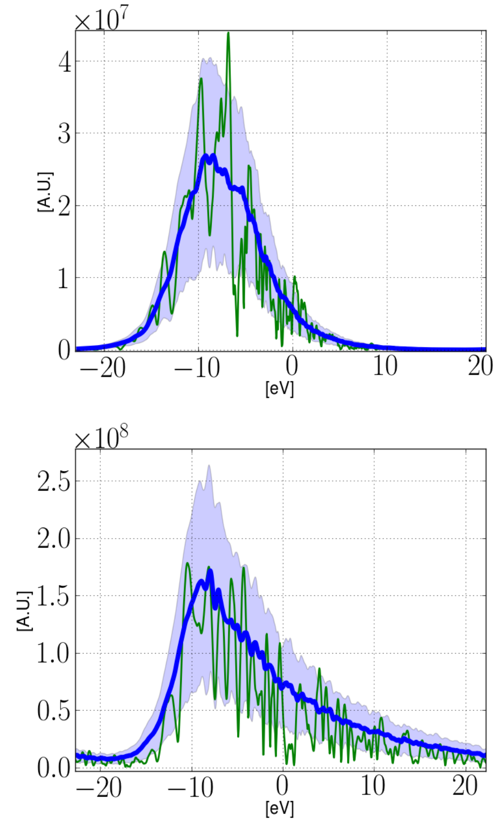

Figure 8: SASE3 baseline for 14 GeV electron energy, 0.1nC bunch charge, 1keV photon energy. Spectrum: mean (blue), rms (shaded), and median (green). Saturation (top) and tapered (bottom).

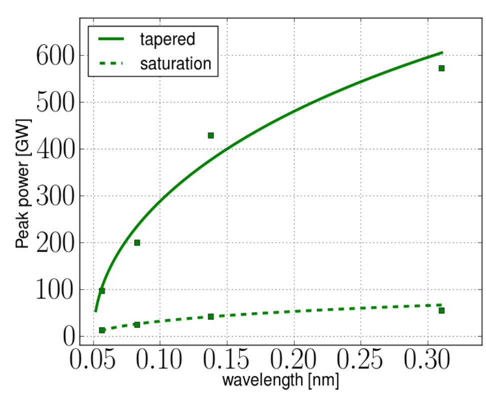

Figure 9: Peak power as a function of photon energy for SASE1 baseline for 14 GeV electron energy, 0.1nC bunch charge

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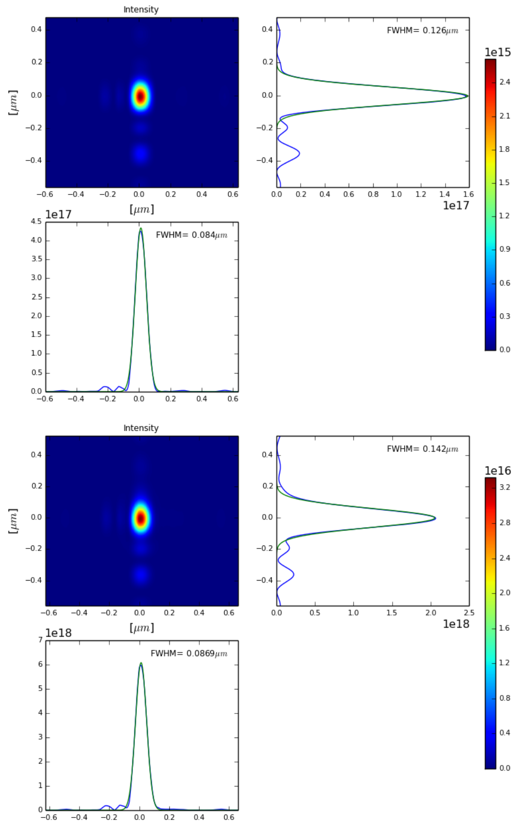

Figure 10: Photon beam distribution at the focus of the SPB instrument, 9keV. Saturation (top) and tapered (bottom) regime.

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