PROSPECTS FOR CW OPERATION OF THE EUROPEAN XFEL IN HARD X-RAY REGIME

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Abstract

The European XFEL will operate nominally at 17.5 GeV in SP (short pulse) mode with 0.65 ms long bunch train and 10 Hz repetition rate. A possible upgrade of the linac to CW (continuous wave) or LP (long pulse) modes with a corresponding reduction of electron beam energy is under discussion since many years. Recent successes in the dedicated R&D program allow to forecast a technical feasibility of such an upgrade in the foreseeable future. One of the challenges is to provide sub-Ångstrom FEL operation in CW and LP modes. In this paper we perform a preliminary analysis of a possible operation of the European XFEL in the hard X-ray regime in CW and LP modes with the energies of 7 GeV and 10 GeV, respectively. We show that, with reasonable requirements on electron beam quality, lasing on the fundamental will be possible in sub-Ångstrom regime. As an option for generation of brilliant photon beams at short wavelengths we also consider harmonic lasing that has recently attracted a significant attention.

INTRODUCTION

The European XFEL [1] will be the first hard X-ray FEL user facility based on superconducting accelerator technology, and will provide unprecedented average brilliance of photon beams. The XFEL linac will operate nominally at 17.5 GeV in a burst mode with up to 2700 bunches within a 0.65 ms long bunch train and 10 Hz repetition rate. Even though the RF pulses are much longer than those available at X-ray FEL facilities, based on normal conducting accelerators, in the context of this paper we will call this SP (short pulse) mode of operation.

In order to cope with high repetition rate within a pulse train, special efforts are being made to develop fast X-ray instrumentation [2]. Still, many user experiments would strongly profit from increasing distance between X-ray pulses while lengthening pulse trains and keeping total number of X-ray pulses unchanged (or increased). Such a regime would require an operation of the accelerator with much longer RF pulses (LP, or long pulse mode), or even in CW (continuous wave) mode as a limit. A possible upgrade of the XFEL linac to CW or LP modes with a corresponding reduction of electron beam energy is under discussion since many years [3]. Recent successes in the dedicated R&D program [4] allow to forecast a technical feasibility of such an upgrade in the foreseeable future.

One of the main challenges of CW upgrade is to provide sub-Ångstrom FEL operation which is, obviously, more difficult with lower electron energies. One can consider improving the electron beam quality as well as reducing the undulator period as possible measures. An additional possibility is a harmonic lasing [5–8] that has recently attracted a significant attention [8]. Harmonic lasing can extend operating range of an X-ray FEL facility and provide brilliant photon beams of high energies for user experiments.

CW UPGRADE OF THE LINAC

A possible upgrade of the XFEL linac to CW or LP modes holds a great potential for a further improvement of X-ray FEL user operation, including a more comfortable (for experiments) time structure, higher average brilliance, improved stability etc. The drawbacks are a somewhat smaller peak brilliance and a reduced photon energy range, both due to a lower electron beam energy. Both disadvantages can, however, be minimized by an improvement of the electron beam quality and application of advanced FEL techniques. Moreover, one can keep a possibility to relatively quickly switch between SP and CW modes thus greatly improving the flexibility of the user facility.

For a CW upgrade of the linac, the following main measures will be needed [4]:

i) Upgrade of the cryogenic plant with the aim to approximately double its capacity;

ii) Installation of new RF power sources: compact Inductive Output Tubes (IOTs);

iii) Exchange of the first 17 accelerator modules by the new ones (including a larger diameter 2-phase helium tube, new HOM couplers etc.) designed for operation in CW mode with a relatively high gradient (up to 16 MV/m). This ensures that the beam formation system (up to the last bunch compressor) operates with a similar energy profile as it does in SP mode. Then 12 old accelerating modules are relocated to the end of the linac;

iiii) Installation of a new injector generating a high-brightness electron beam in CW mode.

The first two items can be realized in a straightforward way; the third one is based on the steady progress of the TESLA technology [9] and is not particularly challenging. Until recently the main uncertainty was connected with the absence of CW injectors providing a sufficient quality of electron beams. However, last year there was an experimental demonstration of small emittances (for charges below 100 pC) at a CW photoinjector using a DC gun followed immediately by acceleration with superconducting cavities [10]. The measured parameters are already sufficient for considering this kind of injector as a candidate for CW upgrade of the XFEL linac (although the operation would be limited to low charge scenarios). As an alternative one can consider a superconducting RF gun that can potentially produce also larger charge bunches with low emittances (the progress reports can be found in [11, 12]) or even a normal conducting

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Table 1: Main Assumptions for CW/LP Upgrade of the XFEL Facility

Parameter	Unit	Value
Beam		
Maximum charge per bunch	[nC]	0.5
Time between subsequent bunches	[μs]	4
Average current	[mA]	0.125
Maximum beam energy in CW mode	[GeV]	7.8
Main Linac		
Number of 8-cavity cryomodules	-	96
1.8K cryogenic dynamic load per cryomodule	[W]	16
1.8K cryogenic static load per cryomodule	[W]	4
Q_0 of cavities	-	2.8×10^{10}
Maximum E_{acc} for CW mode	[MV/m]	7.3
Q_{load} of input coupler	-	2×10^7
Mean RF-power per cavity	[kW]	< 2.5
Assumed microphonics: (peak-peak)/2	[Hz]	32
Injector Section up to 2 GeV		
Number of 8-cavity cryomodules in linacs L0 / L1 / L2	-	1/ 4/ 12
Maximum E_{acc} for CW mode in linacs L0 / L1 / L2	[MV/m]	16 /11/ 15
1.8K total cryogenic load per cryomodule in linacs L0 / L1 / L2	[W]	91 / 45 / 80
Q_0 of cavities	-	2.5×10^{10}

RF gun [13]. In the latter case a special regime can, in principle, be organized when a continuous sequence of short RF pulses is used [14] instead of powering the gun in true CW mode.

In this paper we do not present a comprehensive technical description of the CW upgrade, it will be published elsewhere [15]. Here we only summarize some technical details in Table 1.

To predict a possible electron energy range in CW and LP modes, and to test the XFEL cryomodules in these regimes, a series of measurements is being performed at DESY [4]. The measurements demonstrate stable behavior of the modules in these regimes, and allow to conservatively predict that the energy can reach 7 GeV in CW mode, and 10 GeV in LP mode with 35% duty factor [4]. Recent measurements of a cryomodule equipped with large grain Nb cavities and improved HOM couplers demonstrated even better performance, and allow for more optimistic forecasts (as it is reflected in Table 1). Moreover, all these measurements have been done with pre-series XFEL cryomodules which have not yet reached an ultimate performance. In other words, one can hope for higher electron energies after CW upgrade. Nevertheless, in this paper we conservatively consider electron energy range between 7 GeV and 10 GeV.

LASING IN THE BASELINE UNDULATOR

Apart from the standard regime of the FEL operation, namely lasing at the fundamental wavelength to saturation, in this paper we will also consider harmonic lasing as an option for reaching short wavelengths. Harmonic lasing in single-pass high-gain FELs [5–8] is the radiative instability at an odd harmonic of the planar undulator developing independently from lasing at the fundamental. Contrary to nonlinear harmonic generation (which is driven by the fundamental in the vicinity of saturation), harmonic lasing can provide much more intense, stable, and narrow-band FEL beam if the fundamental is suppressed. The most attractive feature of saturated harmonic lasing is that the brilliance of a harmonic is comparable to that of the fundamental. Indeed, a good estimate for the saturation efficiency is $\lambda_w/(hL_{sat})$, where λ_w is the undulator period, L_{sat} is the saturation length, and h is harmonic number. At the same time, the relative rms bandwidth has the same scaling. If we consider lasing at the same wavelength on the fundamental and on a harmonic (with the retuned undulator parameter K), transverse coherence properties are about the same since they are mainly defined by emittance-to-wavelength ratio. Thus, also the brilliance is about the same in both cases. In many cases, however, the saturation length for harmonics can be shorter than that of the fundamental at the same wavelength. As a consequence, for a given undulator length one can reach saturation on harmonics at a shorter wavelength. It was shown in a recent study [8] that the 3rd and even the 5th harmonic lasing in X-ray FELs is much more robust than usually thought, and can be widely used at the present level of accelerator and FEL technology.

In the following we will consider the range of beam energies from 7 to 10 GeV, assuming that the former can be achieved in CW mode, and the latter - in LP mode with about 35% duty factor [4]. The hard X-ray undulators SASE1 and SASE2 of the European XFEL have 4 cm period, and the largest K-value of 3.9 is achieved at the gap of 10 mm. The

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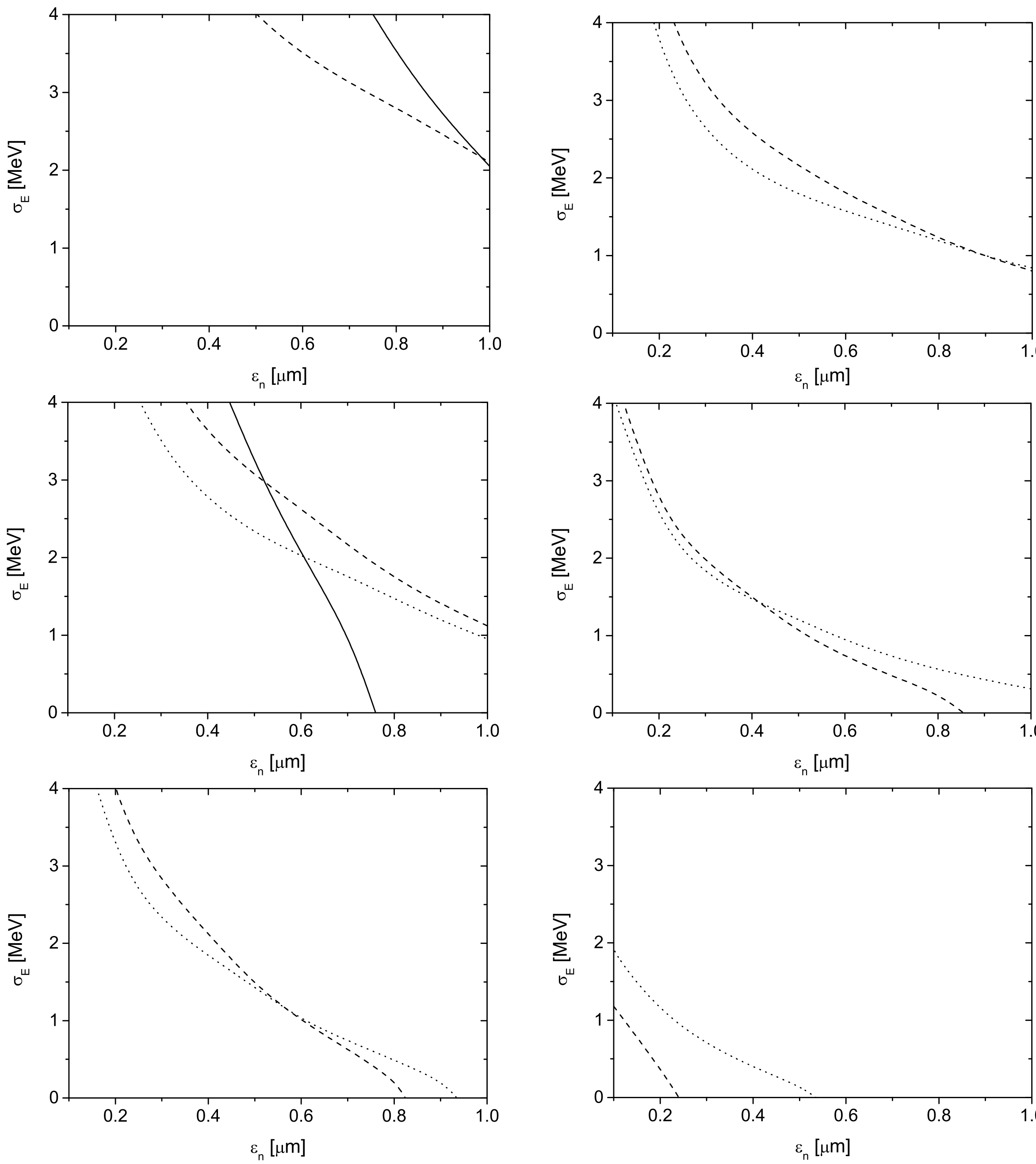

Figure 1: Energy spread versus normalized emittance for which the saturation in SASE1 undulator is possible at 1 Å(upper graphs), 0.75 Å(middle graphs), and 0.5 Å(lower graphs). The beam energy is 10 GeV (left column) and 7 GeV (right column), and the peak current is 5 kA. Beta-function is optimized for the highest gain when the optimum is larger than 15 m, otherwise beta-function is 15 m. Solid, dash, and dot curves correspond to the 1st, the 3rd, and the 5th harmonic lasing, correspondingly.

net magnetic length of the undulator is 175 m. Our task is to define the range of achievable photon energies depending on electron beam quality. We consider lasing on the fundamental as well as on the 3rd and the 5th harmonics. The formulas from [8] are used to calculate the saturation length. We assume that the peak current is 5 kA in all considered cases (different compression scenarios we leave for future studies). We optimize beta-function in the undulator for the shortest gain length. However, when the optimum beta is smaller than 15 m (which we assume as a technical limit), we set it to 15 m.

In Fig. 1 we present energy spread versus normalized emittance for which the saturation is possible at 1 Å, 0.75 Å, and 0.5 Å for the electron energies of 7 and 10 GeV. The corresponding photon energy range is 12.4–24.8 keV. In the case of 10 GeV the lasing at 1 Å is not possible on the fifth

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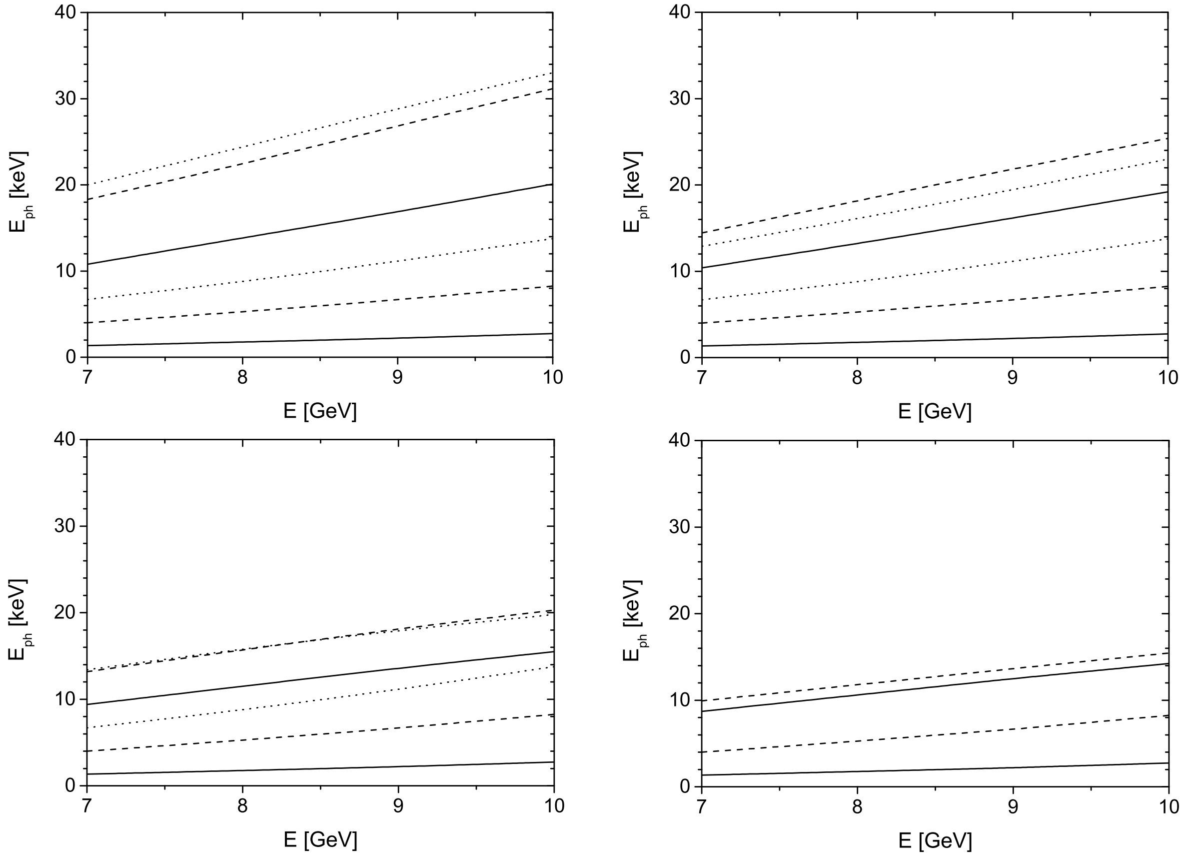

Figure 2: Range of photon energies accessible with the fundamental (between the solid lines), the third harmonic (between the dash lines), and the fifth harmonic (between the dot lines). Upper left: $\epsilon_n = 0.4\,\mu\text{m}$, $\sigma_{\mathcal{E}} = 1$ MeV, upper right: $\epsilon_n = 0.4\,\mu\text{m}$, $\sigma_{\mathcal{E}} = 2$ MeV, lower left: $\epsilon_n = 0.8\,\mu\text{m}$, $\sigma_{\mathcal{E}} = 1$ MeV, lower right: $\epsilon_n = 0.8\,\mu\text{m}$, $\sigma_{\mathcal{E}} = 2$ MeV. The undulator period is 4 cm, maximum K is 3.9, the peak current is 5 kA. Beta-function is optimized for the highest gain when the optimum is larger than 15 m, otherwise beta-function is 15 m.

harmonic because K is not sufficiently large. However, lasing to saturation on the fundamental and on the 3rd harmonic is possible practically for any reasonable beam quality. Resonance at 0.5 Å cannot be achieved on the fundamental, but lasing to saturation on the 3rd and on the 5th harmonics is possible for a sufficiently bright electron beam. In the case of 7 GeV the resonance at 1 Å and at shorter wavelengths is not possible on the fundamental. However, lasing to saturation on the 3rd and the 5th harmonics in sub-Ångstrom regime is possible (although at 0.5 Å it would require extremely bright electron beams).

We can also calculate photon energy range that can be achieved in the considered electron energy range depending on electron beam quality. In Fig. 2 we present the results for four different combinations of slice emittance and energy spread ranging from 0.4 µm and 1 MeV (upper left plot) to 0.8 µm and 2 MeV (lower right plot). One can see that harmonics have a significant advantage over the fundamental only if the electron beam is bright enough. One can notice that, for example, lasing on the 5th harmonic is not possible for the most pessimistic parameter set.

Finally, let us note that the baseline undulator with a relatively large period and large K value has an advantage of a big tunability range, as one can see from Fig. 2. Moreover, one can keep the usual operation range after switching back to the SP mode. Another advantage is that keeping a relatively large gap (10 mm) is favorable in the context of CW operation with a high average power of the electron beam. However, we have also considered a scenario with a shorter period undulator, the results can be found in [16].

REFERENCES

[1] M. Altarelli et al. (Eds.), XFEL: The European X-Ray Free-Electron Laser. Technical Design Report, Preprint DESY 2006-097, DESY, Hamburg, 2006 (see also http://xfel.desy.de).

[2] A. Koch et al., J. Phys.: Conf. Ser. **425**(2013)062013

[3] R. Brinkmann, Proc. of the LINAC2004 Conference, Lübeck, Germany, MO102, [http://www.jacow.org]

[4] J. Sekutowicz et al., Proc. of the FEL2013 Conference, New York, USA, p. 189, [http://www.jacow.org]

[5] J.B. Murphy, C. Pellegrini and R. Bonifacio, Opt. Commun. **53**(1985)197

[6] Z. Huang and K. Kim, Phys. Rev. E, 62(2000)7295.

[7] B.W.J. McNeil et al., Phy. Rev. Lett. 96, 084801 (2006)

ISBN 978-3-95450-133-5

[8] E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST-AB **15**(2012)080702

[9] R. Brinkmann et al. (Eds.), TESLA technical design report, Part II: Accelerator. Preprint DESY 2001-11, Hamburg, 2001.

[10] C. Gulliford et al., Phys. Rev. ST-AB **16**(2013)073401

[11] S.A. Belomestnykh, Proc. of the FEL2013 Conference, New York, USA, p. 176, [http://www.jacow.org]

[12] M. Schmeisser et al., Proc. of IPAC2013 Conference, San Sebastian, Spain, p. 3146, [http://www.jacow.org]

[13] C.F. Papadopoulos et al., Proc. of the FEL2013 Conference, New York, USA, p. 391, [http://www.jacow.org]

[14] V. Vogel et al., Proc. of IPAC2011 Conference, Shanghai, China, p. 282, [http://www.jacow.org]

[15] J. Sekutowicz et al., “Duty factor upgrade of the XFEL linac", to be published.

[16] R. Brinkmann, E.A. Schneidmiller, J. Sekutowicz, M.V. Yurkov, report DESY-14-025, March 2014; arXiv:1403.0465

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