40th International Free Electron Laser Conference,Trieste JACoW Publishing
ISBN: 978-3-95450-220-2 ISSN: 2673-5474 doi: 10.18429/JACoW-FEL2022-TUP50

AN XFELO DEMONSTRATOR SETUP AT THE EUROPEAN XFEL*

P. Rauer†, W. Decking, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
I. Bahns, D. La Civita, J. Gruenert, M. Di Felice, A. Koch,
L. Samoylova, H. Sinn, M. Vannoni, European XFEL GmbH, Schenefeld, Germany
J. Rossbach, Universitaet Hamburg, Hamburg, Germany

Abstract

An X-ray free-electron laser oscillator (XFELO) is a next generation X-ray source promising radiation with full three-dimensional coherence, nearly constant pulse to pulse stability and more than an order of magnitude higher spectral flux compared to SASE FELs. In this contribution the concept of an R&D project for installation of an *XFELO* demonstrator experiment at the European XFEL facility is conceptually presented. It is composed of an X-ray cavity design in backscattering geometry of 133 m round trip length with four undulator sections of 20 m total length producing the FEL radiation. It uses cryocooled diamond crystals and employs the concept of retroreflection to reduce the sensitivity to vibrations. Start to end simulations were carried out which account for realistic electron bunch distributions, inter RF-pulse bunch fluctuations, various possible errors of the X-ray optics as well as the impact of heat load on the diamond crystals. The estimated performance and stability derived from these simulations shall be reported and foreseen issues shall be discussed.

INTRODUCTION

In order to overcome one of the major flaws of SASE based FEL radiation in the hard X-ray regime, which is the low degree of monochromaticity and the lack of of longitudinal coherence, multiple schemes have been proposed and partly realized over the recent years. Promising schemes are the *X-ray Regenerative Amplifier FEL* (XRAFEL) proposed by *Z. Huang* in 2006 [1] and the *X-ray Free Electron Laser Oscillator* (XFELO) proposed by *K.J. Kim* in 2008 [2]. Both schemes are based on trapping FEL radiation inside a X-ray optical cavity, using monochromatizing crystals based on Bragg reflection instead of total reflecting optical mirrors [1, 3]. While the XFELO is closely related to the low gain FELO scheme, the XRAFEL is based on the strong gain FEL amplifier scheme. In the following, both schemes will be summarized under the term *XFELO*. Due the promise of delivering outstanding radiation properties, *XFELO*s have received growing interest in the recent years [3–14].

European XFEL is developing an *XFELO* demonstrator to be installed at the end of one of the hard X-ray undulator lines (SASE1) in the first quarter of 2024. The principal goal of the demonstrator is to prove the working concept - meaning seeding and increasing longitudinal coherence by several orders of magnitude over subsequent round trips, from synchrotron radiation to almost monochromatic FEL amplifier radiation. It is not primarily meant for user-operation, and therefore not optimized to this end.

In this proceeding, the fundamentals of the experimental setup as well as the expected output characteristics shall be sketched. More detailed information will be given in a separate publication [15] or can be looked up in ref. [16].

A PROOF-OF-CONCEPT *XFELO* EXPERIMENT

The X-ray cavity is designed in a simple two crystal backscattering geometry, following the principle of maximum simplicity to avoid mechanical complications. Hence, features like wavelength tunability [3, 7] are omitted. The crystals are two optically thick ($t_C \approx 250\,\mu$m) diamond crystals. This increases the robustness of the setup against thermal load, which is further improved by cooling the diamonds to a temperature of $T = 77$ K [10, 11, 17–19]. In between the crystals, four 5 m long variable gap undulator sections are positioned and two chicanes are used to in- and out-couple the electrons. The crystal to crystal distance is fixed to $L_{C-C} \approx 66.42$ m, which matches an electron bunch repetition rate of $f_{\mathrm{rep}}^{\mathrm{el.}} = 2.25$ MHz, being a common repetition rate at the European XFEL accelerator. Each reflecting crystals is combined with two grazing incidence mirrors aligned orthogonally with respect to each other and the crystal. This forms a so called retroreflector, which may decouple the setup from outer vibrations (see [15] or [16] for reference). Additionally, by applying a slight meridional curvature $R_m \approx 20$ km on the total reflecting mirrors, focusing of the X-ray pulses can be achieved.

In Fig. 1 the evolution of the pulse energy of the *XFELO* demonstrator for a photon energy of $E_c = 9.05$ keV is displayed. The different curves correspond to the X-ray pulse directly after the undulator (blue), reentering the undulator as seed for the subsequent round trip (red) and the transmitted pulse (yellow). The simulations include various different error sources, such as statistical electron beam shot to shot fluctuations common for the European XFEL accelerator [20], crystal misalignment and mirror surface profile error of $h_{\mathrm{rms}} = 1.5$ nm. Figure 1(a), which neglects the impact of heat load on the crystals, shows that the pulse energy trapped inside the X-ray cavity reaches up to very high value, which corresponds in combination with a very small bandwidth of only $\sigma_{E_{\mathrm{ph}}} = 20.4(5)$ meV to unparalleled peak spectral densities. Owing to the simplistic transmission through a thick crystal, only the spectral side lobes regenerated at every round trip are transmitted. This leads to much lower trans-

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* Work supported by (FKZ 05K16GU4)

† patrick.rauer@desy.de

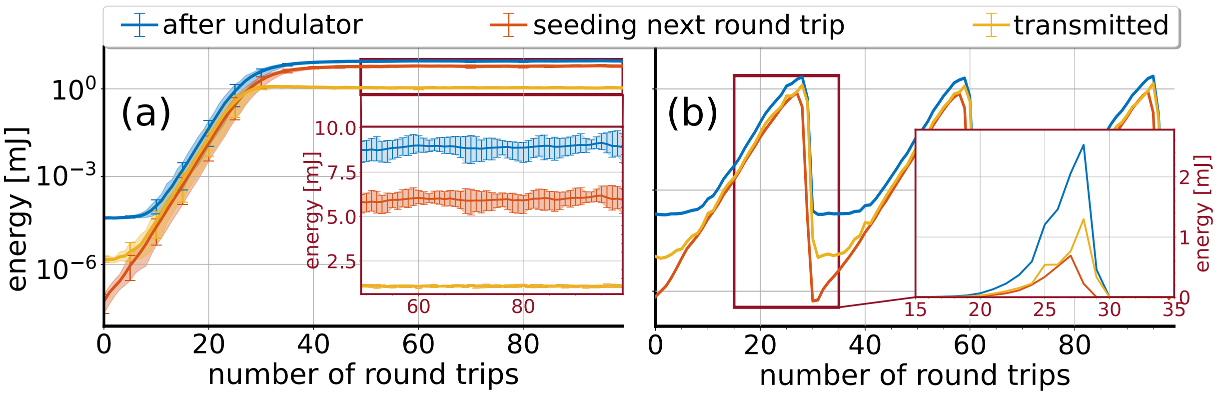

Figure 1: Pulse energy evolution in logarithmic scale for a photon energy of $E_c = 9.05$ keV, corresponding to a diamond C 111 orientation, neglecting heat load (a) and including heat load in the calculation (b). The inset show the pulse energies around the maxima in linear scale. The heat load evidently strongly destabilizes the output.

mitted pulse energies at around $Q_{tr} \approx 0.95(5)$ mJ. Yet, still showing a very small bandwidth of only $\sigma_{E_{\mathrm{ph}}} = 69(2)$ meV, the expected peak spectral flux is still much higher compared to SASE.

However, as evident from Fig. 1(b), when including the impact of thermal load into the fully coupled simulations, the output gets strongly destabilized, even at an optimized crystal base temperature of $T_c = 77$ K. This is fully understandable, regarding the intense and focussed, X-ray pulses interacting with the crystal at a megahertz repetition rate.

In a more detailed publication [15], the details of the X-ray output characteristics, with and without heat load, as well as its implications on the demonstrator experiment, will be explained in much more detail.

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