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GENERATION OF HIGH POWER, HIGH INTENSITY, ULTRA SHORT X-RAY FEL PULSES

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Abstract

X-ray Free Electron Lasers combine high pulse power, short pulse length, narrow bandwidth and a high degree of transverse coherence. Any increase in the photon pulse power, while shortening the pulse length, will further push the frontier on several key XFEL applications including single molecule imaging and novel nonlinear X-ray methods. This work shows experimental results at the Linac Coherent Light Source raising its maximum power to more than 300% of the current limit, while reducing the photon pulse length to 10 fs. This was achieved by minimizing residual transverse-longitudinal centroid beam offsets (beam yaw) and dispersion when operating over 6 kA peak current with a longitudinally shaped beam. Even shorter pulses of 3 fs were achieved by combination of this high current mode with an emittance spoiling foil.

INTRODUCTION

The X-ray Free Electron Lasers are the brightest X-ray light-sources for scientific applications [1–4], having a peak brightness of about nine order of magnitude higher than storage-ring synchrotron sources. Single particle imaging [5], for example, requires intense photon pulses to avoid structural modifications during the probe pulse duration. Similarly, serial femtosecond X-ray crystallography and X-ray spectroscopy studies would benefit from brighter and shorter X-ray pulses exploiting this same principle [6, 7]. XFELs have also revealed a variety of nonlinear phenomena when intense X-ray pulses interact with atoms and molecules [8, 9], including stimulated X-ray emission [10, 11]. Even shorter pulses of around 3 fs are necessary for more advanced techniques like incoherent diffraction imaging [12].

In an FEL the achievable power at saturation scales with the electron bunch current as $P_{sat} \propto I^{4/3}$ [13], and also when post-saturation taper is usually applied to extract more power [14]. Therefore an increase in the current leads to higher saturation power. However, increasing the electron bunch current is not trivial, being limited, among other reasons, by Coherent Synchrotron Radiation (CSR) introducing beam yaws. Recent papers based on theory, simulations and measurements proposed a method to remove the beam yaw [4,15,16]. They are all based on careful control of dispersion at locations with a strong energy chirp (e.g. the bunch compressors) by multi-pole magnets or orbit bumps. Removal of the resulting dispersion is achieved by subsequent correctors. This requires a minimal set of four correctors, linearly independent in energy chirp and phase advance, to correct for both beam yaw and dispersion simultaneously.

Further reduction of the pulse length is achievable by selective lasing suppression. Either by any Fresh-slice [17] based method or an emittance spoiling foil [18]. The aluminum foil scatters part of the streaked electron beam lowering its beam quality beyond the threshold required for SASE. The unspoiled slotted center area will be lasing at nearly the same power, resulting in shortened photon pulses. The minimal achievable bunch length is given by the ratio of energy chirp to slice energy spread of the bunch at the location of the emittance spoiling foil. This is due to the fact that the transverse streaking at the foil happens in energy whereas the FEL bunching in the undulator happens in longitudinal position. Note that only the combination of those two techniques allows to improve upon power for very short photon pulses.

SETUP

The LCLS [1] is equipped with a pair of tweaker quadrupole magnets in each bunch compressor and one pair in the final dogleg. In addition there are several identified locations for orbit bumps. Being localized orbit control to transversely displace the electron beam with respect to one or several quadrupole magnets without affecting the downstream orbit. The combination of the two BC2 tweaker quadrupole magnets with any two dispersion correctors downstream of the final linac is enough for simultaneous linear correction of both beam yaw and dispersion. In practice this was achieved by a combination of dogleg tweakers and orbit bumps in the LTU.

The emittance spoiling foil neither influenced the beam yaw nor dispersion fundamentally. This facilitated the combination of this two operation scheme. The higher peak current increased the slice energy spread significantly thereby setting an lower limit of the achievable bunch length. This effect has been partially compensated by minimizing the laser heater power. The resulting micro-bunching amplification effects were mitigated however. Figure 1 shows a schematic drawing of the used setup accompanied by elegant [19] simulations of both the dispersion and the beam yaw for the corrected and uncorrected case.

As the selection of the lasing slice depends on the energy at the second bunch compressor there will be a temporal jitter of the lasing slice within the bunch. The applied beam yaw correction leads to a more uniform core lasing therefore preventing this jitter to propagate into a power jitter as well therefore stabilizing the power. Furthermore, this more uniform lasing of a single slice in principle allows for even better core tuning as one of the temporal dependent suppression effects was removed.

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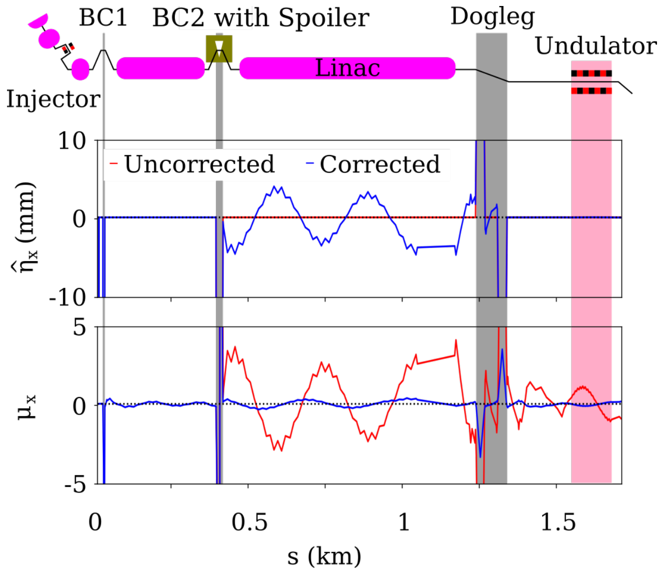

Figure 1: Elegant [19] simulation of the LCLS showing beam yaw (μ) and dispersion (η) prior and after beam yaw correction. Included sources of beam yaw are the transverse wakefields and the CSR. The correction was done using a Singular Value Decomposition algorithm as further detailed in [15]. The dispersive areas housing the tweaker quadrupole magnets are highlighted in gray. Note that leaked lattice dispersion is increased between BC2 and the dogleg, measurements at LCLS agree with both phase and magnitude of this intermediate increase. The final photon pulse was further shortened by the emittance spoiling foil in BC2.

RESULTS

The high current mode was successfully experimentally demonstrated at the LCLS operating in a high-current mode for hard X-rays [4] and has subsequently been used in several user deliveries producing over 300 GW of peak power in short pulses. The configuration readily reproduced for several experiments and is now a standard operation mode for pulse lengths in this regime. It has been well documented and supported by dedicated tuning algorithms.

The established high current mode was now used as a stepping stone to demonstrate the first time combination of it with the emittance spoiling foil to generate even shorter pulses. Figure 2 shows the longitudinal phase space after the undulator for a beam with inserted emittance spoiling foil. The increased energy spread leads to an artificial increase in the perceived pulse length in the longitudinal phase space after the undulator. This and other artifacts make it difficult to do any temporal X-ray reconstruction relying on the longitudinal phase space after the undulator. However assuming that the power didn't decrease significantly due to the foil, as observed in other foil experiments, the change in pulse energy suggest a pulse length below 3 fs.

This observation is in good agreement with preliminary analysis of the speckle contrast measured from the solution in the user sample [20]. Further investigation in this matter

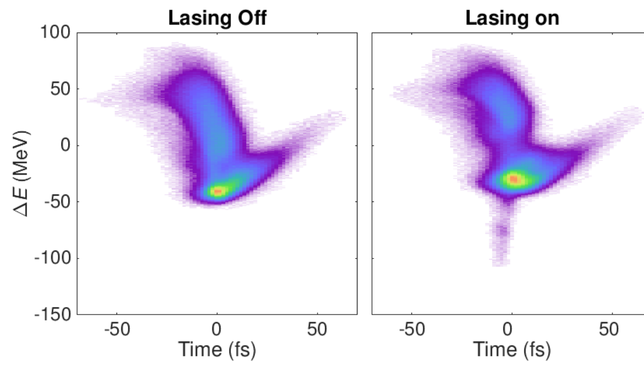

Figure 2: Typical shot of the longitudinal phase space after the undulator showing a lasing suppressed (left) and lasing (right) shot. Note that the size of the lasing shot is artificially increased due to the foil therefore making temporal X-ray reconstruction more difficult. Simulations suggest a pulse length < 3fs with a measured pulse energy of 420μJ with 7.4 keV photon energy.

will follow to give an independent measurement of the pulse length.

DISCUSSION

The combination of the yaw correction with longitudinal beam shaping [21] allowed to increase the peak current above 6 kA and the peak power to more than 300 GW as reported in [4]. Combination of this technique with an emittance spoiler furthermore allowed for even shorter pulses below 3fs. Future applications requiring sill shorter pulses could be obtained by selection of narrower slots in the emittance spoiling foil or the combination of high current with any proposed fresh slice schemes [17, 22]. The reduced gain length is especially appealing for multi-color and multi-stage applications at both hard and soft X-rays. For soft X-ray diffraction can be a limiting factor whereas for hard X-ray the finite amount of undulators (depending on the scheme half or a third of the undulator line per selected slice) severely limit the available power. Future experimental effort will strive in the combination of the high current mode with one or multiple fresh-slice techniques.

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