X-RAY FEL R&D: BRIGHTER, BETTER, CHEAPER

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Abstract

The X-ray free-electron lasers (FELs), with nine to ten orders of magnitude improvement in peak brightness over the third-generation light sources, have demonstrated remarkable scientific capabilities. Despite the early success, X-ray FELs can still undergo dramatic transformations with accelerator and FEL R&D. In this paper, I will show examples of recent R&D efforts to increase X-ray coherence and brightness, to obtain better control of X-ray temporal and spectral properties, and to develop concepts for compact coherent sources.

INTRODUCTION

X-ray FEL or XFEL is a breakthrough in light source development and enables atomic-scale imaging at femtosecond (fs) time resolution [1–3]. Despite the early success, it is widely recognized that XFELs continue to have significant potential for improvement. New methods have been rapidly developing to provide FEL seeding, extremely short x-ray pulses, variable double pulses, two-color FEL generation, and polarization control. Many of the proposals were implemented in the LCLS since 2011 through the so-called FEL R&D program that I have the privilege to contribute. Here I present a personal (incomplete) overview. I also like to discuss dreams/progress towards compact XFELs and conclude with some final remarks.

IMPROVING TEMPORAL COHERENCE (BRIGHTER)

Typical XFEL pulses are made of a few tens to hundreds of coherent spikes of fs duration, each with no fixed phase relation to the others due to the self-amplified spotaneous emission process. Longitudinal coherence can be imposed by a post-SASE monochromator, but typically with reduced intensity and increased intensity fluctuations. External seeding at radiation wavelengths down to a few nanometers was demonstrated at the FERMI FEL at Synchrotron Trieste with high-gain harmonics generation from an UV laser [4]. At shorter radiation wavelengths around 1 nm or below, external laser seeding becomes increasingly difficult, while self-seeding can be a viable alternative.

Following a proposal from DESY [5], a collaboration between SLAC, Argonne and the Technical Institute for Superhard and Novel Carbon Materials in Russia successfully implemented hard X-ray self-seeding at LCLS in 2012. One out of 33 undulator sections (U16) was removed in order to install a chicane and an in-line single diamond crystal. The thin crystal transmits most of the SASE pulse but also generates a trailing monochromatic seed pulse. The chicane can delay the electron bunch to temporally overlap with the seed and to amplify the seed in the second part of the undulator array (U17-U33). Self-seeding at the angstrom wavelength scale, with a factor of about 40 bandwidth reduction, was demonstrated [6]. Hard X-ray self-seeding is in operation since 2013 and provides seeded beams from 5 keV to 9.5 keV with two to four times more photons per pulse than SASE using a post-monochromator. In a recent warm dense matter dynamic compression experiment, the unique properties of the seeded X-rays provide plasmon spectra of this complex state that yield the temperature and density with unprecedented precision at micrometer-scale resolution [7].

After the success of hard X-ray self-seeding, a compact soft X-ray self-seeding system was designed and implemented upstream of the hard X-ray self-seeding section in 2013 [8]. This system covers the photon energy range from 0.5 keV to 1 keV with a fwhm bandwidth of 2×10^{-4}. The SXRSS system relies on a grating monochromator consisting of a variable line spacing toroidal grating followed by a plane mirror, slit and two mirrors. The four-dipole chicane is similar to the hard X-ray one and displaces, de-bunches and delays the electron beam. Although still being optimized, the soft X-ray self-seeding system has demonstrated a bandwidth of $3\text{-}5\times10^{-4}$, wavelength stability of 1×10^{-4}, and an increase in peak brightness by a factor of up to 5 across the photon energy range [9].

One of the main challenges for seeded FELs is the electron energy stability. Since the radiation wavelengh is fixed by seeding, the relative electron energy jitter should be less than the fractional FEL bandwidth divided by 2. Intense efforts have been launched to reduce the LCLS energy jitter. These includes injector RF tune-up and compression scheme optimization [10]. Underlying hardware instability has also been carefully scrutinized and improved over recent years [11]. High-power RF terminating loads and higher-rated deuterium thyratrons are forthcoming. Since 2012, both hard and soft X-ray energy jitters have been reduced by a factor of 2, and the hard X-ray self-seeding pulse intensity has increased by about a factor of 3 [12].

The measured spectrum of the soft X-ray self-seeding at LCLS has a pedestal-like distribution around the seeded frequency [9], which limits the spectral purity and seeding applications without a post-undulator monochromator. In a separate contribution to these proceedings [13], we study the origins of the pedestals and focus on the contributions of microbunching instability prior to the FEL undulator. We show that both energy and density modulations can induce sidebands in a seeded FEL. Theory and simulations are used to analyze the sideband content relative to the seeding signal. The results place a tight constraint on the longitudinal phase space uniformity for a seeded FEL.

ISBN 978-3-95450-134-2

CONTROL X-RAY PULSE PROPERTIES (BETTER)

To accommodate user requests for shorter X-ray pulses, LCLS has developed two operating modes to deliver pulses with durations in the few-fs range: a low-charge operating mode [14] and a slotted-foil method [15]. In the low-charge mode (20 pC), the reduced bunch charge provides improved transverse emittance from the gun compared to nominal operation and also mitigates collective effects in the accelerator, allowing for extreme bunch compression. The compressed electron bunch length is measured to be < 5 fs fwhm, using the X-band transverse deflector installed after the LCLS undulator in 2013 [16]. In this low-charge mode, the FEL pulse consists of only 1 or 2 coherent spikes of radiation and has better temporal coherence. Another method for femtosecond pulse generation is to use an emittance-spoiling slotted foil, which has been used at LCLS since 2010. When the dispersed electron beam passes through a foil with single or double slots, most of the beam emittance is spoiled, leaving very short unspoiled time slices to produce femtosecond X-rays. To achieve a variable pulse duration and separation, an aluminum foil (3 μm thickness) with different slot arrays was implemented. Depending on the bunch charge and the final current, a single slot with variable slot width can control the X-ray duration from 50 fs down to $\sim$ 4 fs, while V-shape double slots with different slot separation can provide two short X-ray pulses separated by about 10 fs to 80 fs for pump-probe experiments [17].

Two-color pulses are another example of custom-made X-rays from an FEL, where two pulses of different photon energy are generated with a variable time delay. One method relies on generating two X-ray colors by dividing the LCLS undulator beamline into two sections longitudinally with a distinct K associated with each section [18]. The same electron beam lases twice in two sections of the undulator so the FEL power of each color is between 5% and 15% of the full saturation power. The second method generates two colors simultaneously in one undulator using two electron bunches of different energies [19]. This method requires generation, acceleration and compression of double electron bunches within the RF wavelength of the accelerator system [20]. Each X-ray pulse is generated by one electron bunch and can reach the full saturation power, improving the two-color intensity by one order of magnitude in comparison with the first method. This “twin-bunch” approach can also be combined with hard X-ray self-seeding using appropriate crystal orientations to generated two-seeded hard X-ray colors [21]. The time delay between pulses can be adjusted from nearly overlapping to ~100 fs [19].

LCLS generates linearly polarized, intense, high brightness x-ray pulses from planar fixed-gap undulators. A new 3.2-m-long compact undulator (based on the Cornell University Delta design [22]) has been developed and installed in place of the last LCLS undulator segment (U33) in 2014 [23]. This undulator provides full control of the polarization degree and K value. Used on its own, it produces fully polarized radiation in the selected state (linear, circular or elliptical) but at low intensity. To increase the output power by orders of magnitude, the electron beam is micro-bunched by several ($\sim$ 10) of the upstream LCLS undulator segments operated in the linear FEL regime. As unavoidable by-product, this micro-bunching process produces moderate amounts of horizontally linear polarized radiation which mixes with the radiation produced by the Delta undulator. This unwanted radiation component has been greatly reduced by the reversed taper configuration [24]. Full elimination of the linear polarized component was achieved through spatial separation combined with transverse collimation. As a result, close to 100% circularly polarized soft X-rays with pulse intensity over 200 μJ have been delivered to study magnetic circular dichroism and ultrafast magnetization reversal [23].

COMPACT COHERENT SOURCES (CHEAPER)

Both synchrotron storage rings and XFEL are large X-ray light source facilities. At the moment, synchrotrons can provide 30-60 beamlines per machine, while XFELs only support 1-2 beamlines. Hence synchrotron facilities are much more cost effective to operate than XFELs even though they are both expensive to build. Therefore, it is very desirable to develop compact coherent X-ray sources that are at a small fraction of cost and size of big XFELs. Realization of compact XFELs that can be installed at many universities and research institutions will further revolutionize the ultrafast X-ray sciences. Many ideas exist to make compact coherent sources. Some rely on inverse Compton scattering (replacing cm-period undulator with μm wavelength laser and hence lower electron beam energy by a factor of 100. While others attempts to take advantage of the advanced accelerator methods to produce high-energy, high-brightness beams in a compact way (e.g., plasma accelerator boosts acceleration gradient by more than a factor of 100).

Laser plasma accelerators (LPAs) have made tremendous progress in generating high-energy ($\sim$ 1 GeV and above), high peak current (1-10 kA), and low-emittance ($\sim$ 0.1 μm) beams [25–28]. Such an accelerator was used to produce EUV spontaneous undulator radiation [29]. Due to the challenges in controlling the injection process, LPA beams have rather large energy spread, typically on a few percent level. Such energy spread hinders the short-wavelength FEL application. Nevertheless, active research and development efforts have been pursued to develop compact FELs based on these novel accelerators [30–32].

Transverse gradient undulator (TGU) has been proposed to reduce the sensitivity to electron energy variations for FEL oscillators [33] and to enhance the FEL interaction for high-gain FELs driven by large energy spread beams of laser plasma accelerators [31]. In Ref. [31], we have analyzed and simulated a compact soft x-ray FEL example using a laser plasma beam with 1 GeV central energy and 1% rms energy spread. For a peak current of 10 kA and a normalized emittance of 0.1 μm, the TGU-based FEL

ISBN 978-3-95450-134-2

reaches the multi-GW power in 5-m undulator length at the radiation wavelength of 3.9 nm (the so-called ”water window” soft X-ray regime). We have also showed that the TGU improves the SASE power by about two orders of magnitude and the bandwidth by another order of magnitude over the normal undulator. A later study has also taken into account energy-time correlation of the beam that always exists in a laser plasma accelerator and have obtained similar results [34].

A TGU FEL demonstration experiment at 30 nm radiation wavelength is under development using the laser plasma accelerator [26] at Shanghai Institute of Optics and Fine Mechanics [35]. The electron beam energy is between 400 to 600 MeV, with the measured rms energy spread about 1% [36]. A 6-m TGU with the undulator period 2 cm and the transverse gradient of $\sim 50\ \mathrm{m}^{-1}$ is being manufactured at Shanghai Institute of Applied Physics for this experiment [37]. Controlling and transporting these beams with unusual characteristics (large angular divergence and energy spread) will be a major challenge in such an experiment.

CONCLUSIONS

In summary, I have showed examples that vigorous accelerator and FEL R&D can drastically improve FEL coherence and brightness. These improvements in turn demand much better control of electron beams, as well as advanced diagnostics and undulator development. I have briefly discussed possibilities and challenges for realizing compact XFELs. These efforts are worth pursuing and will be complementary to the development of large facilities.

ACKNOWLEDGEMENTS

I would like to thank Kwang-Je Kim, who introduced me to the beautiful and intricate FEL world, and thank Argonne LEUTL team that first demonstrated SASE saturation!

I wish to thank the entire LCLS team and talented SLAC accelerator research staff and engineers. They made all these possible and are so much fun to work with!

This work was supported by Department of Energy Contract No. DE-AC02-76SF00515.

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