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BEAM ON DEMAND FOR HIGH-REPETITION-RATE X-RAY FREE-ELECTRON LASERS *

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Abstract

High repetition rate free-electron lasers (FELs) with multiple undulator beamlines will advance the frontiers of X-ray science significantly from the remarkable success of existing X-ray FEL facilities. The wide-ranging requirements for the photon properties from multiple beamlines are extremely challenging to satisfy by the same electron beam from a single superconducting accelerator. To realize the full potential of a high-rep rate FEL facility, a new emerging concept of "beam on demand" is proposed here. The concept is based on the advanced beam dynamics and radio-frequency techniques to provide beam properties (energy, bunch length, current and its profile) tailored to each undulator line at the desired repetition rate. The realization of this concept will allow optimization of photon properties of individual beamlines to maximize their performance.

INTRODUCTION

X-ray free-electron laser (FEL) facilities based on normal conducting (NC) accelerators [1–4] have achieved tremendous success all over the world that opens up vast opportunities for atom and molecule dynamics research at femtosecond scale. The peak spectral brightness of X-ray FELs is about 10 orders of magnitude higher than that of the most powerful storage ring light source. However, the enhancement factor in average spectral brightness is reduced to 2-3 orders of magnitude due to the very low beam repetition rate (~100 Hz) in NC accelerators. In this case high-repetition rate is viewed as a key capability of a new generation FEL facility. The beam repetition rate of the Linac Coherent Light Source II (LCLS-II) driven by a superconducting accelerator under construction at SLAC can reach up to 1 MHz [5], comparable with that of a storage ring light source. On the other hand, compared with the storage-ring-based light source which often has tens of beamlines, the current FEL facility (including LCLS-II) typically has a 2 to 3 beamlines, which limits the user access and beam time. A remaining challenge of a high-repetition-rate (HRR) X-ray FEL facility is to support multiple beamlines simultaneously while maintaining the high flexibility of photon properties that have been the hallmark of an X-ray FEL.

To realize the full potential of an HRR FEL facility like LCLS-II, a new emerging concept of "beam on demand" is proposed here. The concept is based on the advanced beam dynamics and radio-frequency (RF) techniques to provide beam properties tailored to each undulator line at the desired repetition rate. The beam properties that will be pursued include, but are not limited to, beam energy, beam charge, bunch length, beam current and current profile. The realization of this concept will allow optimization of the photon properties of each individual beamline to maximize their performance, which helps expand LCLS-II and its high-energy upgrade. In the following sections we will introduce three potential schemes of "beam on demand" for HRR X-ray FELs.

SHOT-BY-SHOT CONTROL OF BUNCH LENGTH AND PEAK CURRENT

With fixed beam energy and undulator parameters, the photon properties of the FEL pulses are mostly determined by the electron parameters, among which peak current is the most adjustable. In the FEL theory, the well-known Pierce parameter $\rho \propto I^{1/3}$ where I is the beam current [6]. We can vary the peak current of electron beams to optimize the FEL gain length ($L_G \propto I^{-1/3}$) and frequency bandwidth ($\Delta\omega/\omega \propto I^{1/3}$) [7]. Typically, high peak current is more favorable in hard X-ray range compared with soft X-ray range. Moreover, the electron bunch length is usually much larger than the slippage length in FEL and the duration of X-ray pulse is mostly determined by the electron bunch length. When we use one SRF linac to feed multiple undulator lines, a flexible method to control the bunch length and peak current of electron beam shot-by-shot is highly desired.

In typical FEL facilities, the bunch length and peak current of electron beam are controlled by the multi-stage magnetic compressors. The cascading configuration of two-stage bunch compressors can compress bunch length and increase peak current by a factor of ~100. For each undulator line, we can control the beam compression independently by varying the RF phase (i.e., energy chirp) prior to the bunch compressor. However, in superconducting linac based FELs, the high-Q SRF cavities, with its 1-ms fill-time, cannot be changed within one bunch spacing (~1 µs).

To achieve shot-by-shot control of bunch length and peak current in a SRF linac, a concept that uses a normal-conducting RF chirping cavity located upstream of the first compressor has been proposed [8], as shown in Fig. 1. A filling time of < 250-ns of the chirping cavity is chosen specifically to be able to change the applied RF voltage between bunches. At either zero-crossing phase, the induced energy chirp, determined by the cavity voltage and RF frequency, can be adjusted shot-by-shot while keeping the same beam energy. A preliminary study for LCLS-II has been conducted [8]. The shape and RF frequency of the cavity are

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optimized to satisfy the fill time requirement and minimize the input RF power.

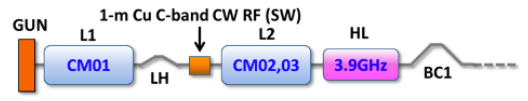

Figure 1: The intended location of the NC chirping cavity in LCLS-II.

Figure 2 presents the bunch length and core-part current of the LCLS-II nominal beam at different cavity voltages of a C-band chirping cavity. The longitudinal phase space of the beam at different cavity voltage are also shown for comparison. We see that within 1 MV cavity voltage, we can vary the rms bunch length from 80 fs to 10 fs and the core-part current from 500 A to 2700 A, which can cover the requirements for bunch length and peak current from soft X-ray to hard X-ray operation according to the previous experience in LCLS.

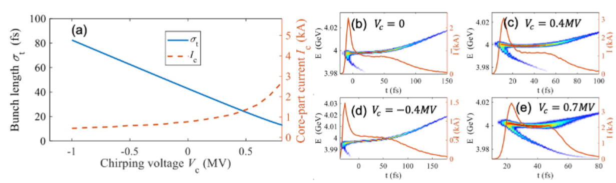

Figure 2: (a) Bunch length and core-part current at different cavity voltage of C-band cavity. (b)-(e) longitudinal phase space of electron beam at different cavity voltage.

SHOT-BY-SHOT CONTROL OF BEAM ENERGY

X-ray FELs driven by a superconducting radio-frequency (SRF) linac are capable of delivering MHz electron beams, which is high enough to support multiple undulator lines. At each undulator line, beam energy is one of the most important beam properties, determining the photon energy and lasing efficiency [6]. To further extend the photon energy range, schemes of independently control of the electron beam energy for multiple undulator lines are highly desired, which will greatly impact the design and operation of future SRF-based X-ray FEL facilities.

In NC FEL facilities, a scheme using sub-harmonic trigger in RF units [9] has been adopted to feed a couple of undulator lines. However, this method is not applicable to SRF cavities. To provide different beam energies for multiple undulator lines from an SRF linac, different schemes have been proposed. The first scheme is to extract electron beams from the SRF linac with a fast kicker and a bypass line, as shown in Fig. 3 (a). This scheme is adopted as the baseline design of the present SRF XFEL facilities [5, 10, 11]. The maximum available beam energy at the kicker position is limited by the capacity of its upstream SRF linac. Any adjustment of the bypass line energy would affect the final line energy. Besides, the beam extraction system for MHz GeV electron beams requires MHz-triggered sub-microsecond high-voltage kickers and strong septum magnets, which make it lengthy and costly to add the extraction bypass beamline to the SRF linac.

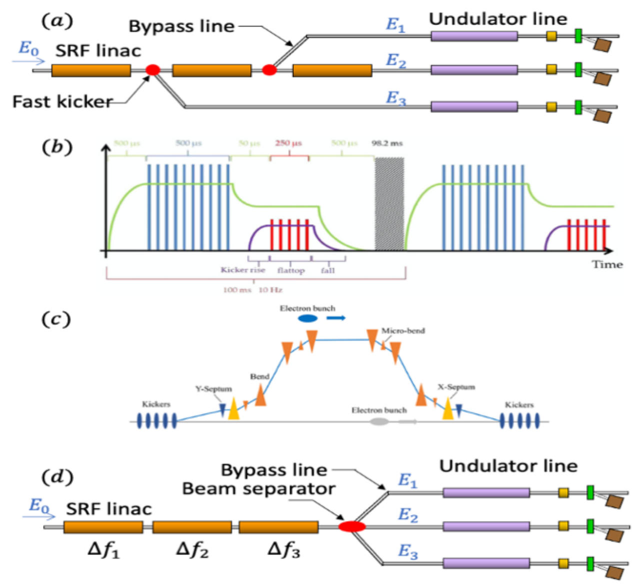

Figure 3: Four schemes to produce different energies for multiple undulator lines from an SRF linac.

The second scheme to produce multi-energy beams is modulating the long RF pulse in the SRF cavities, which is presented in Fig. 3 (b) [12]. The flat-top parts in the RF pulse are used to accelerate electron beams with different gradients. This scheme only works for SRF linac operated in burst mode and is not applicable to continuous-wave (CW) mode like the SRF linac in LCLS-II.

Figure 3 (c) shows the third scheme using achromatic and isochronous electron delay system and fast kickers [13]. The delay system is located upstream of the last section of the linac and the acceleration phases of the electron beams in the last section are controlled by the customized time delay to achieve different energies. The requirements for achromatic and isochronous make the delay system complicated and the adoption of fast kickers makes it lengthy.

The fourth scheme, as shown in Fig. 3 (d), is recently proposed for multiple-energy operation in an SRF linac based on an off-frequency detune method [14]. It is well known that the resonant frequency of an SRF cavity is very sensitive to small mechanical perturbations and a frequency tuner is adopted in design to maintain the frequency. For CW electron beams with fixed time spacing, purposely detuning the resonant frequency of SRF cavities can result in different acceleration phases. By combining a series of frequency detunes and optimizing the acceleration phases, we can produce periodic beam energies to support multiple undulator lines simultaneously. The main advantage of this method is the possibility to control the beam energy of each undulator line independently in a wide range, which can extend the parameter space of the FEL pulses and improve the facility performance. Moreover, the required frequency detune range of the SRF cavities is not larger than half of the beam

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repetition rate and does not depend on the number of energy patterns or undulator lines, which keeps the flexibility for future addition of new beamlines.

However, to achieve these advantages, we have to sacrifice some energy gain of the SRF linac. When the number of beam energies is larger than two, we need some additional (≲10%) energy gain of the SRF linac to achieve the same largest beam energy with the kicker/extraction method. There are also some technical and lifetime challenges about the cavity tuner to cover the required detune range.

SHOT-BY-SHOT BEAM SHAPING

Shaping of these beam properties as a function of time is highly desired to meet the various user demands for FEL properties, such as ultra-short, high-power, multi-color and so on. Many beam shaping techniques have been proposed to produce FEL pulses with some special characteristics. However, many of them are not applicable to high-repetition-rate beams due to beam loss or other limitations. Recently a new concept of laser heater shaping becomes attractive as the development of HRR FELs. A laser heater is a tool to add energy spread to a bunch. It works by placing an inverse-FEL in the middle of a chicane, such that dispersion destroys the microbunching structure and leaves behind only a symmetric energy spread [15]. Conventionally, the energy spread is typically applied along the bunch uniformly to suppress the collective instabilities that develop during acceleration and bunch compression. If instead the laser heater intensity profile is modulated as a function of time, then we will create a time-dependent energy spread which can be used to shape the beam current profile and X-ray pulse properties. Laser heater shaping is an attractive and promising alternative for HRR FELs. It is directly applicable to high-average-power beams and of great potential to achieve shot-by-shot shaping for multiple FEL lines.

Figure 4 shows three application examples of laser heater shaping. The first one is to control the temporal property of FEL pulses. As shown in Fig. 4 (A), by accurately manipulating the intensity profile of the IR laser over the duration of electron beam in the laser heater, the longitudinal emittance of the beam is modified selectively thus controlling the duration of the resulting X-ray pulse down to femtosecond time scale [16]. In Fig. 4 (B), a long-wavelength modulation on the IR laser intensity is introduced by chirped pulse beating technique and used to produce energy spread modulation on the electron beam. This pre-modulation of the electron beam prior to the undulator enables the generation of multicolor pulses in a seeded FEL [17]. Figure 4 (C) has been recently investigated with generation of electron bunch train through laser-beam interaction [18]. A laser pulse with periodic intensity envelope is used to modulate the slice energy spread of the electron beam, which can then be converted into density modulation after a dispersive section. Moreover, the laser heater shaping is recently considered to generate electron beams with desired properties for the production of ultra-short FELs [19] and stable, highly coherent, narrow-band X-ray pulses by the enhanced self-seeding scheme [20]. These applications reveal a great potential of the laser heater shaping, using a standard beamline element to create a highly flexible platform for beam shaping at MHz repetition rate.

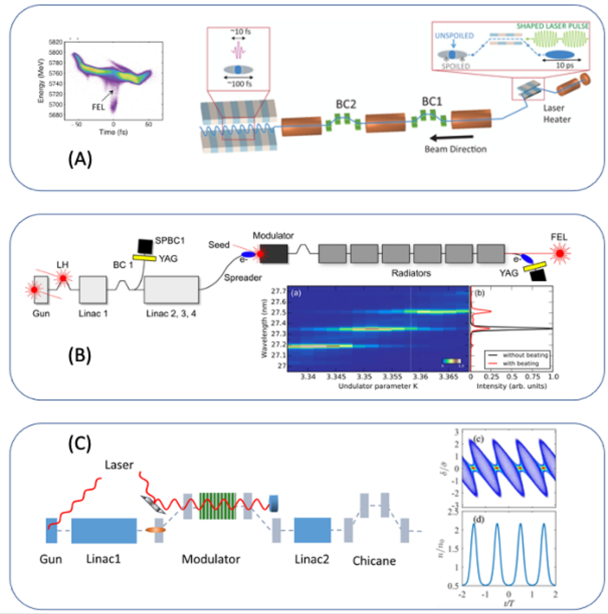

Figure 4: Three applications of laser heater shaping.

In addition to laser heater, it is also possible to achieve shot-by-shot beam shaping at the injector. The LCLS-II injector includes a normal-conducting continuous-wave (CW) RF gun operating at 186 MHz, a 1.3 GHz buncher and one superconducting accelerator section. Recently, a new method is proposed to produce high-power HRR THz pulses at LCLS-II [21] through only varying the laser pulse duration and the injection time. In Fig. 5, the bunching factor at 20 THz of the beam with different beam charge are presented for different laser pulse length and beam injection time in the gun [21]. Note that even for a fixed initial laser pulse length, the beam profile can be varied a lot by shifting the injection time. The fast switch of the laser properties can be achieved by the control of acoustic-optical/electro-optical modulator in the laser system. The final available range will be limited by the concern to preserve beam transverse emittance.

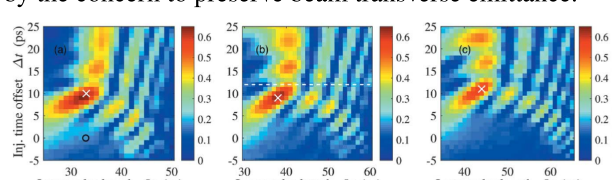

Figure 5: Beam compression for different laser pulse length and injection time offset [21].

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