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MULTI-ENERGY OPERATION ANALYSIS IN A SUPERCONDUCTING LINAC BASED ON OFF-FREQUENCY DETUNE METHOD*

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Abstract

The free-electron laser facilities driven by a superconducting radio-frequency (SRF) linac provide high-repetition-rate electron beam, which makes it feasible to feed multiple undulator lines at the same time. In this paper, we study a method of controlling the beam energy of multiple electron bunches by off-frequency detuning of the SRF linac. Based on the theoretical analysis, we present the optimal solutions of the method and the strategy to allocate linac energy for each possible off-frequency detune. The initial acceleration phases before detuning of the SRF linac can be optimized to reduce the necessary SRF linac energy overhead. We adopt the LCLS-II-HE configuration as an example to discuss possible schemes for two undulator lines.

INTRODUCTION

The successful operation of several hard x-ray free-electron laser (XFEL) facilities [1–4] over the world represents a revolution in the development of light source. Most of the present-day XFELs are driven by copper linac with a repetition rate around 100 Hz. This low repetition rate determines only a modest average brightness, similar to that of the third generation storage ring based sources. Another drawback of these facilities is that they typically only serve one user end-station at a given time.

XFELs driven by a superconducting radio-frequency (SRF) linac are capable to deliver Mega-Hertz (MHz) electron beams, which greatly enhances the photon average brightness and supports multiple beamlines in parallel and/or cascading configurations [5–8]. In this case, the photon energy from different beamlines can be varied by adjusting the undulator gap for a given electron beam energy. To further extend the photon energy range, schemes to control the electron beam energy of every undulator line independently are highly desired.

To provide different beam energies for multiple undulator lines from a SRF linac, different schemes can be applied. For example, one can extract electron beams with a fast kicker at the desired energy point and then send them to the undulator line through a bypass line, as shown in Fig. 1 (a). This scheme is adopted as the baseline design of the present SRF XFEL facilities [6–8]. In this scheme, we can make full use of the energy capability of the SRF linac. However, since the kicker positions are fixed, the beam energy for each undulator line is almost constant. Besides, adding the extraction regions to the SRF linac is lengthy and costly. Recently, another scheme using achromatic electron delay system is proposed to produce multi-energy beams for the SRF linac-driven XFELs [9].

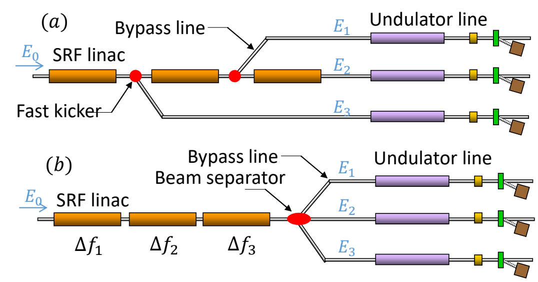

Figure 1: Two schemes of multi-energy operation of a SRF XFEL: (a) kick the beam to bypass line at desired energy point (b) control the beam energy independently by off-frequency detune of SRF cavities.

In this paper, we study a new scheme for multiple-energy operation of a SRF linac based on the off-frequency detune method [10,11]. The SRF cavities are very sensitive to small mechanical perturbations due to their narrow bandwidth. The resonant frequency can be varied by compressing the cavity. With enough detune range, we can produce periodic energy pattern in CW electron beams. The main advantage is the possibility to control the beam energy independently and extend the XFEL parameter space. In addition, we can adopt the dispersive energy separator, rather than the fast kicker/septum system, to separate beams to different undulator lines.

THEORETICAL ANALYSIS

For CW electron beams, we assume the beam repetition rate f_r and the time separation $T = 1/f_r$. At the nominal resonant frequency of the cavity f_c, all electron beams are accelerated at the same phase ψ_c, as shown in Fig. 2. When the frequency is detuned by Δf and the acceleration phase of the first beam is kept at ψ_c, the acceleration phase of the j-th electron beams is $\psi_c + (j-1)\Delta\phi$ with phase difference of two neighbouring beams (or we can call it as phase shift)

$$\Delta\phi = 2\pi T \Delta f\,. \qquad (1)$$

In order to reduce the off-frequency detune range, we limit the range of the phase shift to be $\Delta\phi \in [-\pi, \pi]$.

To support M undulator lines, the acceleration phase of the (M+1)-th beam has to be the same with the first one, which can be named as the periodic condition

$$\psi_c + M\Delta\phi = \psi_c + 2\pi k\,, \qquad (2)$$

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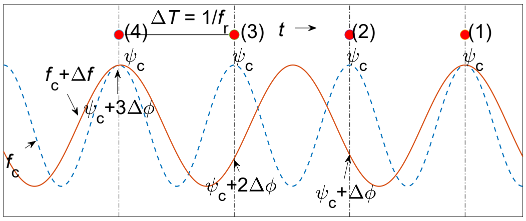

Figure 2: Acceleration phase changes of the CW electron beams by the off-frequency detune of the SRF cavities. Here we use $M = 3$ and acceleration phase of the fourth beam is the same with the first one.

where k is an integer. The possible phase shifts are

$$\Delta\phi_k = \frac{2\pi k}{M}, \tag{3}$$

where $k = 0, \pm 1, ..., \pm(K-1), \pm K$, $K = \lfloor M/2 \rfloor$ and the function $\lfloor x \rfloor$ returns the largest integer smaller than or equal to x. However, in a SRF cavity with acceleration voltage V_k, acceleration phase ψ_k and phase shift $\Delta\phi_k$, the energy gain of the j-th beam in sequence can be expressed as

$$\begin{aligned}\Delta E_j &= eV_k \cos(\psi_k + (j-1)\Delta\phi_k) \\ &= eV_k \cos(-\psi_k + (j-1)\Delta\phi_{-k}),\end{aligned} \tag{4}$$

with e denoting the electron charge. So the acceleration cavity can be replaced by the one with $-\psi_k$ and $\Delta\phi_{-k}$. In this way, we can further reduce the range of the phase shift to be $\Delta\phi \in [0, \pi]$, and the available k is

$$k = 0, 1, ..., (K-1), K. \tag{5}$$

The corresponding off-frequency detune can be expressed with the beam repetition rate $\Delta f = \frac{k}{M} f_r$. The full tunable range of the off-frequency detune is

$$\Delta f_{\max} = \begin{cases} \frac{1}{2} f_r\,, & M \text{ is an even number} \\ \frac{1}{2}(1 - \frac{1}{M}) f_r\,, & M \text{ is an odd number} \end{cases} \tag{6}$$

The off-frequency detune range for 3 undulator lines is $\frac{1}{3} f_r$, smaller than the cases of 2 and other numbers.

To support M undulator lines, the whole SRF linac is divided into S sections. The maximum total energy gain of the S linac sections, $E_G = \sum_{s=0}^{S-1} eV_s$, is usually larger than the maximum achievable beam energy. In this method, we need more SRF cavities to achieve the designed energy of the facility than usual. We adopt the linac energy overhead factor (η) to evaluate different energy allocation solutions, which can be defined as

$$\eta = \frac{E_G + E_0}{E_{\max}} - 1 \geq 0, \tag{7}$$

where $E_{\max}$ is the largest beam energy among all lines.

When $S > K + 1$, there are at least two sections having the same phase shift. Assuming the s-th and t-th sections have the same phase shift $\Delta\phi$, the energy gain of the j-th beam in sequence is

$$\begin{aligned}\Delta E_j =& eV_s \cos(\psi_s + (j-1)\Delta\phi) \\ &+ eV_t \cos(\psi_t + (j-1)\Delta\phi) \\ =& eV_{st} \cos(\psi_{st} + (j-1)\Delta\phi),\end{aligned} \tag{8}$$

with V_{st}, ψ_{st} being the maximum acceleration voltage and initial acceleration phase of the combined section. The acceleration voltage V_{st} can be solved as

$$\begin{aligned}V_{st} &= \sqrt{V_s^2 + V_t^2 + 2V_sV_t\cos(\psi_s - \psi_t)}, \\ &\leq V_s + V_t\,.\end{aligned} \tag{9}$$

The equality is achieved only when $\psi_s = \psi_t$. So the linac sections with the same phase shift can be combined into one section to obtain lower overhead factor, so we can let $S = K + 1$. In this case, the energy gain of the M lines $(E_1, E_2, ..., E_M)$ can be written as

$$\begin{cases} eV_0\cos(\psi_0) + eV_1\cos(\psi_1) + ... + eV_K\cos(\psi_K) = \Delta E_1\,, \\ ... \qquad ... \qquad ... \\ eV_0\cos(\psi_0) + eV_1\cos(\psi_1 + \frac{2\pi(j-1)}{M}) + ... + eV_K\cos(\psi_K + \frac{2\pi K(j-1)}{M}) = \Delta E_j\,, \\ ... \qquad ... \qquad ... \\ eV_0\cos(\psi_0) + eV_1\cos(\psi_1 + \frac{2\pi(M-1)}{M}) + ... + eV_K\cos(\psi_K + \frac{2\pi K(M-1)}{M}) = \Delta E_M\,. \end{cases} \tag{10}$$

Here $\Delta E_j = E_j - E_0$ means the energy change of the j-th beam. For $k = 0$, it can be solved by summing over all equations as

$$eV_0 = \frac{1}{M}\sum_{j=1}^{M} \Delta E_j\,. \tag{11}$$

Here we already let $\psi_0 = 0$ to reduce the energy overhead factor. The equation above can be rewritten as

$$E_0 + eV_0 = \frac{1}{M}\sum_{j=1}^{M} E_j\,, \tag{12}$$

which means that the average energy of all undulator lines determines the beam energy before the off-frequency detune. When $k > 0$ and $2k \neq M$, replacing $\cos(\theta)$ with

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$\frac{1}{2}\left(e^{i\theta}+e^{-i\theta}\right)$ and summing over all equations after multiplying a factor of $e^{\pm i(2\pi k(j-1)/M)}$, we can obtain

$$eV_k M e^{\pm i\psi_k} = 2\sum_{j=1}^{M} \Delta E_j e^{\mp i\frac{2\pi k(j-1)}{M}} . \tag{13}$$

The initial acceleration phase ψ_k can be expressed as

$$\psi_k = \text{arctan2}\Big(-\sum_{j=1}^{M}\Delta E_j \sin(\frac{2\pi k(j-1)}{M}), \sum_{j=1}^{M}\Delta E_j \cos(\frac{2\pi k(j-1)}{M})\Big) . \tag{14}$$

The energy gain of each section eV_k is

$$eV_k = \frac{2}{M}\Big(\big(\sum_{j=1}^{M}\Delta E_j \sin(\frac{2\pi k(j-1)}{M})\big)^2 + \big(\sum_{j=1}^{M}\Delta E_j \cos(\frac{2\pi k(j-1)}{M})\big)^2\Big)^{1/2} . \tag{15}$$

When $2k = M$, after multiplying $e^{i\pi(j-1)}$ to each equation we can get

$$eV_K \cos(\psi_K) = \frac{1}{M}\sum_{j=1}^{M}\Delta E_j e^{i\pi(j-1)} . \tag{16}$$

Similarly with the case of $k = 0$, we can let $\psi_K = 0$ or $\psi_K = \pi$ to reduce energy overhead. So the on-crest energy gain of the section with $f_r/2$ detune ($K = M/2$) is

$$eV_K = \frac{1}{M}\left|\sum_{j=1}^{M}\Delta E_j e^{i\pi(j-1)}\right| . \tag{17}$$

APPLICATION IN THE LCLS-II-HE

The LCLS-II-HE is a high energy upgrade of the LCLS-II, a superconducting CW XFEL facility at SLAC, which will increase the beam energy from 4 GeV to 8 GeV. It will provide ultrafast X-rays from the soft and hard undulator lines at repetition rate up to 1 MHz. The beam energy range is 3 ~ 4 GeV for soft X-ray undulator line and 3.3 ~ 8 GeV for hard X-ray line. The present baseline design of the LCLS-II-HE adopts the scheme which kicks the beam out of the SRF linac at ~4 GeV.

A compact frequency tuner has been designed for the LCLS-II project, including slow/coarse tuner and fast/fine tuner. The schematic and test performance of the tuner can be found in Refs. [12, 13]. Coarse frequency tuning is achieved with a motor-driven end-lever tuner. When the cavities are cooled to 2K and the frequency is set to 1.3 GHz, there is typically a +/-200 kHz range available over which the tuner can change the cavity frequency. With minor modifications to the tuner design, the low end of the tuning range could likely be extended to -500 kHz, which would allow two energy operation at about 1 MHz. However multi-beam operation can still be achieved with the current tuner design at lower beam repetition rates.

To support two undulator lines, the first method is the two-beam scheme. The whole linac is divided into two parts and the frequency detune of the second part is half of the beam rates. According to general solutions for $M = 2$, we can produce any set of beam energies without energy overhead in the last 4 GeV SRF linac. For 1 MHz beam, the frequency detune is 500 kHz.

Secondly, we can use the three-beam scheme as well. The first beam is sent to the HXR undulator line and the other two with the same energy are for the SXR. So the beam repetition rates in the two undulator lines are different. In this case, the energy overhead factor is zero for any two energies and the required frequency detune is one third of the total beam repetition rate, i.e. 333 kHz for 1 MHz beam.

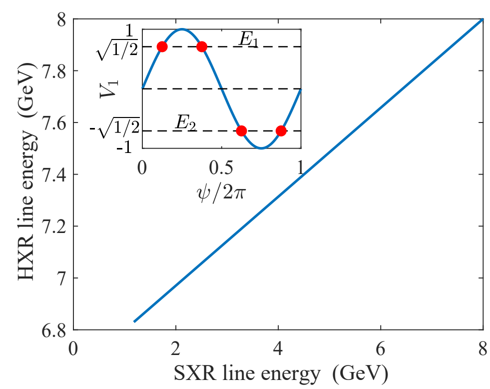

Figure 3: Available beam energies for SXR and HXR lines when using the special solution of four-line scheme.

The third method is to use a special solution of the four-beam scheme. In this scheme, the SRF linac needs to be divided into three sections with frequency detune of 0, $f_r/4$ and $f_r/2$. For a special set of beam energies, the energy gain of the third section can be zero and the maximum off-frequency detune is only $f_r/4$. With the acceleration phases of the four beams in the inserted figure of Fig. 3, we can produce two groups of energy. The final two energies can be varied by changing the fraction of detuned SRF linac. With the parameters of the LCLS-II-HE, the available energies are shown in Fig. 3. The two energies are correlated and the minimum SXR line energy (1.18 GeV) can be achieved when we detune the last 4 GeV linac. When the SXR line energy is 3~6 GeV, the corresponding HXR line energy is 7.14~7.65 GeV, which is smaller than 8 GeV. Despite of these limitations, the small off-frequency detune range (250 kHz for 1 MHz beam) makes it still very promising in practice.

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