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# Wakefield issue and its impact on X-ray photon pulse in the SXFEL test facility

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ABSTRACT

Besides the designed beam acceleration, the energy of electrons is changed by the longitudinal wakefields in a real free-electron laser (FEL) facility, which may degrade FEL performances from the theoretical expectation. In this paper, with the help of simulation codes, the wakefields induced beam energy loss in the sophisticated undulator section is calculated for Shanghai soft X-ray FEL, which is a two-stage seeded FEL test facility. While the 1st stage 44 nm FEL output is almost not affected by the wakefields, it is found that a beam energy loss about 0.8 MeV degrades the peak brightness of the 2nd stage 8.8 nm FEL by a factor of 1.6, which however can be compensated by a magnetic field fine tuning of each undulator segment. And the longitudinal coherence of the 8.8 nm FEL output illustrates a slight degradation, because of the beam energy curvatures induced by the wakefields.

## 1. Introduction

Free-electron laser (FEL) at X-ray wavelengths delivers intense pulses on ultra-short time scales, which is used to detect the dynamic processes, such as chemical-bond formation, charge transfer and light-induced superconductivity, or to characterize the macromolecular structure without damage [1,2]. Currently, several X-ray FEL facilities are under operation and/or construction around the world [3–7]. In pursuit of fully coherent FEL pulses at 8.8 nm wavelength, the baseline design of Shanghai soft X-ray FEL (SXFEL) test facility is two-stage seeded FEL scheme [8].

As well known, stringent beam energy control and fine undulator magnetic field set along the whole undulator system is required to maintain the FEL lasing and the FEL bandwidth. In a real FEL machine, the electron beam is not always on the targeted energy because of the drift and instability of the accelerating field and the beam energy loss due to the longitudinal wakefields [9]. In general, the beam energy deviations in the LINAC can be monitored and compensated by the beam energy feedback system before entering the undulator section. While it is the passive wakefields within the undulator section that degrade the FEL performance by pushing electrons off their resonance energies, especially within those sophisticated vacuum chambers and pipes for a multi-stage seeded FELs. Therefore in this paper, on the basis of technical design aspects of SXFEL, the wakefields caused beam energy loss, thus its impact on X-ray FEL pulse generation, and the coping strategy are presented. A distributed wakefields arisen from resistive wall [10–12], surface roughness [13–19] and discontinuities of beam pipes [20–23] are considered. It is shown that, the peak brightness of the final 8.8 nm FEL will degrade by a factor of 1.6 with a gradual beam energy drop off about 0.8 MeV in the whole undulator section. It can be compensated by a fine tuning of the radiator undulators. Meanwhile, the wakefields induced beam energy curvatures shows slight dilution to the longitudinal coherence of the final 8.8 nm FEL.

This paper is organized as follows. In the introduction, the Shanghai soft X-ray FEL test facility is briefly described. In the following section, numerical calculations of the resistive wall, surface roughness and geometrics wakefields are given. Furthermore, the beam energy loss impact on FEL performance and the coping strategy are illustrated. Finally, we summarize the results of the paper.

## 2. Introduction of SXFEL

The SXFEL is based on the frequency up-conversion scheme of an initial coherent seed pulse in an FEL amplifier employing multiple undulators, namely high-gain harmonic generation (HGHG) [24–26]. The initial signal is provided by a conventional pulsed laser operating at 264 nm wavelength. The energy of the electron beam is modulated via the resonant interaction with the 264 nm seed laser in the so-called “modulator”, then a chromatic dispersive chicane is used to develop density bunching with

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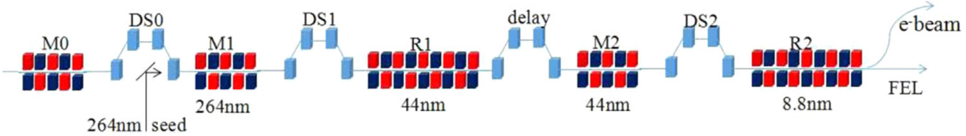

**Fig. 1.** Schematic layout of SXFEL test facility.

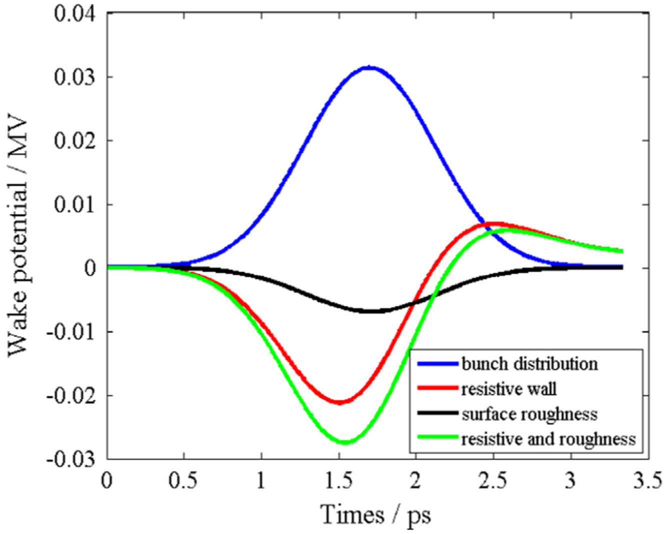

**Fig. 2.** Wake potential of a 3.34 m long vacuum chamber that has resistive wall (red), roughness (black), and both resistive wall and roughness (green). The resistive wall calculation includes AC conductivity of aluminum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

harmonic components, finally coherent FEL radiation at the 44 nm wavelength, i.e., the 6th harmonic of the seed laser is produced by the micro-bunched beam in the downstream “radiator”. In order to achieve the designed wavelength, a second stage HGHG from 44 nm to 8.8 nm is used in SXFEL. As illustrated in Fig. 1, an extra pair of modulator M0 and dispersive chicane DS0 are reserved before the first stage HGHG to enable the echo-enhanced harmonic generation (EEHG) scheme [27,28], which is expected to overcome the limited frequency up-conversion efficiency of HGHG.

The SXFEL photo-injector is based on the 1.6-cell electron gun developed at BNL/SLAC/UCLA. Following standard layout, the design includes a solenoid for emittance compensation and acceleration to 130 MeV with two S-band sections [29]. The electrons are then sent into the laser heater system where a 795 nm Ti-sapphire laser with the pulse length of 10 ps, to suppress the micro-bunching instability and control the deviation and the distribution shape of sliced beam energy. The main LINAC accelerates the electron beam to 840 MeV and compresses the beam to its final duration and peak current. At the exit of LINAC, depending on the FEL lasing requirements, a bunch length of 1 ps (FWHM) and a peak current of 500 A or higher can be delivered with a 500 pC bunch charge, and the normalized emittance should not exceed 1.0 μm-rad to satisfy the desired photon throughput. These specifications are numerically predicted by the beam dynamic simulations, including a safety margin against collective instability effects. Meanwhile, the LINAC magnetic focusing system is designed to minimize the emittance dilution due to transverse wakefields, momentum dispersion and coherent synchrotron radiation in bending magnets.

## 3. Wake potential calculations

It is worth stressing that the linear accelerator section consists of relative simple and large aperture structures when compared with the sophisticated undulator sections in a seeded FEL facility, and the peak current of the electron beam is low when passing through the impendence items before the final bunch compressor. Therefore, the beam energy loss due to wakefields is small in the linear accelerator, and more importantly it can be compensated by tuning the amplitude and the phase of the RF cavities. Therefore in this paper, we concentrate on the wakefields of the undulator section of SXFEL.

### *3.1. The resistive wall and surface roughness*

The resistive wall and surface roughness are usually considered for the vacuum chambers of the undulators. All the undulators of SXFEL have been chosen to be out vacuum planar undulators, which are hybrid permanent magnets type. The wavelength can be tuned by changing the undulator gap at constant beam energy. For example, the magnetic length of the individual segment is 3.0 m (containing 75 periods) for the stage-1 radiators and 3.0 m (128 periods) for the stage-2 radiators, respectively. And a 3.34 m long aluminum vacuum chamber with an elliptical cross section of $6 \times 15$ mm aperture will be used for all the radiator undulators, while the stage-1 and stage-2 radiators consist of 3 and 6 undulator segments.

With a round pipe approximation of 3 mm radius, the calculation of the short range wakefields of a resistance chamber can be accomplished by the formulas from Ref. [12,17]. The surface measurements of the vacuum chamber sample by using atomic force microscope [16], similar to that used in SXFEL, agrees well with the small-angle approximation theory [17,18]. Thus, the roughness model used consists of small amplitude of 100 nm, shallow sinusoidal corrugations.

In Fig. 2, the wake potentials for one segment of the undulator vacuum chamber are presented. It is found that the total wakefield is dominated by the resistive wall effect. Using the results shown in Fig. 2, the beam energy loss within a 3.34 m long undulator chamber can be obtained. For a Gaussian bunch distribution with FWHM pulse duration of 1 ps. Here, the mean beam energy loss due to the resistive wall and roughness are approximately 11.3 keV and 4.9 keV, respectively.

### *3.2. Geometrics wakefield*

In a multi-stage seeded FEL facility, on one hand, the delay chicane and various beam diagnostic devices are placed between different stages. On the other hand, cavity beam position monitors, profiles, quadrupoles, correctors and phase-shifters are installed between the undulator segments to monitor and correct the electron's behaviors. Thus, from the point view of wakefields, within the undulator section, the beam pipes need to be interrupted and connected by flanges, bellows and so on.

Besides the resistance and roughness wakefields mentioned above, here the wakefields generated in these geometrics are also calculated for SXFEL. The Napoly indirect method is employed by the wakefield code ABCI [30] for 2D calculations. For short bunches, ABCI employs a moving mesh that encloses the longitudinal and transverse direction. As a typical example, the insert component module between two adjacent undulator segments (see Fig. 3) is illustrated here, which consists of flanges, bellows, profile