Nuclear Inst. and Methods in Physics Research, A 884 (2018) 11–17

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Bandwidth broadening of X-ray free electron laser pulses with the natural gradient of planar undulator

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ARTICLE INFO

Keywords:
Large bandwidth
Deflecting cavity
Corrugated structure
Natural gradient

ABSTRACT

Besides the target to pursue the narrow bandwidth X-ray pulses, the large bandwidth free-electron laser pulses are also strongly demanded to satisfy a wide range of scientific user experiments. In this paper, using the transversely tilt beam enabled by deflecting cavity and/or corrugated structure, the potential of large bandwidth X-ray free-electron lasers generation with the natural gradient of the planar undulator are discussed. Theoretical predictions and numerical simulations demonstrated that X-ray bandwidth exceeding 5% can be observed with the optimized free-electron laser parameters.

1. Introduction

X-ray free-electron laser (FEL) facility as the primary candidate for fourth-generation light source holds the promise to provide extremely bright X-ray photons with femtosecond pulse duration. The leading-edge instruments offer several capabilities in a wide range of scientific applications in chemistry, biology, material science and physics [1,2]. Currently, the operated or constructed FEL facilities around the world are generally based on the self-amplified spontaneous emission (SASE) [3–7] and seeded [8–10] FEL schemes. SASE FELs produce coherent radiation with final bandwidth between 10^{-3} and 10^{-4} [7], while the seeded FELs even further reduce the bandwidth to the Fourier transform limit [11–13].

However, besides aiming at minimizing the bandwidth of the produced radiation, large bandwidth FEL pulse is also of great interest. With the help of the ultra-brightness of X-ray FEL and generation of broad bandwidth, it shows promise for revealing essence of molecular structures and solving remained problems, which will facilitate the progress in a variety of research fields, for example, studying microcrystalline materials [14,15], analysing single-cell [16], determining multi-wavelength anomalous diffraction phase information [17]. Moreover, compared with narrow bandwidth operation, large bandwidth FEL allows for wavelength tuning in a more flexible way. More recently, large bandwidth FEL schemes were newly proposed [18,19], which mainly relies on the electron beam energy chirp formed in linear accelerators and/or the magnetic field gradient customized in the undulator.

The generation of FEL relies on the relativistic electron beam which moves along a periodic array of dipole magnets and wiggles transversely to emit electromagnetic radiation [6,20,21]. According to FEL resonant condition, both time–energy correlation in the electron bunch and space-field correlations in the undulator can broaden the FEL bandwidth. Generally, the simplest and natural way to obtain large bandwidth FEL is using an energy chirped electron beam [22]. However, large energy chirp will be hindered and challenged for the X-ray FEL. Apart from it, there are many other approaches to produce the energy chirp, for instance, utilizing the space charge effects of an extremely compressed beam [23], modifying the longitudinal laser profile of photo injector [24] and using the over-compressed beam combined with wakefields from the rf structures or corrugated structures [19,25–27]. Alternatively, the application of transverse gradient undulator may contribute a full bandwidth of 10% in soft X-ray of 1 nm wavelength [18,28]. Motivated by these early works, in this paper, utilizing currently existed instruments and mature accelerator technologies, X-ray FEL bandwidth broadening enabled by the natural gradient (vertical gradient usually) in a planar undulator is studied. It is demonstrated that a full bandwidth from 2% to 5% could be obtained in hard X-ray region of 0.1 nm. Moreover, if the required X-ray pulse energy is not very high in some user experiments, i.e., FEL saturation is not mandatory, full bandwidth over 10% can be achieved in simulation.

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https://doi.org/10.1016/j.nima.2017.12.005
Received 16 September 2017; Received in revised form 15 November 2017; Accepted 4 December 2017

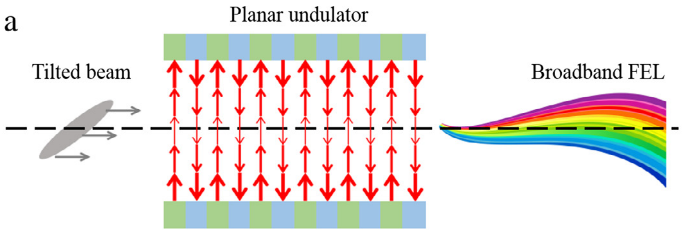

Fig. 1. The schematic layout of the proposed scheme: (a) the tilted beam travelling through the planar undulator with natural gradient to produce broad bandwidth FEL pulse and (b) displays the vertical magnetic field of undulator cross section. The thickness of arrows represents the magnetic field strength.

2. Principle of scheme

In this paper, in addition to the techniques mentioned above, a simple scheme which consists of transverse–longitudinal coupling section and planar undulator section is proposed. As illustrated in Fig. 1, a de-chirper device [29–35] or transverse deflecting structure (TDS) [36,37] is installed before the undulator to introduce a vertical tilt to the electron beam. It is expected that such a beam passes through a planar undulator and produces FEL radiation with large bandwidth. The initial electron beam has the following properties depending on the FEL lasing requirements, 6 GeV beam energy and 3 kA peak current can be delivered with 200 pC bunch charge, with sliced emittance less than 0.3 μm-rad to satisfy the desired photon output. In this scheme, it is convenient to change the gap of de-chirper or deflecting voltage of TDS, thus the beam will experience different transverse kick and can be characterized with various tilt amplitudes, then, one can simply tune the FEL bandwidth. In principle, the longitudinal wakefield of the corrugated structure could be used to further increase the beam energy chirp, and thus the FEL bandwidth.

2.1. Generation of beam transverse tilt

As aforementioned, an electron beam with a transverse tilt travelling through a planar undulator produces broad bandwidth X-ray FEL pulse. The beam transverse tilt can be generated with several methods. For example, applying a RF deflector to kick beam or introducing the transverse wakefields of accelerating structures or corrugated structures in the FEL facility.

The RF deflecting cavities have been widely used in the beam diagnostics of FEL and many other accelerators [36,38–43]. In the deflecting cavity, the deflecting voltage is zero for the longitudinal centre of the bunch and provides a linear transverse deflection to the rest of the bunch. The transverse displacement of the bunch slice is proportion to the deflecting voltage, thus, the beam transverse tilt can be easily tuned through the deflecting voltage of the TDS structures. For example, if a total power of 40 MW was fed to a pair of X-band deflecting structures, a wide range of transverse tilt could be achieved. Here a typical Gaussian electron bunch is used to explain. Fig. 2 represents the t–y phase space of the electron beam with 0.5 mm vertical tilt amplitude. It can be achieved by a 40 MV deflecting voltage together with a 14 m drift, which has been verified by the ELEGANT [44] simulation.

A corrugated structure is usually a pipe or a pair of parallel plates with small bumps on the wall in a form of periodic ridges [29–35]. When interacting with the longitudinal wakefields, the corrugated structures are mainly responsible for beam energy chirp. While if the electron beam enters the structure with an offset from the axis, travelling close to one jaw of the structure, it excites the transverse dipole wakefields, where the bunch head receive no kick while the bunch tail will be transversely kicked. On the basis of the wakefield theory [31,33,35], it is interesting note that the bunch tail would experience a larger transverse kick with further distance away from axis, in addition, the transverse tilt amplitude could be also simply tuned by varying the gap of the structure.

Recently, on the basis of transverse beam tilt generated by the de-chirper at LCLS, a set of multi-colour X-ray FEL experiments was successfully accomplished [45]. For the large bandwidth FEL application, the corrugated structure has a small gap of millimetre order. In the broad bandwidth X-ray FEL case here, if a beam vertical tilt of 0.5 mm is required, roughly it can be achieved when the electron beam passes through a 2.5 m long LCLS similar corrugated structure with a vertical offset of 0.64 mm.

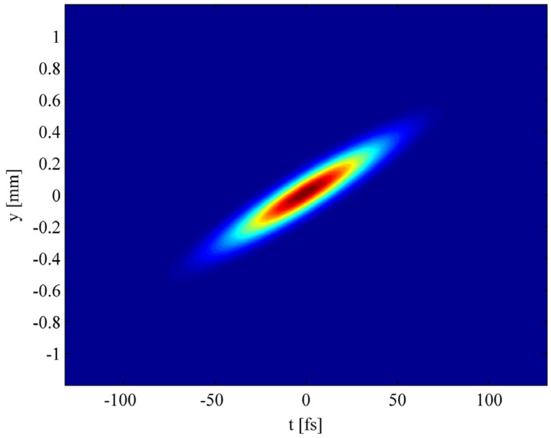

Fig. 2. The simulated electron beam after the deflecting and drifting, the plot is the bunch phase space with vertical tilt amplitude of 0.5 mm. The bunch head is in the left.

2.2. Natural gradient of a planar undulator

Considering a planar undulator in which the amplitude of the magnetic field in the vertical direction:

$$B(y) = B_0\left(1+\frac{1}{2}k^2y^2\right). \tag{1}$$

Here $k = 2\pi/\lambda_u$, λ_u is the undulator period and B_0 is the peak magnetic field in the mid-plane. When a relativistic electron beam entering into the undulator, it will wiggle periodically in the horizontal x direction and emit radiation with the resonant wavelength [21]. If one neglects the high order term k^4y^4, one can derive that:

$$\lambda(y) = \lambda_0 + \frac{\lambda_u}{2\gamma_0^2}\cdot\frac{K_0^2}{2}\cdot k^2y^2. \tag{2}$$

Here K_0 is the dimensionless undulator parameter in the mid-plane and γ_0 is the electron energy in units of the electron rest energy. The FEL wavelength deviation in terms of the resonant wavelength λ_0 can be concluded:

$$\frac{\lambda(y)-\lambda_0}{\lambda_0} = \frac{{K_0}^2}{2+{K_0}^2}k^2y^2. \tag{3}$$

2.3. Weak focusing lattice

The electron beam size in the undulator has a great influence on FEL lasing. On the one hand, large beta function will enlarge the electron beam transverse cross section, which leads to the reduction of the