REVIEW OF ELECTRON BEAM MANIPULATION BY USING CORRUGATED DEVICE FOR LIGHT SOURCES*

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Abstract

In modern high-gain free-electron laser scheme, the longitudinal phase space of the electron beam is very important for efficient lasing. The linear energy chirp and the nonlinear radiofrequency curvature should be corrected before the entrance of the undulator. Corrugated devices are passive wakefield devices for such electron beam manipulations, which are recently proposed and partially demonstrated in experiment. In this paper, a brief review of corrugated device study is presented, including the theories, machine cases and experimental results.

INTRODUCTION & THEORIES

In modern high-brightness LINAC based free-electron lasers (FELs), undesired time-energy correlation in the beam (i.e., linear energy chirp & nonlinear curvature) is left in the beam because of bunch compression and beam acceleration, which may broaden the FEL bandwidth and decrease the FEL gain. Thus, the residual time-energy correlation should be corrected before entering the FEL undulator. Generally, off-crest acceleration and wakefield in the following LINAC modules are used for the beam energy de-chirper, while the harmonic cavity is used for nonlinear RF curvature compensation. However, such RF related solutions are costly and inefficient in the advanced light sources.

Using the strong longitudinal wakefields excited by the electron beam itself in dedicated structures inserted into the LINAC is an alternative RF-free approach to correct the undesired energy correlation. The structures suggested for such purposes include a beam pipe with a thin dielectric layer [1], a resistive pipe of small radius [2] and a metallic beam pipe with periodic corrugations [3]. Among of them, the corrugated metallic structure attracts great interest of light source community, because both the frequency and the amplitude of its wake could be easily adjusted by choosing the corrugated structure parameters.

The original design and calculation of the corrugated structure is based on a round pipe [3]. In practical case, a rectangular geometry is preferred, as it provides operation flexibility and is effective for different electron bunch cases. As illustrated in Fig. 1, a pair of corrugated planes wrapped in the vacuum chamber is inserted to specific position of FEL schemes. The chamber support usually includes two separated motors to allow independent transverse positioning for each corrugated jaw, providing remote control of the full transverse separation, as well as the transverse central position.

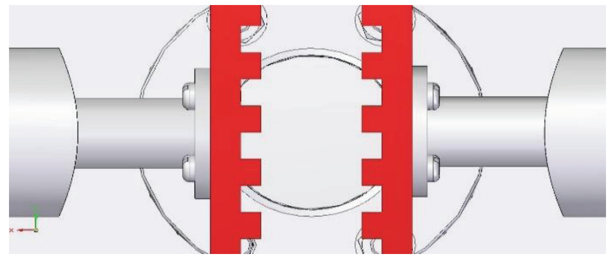

Figure 1: Layout of corrugated structures used in free-electron laser schemes.

The corrugations are characterized by period *p*, depth *δ*, gap *g* and plane separation *2a*. For a rectangle geometry, the longitudinal wake function of the fundamental mode is approximately written as, [4-5]

$$W(s) = \left(\frac{\pi^2}{16}\right)\frac{Z_0 c}{\pi a^2} H(s)\cos(ks), \quad (1)$$

where *H*(*s*) is a unit step function and *k* is the wave number of the fundamental mode given by

$$k = \sqrt{\frac{p}{g\delta a}}. \quad (2)$$

Then the wake potential is given by the convolution

$$W_\rho(s) = \int W(s')\rho(s-s')ds', \quad (3)$$

where $\rho(s)$ is the charge density of the electron bunch.

MACHINE CASE STUDIES

It is indicated that, corrugated structures can be used to remove the linear energy chirp [3], to linearize the high-order RF energy curvatures [6-7], to stabilize the beam energy jitter [8] and to emit high power terahertz wave [9], provided that the electron bunch length and the structure parameters are well matched. And recently, a set of test experiments that use the passive wakefield devices to control the electron beam space has been successfully demonstrated. It is believed that corrugated devices may greatly improve FEL performances, and almost every new FEL facility is considering the corrugated structures to control the longitudinal phase space of the electron beam.

NGLS

The corrugated structure is initially designed as a beam de-chirper for the Berkeley's next generation light source (NGLS), which is now evolve to LCLS-II. In original design of NGLS, the beam is accelerated to 1.8GeV after

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the bunch compressor in a superconducting LINAC. To cancel the energy chirp with radiofrequency alone, the beam is needed to be run at 25 degree behind RF crest, resulting in 10% loss in efficiency of acceleration & cryo-module. It is found that, a linear chirp of -40MeV/mm can be induced into the NGLS beam, by passing through a corrugated, metallic pipe of 3mm radius, 8.2m length, and corrugation parameters full depth 0.45mm and period of 1mm. It is 15 times as effective in the role of de-chirper as an S-band accelerator structure used passively [3].

Swiss-FEL

In the soft X-rays (wavelengths from 7 to 70 Angstrom) undulator line Athos of the Swiss-FEL [10], the bunch will be compressed up to a factor 150 by two compression stages. This process leaves an energy chirp, which has to be removed before the lasing process in the undulator lines. For Athos, midway in the LINAC, the wakefield generated by the C-band structures are not sufficient to cancel it. A possible solution is to use the longitudinal wakefields generated by a corrugated surface. A special tracking to optimize the layout for a feasible experiment in Swiss-FEL injector test facility was performed [11]. It shows that in an optimal setup corresponding to the 5ps driven laser and a compression factor of 3, the corrugated structure allows compensating 2% energy chirp at almost 100MeV.

SDUV-FEL

The output pulse properties in seeded FEL schemes, especially the bandwidth and the central wavelength, are sensitive on the beam time-energy correlation [12-15]. Thus, particular attentions are devoted to preserve the temporal uniformity of the beam current and energy, e.g., a high-harmonic (x-band) cavity is installed before the magnetic chicane to linearize the longitudinal phase space of the electron beam and thus reduce the FEL bandwidth. However, as a test facility, there is no harmonic cavity in SDUV-FEL [16-20], because of its numerous efforts and costs. Considering the urgent requirement for the beam linearization and the available free space at SDUV-FEL, a 0.3m long corrugated structure as a beam linearizer was studied. With parameters p=0.6mm, δ=2.0mm, g=0.3mm, and a=1.0mm, the corrugated structure induced energy loss along the electron bunch is a sinusoidal form with a wavelength of about two times as the bunch length, which could be used as a linearizer for the temporal phase space manipulation.

DCLS

Dalian coherent light source (DCLS) is the first high-gain FEL user facility in China [21], in which the output pulse stability at the ultraviolet spectral region is mainly determined by shot-to-shot beam energy jitter of LINAC. Recently, a beam stabilizer on the basis of corrugated de-chirper is studied for the 300MeV LINAC of DCLS. In the study [9], a 1.5m long corrugated structure is added after the main LINAC, which allows an on-crest beam acceleration after the bunch compressor. Analytical and numerical calculations show that a 30% improvement of the beam energy stability can be achieved.

SXFEL

Shanghai soft x-ray free-electron laser (SXFEL) aims to generate an 8.8nm FEL from a 264nm conventional seed laser through a two-stage HGHG [22]. The electron beam energy is 840MeV, with a slice energy spread of about 100keV and beam peak current over 500A. For a two-stage seeded FEL, a flat-top current distribution in a large temporal range is very important, thus a corrugated structure used for beam temporal profile optimization was recently carried out. Figure 2 presented the preliminary result of the operation of a 0.5m corrugated structure in SXFEL. It is planed that a genetic algorithm will be used to further improve the optimization results in future.

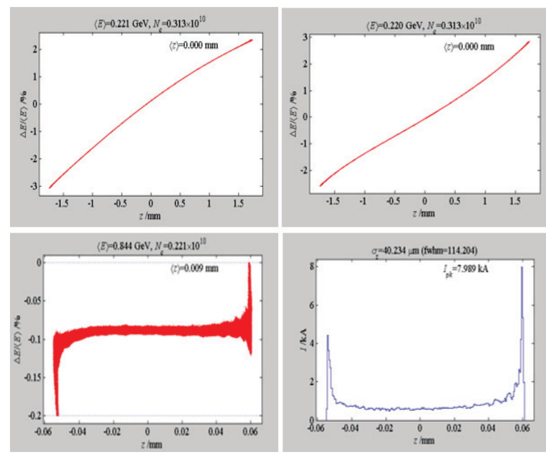

Figure 2: Simulation results of corrugated structure. used in SXFEL. Top row: the longitudinal phase space of the electron beam before and after the corrugated device. Bottom row: the longitudinal phase space and the current distribution at the exit of LINAC.

Besides the cases mentioned above, corrugated devices are also being considered for PAL-XFEL [23], LCLS and LCLS-II [24-25].

EXPERIMENTAL DEMONSTRATIONS

Because of its advantages of corrugated devices in next generation FELs, several experiments was immediately proposed & launched. In this section, we briefly describe the results of three leading groups.

PAL-ITF

The first experimental study of a corrugated-wall de-chirper, in particular, one with a rectangular cross section and adjustable jaws was conducted at the PAL-ITF, an LINAC facility designed to test and develop the injector technology for PAL-XFEL [23]. A rectangular geometry was used, since it provides operational flexibility and can be effective for variable bunch charge and length. The time-resolved measurements at PAL-ITF confirmed both the linearity and the scale of the wake-induced chirp of the corrugated device, as predicted by the wakefield

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model. Reasonable agreement between measurement and model in both the longitudinal and transverse planes is obtained if one regard the bunch charge as a fitting parameter and choose Q=150pC, which is a value 25% smaller than the measured but uncertain value of 200pC.

BNL-ATF

RadiaBeam Systems has designed and manufactured a compact, low-cost corrugated plate with an adjustable gap for beam de-chirper. Its de-chirping characteristics were measured at the Accelerator Test Facility (ATF) of Brookhaven National Laboratory (BNL). An 18cm long pair of aluminium plates with 1mm corrugations removed about 50% of 0.4MeV/mm chirp from 58MeV beam with 3.4ps bunch length [26-27], which shows a consistent result with the ELEGANT simulation. And a full-scale test with 2m long sections is currently planned at LCLS for 2015 [25].

SDUV-FEL

More recently, a corrugated structure experiment was proposed at the SDUV-FEL. While the abovementioned experiments were tested on LINAC, SDUV-FEL provides a possibility of the first operation of a metallic corrugated structure in an existing FEL facility. As shown in Fig. 3, a typical high-gain harmonic-generation scheme [28] is utilized in SDUV-FEL experiment, where FEL bandwidth narrowing and the FEL central wavelength shifting at high harmonics of the seed laser are expected to obtain.

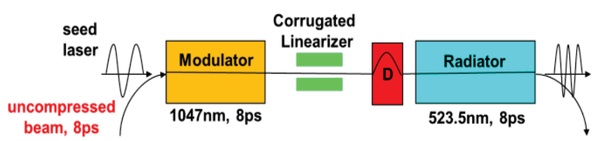

Figure 3: The corrugated experiment setup proposed at SDUV-FEL.

CONCLUSION

In this paper, we briefly review the status of corrugated strictures used in modern high-gain free-electron lasers. To date, the theoretical possibility of a passive corrugated de-chirper is widely investigated for different machines. Meanwhile, the beam experiments of the de-chirpers were successfully carried out on LINACs at PAL & BNL, and the first operation of a corrugated structure in a real FEL facility was proposed and under way at SDUV-FEL.

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