

Simulation studies on laser pulse stability for Dalian coherent light source^{*}

DENG Hai-Xiao(邓海啸)¹⁾ ZHANG Meng(张猛)²⁾ GU Duan(谷端) LIU Bo(刘波)
GU Qiang(顾强) WANG Dong(王东)

Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

Abstract: Dalian Coherent Light Source will use a 300 MeV LINAC to produce fully coherent photon pulses in the wavelength range between 150–50 nm by high gain harmonic generation free electron laser (FEL) scheme. To generate stable FEL pulses, a stringent tolerance budget is required for the LINAC output parameters, such as the mean beam energy stability, electron bunch arrival time jitter, peak current variation and the transverse beam position offset. In order to provide guidance for the design of the Dalian Coherent Light Source, in this paper, the sensitivity of FEL pulse energy fluctuation to various error sources of the electron bunch was performed using intensive start-to-end FEL simulations.

Key words: free electron laser, beam energy jitter, pulse energy fluctuation, stability

PACS: 41.60.Cr **DOI:** 10.1088/1674-1137/38/2/028101

1 Introduction

Free electron lasers (FEL) hold great promise as a high power photon source with a tunable wavelength. In order to satisfy the dramatically growing demands within material, biological and chemical sciences, many FEL user facilities have been constructed and are being proposed worldwide, from the extreme ultraviolet (EUV) to hard x -ray spectral region [1–5]. Currently, the FEL community is on the way to more sophisticated schemes, e.g., in pursuit of compact size [6–9], flexible polarization [10–15] and full coherence [16–22]. The Dalian Coherent Light Source (DCLS) is a FEL user facility based on the principle of single-pass, high-gain harmonic generation [16], which is located in the northeast of China. With the state-of-the-art techniques of the optical parametric amplification (OPA) seed laser and the flexible gap undulator, DCLS is dedicated at the EUV spectral regime of 150–50 nm with the pulse energy exceeding 100 μ J.

At present, it is believed that the scientific application for DCLS will firstly focus on the Physical Chemistry with time-resolved pump-probe experiments and EUV absorption spectroscopy techniques. The time domain experiments are mainly related to the FEL pulse duration, e.g., less than 100 fs, which can be easily achieved by utilizing an ultra-short seed pulse for DCLS.

However, another important and inevitable topic associated with both the time and spectral domain experiments for DCLS is FEL laser pulse stability, i.e., shot-to-shot fluctuation, which will be strongly sensitive to numerous error sources of the electron beam and the see laser time jitter. According to the FEL physical design and corresponding tolerance budgets illustrated in Section 2, this paper numerically investigates on the laser pulse stability for DCLS. Section 3 mainly concentrates on the jitter results of the LINAC output parameters, which will serve as the input conditions for the start-to-end FEL simulations in Section 4. This paper concludes with the final remarks in Section 5.

2 FEL design and tolerance budgets

DCLS is the first high gain FEL user facility in China. The layout of DCLS (seen in Fig. 1) includes a seed laser system, injector system, linear accelerator and undulator system. The injector and LINAC provide electron beams with an energy of 300 MeV, a bunch charge up to 500 pC, a peak current up to 300 A and a normalized transverse emittance better than 1 μ m-rad. The undulator system consists of one segment of modulator and four segments of radiator, where the period length is 50 mm and 30 mm, respectively. The Ti-Sa laser sys-

Received 19 April 2013, Revised 19 June 2013

^{*} Supported by National Natural Science Foundation of China (21127902, 11175240, 11205234, 11322550) and Knowledge Innovation Program of Chinese Academy of Sciences

1) E-mail: denghaixiao@sinap.ac.cn

2) E-mail: zhangmeng@sinap.ac.cn

©2014 Chinese Physical Society and the Institute of High Energy Physics of the Chinese Academy of Sciences and the Institute of Modern Physics of the Chinese Academy of Sciences and IOP Publishing Ltd

tem can feed the seed pulse with an energy of $100\ \mu\text{J}$, a wavelength range of $250\text{--}400\ \text{nm}$ by the OPA technique and the pulse duration can be switched between $1\ \text{ps}$ and $130\ \text{fs}$, thus to generate the FEL pulse with different temporal properties.

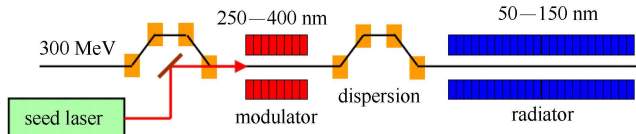


Fig. 1. Layout of Dalian coherent light source.

DCLS generates FEL pulses with continuously tunable frequency, which is truly useful to the specific FEL users. In order to maximize the FEL pulse energy, with a fixed conversion efficiency from electron to light, the electron beam power should be as large as possible for the interested wavelength. Thus, for different radiation wavelengths for DCLS, one should tune the wavelength of the OPA seed laser and the undulator gaps simultaneously to satisfy the FEL resonance while keeping the electron beam energy at maximum $300\ \text{MeV}$. Fig. 2 shows the peak power of the radiation pulse at different wavelength for DCLS, in which the well-known empirical analytical formulas [23] and the well benchmarked FEL code, GENESIS [24] is used. The results show that, under the conditions of the bunch charge of $500\ \text{pC}$, seed laser pulse of $1\ \text{ps}$ (FWHM) and beam energy of $300\ \text{MeV}$, the output pulse energy should be the $100\ \mu\text{J}$ level and the photon number per pulse can be up to 10^{13} order. It is worth stressing that DCLS performances are optimized at a spectral region larger than $100\ \text{nm}$, since the users are especially interested in the efficiency excitation of

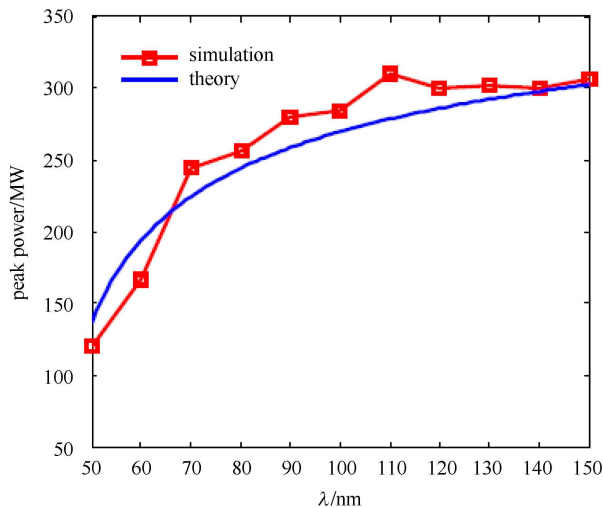


Fig. 2. Analytical and numerical results of DCLS output peak power at different radiation wavelength.

hydrogen atom and methyl radical [25]. Moreover, the undulator tapering technique could further augment the DCLS output by a factor of two with no difficulty.

To estimate the sensitivity of DCLS output, extensive time-dependent GENESIS simulations were performed in which various electron beam quantities and the seed laser timing were varied independently around their ideal values. As the tolerance budgets summarized in Table 1, the beam energy, bunch charge, normalized emittance, peak current and slice beam energy spread requirements are from the specification of $100\ \mu\text{J}$ output pulse energy at $50\ \text{nm}$, i.e., the wavelength with the largest sensitivity.

Table 1. Main tolerance budgets of DCLS.

parameter	specification
RMS peak current jitter	<10%
RMS normalized emittance/ $(\mu\text{m}\cdot\text{rad})$	<1
RMS slice energy spread/keV	<20
RMS beam position jitter/ μm	<10
RMS beam energy jitter	<0.1%
RMS beam arrival time jitter/fs	<150
RMS seed laser timing jitter/fs	<100

In DCLS user operation, shot-to-shot repeatability of the output photon number should be as good as possible. Ideally, the shot-to-shot fluctuation in normalized pulse energy is expected to be less than 5% for the nonlinear phenomena experiments, which seems unlikely with the presently expected accelerator and injector performance. However, many of the experiments can tolerate fluctuation as high as 25% by recording the shot-to-shot pulse photon number for post-processing [26]. The sensitivity scans show that the initial beam energy jitter plays a crucial role in the DCLS output stability, especially at the $50\ \text{nm}$ wavelength, where the FEL pierce parameter [27] is only 0.14%. Then a $10\ \mu\text{m}$ transverse beam position jitter at the undulator entrance obviously requires a beam based alignment procedure for LINAC [28]. Finally, $1\ \text{ps}$ electron beam pulse and $1\ \text{ps}$ seed pulse seems to have greatly relaxed the tolerance requirement on timing between the electron beam and the seed laser.

3 Jitter sensitivity from LINAC

Photo-cathode RF injector and one bunch compressor LINAC is used to generate a $300\ \text{A}$ peak current electron beam for DCLS. Before the bunch compressor chicane, two S -band accelerating structures (L1–L2) generate the required energy chirp for bunch compression and four S -band accelerating structures (L3–L6) after are used to accelerate the electron beam to $300\ \text{MeV}$, while removing the correlated energy spread. FEL operations foresee stringent requirements for the stability of the LINAC output parameters, such as the beam arrival

time, peak current and average beam energy. In order to understand the jitter sensitivity of these parameters to various error sources along the LINAC, an elaborate study using particle tracking codes has been performed.

The beam sensitivity of LINAC is investigated by summing the uncorrelated random effects for DCLS, i.e., 250 fs injector timing jitter, 5% bunch charge jitter, 0.1% RF voltage jitter, 0.1° RF phase jitter and 0.02% bunch compressor dispersion jitter, which lead to a 0.09% beam energy jitter, 5.33% peak current jitter and 137 fs beam arrival time jitter for the current LINAC design of DCLS, as shown in Fig. 3. According to the tracking results, the uppermost source of the mean beam energy jitter is the accelerating structures L1–L2 where the linear energy chirp is generated, the beam current jitter mainly comes from the injector and the beam arrival time jitter is almost evenly distributed along the LINAC.

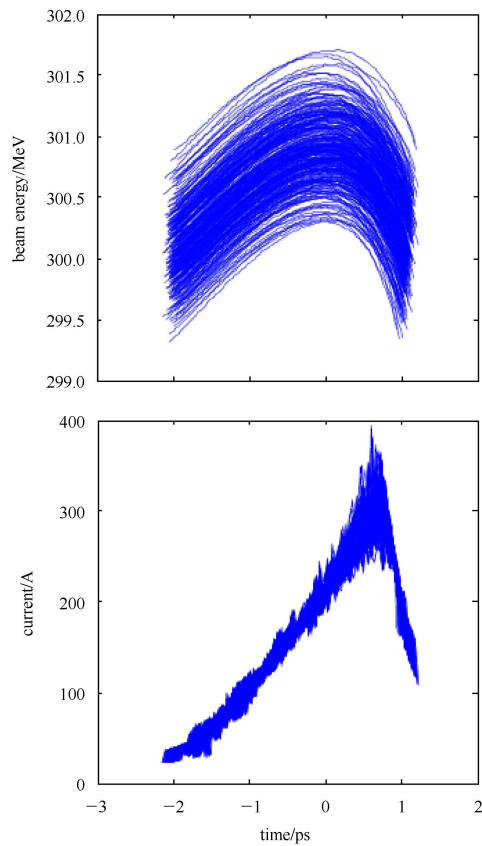


Fig. 3. LINAC tracking results of 300 shots start-to-end simulations, without X-band cavity.

The electron orbit in LINAC is strongly related on the quadrupole magnet offsets. Without proper correlation, the maximum beam transverse error could be up to 1.5 mm, which is far from the requirement for FEL lasing. Therefore, a beam based correction [28] is used firstly to minimize the quadrupole offsets with respect to the beam orbit. Then one random orbit with maximum

offset is chosen for beam transverse jitter calculation because of the implicit influence. A 0.1% RMS jitter is applied to all the power supplies of the magnets that have effects on the beam orbit, e.g., bending magnets, correctors and quadrupoles, no more than $10\ \mu\text{m}$ beam jitter is modeled in both horizontal and vertical axis.

An X-band structure is widely utilized for linearizing the bunch compression process in large-scale hard X-ray FEL; here we consider LINAC beam dynamics for DCLS with an X-band cavity. Considering its small beam energy and compact machine size, the electron beam should be chirped more for a flatter top current profile for DCLS, as shown obviously in Fig. 4. On the basis of these settings and tracking results, one can easily conclude that the mean beam energy jitter for the X-band case is slightly more stringent than the nominal case, while the sliced energy spread and the sliced transverse emittance are almost similar in both cases.

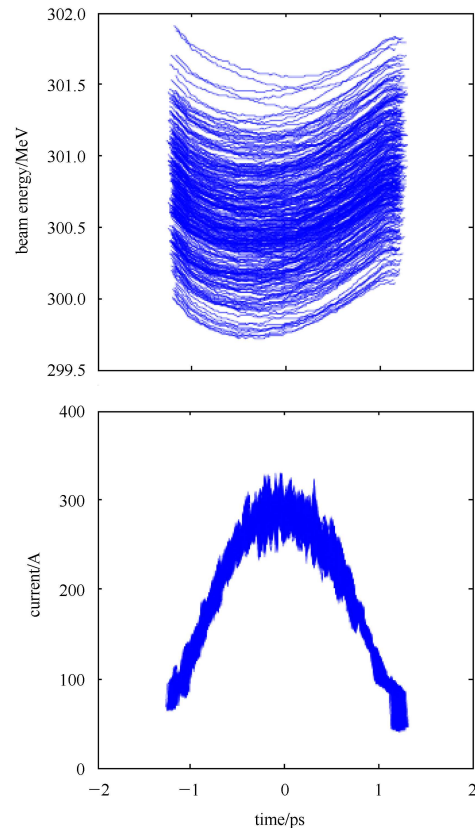


Fig. 4. LINAC tracking results of 300 shots start-to-end simulations, with X-band linearization.

4 Start-to-end simulations on FEL pulse stability

By importing those 300 shots LINAC tracking results to the DCLS undulator system, we obtain the start-to-end statistical information on FEL performance under two tolerance sets, as shown in Table 2.

Table 2. Start-to-end laser pulse stability of DCLS.

X-band	OFF	ON
LINAC RF amplitude jitter (%)	0.1	0.1
LINAC RF phase jitter/(°)	0.1	0.1
LINAC power supply jitter (%)	0.1	0.1
beam energy jitter (%)	0.09	0.12
beam peak current jitter (%)	5.9	4.0
beam transverse position jitter/ μm	10/5	10/10
beam arrival time jitter/fs	140	138
seed laser timing jitter/fs	100	100
50 nm photon number fluctuation (%)	26	42
100 nm photon number fluctuation (%)	16	15
150 nm photon number fluctuation (%)	10	12

The FEL simulation setup used here has been optimized in terms of undulator lattice and seeding parameters in order to maximize the output peak power extracted from an ideal bunch. The setup for the start-to-end simulations is the following: the 5 MW seed laser with a Gaussian profile (1 ps FWHM in longitudinal and 0.5 mm RMS in transverse) and a 100 fs RMS timing jitter, the modulator tuned at 250 nm, the radiator tuned at 50 nm and the dispersive section with $R_{56}=0.18$ mm. As illustrated in Fig. 5, the mean pulse energy and the standard deviation of 50 nm FEL is about 60 μJ , 26% and 72 μJ , 42% for the cases with the X-band OFF and

ON, respectively.

The 50 nm wavelength of DCLS shows the most stringent requirement on the quality and tolerance of the electron beam. When we compared with other error sources, e.g., laser-beam timing and beam transverse position jitter, the mean beam energy jitter is almost close to the pierce parameter of 50 nm FEL. According to the start-to-end LINAC tracking results, the X-band cavity is helpful for compressing more electron particles to the beam core with a larger energy chirp before the bunch compressor and thus leads a 0.12% RMS beam energy jitter, which is larger than the 0.09% beam energy jitter associated with the X-band structure OFF. Therefore, the X-band cavity enhances the radiation power and purifies the radiation spectrum of 50 nm FEL while reducing its pulse stability.

Moreover, when one considers the undulator resonant equation, the FEL wavelength jitter should be two times that associated with the mean beam energy jitter. However, this is not true in DCLS where the radiation wavelength is mainly defined by the seed laser and partially depends on the undulator resonant wavelength. The DCLS output spectra results are in agreement with predictions; the obtained fluctuation of the central wavelength is much lower when compared to the beam energy jitter and thus does not affect the FEL performance.

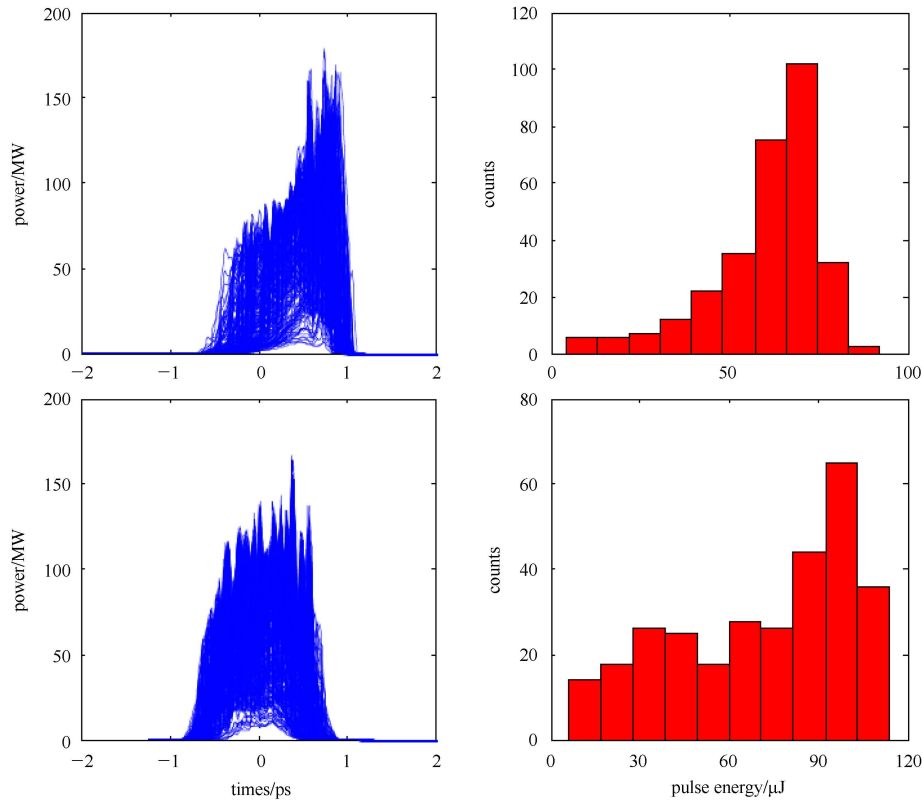


Fig. 5. Start-to-end results of 50 nm pulse distributions from 300 shots. Top: without X-band cavity, Low: with X-band linearization.

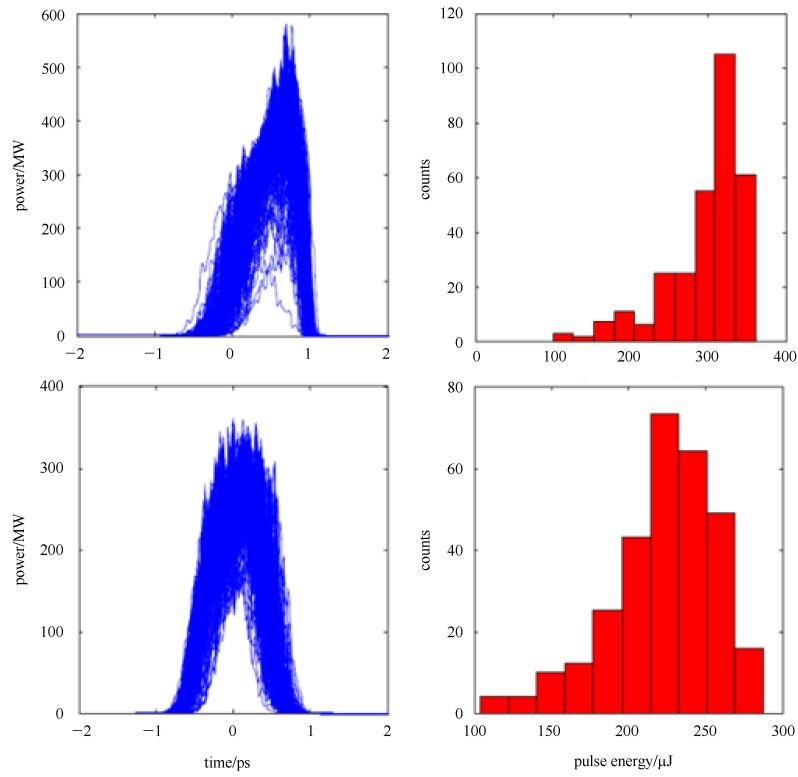


Fig. 6. Start-to-end results of 100 nm pulse distributions from 300 shots. Top: without X-band cavity, Low: with X-band linearization.

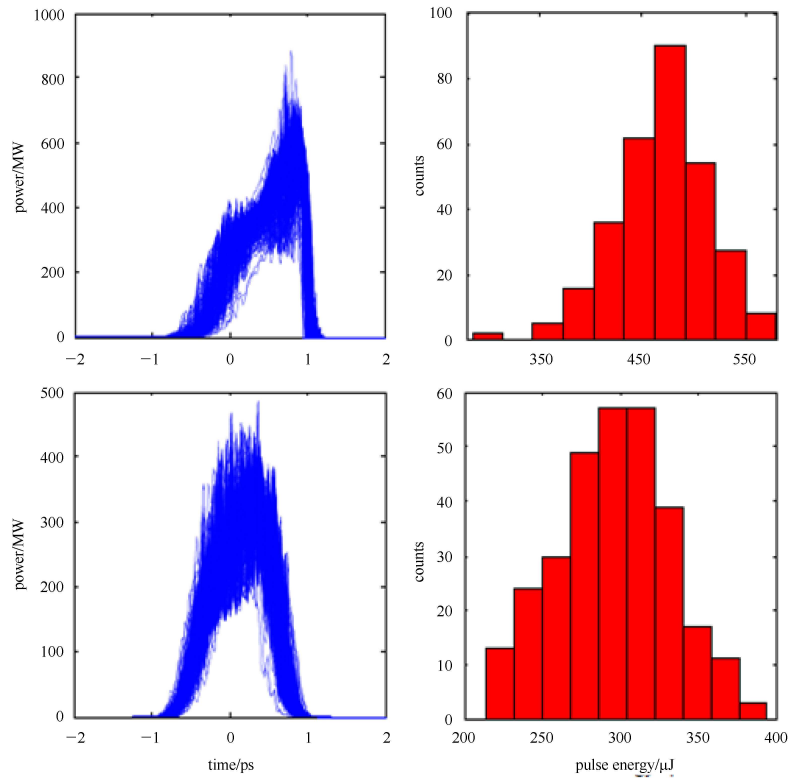


Fig. 7. Start-to-end results of 150 nm pulse distributions from 300 shots. Top: without X-band cavity, Low: with X-band linearization.

In order to verify the conclusions on 50 nm start-to-end simulations, which indicates the mean beam energy jitter as the most limiting factor for achieving a good output stability, the DCLS output pulse stabilities of 100 nm and 150 nm cases are also characterized, in which the FEL pierce parameter is several times larger than the electron beam energy jitter and the FEL saturates in two segments of the radiator. Figs. 6 and 7 show the corresponding output pulse distribution and the pulse energy statistics from the start-to-end simulation results. The average pulse energy and the standard deviation of the 100 nm FEL distribution is about 248 μJ , 16% and 186 μJ , 15% for the cases with and without an X-band cavity. Meanwhile, the average pulse energy and the deviation of the 150 nm FEL is about 468 μJ , 10% and 296 μJ , 12% for the cases with and without the X-band structure, respectively. Here, the larger pulse energy for the case without the X-band structure mainly benefits from the beam current spike, which exceeds the nominal 300 A, as shown in Fig. 3.

5 Conclusions

Dalian Coherent Light Source is expected to generate fully coherent laser pulses by seeded FEL scheme in the wavelength range between 150–50 nm with a pulse photon number of 10^{13} order. In this paper, with the help of

intensive start-to-end FEL simulations, the DCLS laser pulse stability sensitivity to various error sources, e.g., magnet power supply instability, RF jitter and timing jitter, was investigated. FEL pulse stability performance is mainly affected by the electron beam energy jitter for DCLS. For the current design of the DCLS machine without an X-band, the RMS variation of laser pulse energy is about 26% for the 50 nm radiation wavelength and becomes much better in the long wavelength regime.

For comparative purposes, FEL pulse stability with the X-band cavity was also studied in this paper. In order to compress more electrons to the beam core with a larger energy chirp before the bunch compressor, the X-band cavity leads to a 0.12% beam energy jitter, which contributes to the FEL stability degradation at short-wavelength for DCLS. However, it is worth stressing that the X-band linearization is helpful for suppression of the coherent synchrotron radiation effects in the bunch compression and removal of the correlated beam energy chirp after the bunch compression. Thus in further studies, the X-band structure demonstrates a better distribution of emittance, energy spread and beam current, and thus a much more pure radiation spectrum for DCLS.

The authors would like to thank Tong Zhang, Chao Feng, Lie Feng, Taihe Lan, Xingtao Wang and Zhentang Zhao for helpful discussions.

References

- 1 McNeil B, Thompson N. Nature Photon, 2010, **4**: 814
- 2 Ackermann W et al. Nature Photon, 2007, **1**: 336
- 3 Emma P et al. Nature Photon, 2010, **4**: 641
- 4 Ishikawa T et al. Nature Photon, 2012, **6**: 540
- 5 Allaria E et al. Nature Photo, 2012, **6**: 699
- 6 DAI J, DENG H, DAI Z, Phys. Rev. Lett., 2012, **108**: 034802
- 7 DENG H et al. Chinese Phys. C (HEP & NP), 2013, **37**: 102001
- 8 HUANG Z et al. Phys. Rev. Lett., 2012, **109**: 204801
- 9 CHANG C et al. Phys. Rev. Lett., 2013, **110**: 064802
- 10 WU Y K et al. Phys. Rev. Lett., 2006, **96**: 224801
- 11 DING Y et al. Phys. Rev. ST Accel. Beams, 2008, **11**: 030702
- 12 LI Y et al. Nucl. Instrum. Methods A, 2010, **613**: 163
- 13 ZHANG T et al. Nucl. Instrum. Methods A, 2012, **680**: 112
- 14 Spezzani C et al. Phys. Rev. Lett., 2011, **107**: 084801
- 15 DENG H et al. Chinese Phys. C (HEP & NP), 2013, **37**: 118101
- 16 YU L H. Phys. Rev. A, 1991, **44**: 5178
- 17 WU J H, YU L H. Nucl. Instrum. Methods A, 2001, **475**: 10
- 18 Stupakov G. Phys. Rev. Lett., 2009, **102**: 074801
- 19 XIANG D et al. Phys. Rev. Lett., 2010, **105**: 114801
- 20 ZHAO Z T et al. Nature Photon, 2012, **6**: 360
- 21 DENG H, FENG C, Phys. Rev. Lett., 2013, **111**: 084801
- 22 LIU B et al. Phys. Rev. ST Accel. Beams, 2013, **16**: 020704
- 23 Kim K J, XIE M. Nucl. Instrum. Methods A, 1993, **331**: 359
- 24 Reiche S. Nucl. Instrum. Methods A, 1999, **429**: 243
- 25 DAI D et al. Science, 2003, **300**: 1730
- 26 FERMI@Elettra Conceptual Design Report, Jan. 2007
- 27 Bonifacio R et al. Opt. Commun., 1984, **50**: 373
- 28 GU D et al. High Power Laser and Particle Beams, 2012, **24**: 2183 (in Chinese)