BEAM TRANSPORT LINE OF THE LPA-FEL FACILITY BASED ON TRANSVERSE GRADIENT UNDULATOR

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Abstract

Free electron lasers (FELs) based on Laser Plasma Accelerators (LPAs) present a main research direction for achieving next generation compact advanced light sources. There are several major challenges of the LPA beam to generate high-brilliance FEL radiation including the large initial angular divergence and the large energy spread. Based on the LPA facility in SIOM that has successfully obtained quasi-monochromatic beam with the central energy of hundreds of MeV, a specific design of a beam transport line is proposed to realize FEL gain using Transverse Gradient Undulator to compensate the relatively large beam energy spread. This beamline uses a single dipole, several strong focusing quadrupoles and correcting sextupoles to match proper beta functions and linear dispersion from the LPA beam to FEL radiation. The corresponding experimental facility of LPA-FEL in SIOM has been set up and will perform first tests to generate FEL radiation.

INTRODUCTION

Laser plasma acceleration has a remarkable advantage compared to traditional RF acceleration that can generate a GeV beam within an accelerating distance of centimetre scale. Hence, LPA technique gives us the possibility for the realization of table-top FEL and achievement of next generation compact advanced light sources [1].

Shanghai Institute of Optics and Fine Mechanics (SIOM) developed their own 100 TW laser system and used it to successfully generate an all-optical cascaded LPA and obtained quasi mono-energetic electron beam with energy up to 1.3 GeV [2, 3]. For the next step, it is purposed to realize the all-optical LPA-FEL with an external seed laser based on high harmonic generation (HHG) [4]. The major challenges of realization are from the intrinsic properties of the LPA beam which has rms divergence of 1mrad and rms energy spread of 1%.

To overcome the adverse impact of large energy spread on FEL generation, the method of Transverse Gradient Undulator (TGU) was proposed to compensate the energy spread effect though matching the dispersion of the electron beam with the transverse gradient field of TGU to satisfy the FEL resonant condition [5]. There have been some preliminary investigations of TGU FEL radiation based on the LPA beam in SIOM [6, 7].

However, due to the initial large angular divergence and large energy spread, a featured scheme of beam transport line from LPA to FEL should be of great concern. In this contribution, a specific transport line is proposed for FEL amplification based on TGU that aims to focus the beam size and match Twiss parameters and transverse dispersion for the LPA beam with large divergence and energy spread. Combining the scheme with TGU, FEL simulations are also presented.

In addition, a brief progress and a look of the LPA-FEL facility are included in the contribution. The proposed scheme was adopted on the LPA facility in SIOM and it has been set up basically. As planned, the first experiment of the facility is to test SASE FEL with TGU operated at the EUV wavelength.

OPTICS OF BEAM TRANSPORT

Initially a compact beam transport line was considered as the original design scheme based on the beam parameters of the LPA facility in SIOM. While subjected to the practical layout and the project progress, the current practicable layout with physical mechanisms similar to compact design is proposed, as shown in Fig. 1, of which the horizontal branch is not included in the category.

The current beam transport line of the test facility consists of a single dipole, several quadrupoles and several sextupoles. The strong focusing quadrupoles with high gradient magnetic field are applied to focus the LPA beam with large initial divergence but lead a chromatic emittance growth of the beam with large energy spread. Transverse dispersion is introduced by a single dipole to minimize the longitudinal momentum compaction so that the short bunch length and high peak current is maintained. In addition, sextupoles are used to compensate the energy dependence of the focusing system, decrease the chromatic emittances growth and even remove higher-order dispersions.

As listed in Table1, the measurement parameters of the LPA beam in SIOM are presented. Typically, we consider a beam for EUV FEL operation with energy of 380 MeV, normalized rms emittances of 0.44 mm·mrad and rms divergence of 0.3 mrad as the reference for lattice design and beam tracking simulation.

Table 1: Beam Parameters of the LPA Facility in SIOM

Parameter (RMS)	Value	Unit.
Beam Energy	300-500	MeV
Energy Spread	1%	/
Norm. Emittance	0.1-1.0	mm·mrad
Beam Size	1-2	μm
Beam Divergence	0.1-1	mrad
Charge	~80	pC
Bunch Length	~1	μm
Peak Current	~10	kA

Figure 1: Schematic layout of the beam transport line for the LPA FEL facility in SIOM.

For the requirements of TGU radiation, the lattice parameters of the beam line are designed by using MAD [8] where Twiss parameters and dispersion are calculated as the results of the central energy shown in Fig. 2a and the optimized values are achieved with α_x=0.9 β_x=4.5 m, α_y=0.6 β_y=4.0 m and D_x=-0.062 m at the 17m position. The results of deviated energy are different; however, the application of sextupoles can correct the deviated results to close to the central energy as well as possible.

which are much less than the non-corrected results without sextupoles (15.5mm·mrad &5.4mm·mrad) but still not perfect due to the constraint of sextupole strength and additional high order side-effects. Importantly, the longitudinal rms bunch length is just decompressed from 1 μm to ~3 μm, and the peak current is reduced from 10kA to 3.4kA with small R_{56} of 0.3mm. Simultaneously, the slice energy spread is remained about 0.8% and dispersed in transverse position.

FEL SIMULATIONS

To achieve FEL radiation, the tracked LPA beam is sent into TGU undulators simulated by Genesis [11]. A 6m TGU undulator is assumed, which has 2 cm period length, undulator parameter K of 1.15, and transverse gradient of 50 m^{-1} with a resonant wavelength of 30 nm (the optimized resonant gradient of 41 m^{-1}). Focusing isn't required in the undulator line in order to keep the beam dispersion nearly constant in the undulator.
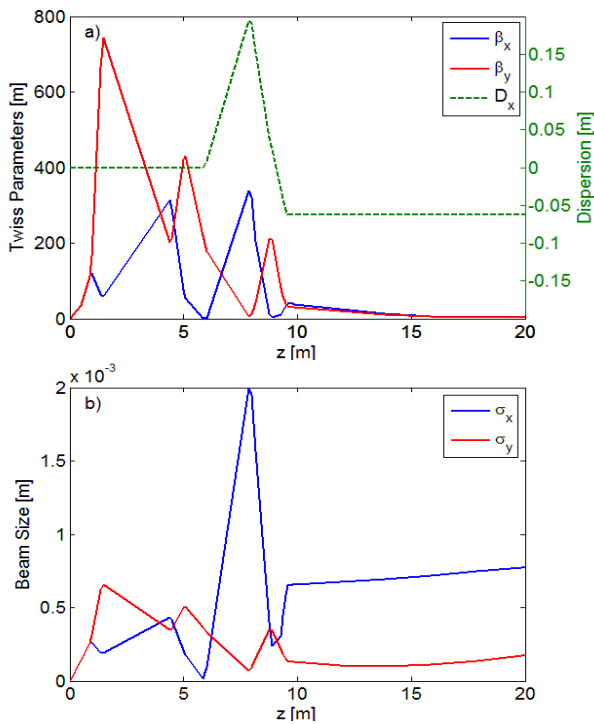

Figure 2: a) Beta functions and dispersion of the particle with central energy along the beam line; b) Evolutions of the LPA beam size along the beam line.

A 6D Gaussian beam with energy spread of 1% generated by Astra [9] is taken as a LPA beam for tracking. The intrinsic energy chirp of the beam is neglected since the bunch length is the same order as the FEL cooperation length (FEL slice length). Then, ELEGANT [10] tracks it through the beamline by which the evolutions of the beam sizes are shown in Fig. 2b. It is illustrated that the evolutions of the beam sizes become relatively stable after a 10 m transport line where the size of y is ~130 μm and x is ~650 μm with additional large transverse dispersion. In addition, as the results of simulation, the optimized emittances correlated with energy spread are ε_x=1.9mm·mrad and ε_y=1.6mm·mrad,
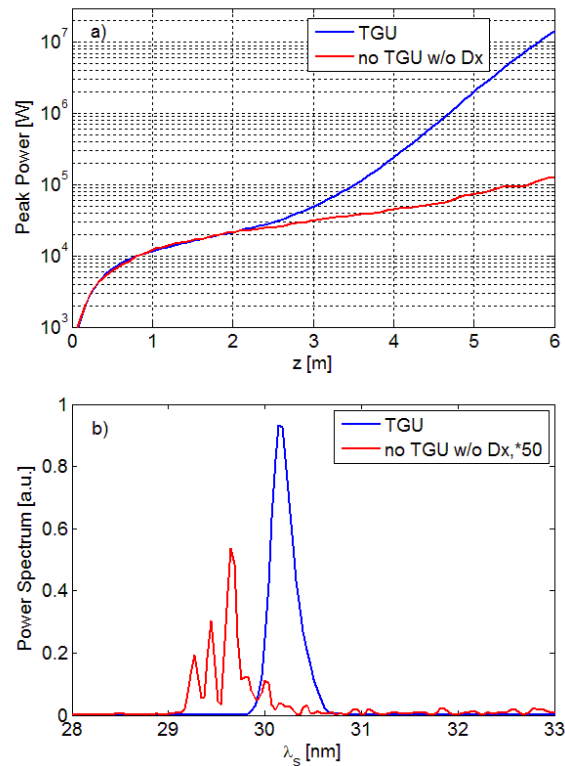

Figure 3: FEL performances. a) Peak power growth of SASE FEL based on TGU case (blue) and no-TGU case (red) at a distance of 6 m. b) Typical single-shot radiation spectrum of SASE FEL based on TGU case (blue) and no-TGU case at the exit of undulator, respectively.

The FEL power working in the SASE regime as a function of the undulator length is shown in Fig. 3a. For the beam with initial divergence of 0.3mrad, SASE FEL of TGU has an exponential gain and improves power rapidly even though it has not yet reached saturation. As a comparison, the result of normal planar undulator radiation is considered where the optimized beam is assumed as same as the tracked beam without dispersion. The SASE FEL power improvement of TGU is about two orders of magnitude than the normal radiation. Fig. 3b shows the comparison of power spectrum for these two cases at the exit of the 6m undulator that the TGU generates a single coherent spike due to the ultra-short pulse duration and rapid power gain while the normal undulator generates several spikes with a large bandwidth relatively because the large gain length of normal case leads that there is not enough exponential gain to select the resonant wavelength coherently.
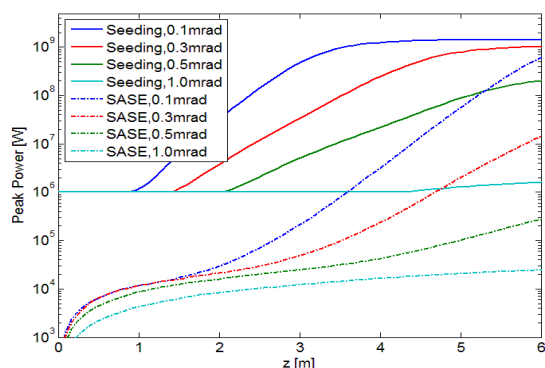

Figure 4: Peak power growth of SASE (solid) and direct seeding (dashed-doted) along the TGU undulator with different initial divergences, respectively.

At this radiation condition, direct seeding is simulated which uses a seed laser source with wavelength of 30nm, peak power of 1 MW and rms spot size of 100 μm generated by HHG. Fig. 4 shows the power of SASE and direct seeding regimes along the TGU undulator with beam of different initial divergences (or emittances), respectively. Decreasing the beam divergence from 1 mrad to 0.1 mrad, FEL power results in a significant promotion, typically the case of 1 mrad achieves FEL amplification hardly within the 6 m TGU undulator. Thus, this scheme is feasible for the beam with initial divergence less than 1 mrad.

TOWARDS FEL EXPERIMENTS

The LPA facility in SIOM adopted the design of beam transport line. And it will complete the device installation and start FEL experiments.

Experimental Setup

According to the layout of the test facility presented in the deflection branch of Fig. 1, a linear beam transport line without sextupoles has been set up presently. In this system, dipole generates deflection with an angle of 0.1 rad where the effects of coherent synchrotron radiation (CSR) would be induced furtherly [12]. The effective length of quadrupoles is 10 cm and the gradient is about 40 T/m (the designed maximum up to 80 T/m). Four TGU undulators with period length of 2 cm and period number of 75 are completed, where the reference central magnetic field of the horizontal axis is 0.615 T, leading to a corresponding undulator parameter K value of 1.15, and the transverse gradient is 50 m^{-1} with additional correction coils of gauss magnitude presented in Fig. 5. In addition, it is noted that sextupoles are proposed with ultra-high strength up to 10^4 T/m^2 which have been designed and being processed.

Figure 5: Image of transverse gradient undulator with a canting angle of 7.5 degree designed in SINAP.

FEL Experiments Plan

Based on the test facility, it is about to begin beam manipulation and the first test for SASE FEL with TGU at the wavelength around 30nm. The platform of HHG laser is setting up that will be applied as seed laser for seeded FEL generation at the next step. To further control the LPA beam, reduce FEL gain length and improve the work efficiency of FEL within short distance, more ultra-high gradient quadrupoles would be assembled for more compact scheme of beam transport line.

CONCLUSION

In this paper, we presented the design of the beam transport line for the LPA-FEL facility in SIOM, and simulated FEL radiation based on TGU undulator. For the lattice design, a single dipole, several quadrupoles and sextupoles are adopted which could not only match proper beta functions and linear dispersion for the beam with large energy spread, but also maintain the short bunch length, high peak current and slice energy spread for TGU radiation. For the FEL simulation, both SASE and Direct HHG Seeding are considered and generate high power gain in a short TGU undulator.

This scheme has been set up and will be tested at the LPA-FEL facility in SIOM that would be expected to verify the feasibility of the beam transport line and demonstrate the advantage of TGU to drive short-wavelength FELs for beams with relatively large energy spreads from laser plasma driven accelerators.

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