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FELS DRIVEN BY LASER PLASMA ACCELERATORS OPERATED WITH TRANSVERSE GRADIENT UNDULATORS

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Abstract

Laser Plasma Accelerators produce beams with a significantly higher energy spread (up to a few percent) compared to conventional accelerators. This high energy spread increases the gain length and therefore the total length of the undulator when used for an FEL. In order to reduce the gain length of the FEL the use of Transverse Gradient Undulators (TGUs) instead of conventional undulators were proposed. In this paper the limits of this concept are discussed using a modified version of the GENESIS program [1].

INTRODUCTION

Recently it was discussed to use Laser Plasma Accelerators (LPA) as a source for Free Electron Lasers (FELs). LPAs are compact sources and reach energies of up to 1 GeV. However, they produce beams with the energy spread of one percent or higher.

In Fig. 1 an example is shown how the energy gain in an FEL depends on the relative energy spread of a beam. In this example the FEL radiation gain is calculated for a conventional undulator for beams with various energy spreads. The calculations were performed with the program GENESIS [1]. The beam energy is 500 MeV, the normalized rms emittance in x and y is 6.10^{-7} m.rad, the beam size is 100 µm. The period length of the undulator is 2 cm and the K value of the undulator is 1.92. The produced synchrotron radiation has a wavelength of 30 nm. The peak current of the electron beam is 4.4 kA.

The assumed rms value of the energy spread is 0% for curve 1, 0.1% for curve 2, 0.5% for curve 3, 1% for curve 4 and 3% for curve 5.

Figure 1 shows for this example that an energy spread of more than 0.1% increases the length of the undulator significantly when a certain output power is requested. Several ideas were proposed to reduce the energy spread of the beam by modulating the plasma density along the trajectory [2,3] or by stretching the bunch [4].

In these proposals the energy spread of the beam is reduced. Another proposal was at the beginning to modify the design of the undulators so that they produce coherent radiation as close as possible to curve 1 in Fig. 1 without reducing the energy spread. The principal idea was first published 1979 [5] for a different FEL concept. A modified version of this concept based on a superconductive undulator was published in [6].

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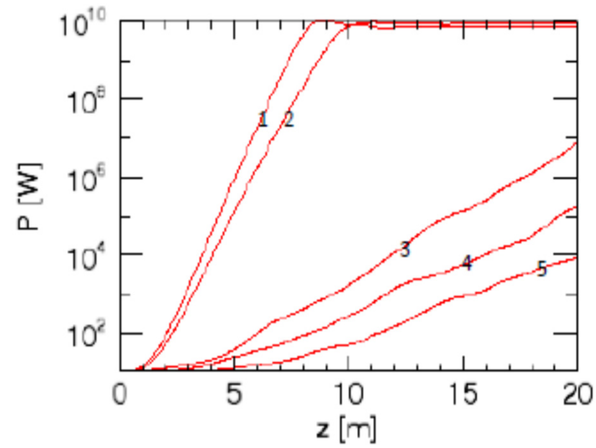

Figure 1: Power gain in an FEL undulator depending on the energy spread of the electron beam. The parameters are listed in the text. The rms value of the energy spread is 0% for curve 1, 0.1% for curve 2, 1.5% for curve 3, 2% for curve 4 and 3% for curve 5. The simulations were performed with the program GENESIS [1]. Beam energy is 500 MeV.

TRANSVERSE GRADIENT UNDULATORS

The concept is sketched in Fig. 2. With a dispersive beam optics consisting of one or several bending magnets, quadrupoles and sextupoles, electrons with different energies generated by a LPA enter the undulator on different x positions.

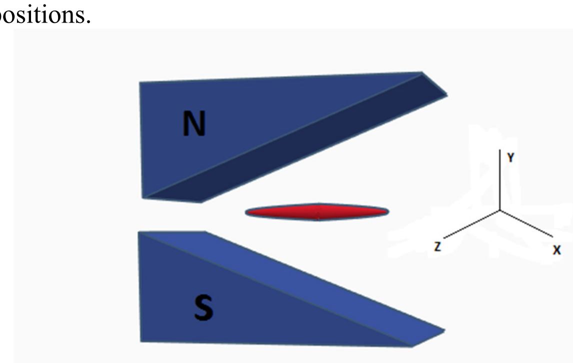

Figure 2: Concept of a TGU based FEL. The B field of the undulator depends on the x position. In addition the x position of the particles in the bunch is related to the particle energy. With the correct x-dependence of both B field and particle energy the energy spread of the emitted radiation is minimized.

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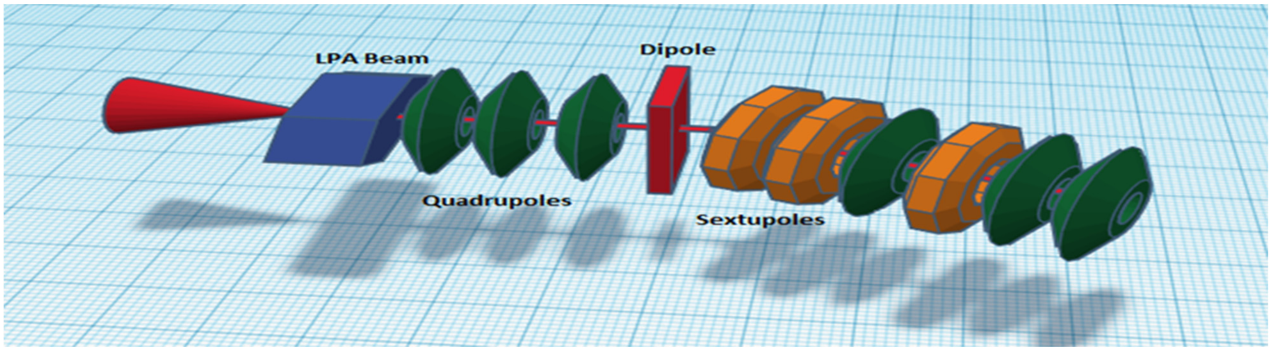

Figure 3: Scheme of the LPA beam transport line [8].

Up to now two versions of the beam optics were discussed and partly tested with beam. For the LPA accelerator at the University of Jena beam optics with two bending magnets was proposed and partly tested [7] and a beam optics with one bending magnet was studied at the Shanghai Institute of Applied Physics [8] which is depicted in the Fig. 3. It consists of a triplet at the first stage (focusing stage), a dipole to disperse the beam and a matching section with three sextupoles to correct the effects of chromatic emittance and nonlinear dispersion.

If the undulator has a field gradient in the x dimension (Transverse Gradient Undulator) and if the dispersion produced by the optics is matched accordingly the photon beam becomes more monochromatic.

The modified undulator equation for a TGU is:

$$\lambda = \frac{\lambda_u}{2\gamma^2(x)}\left(1 + \frac{K^2(x)}{2}\right)$$

$$K(x) = 0.934.\ \lambda_u[\text{cm}].B(x)[\text{T}], \tag{1}$$

where λ is the wavelength of the emitted radiation, λ_u is the undulator period, and B is the magnetic field strength.

According to Fig. 2 a TGU based FEL needs the development of three elements sketched in Fig. 3.

The horizontal beam size σ_x at the entrance of the TGU is

$$\sigma_x = \left(\beta_x\,\varepsilon_x + \mathrm{D}\frac{\Delta \mathrm{p}}{\mathrm{p}}\right)^2. \tag{2}$$

The beam size $\sqrt{\beta_x\,\varepsilon_x}$ is an essential parameter for the TGU radiation; larger beams produce radiation with a higher spectral width since monochromatic electrons with the same energy enter the TGU field at different x positions with different fields.

Up to now three different types of TGUs were considered:

- A canted undulator as sketched in Fig. 2 [9]
- A superconductive undulator with NbTi wires [6] is in the test phase
- A TGU based on an APPLE undulator [10]

SIMULATION OF THE FEL RADIATION

In a first step the properties of the incoherent radiation produced by a TGU were simulated [11]. In a second step a 1 D analysis of a FEL operation was presented [12].

In the simulations it is assumed that the K value varies linearly with x:

$$\left(\frac{\Delta \mathrm{K}(\mathrm{x})}{K_0}\right) = \alpha\ \mathrm{x}. \tag{3}$$

α is the field gradient. Assuming a zero emittance of the incoming electron beam one can show that the particles in the TGU produce monochromatic radiation [7] when

$$D = \frac{(2 + K_0^2)}{(\alpha K_0^2)}, \tag{4}$$

where D is the dispersion of the incoming electron beam.

In a next step the results of a 3D analysis with the GENESIS 1.3 program is presented. The standard GENESIS program [1] does in its original version not allow field gradients in the undulator. Therefore this program was modified [8]. The modifications allow to calculate in first order the radiation produced by a TGU.

The result of the simulations is shown in Fig. 4. As in Fig. 1 the beam energy is 500 MeV. The normalized rms emittance in x and y is 6.10^{-7} mrad, the beam size 100 µm. The period length of the undulator is 2 cm and the K-value of the undulator is 1.92. The produced synchrotron radiation has a wavelength of 30 nm. The peak current of the electron beam is 4.4 kA.

In the calculations ponderomotive forces deflecting the beam transverse to its propagation direction in the undulator are neglected. These forces have to be compensated by correction coils especially in long undulators and are partly implemented in the prototype of the superconducting TGU [13] for test purposes.

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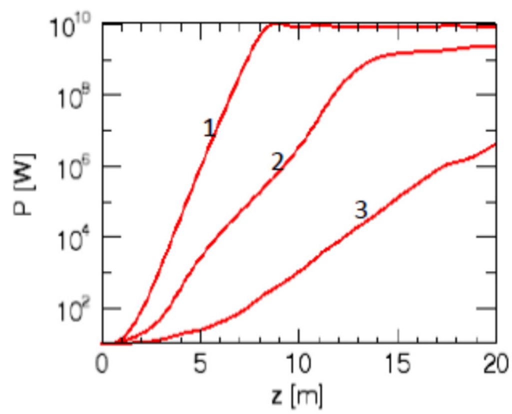

Figure 4: Curve 1 is identical with curve 1 in fig. 1 (zero energy spread). In curve 2 the energy spread is 1.5%, α is 35.5 m^{-1} and the dispersion D = 0.04 m. In curve 3 the energy spread is 1.5% as in curve 2 but both α and D are zero. The beam parameters are listed in the text.

Figure 5 shows the curves 1, 2 and 3 with two additional curves with a higher value for the dispersion D. The optimum curve 2 produces the best results for a beam with an energy spread. This can be directly derived from equation (4). With the parameters α = -35.5 m^{-1} and K_0 = 1.92 the energy spread the energy spread has a minimum influence when the dispersion D = -0.043 m.

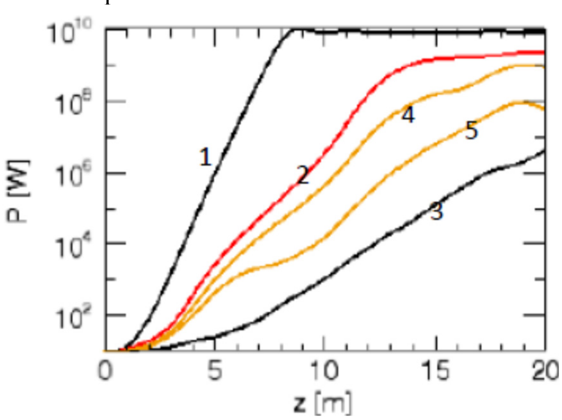

Figure 5: Influence of the dispersion of the incoming beam. The curves 1, 2 and 3 are identical with the curves shown in fig. 3. The dispersion D for curve 2 is -0.04 m, for curve 4 -0.08 m and for curve 5 -0.1 m. α is -35.5 m^{-1} for curve 2, 4 and 5.

SUMMARY

Laser Plasma Accelerators are compact electron sources which can produce high energy electron beams (up to 1 GeV or even higher) with the disadvantage that the energy spread of the particles in the beam is relative high (in the order of up to several percent). As a result, if the undulator is used as an FEL, a long undulator is required and the output power of the FEL is significantly reduced.

In order to overcome this problem it was proposed to modify the undulator layout. The electrons of the incoming beam are transversally separated according to their energy similar as this is done in spectrometer optics. This beam enters an undulator with a transverse field gradient (TGU). If the energy gradient of the beam and the field gradient of the undulator are matched the emitted radiation becomes more monochromatic and the FEL beam gains faster power along the undulator.

The simulation of this effect is subject of this paper. The calculations are performed with a modified version of the GENESIS 1.3 program. The simulations show that the TGU concept might be promising improvement for FELs operated with high energy spread beams. At the moment it is discussed to test the TGU concept with a conventional linac and a chicane (e.g. with the ARES linac at DESY). This experiment would allow controlling the energy spread of the electron beam with a conventional cavity. This could make a comparison between simulations and measurements for the beginning easier.

Beside these more fundamental investigations there are several open technical questions to be solved in detail, for instance the optimum layout of the beam optics in front of the TGU. First experimental studies of the spectrometer optics in front of the TGU were performed [14] showing that the spectrometer optics in front of the TGU is relatively demanding.

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REFERENCES

[1] S. Reiche, GENESIS 1.3, "A fully 3D time-dependent simulation code," *Nucl. Instr. Meth. A*, vol. 429, p. 243, 1999.
[2] R. Brinkmann *et al.*, "Chirp Mitigation of Plasma-Accelerated Beams by a Modulated Plasma Density," *Phys. Rev. Lett.*, vol. 118, p. 214801, 2017.
[3] X. L. Xu *et al.*, "High quality electron bunch generation using a longitudinally density-tailored plasma-based accelerator in the three-dimensional blowout regime," Phys. Rev. AB, 20, 111303 (2017).
[4] A. R. Maier *et al.*, "Demonstration Scheme for a Laser-Plasma Driven Free Electron Laser," *Phys. Rev. X*, vol. 2, p. 031019, 2012.
[5] T. I. Smith *et al.*, "Reducing the Sensitivity of a free electron laser," *J. Appl. Physics*, vol. 50, p. 4580, 1979.
[6] G. Fuchert *et al.*, "A novel undulator concept for electron beams with a large energy spread," *Nucl. Instr. Meth. A*, vol. 672, p. 33, 2012.
[7] C. Widmann *et al.*, "First tests of a beam transport system from a laser wakefield accelerator to a transverse gradient undulator," in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, paper MOPWA045, pp. 216-219.
[8] T. Liu *et al.*, "Compact beam transport system for free- electron –lasers driven by a laser plasma accelerator," *Phys. Rev. AB*, vol. 20, p. 020701, 2017.

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[9] Z. Huang *et al.*, "Compact X-ray Free Electron Laser from a laser plasma accelerator using a Transverse-Gradient Undulator," *Phys. Rev. Lett.*, vol. 109, p. 204801, 2012.
[10] E. Prat, M. Calvi, and S. Reiche, "Generation of ultra-large bandwidth X-ray free-electron laser pulses with a transverse-gradient undulator," *J. Synchrotron Radiation*, vol. 23, no. 4, p. 874, 2016, doi: 10.1107/S1600577516007177
[11] A. Bernhard *et al.*, "Radiation emitted by transverse gradient undulators," *Phys. Rev. Accel. Beams*, vol. 19, p. 090704, 2016.
[12] A. Bernhard *et al.*, "Transverse Gradient undulator-based high-gain FELs – A parameter study," in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, paper TUPWA039, pp. 1502-1505.
[13] V. A. Rodriguez *et al.*, *IEEE Transactions on Applied Superconductivity*, vol. 23, p. 4101505, 2013.
[14] A. Bernhard *et al.*, "Progress on experiments towards LWFA-driven transverse gradient undulator-based FELs," *Nucl. Instr. Meth. A*, (2018), in press, https://doi.org/10.1016/j.nima.2017.12.052