A NOVEL OPTICAL BEAM CONCEPT FOR PRODUCING COHERENT SYNCHROTRON RADIATION WITH LARGE ENERGY SPREAD BEAMS

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Abstract

TGUs (Transverse Gradient Undulators) [1, 2] were originally invented to reduce the spectral width of the (incoherent) undulator radiation caused by an electron beam with a large energy spread (e.g. an electron beam produced by a Laser Plasma Accelerator (LPA)). Later, based on this concept, several proposals investigated the possibility to use the TGU idea for building compact FELs based on SASE or Seeding. In this paper a modified and more compact concept for a LPA driven FEL is investigated.

INTRODUCTION

Electrons entering a conventional undulator emit photons with the wavelength according to the well-known undulator equation :

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

λ is the wavelength of the radiation, λ_u the undulator period and K the K value of the undulator:

$$K=\frac{eB\lambda_u}{2\pi mc}=0{,}934.B[T].\lambda_u[cm]$$

If the bunchlength of the beam entering the undulator is longer than the wavelength of the incoming bunch the emitted radiation is incoherent (= random phase distribution of the photons). There are two possibilities to force the incoming beam to produce coherent radiation:

A. The energy of the incoming bunch is chirped and compressed by a magnetic chicane into a pulse significantly shorter than the wavelength. The short bunch emits e.g. afterwards in an undulator coherent radiation. This technique is in general limited to the generation of coherent THz radiation.

B. In the first part of an undulator either external photons (seeding) or bunch- produced photons (SASE) generate microbunches. These microbunches produce at the end of the undulator coherent EUV or X-ray radiation if the micro bunches are shorter than the wavelength of the emitted radiation.

LPA produced beams are naturally chirped, but there exists limited possibility to influence the chirp from outside. In this paper the assumed main parameters of the LPA beam are based on simulations published in [3]: the correlated energy spread is 10% and the uncorrelated energy spread between 0.1 to 0.3 %. These assumed parameters may vary in other papers [4-6] since measurements of these parameters do not exist at the moment.

Overview of the FELs Concept Based on Transverse Gradient Undulatots (TGU)

The basic concept of a TGU is shown in Fig. 1. The trajectories of the particles with different energies are separated by a dogleg in front of the TGU and enter the TGU at different positions with different K-values (1). If the magnitude of the particle separation and the K value of the undulator corresponds, the produced photon beam energy is monochromatic (but not coherent since the incoming beam is in general still longer than the wavelength).

Recently a superconducting TGU was built and is now under test [7] (Fig. 1).

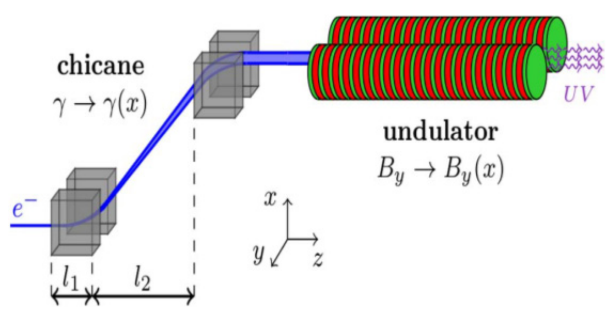

Figure 1: Superconducting TGU [2] to produce monochromatic photon beams with a non-monochromatic electron beam. In [8] the radiation produced by a TGU for various electron beam parameters was calculated.

Coherent Radiation with a TGU

In order to obtain coherent radiation from the TGU it was proposed to combine a TGU [9-13] with microbunching concepts mentioned in B. For the proposals [9,10] the ideas are summarized in [14].

For obtaining coherent radiation with a TGU the three effects: correlated energy spread, uncorrelated energy spread and finite emittance effects have to be taken into account.

A possibility to handle the correlated energy spread is explained first in Fig. 2 for a conventional accelerator with zero emittance and zero uncorrelated energy spread.

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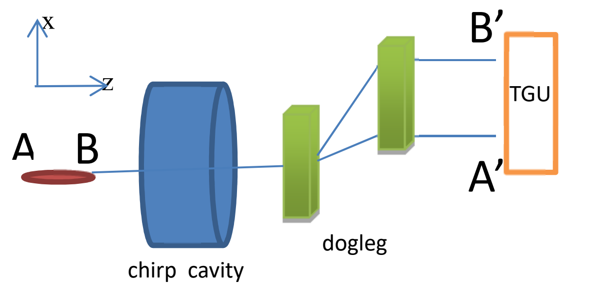

Figure 2: Concept for producing coherent radiation with a TGU. If the chirp and the dogleg is designed so that all electrons arrive at the same time (A-A′ = B-B′) at the surface of the TGU the emitted radiation is monochromatic. If the length of the incoming particle beam entering the TGU is shorter than the laser wavelength the preferred laser concept is described by A, otherwise by B.

The dogleg shown in Fig. 2 consists in this drawing only of bending magnets without quadrupoles and sextupoles in between. In a real design these elements might be necessary to adjust the length differences in the well-known way.

Pathlength of a Chirped Beam in the Dogleg

A detailed numerical study of the path length in a chicane can be found in [15]. The path length difference is

$$\Delta L = L(p+\Delta p) - L(p) =$$

$$= -\left(\frac{L_{mag}}{R}\right)^2 \left[\frac{2}{3} L_{mag} + L_{space}\right] \delta + O\left[\delta^2, \left(L_{mag}\, R\right)^4\right] \qquad (2)$$

L_{mag} is the length of the magnet, L_{space} the space between the magnets and R the bend radius and δ the energy deviation.

As an example for the chicane two 20 cm long magnets in Fig. 2 are used with a field of 1 T. The particle energy varies between 300 MeV and 330 MeV. The bending radius of the electrons in the magnets r[m] is therefore 1m and 1.1 m (r[m] = E [GeV]/(0.3 B[T]). The path length difference in the bending magnet is shown in Fig. 3.

The path length difference of two particles with energy of 300 and 330 MeV are in this example 239 µm. With an assumed drift space drift of 10 cm between the two bending magnets the total path difference of the two particles in the chicane is 2x 239 µm +367 µm = 845 µm in this given example.

In order to compensate the drift length differences the bunch length of the incoming bunch must be also 845 µm or about 2.8 psec.

The transverse beam size at the entrance of the TGU is in this example 0.87 mm.

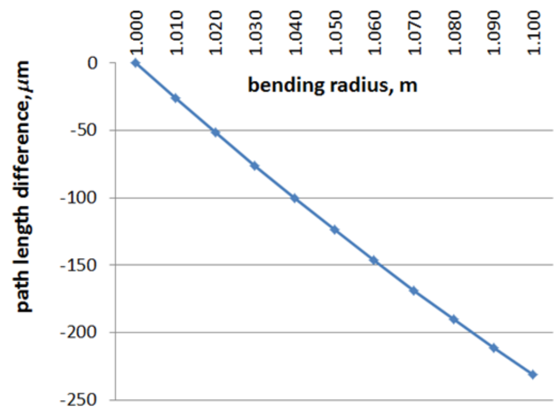

Figure 3: Path length differences in µm for particles with an energy difference of up to 10 % energy deviation bent by a 20 cm 1T magnet. Beam energy: 300 to 330 MeV. This curve shows the nonlinearities in the length already described in equation (2). Since the trajectories are locally separated the trajectory length can be corrected by additional magnets (not discussed in this paper). Figure 4 shows one possibility (among several other) how this can be done.

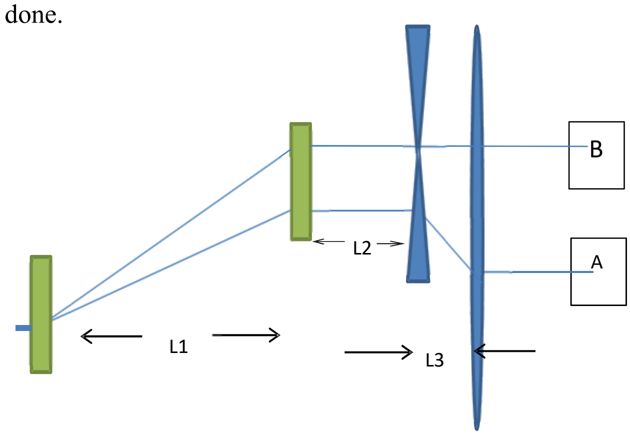

Figure 4: Modification of the concept shown in Fig. 2 for linearizing the pathlength with additional magnets (one out of several possibilities).

In Fig. 4 it is shown that the dogleg parameters (field strength, magnet length, drift space L1 and L3, bunch length and compensating magnets have to be carefully matched.

Uncorrelated Energy Spread

In Fig. 5 it is shown as an example that the uncorrelated energy spread (red lines) is on top of the dominating correlated energy spread. In general it is impossible to measure these parameters. Therefore the effects of both are explained by using simulations published in [3].

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A laser produces an electron beam with a bunch length of 50 µm (166 fsec). The bunch is deflected by a bending magnet (to produce dispersion) and optics forms the bunch so that particles with the highest energies of 398 MeV are at the end of the bunch and the particles at the beginning have energy of 362 MeV. The slope between the two end points is fairly linear. This situation is similar to the idealized model shown in Fig. 2.

The uncorrelated energy spread (following these simulations) is in between 0.1 to 0.2 %.

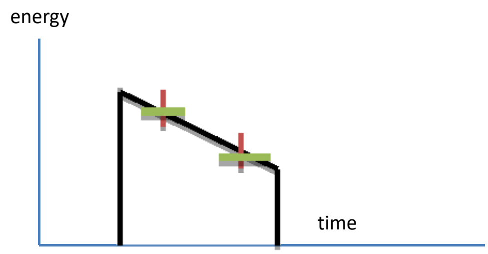

Figure 5: Schematic picture showing both correlated (black lines) and uncorrelated energy spread (red lines). The uncorrelated energy spread adds photons from a larger area (green) and increases the length of the photon train produced by the TGU. Fortunately the high correlated energy gradient (36 MeV in this example) limits this effect.

If the photon pulse becomes longer than about 10 to 20 % of the wavelength at higher photon energies SASE or seeding has to be used to produce coherent photons.

Emittance Effects

The finite emittance of the beam determines the effective length of the bunch entering the TGU as shown in Fig. 6. This is similar to the effect caused by the uncorrelated energy spread.

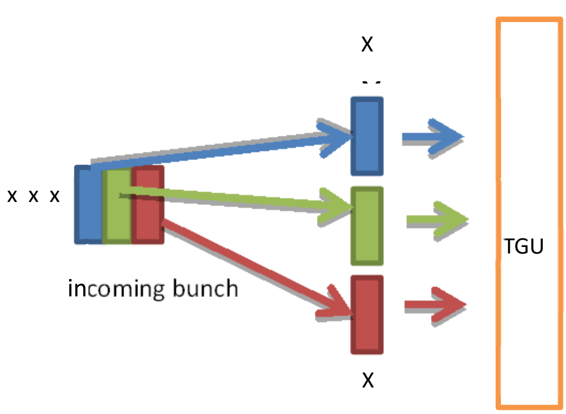

Figure 6: Example for an arrangement for producing coherent radiation. The incoming beam is split by the dog-leg. described by Fig. 4. The thickness of the slices define when a SASE or seeding procedure is required.

The Limit Caused by the TGU

The period length of the TGU adds an additional limitation. Assuming an undulator with a period length λ_u of 1 cm and B= 1 T. The obtainable laser wavelength at the first harmonic is according to (1) is 10 nm for 500 MeV and 1.2 nm for 1500 MeV (at the moment a limit of laser plasma accelerators).

Tuning the laser wavelength by changing the field strength in the undulator might require in addition a change of the chicane parameters due to the nonlinearities of the TGU field. This problem will be investigated as a next step in the near future.

For a first test of the concept tilted permanent or superconducting undulators can be used up to energies of 500 MeV. Superconducting undulators with a period length of 4.8 mm were built and tested with beam [16].

SUMMARY

Laser plasma accelerators have the highest accelerating gradients known up to now. They would be therefore ideal for compact FELs. The disadvantages are that it is impossible to control or change from outside the beam parameters during the acceleration process. In addition the beam parameters are beyond the specifications known from conventional accelerator technology: e.g. the energy spread of the particles is several orders of magnitude higher than with standard accelerators.

It was up to never shown experimentally that an optics works which can produce monochromatic radiation from such a LPA (for instance with a TGU or by stretching the longitudinal bunch dimensions). In this paper a novel optics concept for producing not only monochromatic but also coherent radiation is discussed. Nevertheless, the next steps should include more detailed simulations and first measurements, for instance how reproducible the beam quality of LPA produced beams are and how good the field quality of the TGU should be.

It is therefore proposed to continue the simulations with this concept and perform first experimental tests for instance at conventional accelerators like ARES at DESY [17] or FLUTE at KIT [18] by using the possibility to change the energy spread of the beam by changing the parameters of the bunch compressors.

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