A SUPERCONDUCTIVE UNDULATOR FOR THE MUNICH LASER-PLASMA ACCELERATOR

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Abstract

Laser-plasma accelerators are expected to produce electron beams with bunch charges in the nano-Coulomb range with energies in the GeV range. By employing short-period superconductive undulators (e.g. [1]) this may be utilised for the generation of undulator radiation in the X-ray regime with a compact laboratory-sized set up.

In this contribution we report on the project of testing this concept at the Laser Wakefield Accelerator (LWFA) in Munich. A particular aim of this project is to push the superconductive undulator technology to shortest periods and highest on-axis fields at gap widths sufficiently large to reduce the impact of resistive wall wake fields on the electron beam. This might open a path to the generation of coherent radiation via the SASE process.

INTRODUCTION

With the appearance of Laser-Plasma accelerators [2] several authors discussed the possibility of using these new devices for compact X-ray sources and eventually for lasers based on the SASE process [3]: in an undulator the spontaneously emitted radiation can lead to the formation of micro-bunches. These micro-bunches then radiate coherently. If monochromatic undulator radiation is to be produced or even a laser operation is to be initiated, several conditions have to be met. For instance both the energy spread and the emittance have to be small.

Table 1 summarises the properties of a few laser-plasma accelerators: in 2004 three groups reached beam energies between 70 and 200 MeV, two years later the introduction of capillaries in the plasma discharge allowed to achieve energies up to 1 GeV. However, the energy reproducibility is still very poor in most cases.

Additional parameters of the Munich accelerator not cited in the table are a natural beam emittance ϵ_n of 0.8 $mm \cdot mrad$, a source size σ_x of 2 μm and a pulse length of $\leq$10 fsec.

Recently it was demonstrated by a group in Jena that a Laser-Plasma accelerator in combination with an undulator can produce visible light [8]. This is a first, preliminary test, but it is a very important step towards Laser-wake-field accelerator driven light sources.

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[1] limited by energy resolution of spectrometer

[2] this work

EXAMPLE CALCULATIONS OF UNDULATOR RADIATION

The wavelength of the radiation emitted in an undulator is given by Eq. 1.

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

Where λ is the wavelength of the emitted radiation, λ_u is the period length of the undulator, γ is the relative energy and K is the undulator parameter defined as $K = 0.934 \cdot \lambda_u$[cm]·B[Tesla].

Of great interest, for instance for medical applications, is the X-ray region around 20 keV and higher. Typical K-values of undulators are in between 1 and 2. In order to achieve a certain wavelength the following equation has to be fulfilled:

$$\gamma \approx \sqrt{\frac{\lambda_u}{\lambda}} \qquad (2)$$

For example: if to achieve the photon energy of 20 keV (λ=0.62 Å) with an undulator with the period length λ_u=1 mm a beam energy of 2 GeV would be required. The LBNL Laser-Plasma accelerator cited above does not yet achieve this energy. However ultra-short EUV and soft X-ray pulses would be achievable.

We calculate the expected spectra for a possible advanced superconducting undulator for the Munich LWF accelerator. This undulator is forseen to be based on Nb_3Sn superconducting wire. The assumed parameters are listed in Table 2.

Very important factors are the energy reproducibility and the the energy spread of the electron beam, which is assumed to be ∼10%. This might be an upper limit, but for

Table 1: Survey of recently achieved beam parameters with laser-wake-field accelerators

	Beam energy [MeV]	ΔE/E shot-to-shot	σ_E/E single shot	I_{peak} [kA]
Lund [4]	100	12%		
ASTRA [5]	∼80	30%	3%	0.5
ENSTA [6]	179	12%	(24%)[1]	
LBNL [7]	480	6%	5%	0.7
LBNL [7]	1000		2.5%	0.8
JETI [8]	64	5%	2.2%	2.8
Munich[2]	200		3.4%	1.0

Table 2: The parameters of a possible superconducting undulator for the Munich LWF accelerator

Undulator period	5 mm	Periods	200
Gap width	2 mm	B_{max}	0.96 T
Undulator length	1 m	K-value	0.45

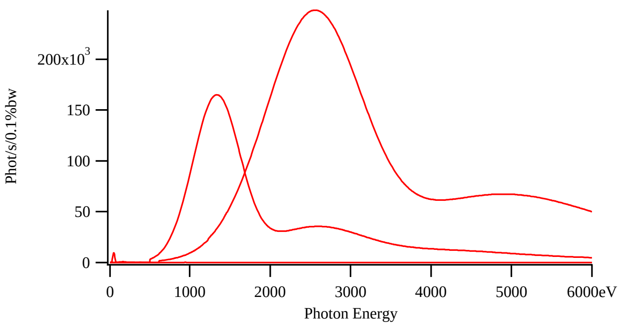

Figure 1: The calculated first harmonics of the photon spectrum for an electron energy of 0.2 GeV (small peak on the left), 1.0 GeV and 1.4 GeV.

demonstration purposes this conservative value was chosen. Fig. 1 shows the first harmonics of the spectra calculated for 0.2, 1.0 and 1.4 GeV electron energy. The line-broadening effect of the energy spread in the electron beam is clearly visible for the higher energies.

GENERATION OF MONO-CHROMATIC PHOTON BEAMS

The generation of monochromatic undulator radiation via the SASE effect requires an electron beam with a very low energy spread. The energy spreads achieved in LWF accelerators are one order of magnitude above the energy spread achieved in conventional accelerators. The high Pierce parameter resulting from the high peak current achievable in LWF accelerators helps to compensate the high energy spread. However, to achieve monochromatic light via the SASE effect relying on spontaneous emission, additional methods to compensate the high energy spread are necessary.

One possibility would be the spectral dispersion of the electron beam combined with an undulator with a laterally varying B field, so that the effective K value changes with the transverse position. The spectral dispersion of the beam can be achieved for example either by deflecting the beam twice by a small angle or by a single deflection by 180°. An additional advantage of the beam deflection in general is, that it allows for an easy separation of the laser from the electron beam and that it facilitates the vacuum design. I.e. getting rid of the remaining plasma before it enters the undulator.

Fig. 2 shows one possibility to achieve an undulator with laterally varying K value by tilting the undulator coils against each other. The electron beam is dispersed in a

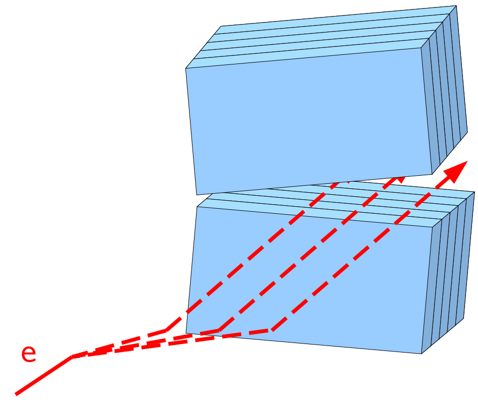

Figure 2: A schematic drawing of the spectral dispersion of the electron beam, combined with a tapered undulator to achieve a laterally varying B-field.

way that electrons with different energies 'see' a B-field and thereby a K-value matched to their energy. The necessary condition for the separation of different energies is, that the dispersion is larger than the beam emittance and the condition for the generation of monochromatic emission is:

$$\frac{1}{\gamma^2}\left(1+\frac{K^2}{2}\right) = const. \qquad (3)$$

From this equation the necessary range of the magnetic field strength to compensate the energy spread can be calculated. Assuming a γ of 400 and a K factor of 2, the value of K has to increase to 2.293 if the energy increases by 10%. With λ_u fixed, the relative change in the magnetic field is the same as for the K value. In this case the magnetic field variation is 14.7%.

Another possibility to achieve a varying K-value is a lateral variation of the period length. In this case the necessary change in period length can be calculated from Eq. 1. With λ and B fixed, λ_u has to increase by 7.4% to compensate for a 10% higher energy. Of course both methods can be combined if this proves necessary.

A third possibility would be to use an undulator geometry with an inherently strong field gradient. For example cylindrical undulator coils with the electron beam entering the undulator at a small lateral displacement. Fig. 3 shows a visualisation of the period length variation and the cylindrical design options. A possible drawback of the cylindrical undulator design would be that the K value does not vary linearly with lateral position. That means that it becomes more difficult to match the dispersion to the variation of the K value.

PHOTON NUMBERS

If the energy spread can be compensated as described above both the spectrum and the brilliance of the emitted light offer unique experimental opportunities. In this section the spectrum and brilliance for an example undulator are calculated under the assumption that the effect of the

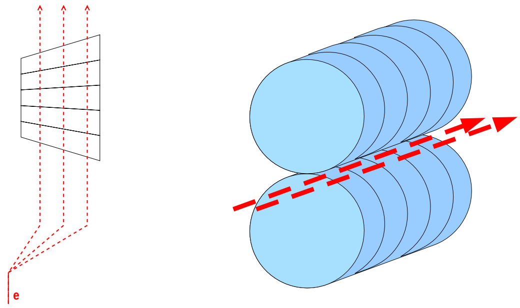

Figure 3: Alternative methods to achieve a laterally varying K-value. Left: variation of the period length (top view), right: cylindrical undulator coils.

energy spread can be reduced by two orders of magnitude, so that an effective energy spread of 1‰ is achieved.

Fig. 4 shows the calculated spectrum, including the higher harmonics, for the undulator detailed in Table 2 and an electron beam with the normalised emittance of the Munich accelerator and 1 GeV energy. Fig. 5 shows the calculated brilliance for the same undulator. The photon number in the first harmonic is of the order 10^{16} in 10 fs and the peak brilliance is $\sim 10^{23}$.

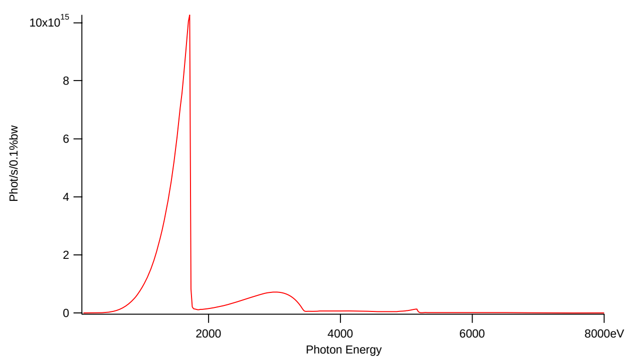

Figure 4: Number of photons vs. photon energy produced in a superconducting undulator for a 10 fs electron pulse driven by a LWF accelerator.

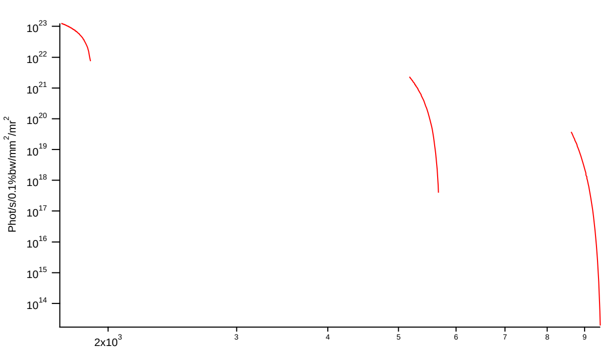

Figure 5: Calculated brilliance of the radiation produced in a superconducting undulator for a 10 fs electron pulse.

These values are calculated with the natural emittance and source size of the Munich accelerator. If magnet optics are used to fit the β factor of the beam to the undulator, the harmonic peaks become much more narrow and the photon number in the first harmonic increases to $2.8{*}10^{17}$ while the peak brilliance stays essentially the same.

These results show that LWF accelerator driven, superconductive undulators could be a very promising source for ultra-short time physics and other applications requiring a high brilliance.

SUMMARY

Laser-plasma / Laser-Wakefield (LWF) accelerators together with specially designed superconductive undulators can be an excellent light source for future femto-second experiments. The comparatively high energy spread of the LWF accelerators can be compensated up to a certain degree by an energy dispersion of the electron beam by a chicane and specially adapted undulator designs. However, due to the high bunch charge the effect of the emission of synchrotron radiation in the chicane may have a non-negligible effect, which might pose a limit on this technology. These effects and the actual undulator design are still under investigation.

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