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Two novel undulator schemes with quadrupolar focusing for the VUV-FEL at the TESLA Test Facility

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Abstract

At DESY in Hamburg a Free Electron Laser for the VUV spectral range at 6.4 nm using Self Amplified Spontaneous Emission is under construction. It will use the electron beam of the TESLA Test Facility. One of the main components is an undulator of 30 m length. In order to keep the electron beamsize small over the full undulator length an alternating quadrupole field has to be superimposed. In this paper two novel undulator schemes with these properties are proposed. The 3D-code MAFIA is used to calculate the magnetic properties. The results are presented and discussed.

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Introduction

At DESY it has been decided to build a Free Electron Laser in the VUV spectral range (VUV-FEL) based on the principle of Self Amplified Spontaneous Emission (SASE) [1]. It will make use of the electron beam of the TESLA Test Facility (TTF), a linear accelerator which is already under construction [2]. The TTF will provide a very low normalized emittance ($\leq 2\pi mm \cdot mrad$), an ultra-short bunch length ($50\mu m$) and a peak current of about 2500 A. These properties will make the TTF an excellent driver for an FEL. At a nominal energy of 1 GeV, it will operate at a wavelength of 6.4 nm. In contrast to FEL's using optical cavities, a SASE FEL needs a very long undulator of a total length of about 30m. Furthermore the undulator needs a superimposed quadrupolar field with an alternating gradient to produce a FODO lattice, which is used to keep the beamsize consistently small over the whole undulator length.

There have been two different undulator schemes reported in literature which have focusing properties. One uses canted poles [3–5], the other makes use of an additional attachment of magnets to provide these properties [6,7]. The undulator structure, which is needed for a VUV-FEL at the TTF differs from other devices with similar properties build so far in three aspects. First, a quadrupole lattice consisting of focusing, non-focusing and defocusing sections is needed to keep the beamsize at a constant low value over the whole length. Second, high gradients of up to 20 T/m are needed. Third, the undulator for the VUV-FEL will have a total length of about 30 meter. The requirements for the quality of the magnetic field will be high and need a precise magnetic characterization.

As a consequence, a magnetic assembly is desired which

- 1.) allows for a superimposed alternating gradient (FODO lattice)
- 2.) provides a sufficiently high gradient
- 3.) allows easy access to the field region for magnetic measurements and for the insertion of vacuum chambers.

In this report we propose two novel hybrid permanent magnet (PM) arrays, which have these properties. Both are planar and allow for completely free access to the field region.

A detailed study and comparison of these structures using the 3-D code MAFIA is presented. Only strong focusing as generated by quadrupolar fields is considered. Natural focusing as is present in any periodic field is neglected. The study is not a final design study. Its intention is to work out the potential of these structures for the undulator for the VUV-FEL.

The basic magnet design is based on Halbach's hybrid configuration [8]. The design parameters for this investigation were chosen to have the photon energy of the first

harmonic at 192 eV at an electron energy of 1 GeV [1]. The magnetic design gap was conservatively assumed to be 12 mm. The period length was chosen to 27.3 mm. The peak field is about 0.5 T. The exact results may vary slightly for the different magnetic configurations investigated throughout this article.

Magnetic fields and gradients

In the iron free region, inside the gap an undulator field with a superimposed quadrupole field can be derived from a scalar potential of the form:

$$\chi = -\frac{B_{max}}{\kappa} \sinh \kappa y \sin \kappa z - Qxy \quad (1)$$

Here B_{max} is the peak field, Q the gradient, $\kappa = 2\pi/\lambda_0$ where λ_0 is the period length. The coordinate system is illustrated in Fig.1.

The magnetic field distribution is therefore given by:

$$\begin{aligned} B_x &= Qy \\ B_y &= B_{max} \cosh \kappa y \sin \kappa z + Qx \\ B_z &= B_{max} \sinh \kappa y \cos \kappa z \end{aligned} \quad (2)$$

The gradient may be obtained by:

$$\frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x} = Q \quad (3)$$

The field distributions, which can be generated by discrete permanent magnet arrays may differ considerably from the ideal ones given by eqs.(2). First, besides the pure quadrupole term Q , higher multipoles, such as octupoles *etc.*, may be present, especially when well away from the symmetry axis. Second, the gradient needs not to be constant along the electron beam direction. However, it will have the periodicity of the period length. It is therefore very useful to distinguish between the local, z -dependent gradient given by $Q = \partial B_y / \partial x$ and a gradient Q_{ave} averaged over an undulator period, which is defined as:

$$Q_{ave}(x, y) = \frac{1}{\lambda_u} \int_z^{z+\lambda_u} \frac{\partial B_y(x, y, z')}{\partial x} dz' = \frac{1}{\lambda_u} \frac{\partial}{\partial x} \int_z^{z+\lambda_u} B_y(x, y, z') dz' \quad (4)$$

where the integral in the second equation is the first field integral.

Four Magnets Focusing Undulator (4MFU)

Fig.1 shows the first proposal using four additional magnets per half-period. The magnets providing the undulator field (magnetized along z) have been recessed by 6 mm so that there is now space for the focusing magnets which are polarized parallel and anti-parallel along the y -direction as can be seen in Fig.1. This configuration is a modified adaptation from Tatchyn's proposal for generating quadrupolar fields with PM arrays [9]. The gap in this configuration is completely free. The achievable gradients depend on the height of the focusing magnets and their separation distance. The gradient becomes independent of the horizontal width of the focussing magnets if the width is choosen large enough. Fig.2 shows the tuning curve for the average gradient if the separation distance is changed. Gradients up to about 25 T/m can be obtained. To be on the safe side and to have some tunability to both sides a separation distance of 5.5 mm was taken with a corresponding gradient of 20 T/m . Fig.3 shows the transverse gradient along z at different x -values. It varies periodically along the electron beam axis with twice the frequency of the fundamental. It is smallest at the indicated pole positions. The RMS beamsize of the TTF is only 0.05 mm . At this x -value the gradient variation corresponds to a variation of the field amplitude with twice the frequency of the fundamental of $8.4 \cdot 10^{-4}$ T which is 0.17% of the peak amplitude. A preliminary list of design parameters can be found in Table 1.

Side Magnets Focusing Undulator (SMFU)

Fig.4 shows the other alternative using side magnets which extend over several poles. The magnets are brought close to the beam by choosing the width of the poles as small as possible (10 mm). The focusing magnets are embedded in the main magnets which produce the undulator field.

Fig.5 shows the average gradient as a function of the separation distance of the side magnets which cannot be smaller than 10 mm . The maximum average gradient is about 22 T/m . Finally, the variation of the mean gradient is shown in Fig.6. It is very x -dependent. However, extrapolation to the RMS beam-size of 0.05 mm shows variational amplitude of $5.4 \cdot 10^{-4}$ T corresponding to 0.11% of the peak amplitude. Table 1 summarizes the design parameters of the SMFU.

Summary and discussions

Two novel PM based hybrid structures with a periodic plus a quadrupole field have been proposed. Their inherent advantages are:

- They are completely planar. There is free access from the side for magnetic measurements and the insertion of a vacuum chamber.
- Field gradients larger than 20 T/m can be obtained for the parameters of the VUV-FEL at the TTF.
- Fine tuning by adjusting the focusing magnets is possible in both cases.
- The peak field in both proposals is independent of the focusing strength thus allowing for focusing, zero gradient and defocusing sections within an undulator without affecting the peak field.

A possible drawback of the SMFU may be its small pole width of only 10 mm as compared to the 12 mm wide gap. On the other hand, the beam of the TTF is very small and exact alignment of the focusing structure is required in any case in order to have the beam on the quadrupolar axis. The periodic variation of the field gradient along the z -axis might induce some effect which has to be investigated.

The work presented in this paper is part of a detailed analysis of a variety of PM structures with quadrupolar focusing. To some extent, the periodic variation of the gradient seems to be a characteristic for all structures, which has been investigated [10]. The influence of the periodic perturbations on the FEL performance will be the subject of another publication. First results indicate that the influence of the gradient variation can be neglected [11].

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Figure captions

- Figure 1. 3-D perspective view of $1\frac{1}{2}$ periods of the 4MFU hybrid undulator.
- Figure 2. The dependence of the average gradient on the separation distance between the focusing magnets.
- Figure 3. The variation of the gradient along the undulator axis for different values of x . Arrows indicate the location of the poles.
- Figure 4. 3-D perspective view of $1\frac{1}{2}$ periods of the SMFU hybrid undulator.
- Figure 5. The dependence of the average gradient on the separation distance between the focusing magnets.
- Figure 6. The variation of the gradient along the undulator axis for different values of x . Arrows indicate the location of the poles.

Table 1		
PARAMETERS FOR	4MFU	SMFU
Period length	27.3 <i>mm</i>	27.3 <i>mm</i>
Peak field	0.5 <i>T</i>	0.5 <i>T</i>
Pole gap	12 <i>mm</i>	12 <i>mm</i>
Pole overhang	0.5 <i>mm</i>	0.5 <i>mm</i>
Focusing magnet separation	5.5 <i>mm</i>	12 <i>mm</i>
Magnet	70×50×10 <i>mm</i>	40×50×10 <i>mm</i>
Pole	50×40×3.65 <i>mm</i>	10×40×3.65 <i>mm</i>
Focusing magnet	15×6×10 <i>mm</i>	15×10× length of quad.
Gradient	20 <i>T/m</i>	20 <i>T/m</i>