Magnetic measurements on the undulator prototype for the VUV - FEL at the TESLA Test Facility

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Abstract

For the VUV - FEL at the TESLA Test Facility a 30 m long combined function undulator is under construction which integrates an alternating sequence of focusing and defocusing quadrupoles (FODO lattice) with an sinusoidally varying undulator field having a period length of 27.3 mm.

A planar magnet structure with a fixed gap using permanent magnet technology has been proposed. A brief description of the magnetic design and its basic working principle is given.

First results of magnetic measurements were performed on a 0.9 m long prototype structure and are reported and discussed in this contribution. The peak field , the gradient of the superimposed quadrupolar field as well as the adjustability of the quadrupole strength and the exact location of its axis in horizontal and vertical direction were measured. The results demonstrate that the proposed combined function magnet structure is very promising for the use in the SASE FEL at the TESLA Test Facility.

1 Undulator Design

At DESY in Hamburg a Free Electron Laser (FEL) for the VUV spectral range down to 6.4nm using the principle of Self Amplified Spontaneous Emission (SASE) [1,2] is under construction. It will use the electron beam of the TESLA Test Facility (TTF) [3,4] and will be built in two stages:

Phase 1 will have a nominal energy of up to 300 MeV which the potential of going up to 390 MeV. It will serve as a system test for the superconducting accelerator and a proof of principle for the SASE FEL. In this case an undulator

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Table 1
Parameters for Phase 1 and 2 of the TTF

		Phase 1	Phase 2
Energy	[GeV]	0.3	1.0
normalized Emittance	[mm mrad]	2	2
Energy spread	[%]	0.17	0.1
Bunch length	[μm]	250	50
Peak current	[A]	500	2500
Radiative wavelength	[nm]	72	6.4
Saturation length	[m]	14	25
Saturation Power	[GW]	0.2	3.0

with a minimum length of 14.33 m is required. A detailed description of Phase 1 can be found in [5]. In Phase 2 see ref. [3], the energy will be raised to 1 GeV and the undulator needs to be extended to at least 28.7 m. For practical reasons it has to be subdivided into modules of about 4.5m length which can be handled and manufactured with the required accuracy. There have to be gaps between undulator sections of about 0.3m for beam position monitors and other diagnostic equipment as well as pumping ports etc. The undulator design for Phase 1 and 2 is kept as identical as possible. Table 1 shows some basic parameters of the TTF in Phase 1 and 2. Table 2 specifies the design parameters of the undulator.

The combined function undulator which is needed for the FEL has to integrate two functions:

(i) It has to provide the sinusoidal field so that the FEL process can take place.

(ii) It simultaneously has to provide the alternating gradient field of about ± 20 T/m for the FODO lattice which is superimposed to the undulator field.

For the small β-function values required for the TTF-FEL (see table 2) there is no alternative to a combined function type undulator. Permanent magnet (PM) technology using state of the art NdFeB magnet material has been chosen for the undulator [6-9]. Fig 1 shows a schematic 3-D view of $1\frac{1}{2}$ periods of the "Four Magnet Focusing Undulator" (4MFU) design which has been proposed to be used for the FEL at the TTF. It is based on a regular Halbach type hybrid structure [10]. There is no gap variation. The gap between the poles is kept fixed at 12mm. To finetune the undulator field the exact strength of each pole can be changed by slightly adjusting each pole tip individually by a few tenths of a millimeter. The magnets between the poles, which are magnetized parallel and antiparallel to the beam axis are recessed by 2.5mm to

Table 2
Undulator and FODO Parameters for Phase 1 and 2

Gap	[mm]	12	
Period Length	[mm]	27.3	
Undulator Peak Field	[T]	0.5	
K - Parameter		1.27	
Design Gradient	[T/m]	18.3	
Number of poles per module		327	
Total length per module	[mm]	4492.2	
Length of FODO quad section	[mm]	136.5	
FODO Period Length	[m]	0.9555	
Number of FODO periods per module		5	
Separation between Undulator Modules	[m]	0.2853	
		Phase 1	Phase 2
Number of undulator modules		3	6
Total length	[m]	14.33	28.67
Focal strength of FODO quads	[m^{-1}]	2.50	0.75
Total natural undulator focal strength	[m^{-1}]	1.788	0.322
Phase advance per FODO cell	[Deg]	52	18
β_{Max} in Undulator	[m]	1.5	3.5
β_{Min} in Undulator	[m]	0.5	2.5
Ave. Beamsize in Undulator	[μm]	55	55

create space for the magnets providing the focusing. These magnets are magnetized parallel / antiparallel to the Y-axis as can be seen in Fig. 1. They can be moved horizontally by set screws. By changing the horizontal separation distance between these magnets in the top and bottom jaw simultaneously the gradient can be changed. Moving all magnets horizontally the horizontal position of the quadrupole axis can be changed accordingly. Increasing / decreasing the separation distance in the top and decreasing / increasing it in the bottom jaw will move the position of the quadrupole axis down or up, respectively. Using geometrical arguments it can be shown that on the quadrupole axis the field generated by the symmetric undulator part is not influenced by the antisymmetric array of focusing magnets and its strength. This was also verified with 3-D calculations using the MAFIA code [6,9]. The 4MFU design therefore combines the following properties:
(i) It is a completely planar structure, which allows for very good access to

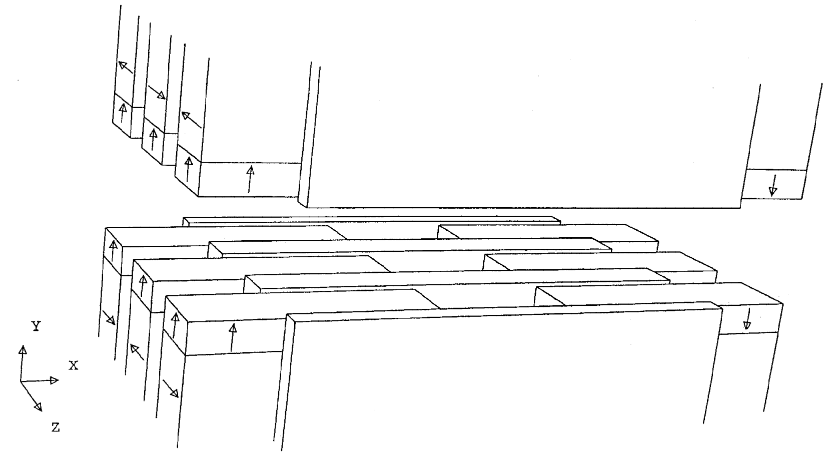

Fig. 1. 3-D perspective view of $1\frac{1}{2}$ periods of the proposed 4MFU structure for the undulator for the TTF. For details see text.

the field region at the beam position allowing for high accuracy field measurements as well as an easy installation of the vacuum chamber without breaking of any magnetic circuits.

(ii) The gradient can be as large as ≈20 T/m.

(iii) The exact value and the precise location of the quadrupole axis is fine tunable.

(iv) Undulator and focusing fields are decoupled. This means that on the quadrupole axis the sign and magnitude of the field gradient has no influence on the undulator field and vice versa.

For these properties the 4MFU principle was chosen as the basis of the undulator setup for the TTF.

2 Prototype Structure

A 0.9m long Prototype structure of this undulator has been built. It is shown in Fig. 2.

In order to reduce design and construction effort, the mechanical support system as well as the girders were already designed for one 4.5m long undulator module for the TTF. Each undulator is planned to consist of 5 magnetic segments of approximately 0.9m each. One of these segments was built and is used for the prototype structure. It is visible at the left end of the stucture. Roughly in the middle of this module the focusing magnet attachment is visible. All components in this prototype structure will later be reused to complete the first 4.5m long undulator module for the Phase 1 undulator.

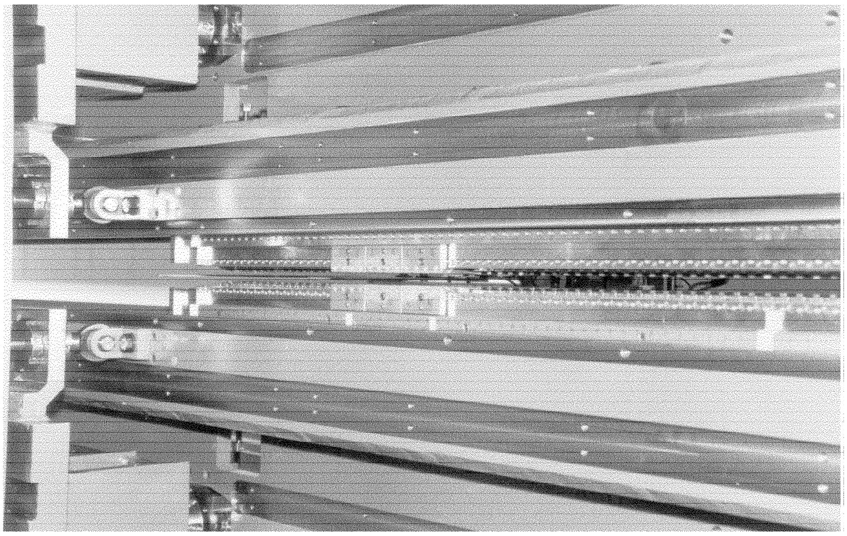

Fig. 2. View of the 0.9m long prototype structure of the 4MFU. One magnetic segment mounted on the left side of the 4.5m long girders designed for the FEL undulator is visible. The focusing section is about in the center of this segment.

3 Magnetic measurements

A new 12m long bench was used to characterize the magnetic performance of the prototype structure. It provides sufficient mechanical accuracy for the magnetic measurements of the combined function undulator for the FEL at the TTF.

Hallprobe measurements using a transverse probe were used to check the quality of the field and to exactly adjust the end poles for field integral correction right before the focusing magnets were installed. This "naked" undulator served as a basis for the following attachment of the focusing magnets.

In order to test the quality as a combined function undulator the focusing strength and the exact location of the quadrupole axis of each quadrupole section was to be measured. The Rectangular Coil Method (RCM) was developed for this purpose and is briefly described: A rectangular coil with a length along the beam axis much longer than that of a quad section is used. At TTF the length of one quad section is 136.5mm and that of a focusing free section is 341.25mm. So this condition can be easily satisfied.

The cross talk resulting from the undulator field can be minimized by choosing the coil length to be a multiple of a period length. we used 327.6mm, which corresponds to 12 periods at a length of the focusing section of 136.5mm. In addition measurements should be averaged over one undulator period. The transverse width of the coil has to be large enough so that the ends are in field free region. 330mm were found sufficient in our case.

If this coil is moved transversely in the horizontal plane along z, starting at z_a of quadrupole having its center at z_0 the flux change $\Delta\Phi$ induced in this coil is given by:

$$\Delta\Phi = N \cdot L \cdot \int_{z_a}^{z} B_y(z') \cdot dz' = N \cdot L \cdot g \cdot \int_{z_a}^{z} (z' - z_0) \cdot dz'$$

$$= N \cdot L \cdot g \cdot \tfrac{1}{2}((z - z_0)^2 - (z_a - z_0)^2)$$

here N is the number of windings of the coil , L is the effective quadrupole length and g is the gradient. The flux is recorded with an analog integrator at equidistant intervalls of z. By fitting a parabola of the form :

$$\Delta\Phi = a \cdot z^2 + b \cdot z + c$$

to the data, the integrated gradient can be evaluated :

$$g \cdot L = 2 \cdot a/N$$

The horizontal center position is given by:

$$z_0 = -b/N \cdot L \cdot g = -b/(2 \cdot a).$$

Analogous results for the vertical (y) direction are obtained if the coil is moved vertically instead of horizontally. In this case $B_y(z)$ has to be replaced by :

$$B_z(y) = -g \cdot (y - y_0)$$

We note that the coefficients of the higher order normal multipoles can be evaluated as well if an appropriate polynomial is fitted. First experience made with this measurement technique shows that a typical reproducibility of 7-8 μm RMS for the quadrupole centers in the horizontal and vertical direction is achievable, so far without any optimization effort. The gradient dertermined in this way was reproducible to 0.5 % RMS.

4 Results and discussion

The objective of the prototype stucture was to test if a combined function undulator following the proposed 4MFU design is doable and suitable for the use in the FEL at the TTF . The most interesting problem was to see how the array of focusing magnets behaves on top of the undulator stucture. First, the "naked" undulator with no focusing magnets attached was measured to have a peak field of almost exactly 0.5T. After this measurement one quadrupolar section was installed and the RCM method descibed above was used to

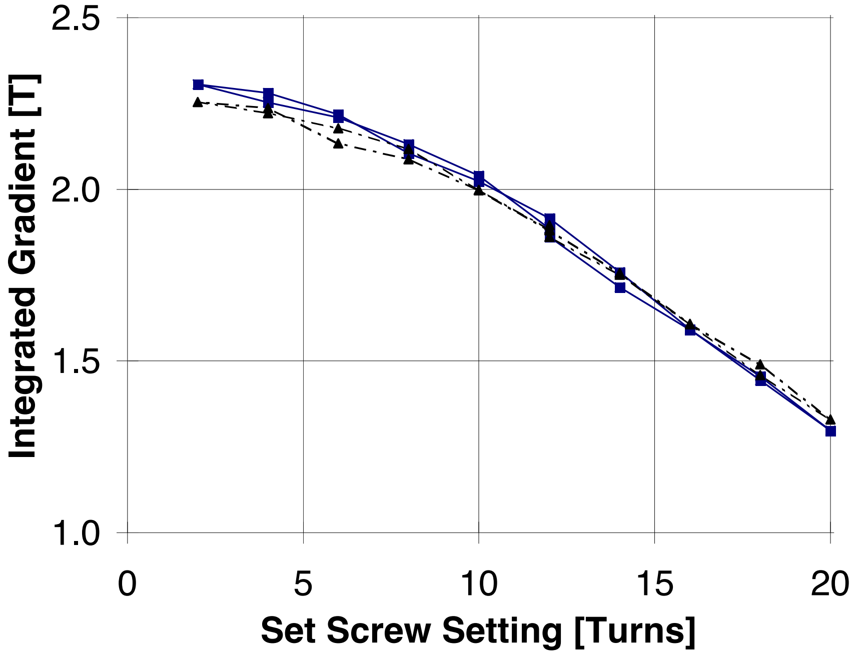

Fig. 3. Integrated Gradient obtained with RC Method. Full Line from Vertical, dot dashed horizontal movement. Set screw pitch is 0.7mm / Turn

measure the properties of this section. Fig. 3 shows the maximum integrated gradient gL as a function of the separation distance of the magnets. Several measurements were taken at identical settings and are hard to distinguish in Fig. 3. The separation distance is most practically measured counting the turns of the set screws which have a 0.7mm pitch. The two curves in Fig. 3 correspond to measurements using vertical and horizontal movement of the coil, i. e. gL is determined independently from B_y and B_z variation They agree better than 1.6%. The small deviation is believed to be due to the artefacts from the superimposed undulator field.

The zero in Fig. 3 corresponds to zero separation distance. It can be seen that it can nicely be adjusted from 2.3 T down to about 1.3 T using the adjustment range of the screws of 20 turns corresponding to 14mm. Using the length of the quadrupole section of 0.1365m as an effective length the maximum average quadrupole gradient is evaluated to 16.85 T/m .

Fig. 4 shows the measured horizontal position of the quadrupole center if all focusing magnets are moved simultaneously. The center is moving at a rate corresponding to the pitch of the set screws. The total range is ± 2.5 mm in this case and can be made larger if required. Note, the zero position shown in Fig. 4 on the vertical axis is arbitrary and does not correspond to the center of the undulator structure.

Fig. 5 finally shows two measurements of the movement of the vertical center. Vertical upward movement can be achieved if the separation distance of the

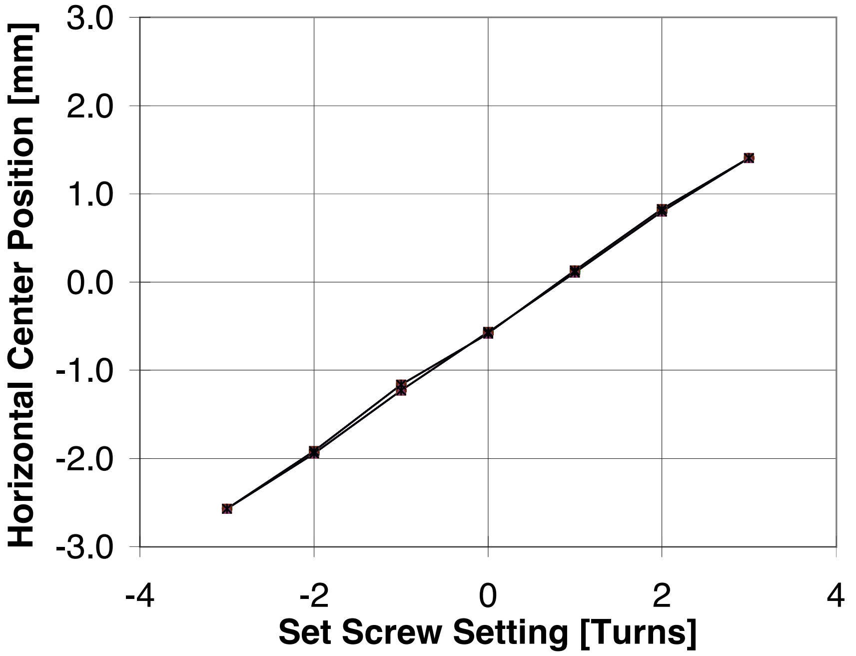

Fig. 4. Horizontal center position as a function of set screw position

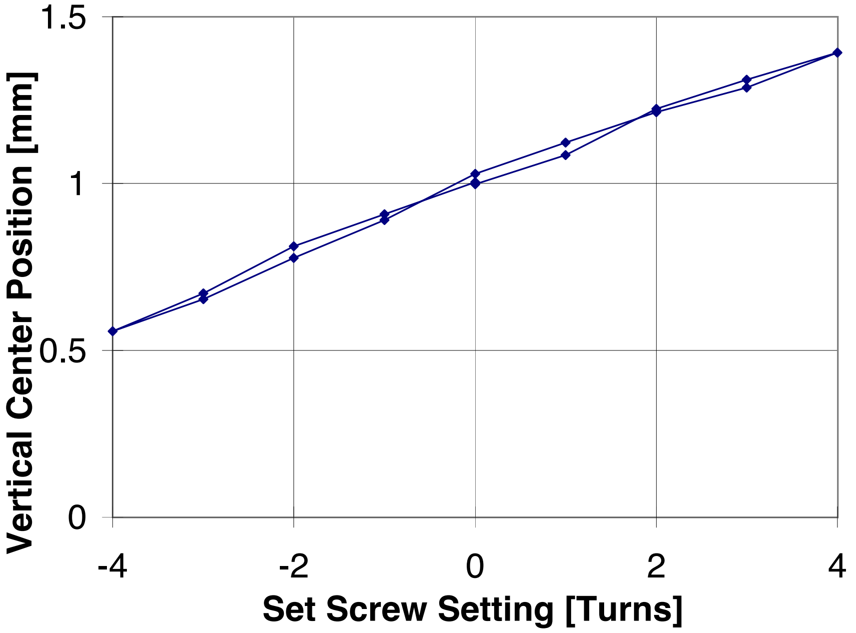

Fig. 5. Vertical center position as a function of set screw position.

upper magnets is increased while that of the lower magnets is decreased. The adjustment range is small, only ±0.4mm, but still sufficient. Again the vertical zero position does not correspond to the zero position of the undulator structure.

The cross talk between the adjustments is small. For example if the vertical center position is changed only minor changes are observed in the horizontal

Table 3
Results of magnetic measurements on the prototype structure

Undulator Peak Field	[T]	0.5
Max. average Gradient @ Separation=0	[T/m]	16.93
Gradient Variation	[T]	1.3 - 2.3
Vertical center adjustment range	[mm]	$\pm$0.4
Horizontal center adjustment range	[mm]	$\pm$ 2.5
Integrated normal Quadrupole @ 4.2mm	[T]	2.078$\pm$0.069
Integrated normal Sextupole —"—	[T/m]	70.6$\pm$69.1
Integrated normal Octupole —"—	[T/m^2]	22856$\pm$151015

center position and the magnitude of the gradient. Moreover such changes can be easiliy adjusted by slight changes in a second iteration step if needed.

The adjustability demonstrated above is very important for a combined function undulator. Extended computer simulations have demonstrated that the overlap between electron and laser beam can only be guaranteed if the alignment of the quadrupole axes is about 10-15 μm [11,12]. So all ten FODO quads of an undulator module have to be aligned with this precision. In this contribution it has been shown that both, the adjustability and a measurement procedure, the RCM which provides sufficient accuracy are readily available.

Table 3 reproduces some of the magnetic results for this structure. The first normal multipole coefficients were also determined in the good field region near the electron beam Because this region extends to only $\pm$ 2mm, the uncertainty at the higher multipoles is rather large.

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