INSERTION DEVICES FOR 4TH GENERATION LIGHT SOURCES

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Abstract

The next generation of light sources will consist of Free Electron Lasers (FEL's) using the principle of Self Amplified Spontaneous Emission (SASE).
They will be driven by Linacs using low emittance photocathodes. Transverse RMS beam sizes are typically 20 - 50 µm and the bunch lengths are of the same magnitude. Worldwide several projects are under construction or in a design phase to cover the whole spectral range down to 0.1 nm. Very long undulators are needed for SASE FELs in order to reach saturation.. Their lengths may easily reach 100m for the X-ray FEL's. In order to minimize the total length and maximize output power they must meet two criteria: First, tough magnetic specifications must be fulfilled in order to have optimum overlap between electron and laser beam. Second, additional external strong focusing is required in order to keep the electron beam size small over the whole undulator length. In this contribution problems related with the design of very long undulators will be addressed. Alternative ways of providing the strong focusing are outlined and special attention is given to the magnetic design of undulators with integrated strong focusing. As an example the work done at the undulator under construction for the FEL at the TESLA Test Facility in Hamburg is presented.

1 INTRODUCTION

At the begin of the 1980 's the principle of Self Amplified Spontaneous Emission (SASE) has been discovered.[1,2] In contrast to conventional FEL's a SASE FEL completely avoids the use of reflecting mirrors. With the development of low emittance RF photo guns during the past ten years SASE FEL's down to a wavelength of 0.1 nm now become technically feasible. It is now widely accepted that SASE FEL's will represent the next, the 4th generation of light sources. [3]
Several projects in the VUV region are under construction at DESY, Hamburg [4], APS, Argonne [5] and NSLS, Brookhaven [6]. Two more have been proposed in the X-ray regime : The Linear Coherent Light Source (LCLS) at Stanford [7] and the X-ray FEL at TESLA in Hamburg [8]

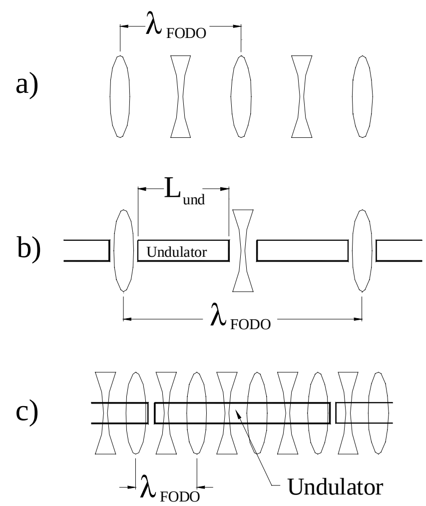

Fig 1 a) FODO Lattice schematic
b) Separated function undulator:
c) Combined function undulator

2 UNDULATORS FOR SASE FEL's

In contrast to Undulators for conventional Sychrotron Radiation (SR) Sources. those for SASE FEL's have to be much longer. Their length may easily reach 100m for X-ray FEL's [7,8]. Additional focusing is required in order to keep the transverse beam dimensions within a well specified variation. Most commonly a sequences of focusing and defocusing quadrupoles a so called FODO lattice is used for this purpose. This is sketched in Fig 1 a-c). Fig. 1a) shows the quad sequence of a conventional FODO lattice. It is characterized by the so called FODO cell length λ_{FODO}. The β function in a FODO lattice varies between a minimum and a maximum value which can be calculated in the thin lens approximation as :

$$\beta_{Max,Min} = 2 \cdot f \pm \lambda_{FODO} / 2 \;\; ; \;\; \frac{1}{f} = c \cdot e \cdot L_Q \cdot \frac{g}{E} \qquad (1)$$

Here f is the focal length of the quads of length L_Q, g is the field gradient, E the kinetic energy , c the velocity of light and e the elementary charge. In order to combine a FODO lattice as sketched in Fig 1 a) with an undulator two possibilities exist: FODO lattice and undulator may be separated, Fig. 1 b) or combined., Fig 1 c). Separated function, Fig 1 b), means that the undulator is interrupted for the quadrupoles. Therefore focusing sections and undulator modules alternate. A minimum FODO cell length of about 3.6 m seems possible assuming 1.5m for a minimum undulator length and 0.3m for the quads. For shorter cell lengths the undulators become too short and the interruptions too long. Smaller cell lengths can be realized if a combined function undulator , Fig 1 c) is considered. It utilizes a magnetic design which combines the generation of the periodic undulator field with a strong focusing quadrupole field. The advantage is now that λ_{FODO} can take very small values well below 1m and interruptions of the undulator structure are not needed at all. The undulator may even be built seamless. The price is a more sophisticated magnetic design which is considerably more complicated to implement..

For a FEL with its set of specific parameters there is a optimum β function which determines what kind of design is to be used in the undulator region. The average β function is given by the strength of the quads only, but its variation is given by λ_{FODO} / 2. The tolerable variation also called beat therefore determines the required FODO cell length. An optimum value cannot be given analytically and can only be found using numerical simulation codes. There is a trade off between other critical FEL parameters such as peak current, bunch length and beam emittance. Codes such as TDA-3D can be used to find the optimum β function as well as the influence of the β beat. As a rough rule of thumb VUV FEL's with electron beam energies in the 1 GeV range need low β values in the order of a very few meters as compared the X ray FEL's with beam energies up to 25 GeV which require β values well above 10m, The tolerable β beat may exceed 50% of its average value or even more

At energies well below 1 GeV the weak natural focusing of an undulator in the vertical plane together with horizontally focusing quads in the intersections can be used. This way has been chosen for the LEUTL project [7]. In the vertical plane therefore the focusing is similar to that of a FODO lattice, where the focusing is done by the undulator which can be considered as a thick distributed lens. The defocusing is done by the quads in between the undulators. Since in the horizontal plane the undulator acts like a drift space only a sequence of focusing quads is effective in this direction. This focusing scheme resembles the separated function approach but at comparable β beat allows for about twice the uninterrupted undulator length.

3 ALIGNMENT TOLERANCES

The closed overlap between the electron and laser beam is essential for the SASE process to take place. As an empirical rule from many simulations it has turned out that an overlap degradation which does not exceed about 20% of the RMS beam size is still tolerable and does not deteriorate the SASE process too much. In this context it is irrelevant if the overlap is disturbed by field errors in the undulator or by misalignment of quadrupoles. Consequently this imposes tough requirements on the second field integral of the undulator field, i. e. the beam excursion as well as on the alignment of the quadrupoles of the FODO lattice.

For example the energy of the Phase I TTF FEL is 300MeV, the transverse beam size is about 60μm. The tolerance on the second field integral in this case is only 12 Tmm^2. A similar argument holds for quadrupole alignment errors. Although a number of correctors should be planned in the undulator section the requirements are still a challenge for insertion device technology as well as for magnetic measurement techniques.

Separated function means that the quads are independent of the undulators. They can be electromagnets. So correctors are straight forward to implement in the coils Quad alignment is now decoupled from the undulator Beam based alignment methods like those developed for the final focus test beam in linear colliders can be applied [9,10]. Besides of different magnetic specifications the undulator in this case has no fundamental difference to those used as light sources in storage rings.

Combined function means that undulator and quadrupoles become one entity and the field of both are superimposed. This can be achieved in two different ways. A straight forward approach is to build a pure permanent magnet structure without iron parts inside a quadrupole, with a bore diameter quite of about 100mm or more. This approach was presented in an early LCLS proposal is now used for the VISA experiment [6]. Alternatively new magnetic designs like the one described below can be found which combine the generation of the undulator and of the quadrupole field in one structure. Here tolerance requirements mix. Correctors maybe limited in strength and difficult to apply due to space limitations. This imposes more stringent tolerances on the alignment and strength of the quads. Moreover new and appropriate measurement techniques are needed to measure the quad properties in the presence of the superimposed undulator field. Beam based alignment techniques have also been developed for combined function permanent magnet undulators which in this case requires the variation of electron beam energy [11-13].

4 COMBINED FUNCTION UNDULATOR

In literature there are several proposals to combine the generation of the undulator field with a strong field gradient.. An overview is given in [13,14]. As one of the first projects of its kind the combined function undulator under construction for the FEL at the TESLA Test Facility will be described in more detail.

The small β-function of only 3m, which is needed to optimize the FEL process was a basic input for the design consideration so that there was no alternative to a combined function undulator at all. Many design proposals found in literature were found inappropriate because they either limit or even block completely the accessibility of the gap region thus making precise magnetic measurements as well as the installation of the vacuum system after magnetic measurements very problematic. Furthermore since the focusing sections were integral parts of the undulator there was no fine tunability neither of the strength nor of the exact location of the quadrupole axis. In contrast the design proposal for the undulator for the VUV-FEL, which was given the name Four Magnet focusing Undulator (4MFU) combines the following properties :

1. It is a completely planar structure, which allows for very good access to the field region at the beam position. This is important for high accuracy field measurements but also for inserting the vacuum chamber without breaking magnetic circuits.
2. The gradient can be as large as 17 T/m. The exact value and the position of the quadrupole axis is fine tunable.
3. 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.

A detailed description may be found in ref [14-17]. Here it is only briefly described and illustrated in Fig 2 : Permanent magnet (PM) technology using state of the art

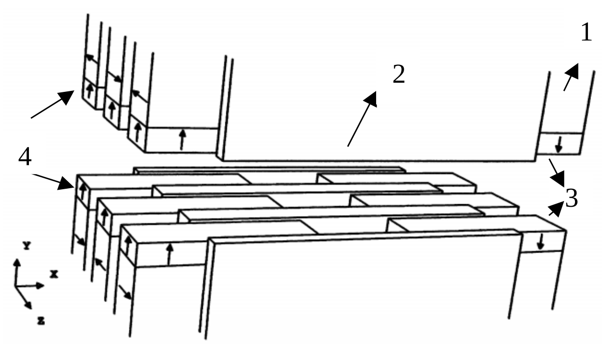

Fig. 2: The Four Magnet Focusing Undulator (4MFU) as an example for a combined function undulator .

1 : Magnets for the undulator field
2 : Poles
3, 4 focusing magnet arrays magnetized parallel antiparallel to the Y-axis

NdFeB magnet material has been chosen for the undulator. Fig 2 shows a schematic 3-D view of 1 ½ periods of the (4MFU) which has been proposed to be used for the FEL at the TTF. It is based on a regular Halbach type hybrid structure [18], consisting of the magnets creating the undulator field (1) and the poles conducting the flux (2). The gap between the poles is kept fixed at 12mm. There is no gap tunability.

In the 2.5mm recess between these magnet and the poles the focusing magnets arrays (3), (4) are placed. They are magnetized parallel / antiparallel to the Y-axis as can be seen in Fig. 2. Each of the four magnet arrays can be adjusted individually in the horizontal direction. This gives the required adjustabilty of the gradient as well as of the position horizontal and vertical quad center This is described in detail in ref. [19].

5 MAGNETIC OPTIMIZATION

Trajectory control in both transverse directions in very long undulators is a crucial problem.. In a long fixed gap device this problem can be solved in a straight forward manner. For the undulator for the TTF it is subdivided into the following steps:

1. At first the "naked" undulator in both transverse directions is optimized and error corrected. "Naked" means that there are no focusing magnets attached yet. The horizontal error field is measured using a suitable coil and integrator technique. The vertical B_y component is measured using a Hallprobe.
2. In the second step, the focusing magnet arrays are attached to the optimized undulator and the axes of the quadrupoles are aligned using the techniques described below.

Precise magnetic measurements are the basis for the verification of the specified values. Without the focusing magnets the undulator is just like any hybrid undulator. The only difference is the larger pole overhang of 2.5mm at the gap side. It has become state of the art to assemble hybrid undulators. Each magnet is individually measured characterized. The assembly of the magnet structure is made on the basis of these data. The method of "Simulated Annealing" was used to find a magnet configuration which minimizes field errors [20].

The horizontal field is measured using a 3x5x10 mm coil with about 3500 windings working in conjunction with an analog integrator. The method has been developed previously [21] and was further improved in sensitivity so that the second horizontal field integral of a 4.5 m long stricture can be measured with an accuracy of a few Tmm^2. The horizontal field errors are small. For their correction a very few horizontal shims should be sufficient. The experience with the first two out of the three undulator modules showed that 14 shims were sufficient for the first and only 3 were needed for the second which is also in accordance with the expectations from the Simulated Annealing procedure.

The vertical field has been optimized using a technique called technique called "Field Fine Tuning by Pole Height Adjustment" [22]. To do so the mechanical design of the structure is such, that all poles are height adjustable using set screws on either side of the poles which allow them to be moved in and out by few tenths of a millimeter. The optimization goal is to obtain an almost perfectly straight trajectory over the whole undulator length. The basic idea of the adjustment method is simple but rather complex to implement for an undulator system with 327 poles. It can be subdivided into the following steps:

- The field distribution along the electron beam axis is measured. The deviation of this field distribution from a hypothetically "ideal" one resulting in a perfectly straight trajectory is calculated.
- The response of a local gap change of one pole *i* onto the field of a neighboring pole *j* is determined experimentally. From these data the coefficients which couple the movement of a pole *i* with field change on a pole *j* can be extracted. Experience shows that there is only short range interaction and only near neighbors interact, i.e. $i - j \le 5$ is sufficient.

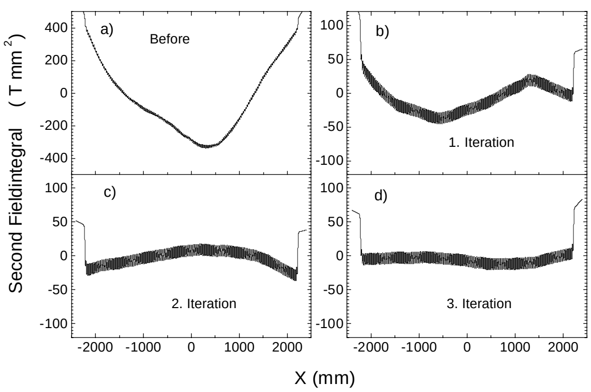

Fig. 3 Trajectory optimization of the first 4.5m long undulator module. Note the different scale in a); The results shown in b – c) have been obtained after three optimization steps

- The local gap changes of all poles, which are needed to produce the required correction, are calculated.
- Finally a list giving the pole numbers and the required local gap changes is generated.

The whole procedure is described in detail in ref [22]. Fig 3 shows the results of trajectory optimization of the first undulator module. Fig 3 a) shows the initial second field integral with an RMS value of 192 Tmm^2 , note the expanded scale in Fig 3 a) Successively three iteration steps are shown. The results are self explaining. After the last step and RMS value 0f 7.1Tmm^2 has been obtained, which is already very close to the 6.5 Tmm^2 which are due to the orbit oscillation. In any case they are well below the required specification of 10Tmm^2 . The optimization of one structure requires not more than 2-3 days. Experience has shown that the first iteration requires by far the most adjustments. Almost every of the 327 poles has to be tuned. The higher the iteration count the smaller were the required corrections. For the last iteration it was found useful to sum up errors over *n* poles and to use only the center pole of this interval for correction where *n* was between 10 and 20.

The alignment of the FODO quads is done using the Rectangular Coil Method (RCM) described in detail in ref [19]. This method allows for the exact location of the quad center as well the precise determination of the integrated gradient of a quad in the presence of the undulator field. Fig 4 a-c) shows results obtained ona prototype structure.

In Fig 4a) the integrated gradient strength of a FODO

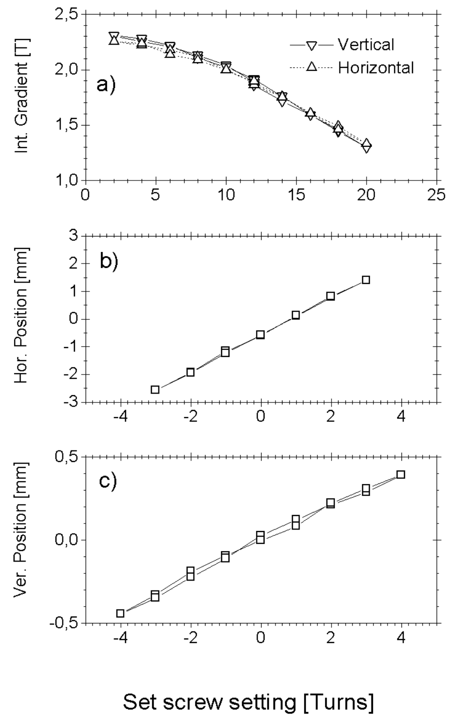

Fig 4 Quad adjustability:
a) Strength
b) Horizontal Position
c) Vertical Position

quad is shown as a function of the set screw settings. The pitch of the screws is 0.7mm. In the case of Fig 4 a) the separation distance of the focusing quads was changed . At zero turn angle there is no separation between the focusing magnets and the integrated gradient is at the maximum strength of 2.3 T. For the quads with an effective length of 0.1365m the maximum field gradient obtained is 16.85 T/m. Fig . 4 b) shows the ability to change the horizontal position of the quadrupole axis. Here a positive / negative sign of the set screw setting means movement of all magnets to the right / left, respectively. It is seen that the axis can easily be moved by +/- three turns which is more than +/- 2 mm. In a similar fashion Fig 5 c) shows the adjustability of the vertical axis. Here a positive/ negative turning sense means that the separation of the magnets in the lower / upper jaw are decreased / increased so that the quad axis is moved up / down and the average separation distance between upper and lower jaw is kept constant. The adjustment range is +/- 0.4mm. In Fig 4 a-c) the adjustments is made back and forth and gives a good impression about reproducibility A more detailed analysis has shown that position measurements can be repeated within 7-8 μm RMS, while the gradient can be determined better than 0.5% RMS.

6 CONCLUSION

In this contribution the requirements on Insertion Devices for 4th generation light sources i.e. those to be used in Linac driven SASE FEL's have been investigated. Very long undulators are required with total lengths up to about 100m for the proposed X-ray FEL's . An important question is whether the focusing has be combined with the undulator or could be separated. The ultimate answer can only be obtained with simulations using FEL code such as TDA-3D, but generally in X-ray FEL's due to their higher beam energy the optimum β-functions are in the range 10-20m Therefore separated function are likely to be used in contrast to VUV - FEL's with much smaller β-functions in the order of a few meters only. Combined function undulators are a real challenge for insertion device technology since they require new developments. The work on the undulator for the TTF may serve as an illustrating example.

In contrast to this the technology for building separated function devices is state of the art and not significantly different from what has been developed for 3rd generation SR labs.

In both cases a new dimension is added by the large lengths especially of the ID's in X-ray FEL user facilities For example the TESLA FEL will consist of a number of undulators each will be up to 100m long [8] Each has about the same total length as all devices of a 3rd generation X-ray source together. The total device length of such a facility can be up to one order of magnitude larger than for the existing facilities

This simple comparison shows that efficient, economic and fast production techniques will play an important role in getting these devices built.. In order to avoid excessively long tuning and manufacturing times as well as excessive production costs new fast, economic and accurate methods have to be found. One way may be to combine modern state of the art motion control technology , i.e. robotic actuators with automated accurate magnetic measurement facility. In this way a magnetic structure can be tuned and optimized automatically.

The method of "Field fine tuning by Pole Height Adjustment" described above together with a suitable magnetic measurement bench can be one part of such a system for undulator optimization. The robotic part on a small scale has already been demonstrated at the Santa Barbara FEL [23,24]. And might serve as an example for further developments. In this way long undulators could be trajectory tuned in a short time.

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