DESIGN OF UNDULATOR FOR THE SHANGHAI DUV-FEL

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Abstract

The design study of the undu1ator for Shanghai deep ultra violate free electron laser source (SDUV-FEL) is presented. The optimum undulator parameters for the FEL performance have been studied. The scheme of focusing and segmentation is discussed. The requirements of undulator magnet field and main technical demand are given.

INTRODUCTION

The project SDUV-FEL [1] was proposed by Shanghai Institute of Applied Physics (SINAP), National Synchrotron Radiation Laboratory (NSRL), and Institute of High Energy Physics (IHEP) in 1998. The design and the relevant R&D of the SDUV-FEL facility have been under way since 2000. The aim of the project is to provide a high-brightness stable narrow-bandwidth coherent deep ultra-violet (DUV) source, and promote an R&D activity oriented to the development of a coherent X-ray source in China.

The SDUV-FEL project plan implement HGHG research in DUV wavelength，for the first step the SASE experiment study will be carried out in the spectral region about 260*nm*. The undulator system includes a modulator section, a dispersive section and a multi-segmented radiator. In this paper, the design study of the radiator undu1ator is presented. The optimisation of modulator and dispersive sections with the HGHG experiment will be given in a separate paper.

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PARAMETER OPTIMIZED

The long undulator with high precision, small gap and transverse focusing is key technology for high gain short wave length FEL. Design and optimization of the undulator is impartible with design and optimisation of whole FEL experiment. The main design parameters of SDUV FEL are listed in the Table 1.

The design target of high gain FEL is to reach the maximum saturation power by the minimum saturation length. In principle the period of undulator should be as short as possible. But owning to wakefield effect, radiation damage and the practical condition limit, the undulator gap cannot be decreased along with the decreasing of undulator period. Therefore when the undulator period is decreased too much, the undulator parameter K will be too small and radiation power will be too weak. For our case, given radiation wavelength (88nm) and electron energy (~300MeV)，the selection range of λ_u and K are not large. Overall consideration gives the undulator parameters as Table 2

Table 1 Main parameters of the SDUV-FEL

FEL Wavelength (*nm*)	88
Electron beam Energy (*MeV*)	269
Bunch charge (*nC*)	1
Peak Current (*A*)	400
ε_N(*mm-mrad*)	4
Local energy spread (%)	0.1

. Table 2 Main parameters of the Undulator

type	hybrid
Gap(*mm*)	10
Period (*mm*)	25
Peak magnetic field (*T*)	0.6
Section number	6
Section length (*mm*)	1512.5
Drift between sections (*m*)	0.1
Average beta function (m)	~3.0
K	1.4

FOCUSING AND SEGMENTATION

The radiator undulator is about 10 meter long. In order to reach the best couple of electron beam and radiation the electron beam must be properly focused.

There are several schemes of focusing. For natural focusing the beta function β_{y0} (*cm*)=$0.241\gamma/B_u$(T) (with parabolic pole face: $\beta_n=\sqrt{2}\beta_{y0}$) is constant, the segment length can be chosen arbitrary. Natural focusing is weak and suitable for longer wavelength FEL. For integrate focusing which combine the focusing quadrupole magnet into the undulator, the technology is complex. The cost for long undulator is too much.

Separate focusing is a relatively simple scheme, which was adopted on the storage rings widely. But the segments length can't be chosen arbitrary. The break length restricted by the quadrupole magnet (and beam monitor) can't be too short. The FEL performance is affected by the "filling factor" of undulator.

The selection of focusing scheme is connected with the average beta function. For a given emittance, a smaller average beta function means a smaller beam size, a larger pierce parameter ρ, i.e. a shorter gain length. But a smaller average beta function also means larger angular spread at the same time. That makes the gain length longer. Therefore an optimal average beta function exists. The optimal beta function tie up with ε、σ_γ、 and I_p, the choice shouldn't be too sensitive to the electron beam parameters.

To accumulate experience for future development of shorter wavelength FEL and considering complexity of technica, separate focusing scheme with FODO lattice is adopted.

For the FODO focusing, in the thin lens approximation, average beta function can be given as [2]:

$$\overline{\beta} = \frac{2f}{\sqrt{1-(\lambda_{FD}/4f)^2}} \ge \lambda_{FD} \tag{1}$$

$$\lambda_{FD} = 2(L_i + l_d) \le \overline{\beta} \le \beta_n \tag{2}$$

λ_{FD} is FODO period length, L_i and l_d is the undulator segment length and break length respectively. f is quadrupole focusing length. From expression (2) it can see that with shorter segment length a larger range of the average beta function can be available.

To make variation of e-beam envelope small, the variation of β should be small, namely

$$\frac{\beta_M}{\beta_m} = \frac{1+\lambda_{FD}/(4f)}{1-\lambda_{FD}/(4f)} \tag{3}$$

should be small. It requires $\lambda_{FD}/(4f) << 1$, this also means prefer shorter segment length.

But the shorter segment length, the less "filling factor" of undulator is. That will cause the FEL saturation power to decrease greatly.

Average beta function, quadrupole focusing length, FODO period length and undulator segment length and break length satisfy the relation:

$$\overline{\beta} > 2f >> \frac{\lambda_{FD}}{2} \ge L_i >> l_d \tag{4}$$

According the fitting formula of Xie Ming [3], the optimized average beta function is β^{opt} =1.26*m* (Fig.1), and $\rho=2.87*10^{-3}$, L_g=76*cm*, Z_R=1.37*m*, $\sigma_\perp$=0.098*mm* for the parameters of Table 1. The gain length dependence on emittance, energy spead and beam peak current are also given in Fig.1. The result demand $L_i+l_d < \beta/2$=0.6*m*, that is too short. In the formula of Xie Ming, the undulator "filling factor" is not considered.

To get more accurate result, the 3D simulation code GENESIS is used. The break length is included in the simulation, which is kept as 20*cm* long. The electron beam is matched into the undulator. The average beta function is varied by varying the quadrupole magnet field strength. The natural focusing effect is also included. From the simulation results (Fig.2 and Fig.3) 1.2*m* to 1.5*m* long segmentation is good choice for shorter gain length, higher saturation power and good control of beam size. So the segment is chosen as 1.5*m* long with a symmetric configuration and the optimal beta function is about 2.8*m*.

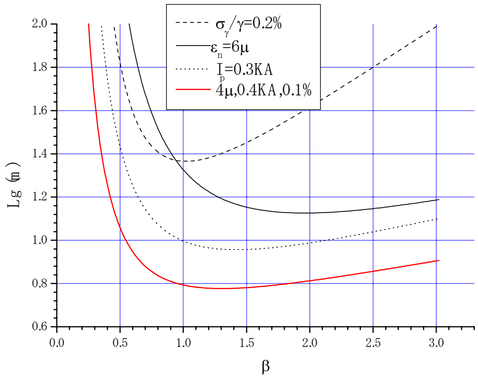

Fig.1 optimized β function by Xie Ming's formula

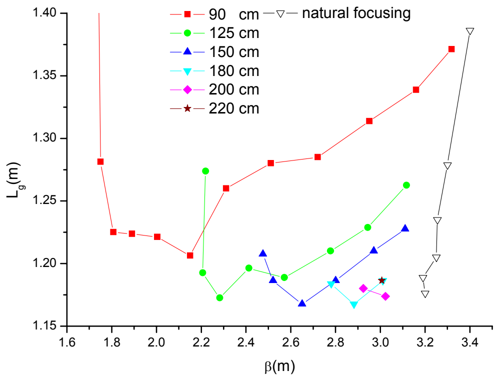

Fig.2 Gain length versus β for different segment length

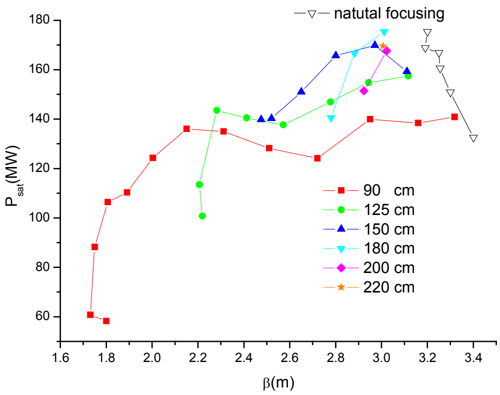

Fig.3 Saturation power versus β for different segment length

All undulator segments should be in good consistency. The segments in succession must be well matched. The phase matching and break length have the relation as follow

$$l_d = M\lambda_u\left(1+\frac{K^2}{2}\right)-\left[z_u+\left(L_i-z_d\right)\right]- \left(\frac{e}{mc^2}\right)^2\left[\int_{z_d}^{\infty}\left(\int_{z}^{\infty}B_u dz'\right)^2 dz+\int_{-\infty}^{z_u}\left(\int_{-\infty}^{z}B_u dz'\right)^2 dz\right] \qquad (5)$$

where the M is an integer. The arrangement of undulators is shown as Fig.4. Where the quadrupole magnet is placed in the break length.

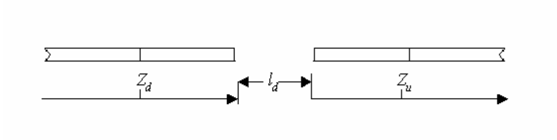

Fig.4 arrangement of undulator

The correctors will be used to correct trajectory, quadrupole offset and match phase. The end pole configuration is being carefully optimized to erase edge field's effect.

MAGNETIC FIELD REQUIREMENT

Field integral

We demand the gain bandwidth due to angular spread to be smaller than natural bandwidth, i.e. $\Delta x' < \sqrt{2\lambda_s\rho/\lambda_u}$. This gives the requirement for the field first integral

$$I(G.m) < 17\sqrt{\rho(1+K^2/2)} \qquad (6)$$

For K=1.38, ρ=2*10^{-3}, it has I$\leq$1$G*m$, it's not too difficult to achieve.

For the field 2nd integral we demand the transverse offset of electrons in the undulator to be smaller than the undulating amplitude of undulator. It gives:

$$\sigma_{II}(G.m^2) < \frac{\lambda_u(cm)K}{12\pi} \qquad (7)$$

For K=1.38 , ρ=2*10^{-3} , we have σ_{II}<9$T*mm^2$, corresponding σ_x<10μm, it is not easy to achieve.

Peak field error

Also from gain bandwidth requirements, it gives

$$\frac{\Delta B}{B} < \left(\frac{1}{2}+\frac{1}{K^2}\right)\frac{\Delta\lambda_s}{\lambda_s} \approx \rho \qquad (8)$$

For our condition, it is about 0.002 and is rather difficult.

Phase error

Phase error will increase FEL gain length. [4,5].

$$L_g \to L_g e^{\frac{\sigma_\phi^2}{3}} \qquad (9)$$

$$\Delta L_g/L_g \cong \sigma_\varphi^2/3 \qquad (10)$$

For σ_φ=10°, the gain length variation is $\Delta L_g/L_g \cong$1%, it is easy to realize.

Effects of quadrupole offsets

The misalignment of quadrupole will cause the FEL saturation length growth and power degradation. From the simulation result (Fig.5 and Fig.6), the tolerance on quadrupole offsets is Δx<20μm , $\Delta x'$<13μrad , the corresponding field integral is 2nd <18$T*mm^2$, 1st <120 $G*cm$.

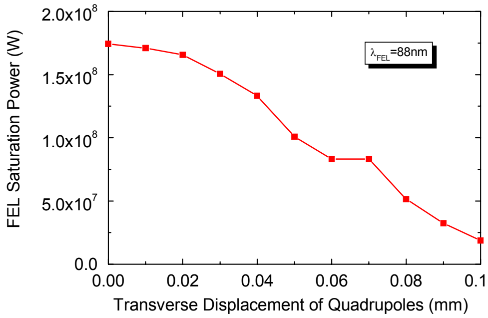

Fig.5 Effects of quadrupole offsets on the saturation power

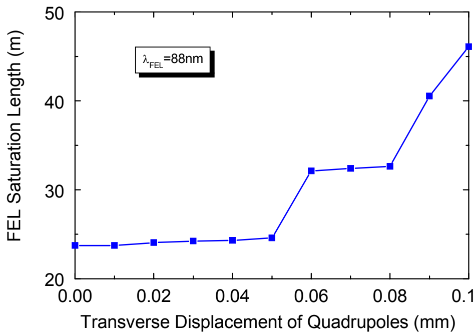

Fig.6 Effects of quadrupole offsets on the saturation length

TECHNICAL DESIGN

Considerations of Hybrid vs. PPM

For the pure permanent magnet (PPM) undulator the design and analysis is convenient, but the magnet block requirement is stringent, it needs more workload. For hybrid undulator the design and analysis is rather complicate. It can give higher peak field than PPM ones when g/λ_u < 0.4 (Fig.7), but the harmonic component may be larger, the field is highly affected by the pole shape. The segments matching problem is more serious for hybrid structure. The radiation damage problem is more serious for PPM structure. For our case (g/λ_u~0.4), either one can be used. The hybrid structure is chosen.

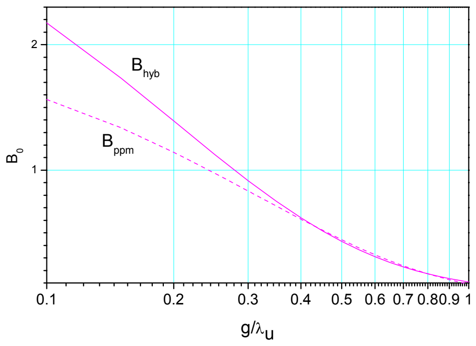

Fig. 7，Peak field versus gap/period

The peak field of hybrid undulator can be calculated by the following empirical formula

$$B_0 = 0.95ae^{-\frac{g}{\lambda_u}(b-c\frac{g}{\lambda_u})} \qquad 0.07 \le g/\lambda_u \le 0.7 \quad (11)$$

$$\begin{cases} a = 0.55B_r + 2.835 \\ b = -1.95B_r + 7.225 \\ c = -1.3B_r + 2.97 \end{cases}$$

where B_r is the remanent field strength of permanent magnet. The permanent magnet material we choose NdFeB N38SH for it has enough high coercivity. The magnet pole, we choose vanadium permendur for its higher saturation field.

Pole geometry optimization

The goal of pole dimension optimization is that with sufficient field strength on the axis insured the field in the pole is far from saturation, the demagnetizing field in magnet block is not large, and magnet material is minimized [6].

Thickness (electron moving direction)： with the thicker permanent magnet the larger field can be achieved, but the harmonic field may be larger too. The thickness rate of pole and magnet block usually is z_p/z_m~1/2.

The height (gap direction) of magnet and pole is chosen as y_m/y_p~1.2. [7]

The width (undulating direction) of magnet and pole are determined by good-field-region requirement ($\Delta B/B<\rho$ in sufficient wide range). Usually y_m/x_m~0.9 is chosen. The final geometry dimension is as follow:

For the magnet: z_m=8±0.011*mm*, y_m=45±0.05*mm*, x_m=60-0.10*mm*, perpendicular of magnet：±0.02 *mm*

For the pole: z_p=4.5+0.012*mm*, y_p=38±0.012*mm*, x_p=40-0.050, -0.089*mm*.

To avoid saturation of the pole, the all edges of pole and magnet facing toward gap are chamfered.

The numerical simulation by OPERA-3D show that the maximum field is 0.64*T*, the good field for $\Delta B/B_0$=0.1% is about ±8.5*mm*. And good field for $\Delta B/B_0$=0.2% is about ±9.9*mm*. The worst demagnetizing field is adjacent to the end corner of pole and just above the chamfer.

Mechanical design

A C type girder support structure is chosen. A fixed gap is adopted to simplify the fabrication. The magnetic force between poles is 710*Kg*. The main mechanical requirements and specifications are:

1) The beam parallelism：0.02*mm*
2) Pole gap tolerance ±0.05*mm*.
3) Neighbour pole gap difference tolerance ±0.03*mm*
4) Pole displacement in “z” direction (top and bottom) ±0.10*mm*

Minor adjustment can be done individually for each pole to tune the field. The base of undulator can be vertically and horizontally adjusted. The alignment precision for horizontal direction is about 5μm, and for vertical direction is given by:

$$\Delta y = \frac{\lambda_u}{\pi}\sqrt{\frac{\Delta B}{2B}} < 0.25mm \qquad (12)$$

Now a two periods prototype of undulator is under construction. The optimal design of undulator end part is under way. The much more detail work will be continued.

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