Design and Tests of Optical Klystron for FEL*

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Abstract

A symmetry Optical Klystron (OK) with independently adjusted modulator, buncher and radiator has been designed and constructed for Storage Ring FEL in NSRL. The designed OK parameters are listed and checked by the 3-dimensional electromagnetic computation code and hall probe measurements. Special considerations are given for correction factors of OK analysis computation of single period buncher and multi-period undulators induced by 3d magnetic effects. The effect of undulator fill factor to the electron energy is analysed.

1 Introduction

The Free electron laser (FEL) has the most exceptional emission performance than synchrotron radiation. Known as the 4th generation light source [1,2], the storage ring FEL (SRFEL) is the most promising coherent light source from VUV to soft X-rays. One way of SRFEL is coherent harmonic generation by firing the electron beam passing through an optical klystron with an external laser. This method, investigated in Orsay, Max lab and NSRL etc. [3-5], avoids difficulties of using high reflection mirrors. In short wavelength region from 124nm down to 0.1nm, this route will be the most practical method.

An optical klystron (OK), which means for FEL research in NSRL, was designed and constructed with NdFeB magnets. The OK consists of three undulators with independently adjusted magnet gaps from 38mm to 140mm. The analysis equations for designing the OK and the design sheet are given and checked by the finite element method, the 3-dimensional electromagnetic computation code, Opera-3d and the measured field. The measured B-H curve of the magnet is used in the computation. The computed induction field in the beam axis, quite well matches the field measured by hall probe with dimensions of 0.1mmx0.1mm. The typical parameters of the optical klystron are given.

After shimming the OK to decrease its first and second field integrals to less than 100$Gs\times cm$ and 1T$\times cm^2$ respectively in varying range of buncher magnet gap, the OK was installed in straight section of Hefei storage ring with inserted square vacuum chamber whose longitudinal and horizontal dimensions are respectively 2672.2mm and 32mm×86mm.

2 Analysis Design of the OK

2.1 Emission wavelength from undulator and resonant energy of electron beam

Emission wavelength from undulator is given as: [2]

$$\lambda = \frac{\lambda_0}{2i\gamma^2}\cdot(1+\frac{k^2}{2}+\gamma^2\vartheta^2)\text{, } i=1,2,3, \quad (1)$$

Where, ϑ is the angle with respect to the beam axis, i is harmonic number, γ is Lorentz factor, k=0.934(Bo/T)·(λo/cm) is the undulator deflection factor.

The fundamental resonant energy of electron beam can be given by (1):

$$E/(MeV) = \frac{\gamma}{1.957} = 0.51\sqrt{\frac{\lambda_0}{2\lambda}(1+\frac{k^2}{2})} \quad (2)$$

2.2 Analysis computation of the induction field

A: Induction field of multi-period undulator

The well-known Halbach equation gives the peak vertical field *By* on the beam axis as: [6]

$$B_y = \frac{2B_r\cdot\sin\frac{\varepsilon\cdot\pi}{M}}{\frac{\pi}{M}}\cdot(1-e^{-\frac{2\pi h}{\lambda_0}})\cdot e^{-\frac{\pi g}{\lambda_0}} \quad (3)$$

Where, B_r is Magnet remanence, M is the number of magnet blocks per period on one side, λ is period, h is the height of blocks, g is magnet gap, ε=4h/λ is the fill factor of undulator.

B: Induction field of single period buncher undulator

The peak vertical field *Bd* of single period undulator on the beam axis is given as:

$$B_d = k_s B_y \quad (4)$$

Where, *By* is induction field of multi-period undulator, $k_s = 0.9$ is correction factor of single period undulator which integral the contributions of other periods of magnet blocks.

The parameter of buncher section□which integral all the dispersive section effects of buncher[8], is given as:

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$$N_d = \frac{d}{2\lambda\gamma^2}\cdot\{1+\frac{e^2}{dm^2c^2}\int_0^d[\int_0^u B(z)dz]^2du+\gamma^2\vartheta^2\} \quad (5)$$

Where, N_d is exactly the number of wavelength of light passing over an electron energy γmc^2 in the dispersive section. It can be compared to N, the number of periods of an undulator which is also the number of wavelength of light passing over a resonant electron in the undulator [8].

2.3 The effects of the OK undulator fill factor to the electron energy

Peak vertical field and experimented Beam Energy can be enhanced as listed in table 1, which is computed by equation 1-4 if 0.5mm air gap was inserted in the magnet blocks in the undulators of modulator and radiator on the OK two ends.

Table 1: The OK typical parameters with 0.5mm gap between magnets and without gaps

	Fill factor ε	period/mm	Peak vertical field By/T	Beam Energy E/MeV
Without gaps between magnets	1	72	0.2988	163
With 0.5mm gap between magnets	0.973	74	0.30304	168

2.4 Force computation

The attraction force of one sinusoid distribution field with peak field B_y and period λ_0 is given as□

$$F_m = \int_0^{\lambda_0}\frac{B_y^2}{2\mu_0}ds$$

$$\approx \int_0^{\lambda_0}\frac{(B_0\cdot\sin\frac{2\pi x}{\lambda_0})^2}{2\mu_0}\cdot wdx$$

$$= \frac{w\lambda_0 B_0^2}{4\mu_0}$$

Where, *w* is width of OK magnets.

2.5 OK Design Results

The OK design sheet is listed in table 2. Three step motors driven by one time-share power supply realize the control system of OK magnet gaps. Three grating meters with 0.01mm resolutions are mounted on three OK sections to measure the magnet gaps.

Table 2: The OK typical parameters Electron Energy E=0.163GeV longitudinal distance between undulator sections=12 mm

	Modulator	Buncher	Radiator
Types	Pure Permanent Magnet	Pure Permanent Magnet	Pure Permanent Magnet
Period/cm	7.2	21.6	7.2
Number of periods	12	1	12
No. Of magnets and their dimensions (mm3)	192 18x18x50	52 18x18x50	192 18x18x50
No. Of half magnets and their dimensions (mm3)	8 9x18x50	16 9x18x50	8 9x18x50
Magnet remanence Br/T	1.2	1.2	1.2
Coercive force Hc/(kA/m)	915	915	915
Gaps/mm	40-140	40-140	40-140
Gap resolution/mm	0.01	0.01	0.01
Peak vertical field/T	0.2988	0.27~0.71	0.2988
Nd		20~130	
Effective length/mm	864	216	864
Maximum attraction force/kg	1535.4	1645.5	1535.4

2.6 3d Finite Element (FE) Computation to the OK buncher

The computed model to the buncher and it's related region is shown in fig. 1. The measured averaged $B_m - H_m$ curve of the magnet blocks is inputted in the 3d electromagnetic computation code, Opera3d. The computed induction field in middle of OK middle plane is shown in fig. 2. Table 3 gives the OK typical magnetic parameters computed by 3d finite element method and analytic equations, which shows that the peak vertical field computed by Opera3d is decreased by 2.24% than that of the analysis computation.

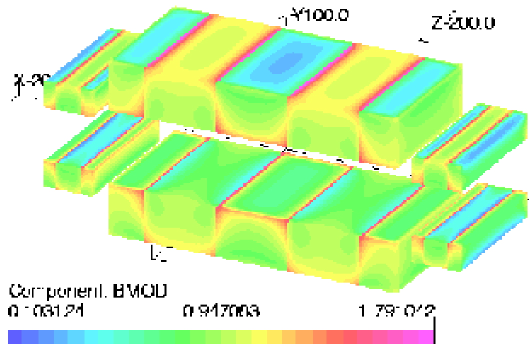

Fig. 1: The OK Buncher and its related region

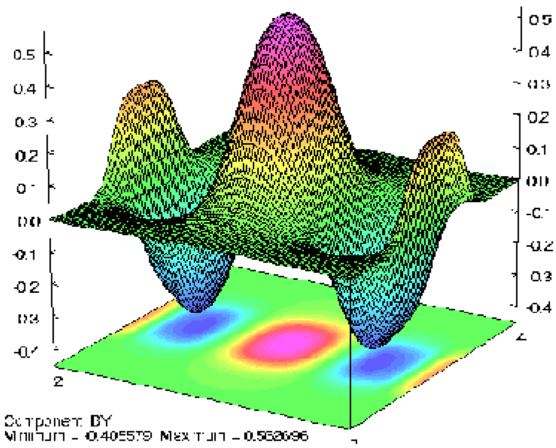

Fig. 2: The computed induction field in middle of OK middle plane

3 Measurements of Optical Klystron

After standard copper blocks calibrate the OK magnet gaps, the vertical field along the beam axis was measured by 0.1x0.1mm Hall probe, which is listed in table 3 and shown in fig.4 respectively. The first and second integrals of the OK field are respectively less than 0.004Tcm and 0.02T.cm^2 by fine tuning the magnet block gaps and shimming method. The peak-peak errors of the field are within ±(0.6~0.8)%.

Table 3: The OK typical magnetic parameters computed by 3d finite element method and analytic equations

	Modulator	Buncher	Radiator
Gaps/mm	40	55	40
Computed by OPERA3d By /T	0.2921	0.564	0.2921
Computed by analysis equation By /T	0.2988	0.567	0.2988
Measured with Hall probe By /T	0.2821	0.5645	0.282

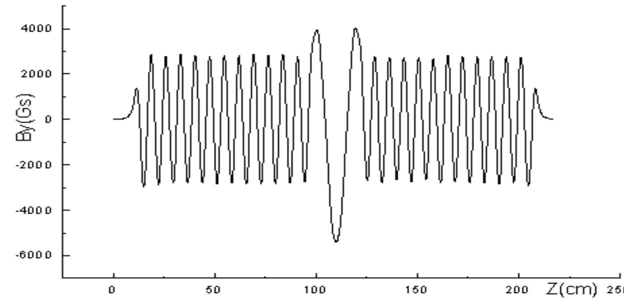

Fig. 3: The field measured by hall probe

4 Conclusions

4.1 Filling 0.5mm airgap into block will increase the peak field by 1.42% in our case, which can be explained by the increased area of magnetic circuit of permanent magnets.

4.2 The test to the OK shows that 3dFE computation is more accurate than analysis design although the analysis design is more straightforward. In our case, k_s, which is the correction factors of OK analysis computation for single period buncher is 0.9 verify that the error resulting in the determination of peak field by other periods of blocks will usually be less than 10%. This can be used to optimize undulator with lots of periods.

4.3 The designed beam energy is 163MeV, which is below the inject energy of HLS, is not very stable while going in for coherent harmonic generation. So, the OK will be upgraded to asymmetry structure with longer period modulator for generating more powerful coherent harmonic after measuring the OK spontaneous emission spectrum. The upgraded OK can be operated above the injection energy. That will be introduced in companion paper in these proceedings deal with this latter topic.

5 Reference

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