DESIGN CONSIDERATIONS FOR A HYBRID UNDULATOR APPLIED IN A TERAHERTZ FEL OSCILLATOR

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Abstract

A planer undulator using hybrid permanent magnet scheme was designed for a Free Electron Laser (FEL) based 2-5THz radiation source. The influences of the undulator tolerances, including peak field error, phase shake and field integrals, on the coherent radiation performance are investigated. And finally specifications of the undulator are determined.

INTRODUCTION

Considering wide applications of high power coherent THz radiation sources on biology, imaging and material science etc., a prototype compact terahertz FEL oscillator is proposed at Huazhong University of Science and Technology, which is considered to generate $60-150\mu m$ terahertz radiation. The concept design of the compact THz FEL oscillator is composed of an independently tunable cell (ITC) thermionic RF gun, a linac booster, a planar undulator and an near concentric wave guided optical cavity [1]. The use of the ITC gun cut off pre-buncher and alpha magnet, which makes the whole facility more compact. The main design parameters of this FEL oscillator are listed in Table 1.

Table 1: Parameters of the THz FEL Oscillator

Beam energy	6-10 MeV
Radiation wavelength	60 - 150 μm
Charge per pulse	≥300pC
Energy spread	0.3%
Normalized Emmittance	$10\pi mm \cdot mrad$
Bunch length	10ps
Macro length	4-6us
Full strength period N_u	25
Period	32 mm
K	1.0
Optical cavity length	2.89m
ROC of mirrors	1.48

UNDULATOR PARAMETERS

For the FEL oscillator for sub-millimeter wavelength generation, the undulator parameters should be optimized according to the electron beam specification and other factors like short pulse effect.

The small signal gain G_0 can be expressed by Equ.(1), which means larger N_u and undulator length will introduce higher gain. However, the single pass gain is significantly influenced by the net effect of inhomogeneous broadening caused by electron beam parameters and slippage effect described as Equ. (2) (where the factor $F = F_{inh} \cdot F_f \cdot F_c$) [2]. N_u should be carefully optimized in case of long wave length radiation, for example when the slippage length $N_u \cdot \lambda_r$ is comparable to the electron bunch length. For 150 μm radiation corresponding to 6MeV energy, when $N_u > 25$, the slippage effect will cause oscillation of the gain procedures and no significant gain enhance exists, even detuning of the cavity is given. Another factor is that larger N_u asks for smaller spread, and in this condition, the contribution on G_0 by N_u cannot compensate the deterioration by spread. Figure 1 shows the peak power at different wavelength, simulated by FELO code [2] with design parameters in Table 1.

$$G_0 = (4\pi \cdot \rho_{fel} \cdot N_u)^3/\pi \propto L_u^2 \cdot N_u^3 \quad (1)$$

$$G_{single} = 0.85 G_0 \cdot F + 0.19(G_0 \cdot F)^2 \quad (2)$$

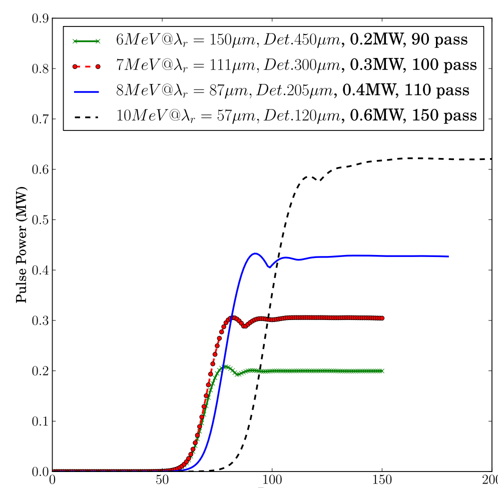

Figure 1: Peak power at 4 energy spot (6-10 MeV), calculated by FELO code.

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DESIGN OF THE MAGNETIC FIELD

PPM (Pure Permanent Magnet) and HPM (Hybrid Permanent Magnet) are considered. Compared to PPM, HPM type has much smaller magnetic field error due to inhomogeneous of the permanent material such as remnant field (Br) and magnetization direction. As well as HPM has higher magnetic field with high permeability soft iron poles, which is important to maintain enough peak field for out of vacuum undulator. For these reasons, we chose hybrid type undulator.

The requirement for first/second field integrals is within $5.0e^{-6}T \cdot m/2.5e^{-6}T \cdot m^2$, that asks for precise design for the end part formation. A scheme is given in Fig. 2, with one correction PM block and one correction pole. RADIA [3] simulation (Fig. 3) with the given size shows field integrals are within the tolerance.

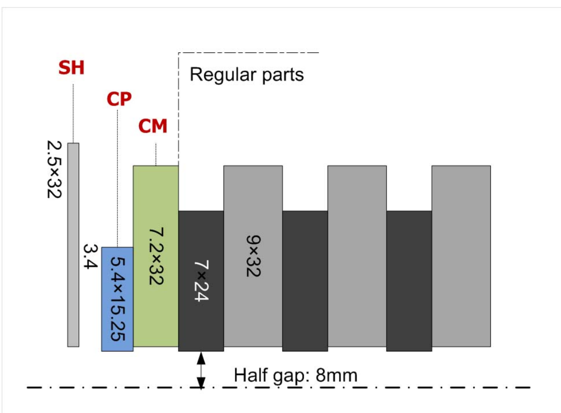

Figure 2: End part formation of the undulator (CM: correction permanent magnet, CP: correction pole, SH: shield).

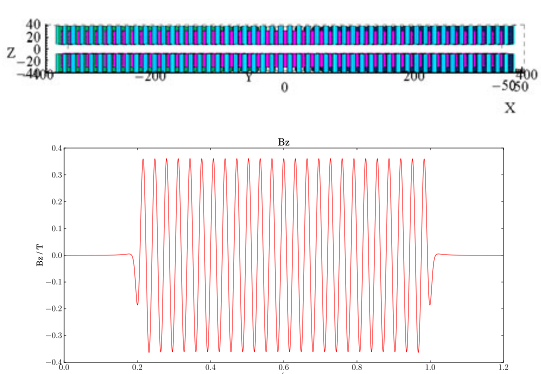

Figure 3: Full undulator model using RADIA, and simulated central vertical field.

CONSIDERATIONS ON UNDULATOR TOLERANCES

The tolerances of this undulator are listed in Table 2.

The basic requirement for field integrals is that the introduced electron trajectory /angle offset should be less than the horizontal electron beam size. For lower rigidity 6MeV beam, the offsets with the given tolerance are 0.125mm / 0.25mrad, is within the beam size with $10\pi mm \cdot mrad$ normalized emmitance.

Peak-peak field error is caused by many factors, including gap error, period error, inhomogeneous of the materials. Basic requirement is that the resulting inhomogeneous broadening in the gain spectrum due to the field error is less than its natural width 1/2Nu, which asks for $\Delta B/B < 3\%$.

However, the influence of the peak field error also includes: (a) Degration of the single pass gain. As shown in Fig. 4, the influence is neglectable for $\Delta B/B < 0.25\%$. (b) Phase shake and beam wander, and the net effect will increase the saturation length and destruct the coherent amplification process in the undulator. For statistic study, 18 data sets corresponding to rms gap error 0.25%, 0.5% and 1% are used. As shown in Fig. 5 and Fig. 6, The phase shake and beam wander caused by 0.25% field error is less than 2 degrees and $80\mu m$.

The overall gain length increase due to phase shake and beam wander is given by $1.0/(1.0 - R)$ [5], where

$$R = \Delta\phi + (\Delta x/\sigma_e)^2 \tag{3}$$

For 0.25% field error, $R = 0.03$, which brings 3% increase of the gain length.

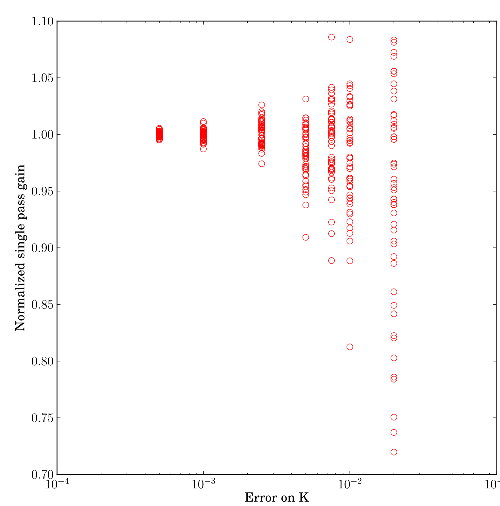

Figure 4: Influence on the single pass gain by undulator field error (in terms of K), simulated by Genesis code [4] in steady state mode.

Stringent tolerance for field fall off within $\pm 5mm$ region is 0.1%. This area is mainly determined by the electron beam trajectory inside the undulator. As shown in Fig. 7, for 7MeV electrons, even at 0.5% peak field error, the trajectory oscillation is limited within 1.5mm.

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Table 2: Tolerances of the Undulator

Peak field	0.34T
rms peak field error	$\leq 0.25\%$
Transverse field roll-off ($x = \pm 5mm$)	$\leq 0.1\%$
Transverse field roll-off ($x = \pm 10mm$)	$\leq 0.25\%$
rms period error	$\leq 0.2\%$
rms phase error	$\leq 2^{\circ}$
High order harmonics (3rd, 5th)	$\leq 0.5\%$
First integral(Normal/ Skew, $\|x\| < 5mm$)	$\leq 5.0e^{-6}T \cdot m$
Second integral (Normal/ Skew, $\|x\| < 5mm$)	$\leq 2.5e^{-6}T \cdot m^2$

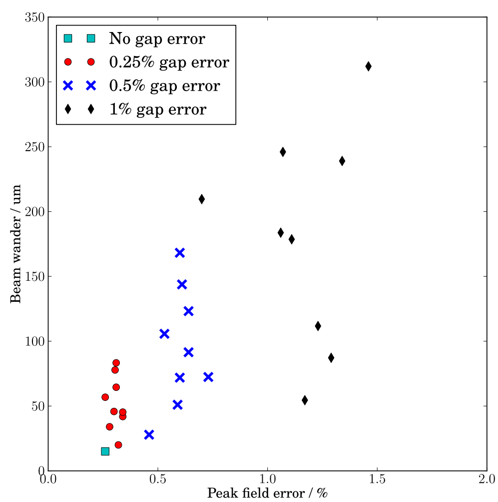

Figure 5: Beam wander at different field errors.

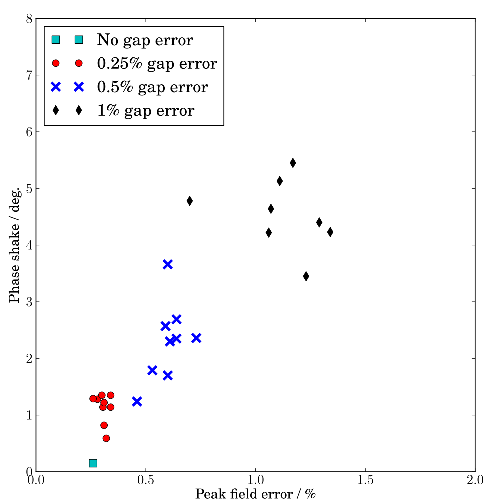

Figure 6: Phase shake at different field errors.

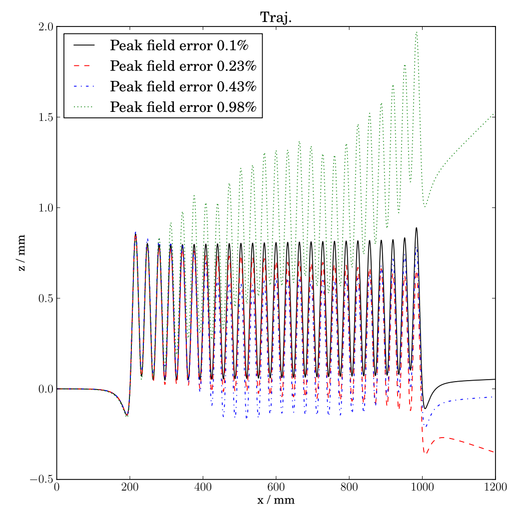

Figure 7: Electron trajectory at different field errors.

SUMMARY

To achieve high efficiency for FEL oscillator, the parameters of the undulator is well designed. Tolerances study are performed to ensure that the deterioration on the amplification process in the undulator cause by field errors is acceptable.

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