MAGNETIC DESIGN OF A HYBRID UNDULATOR FOR COMPACT TERAHERTZ FEL

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Abstract

The design of compact terahertz (THz) radiation source based on free electron laser (FEL) has been implemented, whose concept machine is consisting of a thermionic RF gun (ITC-RF Gun), a LINAC, a hybrid undulator combined with an optical resonance cavity of hole-coupling mode. The aim of the project is to provide a stable coherent THz (1~3THz) source. The hybrid undulator system is the critical component for compact terahertz FEL. Emission wavelength is related to the period and the peak magnetic field of the hybrid undulator. In particular, the magnetic structure by adding side magnet blocks to each pole will increase the field strength, avoid too small gap, and make the system more compact. Simulations using RADIA are presented. The feature of designs, optimization of the magnetic parameters and field analysis will be discussed.

INTRODUCTION

Terahertz wave, which is electromagnetic radiation in a frequency interval from 0.1 to 10 THz, lies a frequency range with rich science but limited technology. Free-electron lasers (FELs) are well established as a versatile source of high-power tunable laser radiation in wavelength ranges where other laser sources are scarce [1]. In particular, the THz range of the spectrum can be conveniently covered by FELs because of the rather modest requirements on the electron beam parameters. [2]

A conceptual design for a compact Terahertz FEL system in Huahong University of Science and Technology is being undertaken in collaboration with University of Science and Technology of China. The compact Terahertz FEL equipment is consisting of a thermionic RF gun, a LINAC, a hybrid undulator combined with an optical resonance cavity of hole-coupling mode, whose aim is to provide a stable coherent terahertz source. Without α-magnet and other bunch compressor, the size of this machine is decreased sharply. A waveguide cavity design is adopt to reduce the diffraction losses and at the same time to achieve an increase in the filling factor. [3]

The undulator is a special magnet system that is designed to produce radiation from the kinetic energy of charged relativistic particles by periodically bending their trajectories. By matching his period magnetic field of the undulator with the optical resonance cavity, the passing electron beam will generate coherent THz FEL radiation with gain, and the radiation power required by THz FEL source can be achieved finally.

Here, a magnetic design study involving the hybrid undulator of the compact terahertz FEL is presented.

UNDULATOR REQUIREMENT

Design and optimization of the undulator is impartible with design and optimization of whole THz FEL system [4]. The main design parameters of THz FEL system are listed in Table 1.

Table 1: Main Design Parameters of THz FEL

THz Wavelength	0.1~0.3mm
Electron Beam Energy	5.71~9.9MeV
Bunch Charge	400pC
Peak Current	20A
ε_N	10mm-mrad
Local Energy Spread	≤ 0.3%
Resonant Frequency	2856MHz
Pulse Repetition Rate	1 ~ 10 Hz
Pulse width	~4μs

The THz FEL delivers wavelengths as set by basic FEL resonance equation,

$$\lambda = \lambda_u \left(1 + K^2/2\right)/2\gamma^2 \tag{1}$$

where λ is the output wavelength, λ_μ the undulator wavelength, γ the electrons' relativistic factor, and K the undulator strength parameter. $K = 93.4 B_0[T] \cdot \lambda_u[m]$ with B0 the undulator peak field.

The small signal gain of the FEL is given by (Brau, 1988; Dattoli, 1992; Benson, 1994)

$$G = 29.4(I/I_A)(N_\mu/\gamma)B\eta_l\eta_f\eta_\mu \ , \tag{2}$$

where I is the current, I_A is a characteristic current 17 kA, N_μ is the number of undulator periods, and $B = 4\xi[J_0(\xi) - J_1(\xi)]^2$ where $\xi = K^2/[2(1+K^2)]$,The last three terms (η_l, η_f, η_w) account for emittance and energy spread effects, gain degradation due to imperfect beam overlap, and slippage between the electrons and the optical pulse [5].

Because the permanent magnet materials based on rare earth-transition metals alloys are available, the very large product (BH) max presented by these materials allows the realization of short period undulator without any electrical power supply. Pure permanent magnet technology and hybrid technology are generally used. Compared with pure permanent magnet types, hybrid structures can decrease the field errors caused by non-homogeneous magnetization of magnetic blocks, and provide higher peak field intensity, which will be better used for the compact terahertz FEL.

The Pierce parameter ρ is a fundamental quantity in FEL theory determining properties. The field roll-off, i.e. the transverse homogeneity of the vertical magnetic field $\Delta B_Z / B_Z(x=0)$, has to be $< \rho$ over a sufficiently broad region.

The FEL process also is very sensitive to any deterioration of the overlap of electron beam and radiation field [6]. Straightness of the trajectory is a significant requirement for the undulator. There is a wide range of possibilities how to trim the field integral gap independently by means of special arrangement and dimension of the last poles or magnets.

The dimension of magnet blocks and poles will be optimized in order to produce sufficient field strength on the axis and good-field-region requirement.

MAGNETIC DESIGN OF HYBRID STRUCTURE

The magnet structure consists of a planar hybrid structure using NdFeB magnets with a remnant magnetization M_r=1.2T. Poles are made of are made of soft iron with high permeability to lower saturation effects in the poles. The peak field B_Z can be calculated approximately according to

$$B_Z[T] = a \cdot \exp\{(b + c \cdot g / \lambda_\mu) \cdot g / \lambda_\mu\} \quad (3)$$

with the parameters g=gap, $a = 3.381$, $b = -4.73$, and $c = 1.198$ [7, 8].

According to THz FEL system parameter, the undulator need o set λμ, K value, period number, absolute peak field and air gap dimensions. The primary design parameters are a period of 46 mm，a nominal magnetic gap of 32mm, 25 pieods, and $K \approx 1$.

A magnetic period is consisted of two rectangular-shaped NdFeB magnet blocks and two soft iron poles. All the poles and magnet blocks are identical except for the end ones, which are used to adjust the field integral more precisely (see Figure 1). The dimension parameters of magnet blocks and poles are shown in Table 2. With respect to the magnets, the pole tips have a small overhang of 1mm into the gap to avoid saturation effects, and the corners and a chamfer have the same amount which approximates a removal of sharp edges.

Table 2: Hybrid Undulator Parameter

parameter	value
Length of a period	46mm
Number of periods	25mm
Magnet materials	NdFeB
B_r	1.2T
Pole materials	Soft iron
Gap	32mm
K	0.92
Gapoff	1mm
Magnet dimension	75×15×50
Pole dimension	50×8×40
Peak field	0.2145 T
Side magnet dimension	2×8×40
Termination pole1	50×8×20
Termination pole2	50×8×8
Termination magnet	75×5.5×50
1st integral	<0.01T•mm
2nd integral	<5 T•mm^2
Deviation displacement	2.5708μm

TERMINATION DESIGN

A symmetric field configuration is chosen so that the 2nd field integral cancels once the 1st field integral is tuned to zero. The termination structures are shown in Fig. 1 and Table 2.

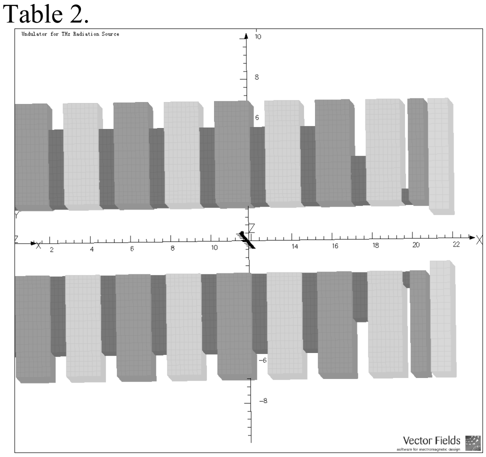

Figure 1: Termination structures.

SIDE MAGNET DESIGN

The magnetic structures by adding side magnet blocks to each pole will increase the field strength, avoid too small gap, and make the whole system more compact. The computed induction field on the transverse axis of the middle plane of the hybrid undulator is shown Fig. 2, which illustrates that the optimized configuration has more than 15mm good field region (Figure 3).

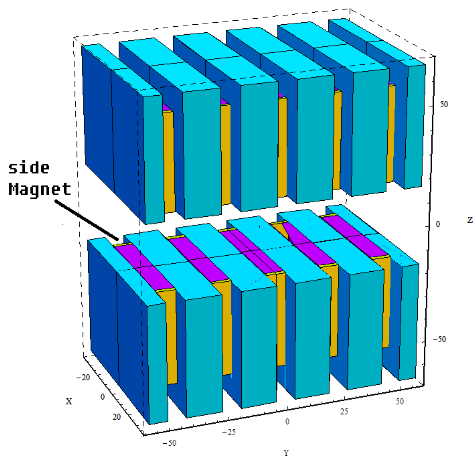

Figure 2: Side magnet structures.

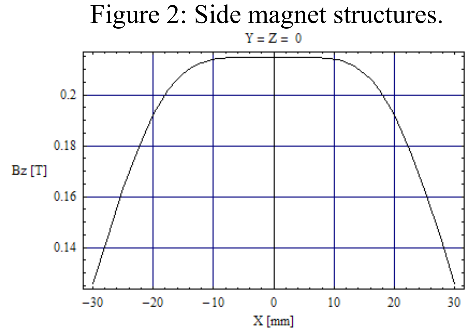

Figure 3: Magnetic field Bz on the transverse axis of the middle plane.

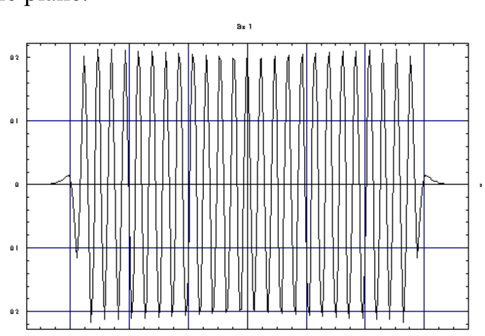

Figure 4: Peak field Bz on the Y axis.

NUMERICAL SIMULATION

The numerical simulation for the case of the electromagnetic undulator has been performed with the 3D code Radia. The simulation results show that the peak field for the general magnet period is 2145 Gs (see Fig. 4), which is close to the theoretical value. The first field integral is less than 0.01T·mm and the second field integral is less than 5T·mm^2.The offset of electron beam position in system is 2.5708 μ m through numerical eclectron (10MeV) tracking (see Fig. 5 and Table 2).

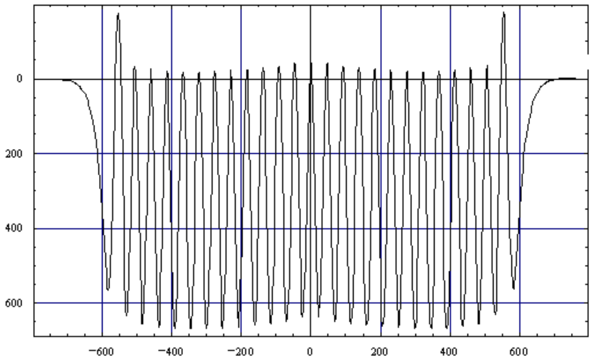

Figure 5: Electron tracking in hybrid undulator.

CONCLUSION

The magnetic design of the hybrid undulator meet THz FEL requirement. Side magnets are adopted, which make the THz FEL system more compact.

But, the field shape and its errors are also dominated by the geometry tolerance of the magnet blocks and poles. Manufacturing the undulator will be quite a challenge requiring machines with appropriate accuracy. Now A X-Y direction Hall measurement equipment has been manufactured for magnetic field adjustment. More detailed work of THz FEL undulator will be continued.

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