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# Design considerations of a planar undulator applied in a terahertz FEL oscillator

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ABSTRACT

To fulfill the physical requirement of a 50–100 μm Free Electron Laser (FEL) oscillator, design considerations of a planar undulator are described. The main undulator parameters are optimized for a trade off between the gain and the FEL's natural extraction efficiency, and the technical aspects including the structure of the permanent magnet (PM), the choice of PM materials and field tolerances are discussed. The lattice of the designed undulator is studied and the beam matching at the entrance of the undulator corresponding to various working points of electron beam energy is performed.



## 1. Introduction

In the past decade, terahertz (THz) science and technology has been developed rapidly. In applications of real-time imaging, security inspection, materials and biomedicals, high power compact THz sources are demanded, due to significant THz absorption in atmosphere or materials and relatively lower sensitivity of THz sensors [1,2]. The Watt level average power is basically required, which is beyond the capability of traditional THz sources.

As a high average power and continuous tunable coherent radiation source, free-electron lasers (FEL) have been proved to be important laser sources covering wide wavelength from hard X-rays to far-infrared (terahertz) region [3]. For long wavelength (THz) radiation, low gain FEL oscillator is widely adopted. In this scheme, the radiated field oscillates in the optical cavity between two reflecting mirrors and interacts with the electron beam within the undulator till saturation is reached.

In IR-THz FELs, the most productive FELIX facility has been operated for around 20 years [4]. Recently, FLARE [5], FHI [6] and ALICE [7] FEL facilities have been developed around the world. With the commercialization of high quality linac injector and continuous cost-down, more IR-THz FELs will be planned for demanding from various applications.

A prototype compact terahertz FEL oscillator was proposed at Huazhong University of Science and Technology (HUST), which is designed to generate 50–100 μm coherent radiation with 1 MW level peak power [8]. The conceptual design is shown in Fig. 1, with the main design parameters listed in Table 1. We choose a thermionic electron gun with an independently tunable cell (ITC) as the electron beam source. Compared to the photo-cathode gun and DC thermionic gun with bunchers and alpha magnet, the system is more simple and compact, and the desired bunch length and momentum dispersion listed in Table 1 can be fulfilled with simulations and experimental results [9]. A S-band (2856 MHz) room temperature linac using copper traveling wave structure is designed to accelerate the electron beam covering the energy from 8.1 to 11.7 MeV. The macro-pulse duration 4–6 μs, which contains a microbunch train with 350 ps separation, is long enough compared to the time of the power build up process which is within 1 μs as estimated in Section 2.1. Longer macro-pulse duration around 10 μs is possible but limited by the modulator/klystron technology and becomes costly. A double-bend achromat (DBA) beam line transports the electron beam to a planar undulator. A symmetrical near-concentric optical cavity is formed by two gold-coated copper toroid mirrors, with the cavity length of 2.93 m. The gap size of the rectangle undulator duct is 10 mm, for the balance of higher undulator peak field and minimal diffraction loss. For 50–100 μm wavelength, the waveguide effect of this duct can be neglected.

As the role of energy transfers from the electron beam to the radiation field, the undulator is not the most expensive but critical component in the FEL facility. In HUST THz-FEL, a planar permanent undulator with a moderate $K$ is adopted for generating fundamental spectrum 50–100 μm. This paper will discuss

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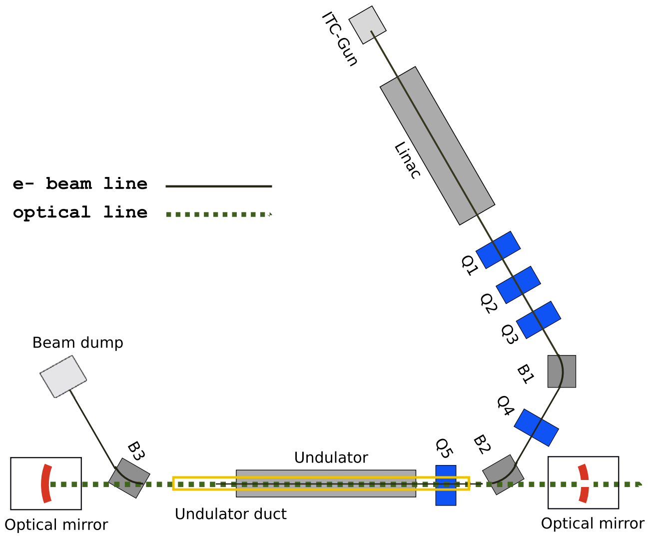


**Fig. 1.** Schematic view of HUST THz-FEL oscillator.

**Table 1**
Parameters of the THz FEL oscillator.

| | |
|---|---|
| Beam energy | 8.1–11.7 MeV |
| Radiation wavelength, $\lambda_r$ | 50–100 μm |
| Bunch charge | ≥200 pC |
| Bunch length (FWHM), $\sigma_s$ | 5–10 ps |
| Energy spread (FWHM) | 0.3% |
| Normalized emittance, $\epsilon_n$ | 15$\pi$mm mrad |
| Microbunch separation | 350 ps |
| Macro pulse duration | 4–6 μs |
| Repetition rate | 10–200 Hz |
| Number of the full strength period, $N_u$ | 30 |
| Undulator period, $\lambda_u$ | 32 mm |
| Undulator parameter, $K$ | 1.0–1.25 |
| Optical cavity length | 2.93 m |
| ROC of mirrors | 1.52 m |
| Peak power | 0.5–1 MW |

determinations of the undulator parameters and tolerances, from the point of view of FEL physics and technical aspects. To optimize the cross-section of the electron beam for achieving better current density and good overlap between the electron beam and the optical mode, electron beam matching in different energy points has been performed, by validating with analytical transfer matrix and numerical ray-tracing methods.

## 2. Parameters of the planar undulator

### 2.1. Parameters determination from FEL physics

For the FEL oscillator that generates sub-millimeter radiation wavelength, the undulator parameters should be optimized according to the electron beam quality and a balance between the gain and the natural extraction efficiency of the FEL.

The small signal gain $G_0$ can be expressed by

$$G_0 = (4\pi \cdot \rho_{fel} \cdot N_u)^3/\pi \tag{1}$$

where $\rho_{fel}$ is the Pierce parameter [10] and is around 0.008 with the present design parameters. However, the maximum single pass gain $G_{max}$ is significantly influenced by the net effect of inhomogeneous broadening of the spectral line caused by electron beam parameters and the slippage effect described by the fitting formula [11]

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

where $F = F_{inh} \cdot F_c \cdot F_f$, $F_c = 1/(1 + N_u\lambda_r/\sigma_s)$ is the factor relating to the slippage effect; $F_f = 1/(1+\overline{w}^2/4\sigma_b^2)$ is the filling factor with $\overline{w}$ being the mean optical mode size over the length of the undulator excluding the waveguide effect, and $\sigma_b$ the electron beam radius; and $F_{inh} = 1/(1+1.7\mu_\gamma^2)(1+\mu_\epsilon^2)$ represents the net inhomogeneous broadening effect on radiation spectral line, which will decrease the gain according to the Madey theorem. $\mu_\gamma = 4N_u\sigma_\gamma/\gamma$ and $\mu_\epsilon = \sqrt{2} N_u \epsilon_n K/\lambda_u (1+K^2/2)$ are longitudinal and transverse inhomogeneous factor respectively.

In the low gain FEL oscillator, the power build up process is non-linear and difficult to be described analytically. But the saturation time can be estimated with an analytical method [3]. While the started FEL radiation power $P_0$ comes from the spontaneous emission which is scaled to $n$, the number of electrons in the bunch, the saturated power $P_{sat}$ is determined by the coherent radiation status, which is scaled to $n^2$. The number of the round-trip $m$ can be derived from the approximated exponential growth of the power build up $P_{sat} = P_0 \cdot (1+G_{net})^m$, where $G_{net} = G_{max} - G_{loss}$ is the net round-trip gain with round-trip loss rate $G_{loss}$ due to internal and transmission losses in the optical resonator. We have

$$m = \ln(P_{sat}/P_0)/\ln(1+G_{net}) = \ln n/\ln(1+G_{net}). \tag{3}$$

Then the saturation time $t = m \cdot 2L/c$ can be estimated. Strictly speaking, the condition $P_{sat}/P_0 = n$ is valid only for full coherent radiation, which means that the electron bunch length should be within the coherent length $l_c \approx \lambda_r \cdot l_g/\lambda_u = \lambda_r/4\sqrt{3}\pi\rho_{fel}$ [13], where $l_g$ is the gain length. Even for $\lambda_r = 100$ μm, $l_c \approx 0.6$ mm is shorter than the electron beam. However in the undulator, the electron micropulse will be bunched to the size comparable to the optical wavelength due to its interaction with the radiation field, and the coherent radiation can be achieved finally. Based on this, when the bunch length is comparable to $l_c$, Eq. (3) can be used for estimation of the saturation time. When the microbunch length becomes large, the fast decrease of the $G_{max}$ which has a cubic relation to the peak current will lead to an unpractical long saturation time exceeding the macro-pulse duration.

#### 2.1.1. Undulator period number $N_u$

For FEL oscillators, shorter undulator period $\lambda_u$ will contribute to larger $N_u$ for higher gain with specified undulator length. However, $\lambda_u$ has a technical limit from the demand of the undulator parameter $K$ relating to the peak field in the undulator, as described in Section 2.2. For 10 mm vertical aperture undulator duct, a minimum gap size $g = 16$ mm is set for considering the thickness of the vacuum pipe. With a reasonable choice of the ratio $g/\lambda_u = 0.5$, $\lambda_u = 32$ mm is determined.

The undulator period number $N_u$ should be carefully optimized for long wavelength radiation, although larger $N_u$ will bring higher single pass gain. The slippage effect will occur when $N_u \cdot \lambda_r$ is comparable to the electron bunch length. However, the oscillation during the saturation procedure caused by the slippage can be compensated and alleviated by optical length detuning.

Main negative effects on the radiation by larger $N_u$ are (1) decrease of the natural extraction efficiency of the undulator, which is defined by the optimal efficiency for conversion of the electron beam power into the output radiation power, and can be approximately estimated by $1/4N_u$ [12] and (2) demand for smaller energy spread, to keep the same $F_{inh}$.

To investigate the optimum $N_u$, the single pass gain and the saturation time are compared using the analytical method described in Section 2.1. While keeping the same parameters of electron beam performance in Table 1, the undulator period