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BEAM INSTABILITY INDUCED BY RF SYSTEM OF AN FEL-THZ SOURCE

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Abstract

An SLAC-like Compact Linac installed on the HUST FEL-THz has been used as an injector to produce high power THz radiation. To meet the requirements of monochromaticity and repeatability for FEL, performance of electron beam and stability of RF system are notable. According to the existing facility, based on measurement results of RF jitter, instability of beam has been calculated, and it has been verified in relevant experiments. Furthermore, stability targets in RF system has been proposed in this paper.

INTRODUCTION

Free-Electron-Laser(FEL) sources driven by relativistic electron beam can produce coherent THz radiation with high power and tunable wavelength. A THz-FEL source has been constructed in Huazhong University of Science and Technology, and under commissioning at present, corresponding parameters are listed in Table 1[1-3].

Table 1: Parameters of THz-FEL Source

Parameter	Value
Beam energy	8~14MeV
Micro-bunch charge	≥200pC
Micro-bunch length	≤10ps
RF frequency	2856MHz
Radiation frequency	3~10THz
Micro-pulse radiation power	3MW

Figure 1 shows the simplified structure of THz-FEL source. In existing RF system, a klystron is operating in saturation region. Power from the klystron is fed into two Independently Tunable Cells (ITC) and a travailing wave linac through waveguides and two power splitters.

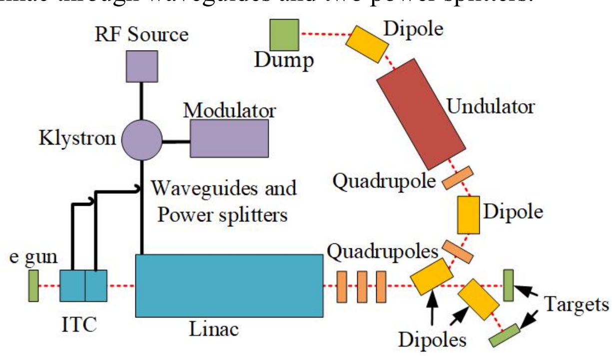

Figure 1: Simplified diagram of THz-FEL source.

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In this paper, the jitters of RF power and beam energy have been measured. Besides, effects of RF system on beam performance has been taken into account theoretically. Furthermore, based on the requirement of electron beam, stability targets in RF system has been proposed as well.

CALCULATION OF STABILITY FOR RF SYSTEM

In acceleration of electron, the amplitude and phase of RF power lead to increases of electron energy according to:

$$\begin{cases} \dfrac{\mathrm{d}\gamma}{\mathrm{d}z} = \dfrac{eE(z)\cos\varphi}{m_0c^2} \\ \dfrac{\mathrm{d}\varphi}{\mathrm{d}z} = \dfrac{2\pi}{\lambda}(\dfrac{1}{\beta_\varphi} - \dfrac{1}{\beta}) \\ E(z) = \sqrt{2\alpha(z)Z_s(z)P(z)} \\ \dfrac{\mathrm{d}P}{\mathrm{d}z} = -2\alpha P - I_b E(z) \end{cases} \tag{1}$$

$$D = \frac{\beta_\varphi c}{3f} \tag{2}$$

where γ is the relative energy of electron, the energy of incident electron from ITC is 2.6MeV, E is the electric field for acceleration, φ is the RF phase where electron locates, λ is the wave length of the RF, α is the attenuation coefficient, Z is the shunt impedance, P is the amplitude of RF power, I_b is the beam current, the length of a cell D=34.9898mm, f is the operating frequency, and c is the velocity of light.

In the design of the HUST-FEL, the requirements of beam instability are shown in Table 2 partly. In usual experiments, we mainly use the beam with the energy of 10MeV and 13MeV [4].

Table 2: Requirements of Beam Instability

Parameter	Value
Beam energy	10/13MeV
Beam current	0.57A
Energy spread	0.13%
Energy jitter	0.17%

According to the Eq.(1) and Eq.(2), beam energy and relative phase at the exit of linac can be calculated based on

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the linac parameters as well as the initial amplitude and phase of RF power.

Figure 2 shows the fluctuation of the electron energy at the exit of linac with the increasing amplitude and the phase of RF power. For a selected energy of electron, initial parameter of RF power located on ridge of the curve leads to lesser energy spread.

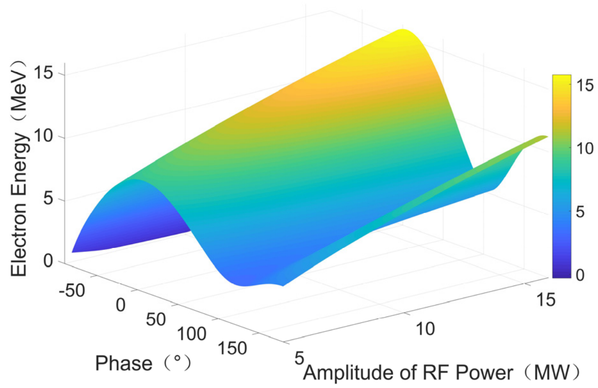

Figure 2: Fluctuation of electron energy with the increasing amplitude and phase of RF power.

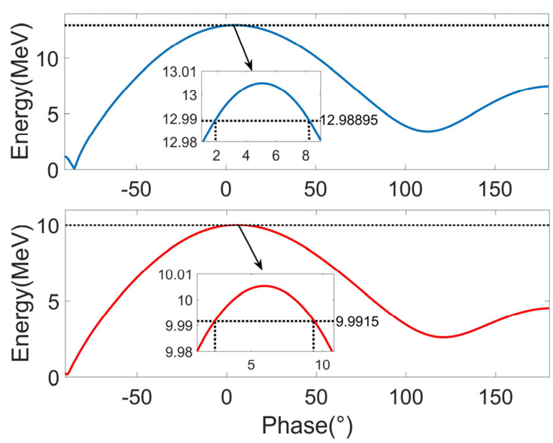

Figure 3: Electron energy fluctuates with the increasing phase and the RF power for selected beam energies.

As shown in the Fig.3., with the RF power of 10.787MW, the phase of 5.094°, where the incident electron locates, leads to the highest energy of electron (13MeV), and phase jitter of (2.466°, 7.74°) leads to the energy jitter of 0.17%. With the RF power of 6.362MW, the phase of 5.94° leads to the highest energy (10MeV), and phase jitter of (2.43°, 9.4°) leads to the energy jitter of 0.17%.

In these calculations, the micro-bunch length is assumed as 1.5ps or 1.542° in phase. As shown in the Fig.4., the phase of 5.22° where the incident electron locates leads to the lowest energy spread (0.008%), and phase jitter of ±3.6° leads to the jitter of 0.13% on energy spread. Besides, the phase of 6.12° leads to the lowest energy spread (0.01%), and phase jitter of ±3.96° leads to the jitter of 0.13% on energy spread.

Meanwhile, shown in Fig.5., at the proper phase, electron energy increases with the increasing amplitude of RF power. In order to limit the jitter of electron energy in 0.17%, the jitter of amplitude should be less than ±0.16% for 13MeV electron beam and ±0.15% for 10MeV electron beam.

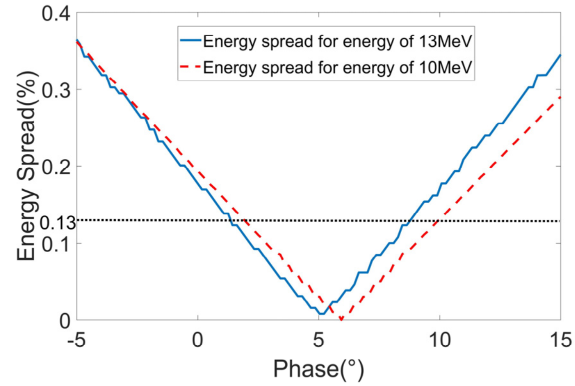

Figure 4: Energy spread change with the increasing phase.

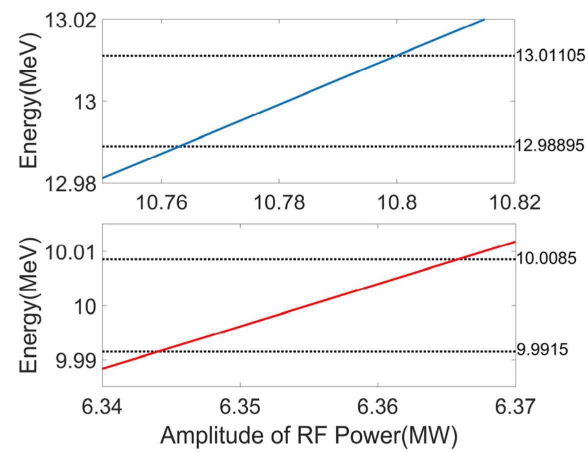

Figure 5: Electron energy increases with the increasing amplitude of RF power for selected beam energies.

MEASUREMENT OF RF STABILITY

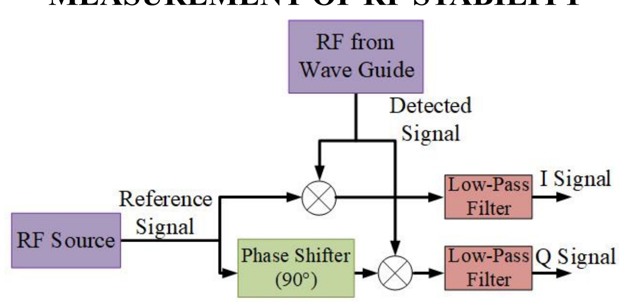

Figure 6: Simplified block diagram of an I/Q demodulator.

The incident RF power of linac can be coupled to I/Q demodulator through the directional coupler and attenuator on rectangular waveguide. The simplified block diagram of the I/Q demodulator is shown in Fig.6.

The reference signal and the detected signal can be expressed as $V_r = A_r \sin(\omega t + \varphi_r)$ and $V_d = A_d \sin(\omega t + \varphi_d)$. The reference signal through the phase shifter can be expressed as $V_r' = A_r \cos(\omega t + \varphi_r)$. The reference signals

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are mixed with detected signal to obtain the I/Q signal, as the following:

$$V_I=\frac{1}{2}A_rA_d\cos(\varphi_d-\varphi_r) \quad (3)$$

$$V_Q=\frac{1}{2}A_rA_d\sin(\varphi_d-\varphi_r) \quad (4)$$

Thus the relative phase $\Delta\varphi=\varphi_d-\varphi_r=\arctan(V_Q/V_I)$. And the amplitude can be measured by calibrated detector tube.

The amplitude and phase jitters of the RF power is shown in Fig.7. In experiments, the maximum value of amplitude jitter is over 0.8%, and the maximum value of amplitude jitter is over 2.9°

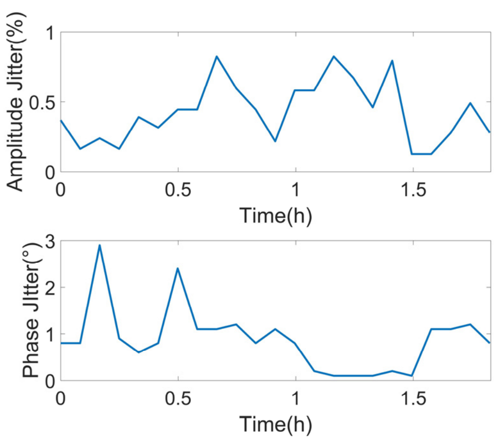

Figure 7: The amplitude and phase jitter of RF power.

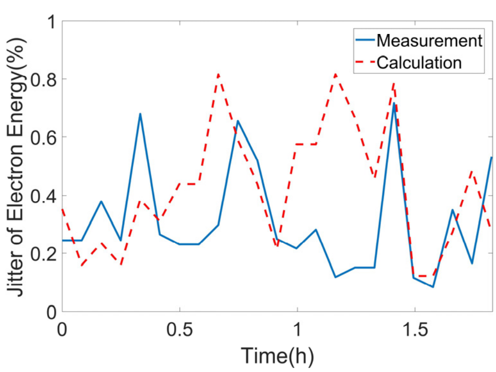

Figure 8: Calculated and measured jitter of electron energy.

Based on the measured jitter of RF power, the instability of electron energy due to the RF jitter can be calculated, and it is mainly affected by amplitude jitter of RF power, as shown in the Fig.8., and the calculation is similar with the measured jitter of electron energy.

However, the performance of electron beam is affected by other distractions, such as asymmetrical temperature drift of linac, mechanical vibrations [5], instability of current in focusing coil, et al. Besides, in I/Q demodulation with the same frequency of reference and detected signal, I/Q signals are direct current signals, the measurement is disturbed by DC noise and bias current in electronic devices and the elimination of these noise is difficult [6]. Thus there is a little inconsistence between the results from calculation and measurement.

Table 3 shows the targets of RF stability in amplitude and phase based on the requirement of electron beam. Besides, taking other parameters of electron beam into account, the amplitude jitter of RF power should be limited in ±0.15% and phase jitter should be limited in ±2.5°. Furthermore, in order to reach the targets, Analog-Digital hybrid Low Level RF controller based on FPGA should be designed.

Table 3: Targets of RF Stability in Amplitude and Phase

RF stability	13MeV	10MeV
Jitter of amplitude	±0.16%	±0.15%
Jitter of phase	±2.628°	±3.038°

CONCLUSION

In this paper, based on the beam dynamics, effects of RF system on beam performance has been discussed. Besides, according to the simulation, in order to limit the jitter of electron energy in 0.17%, the jitter of amplitude should be less than ±0.15%, and the jitter of phase should be less than ±2.5°.

However, in experiments, the maximum value of amplitude jitter is over 0.8%, and the maximum value of amplitude jitter is over 2.9°. Based on the measured jitters of RF power, the calculated jitter of electron energy due to the RF jitter is over 0.8%, which is similar with the measured jitter of electron energy and higher than the requirement of electron beam. Besides, the performance of electron beam is affected by other distractions, thus there is deviation between the calculation and measurement.

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