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NONINTERCEPTIVE BEAM ENERGY MEASUREMENT OF HIGH-FREQUENCY FREE ELECTRON LASERS*

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Abstract

Free electron lasers (FEL), which can generate ultra-high brightness radiation are working horses for radiation science research over the world. For FEL, the higher the repetition frequency of the beam in the device, the higher the user's experimental efficiency, and more experimental stations can conduct experiments simultaneously. Therefore, there is a trend to increase the repetition frequency in its development process. Therefore, it is necessary to develop relevant technologies for high repetition frequency FEL. Beam energy is one of the most fundamental and critical parameters in FEL. This paper developed a fusion algorithm based on beam position monitor (BPM) in the dispersion structure of a FEL, which extracts the transverse position of the beam using both the arrival time and amplitude information of the beam, to achieve high-precision and non-interceptive measurement of beam energy. Provide powerful diagnostic, operational, and maintenance tools for high-frequency free electron laser devices.

INTRODUCTION

For FEL devices, the higher the repetition frequency of the beam in the device, the higher the user's experimental efficiency, and the more experimental stations can be used for simultaneous experiments. Therefore, there is a trend for FEL to develop towards higher frequencies. Correspondingly, high repetition frequency also poses higher requirements for beam diagnosis systems.

Beam energy is one of the most fundamental and critical parameters in FEL. The energy of the beam entering the luminescent structure directly affects the final quality of the laser. Therefore, maintaining long-term stability of beam energy is crucial for the stability of radiation wavelength and laser pulse arrival time. High precision measurement and control of beam energy is a prerequisite for achieving wavelength control of radiation.

There are three commonly used methods for measuring beam energy in FEL. The most commonly used method is based on beam energy profile, and the vast majority of free electron laser devices are equipped with this approach [1]. But this method is interception based, and will affect the device's light supply. The second method is based on the beam arrival time measured by the cavity probe, which can obtain beam energy without interception. SXFEL and SHINE have adopted this scheme [2]. However, the beam signal detected by the cavity probe is relatively long, reaching μs level. As the beam repetition frequency gradually exceeds MHz, this method is no longer applicable. The traditional measurement scheme based on button type beam position detector (BPM) [3] has disadvantages such as low dynamic range and the need for initial beam position calibration.

Based on the above research status, this paper uses a BPM based measurement method in the dispersion structure of FEL, such as a bending magnet (BM) structure. It introduces a method of extracting beam energy using beam arrival time information, which is integrated with the original method of calculating transverse position using amplitude information to further obtain beam energy. This solves the problem of low dynamic range and greatly optimizing the shortcomings of the BPM based method to achieving high-precision and non-destructive beam energy measurement.

This paper achieves non-interceptive energy measurement of high repetition frequency FEL, solving the problem of difficulty in obtaining beam energy in real time without affecting the quality of laser supply.

MESUREMENT PRINCIPLE

We use HOTCAP to achieve high-precision extraction of BPM signal amplitude and phase. HOTCAP was previously used to extract the bunch-by-bunch 3D position in the electron accelerator storage ring [4]. We have proven that it works well in FEL and conduct a detailed diagnosis of the device [5].

A dipole magnet is a common structure in a linear electron accelerator, which can bend the orbit of the beam. For bunches with energy distribution, after passing through a dipole magnet, the original distribution will change in both the horizontal direction (bending direction) and the forward direction due to the different deflection radii. Therefore, the energy distribution information of the beam can be obtained by the distribution changes at this two-dimensional position.

As shown in the Fig. 1, when the bunch passes through the dipole magnet, the bunch with higher energy has a bigger bending radius and is farther away from the deflection centre. Therefore, in the horizontal direction, there will be significant dispersion due to the difference in energy.

There is a formula:

$$B\rho = \frac{\sqrt{W(W+2\varepsilon_0)}}{zc}, \quad (1)$$

where B is the magnetic field strength, ρ is the bending radius, W is the beam energy, ε_0 is the electron static energy, and zc is a constant. If the horizontal position of the beam can be measured at this time, the energy information of the beam can be obtained.

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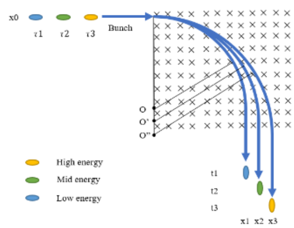

Figure 1: Changes in the transverse position distribution of bunches of different energies in a magnetic field.

Beam Energy Monitor (BEM) Based on Transverse Position Measurement of Beam

Traditionally, it is believed that when the bunch passes through the vacuum chamber where the BPM is located, the amplitude of the signal excited on the BPM electrode is related to the distance from the bunch to the probe. This method requires the bunch orbit to be close to the centre of the vacuum chamber in order to obtain results with high linearity and relative SNR. From the Eq. (1), it can be seen that when the bunch has a 0.2 % energy dispersion, the bending radius also has a distribution close to 0.2 %. When the device is in poor operating condition, that is, when the beam energy dispersion is large, the beam motion trajectory will exceed the linear region.

When the bunch passes through the plane where the BPM probe is located, the arrival time of the signal obtained by the signal acquisition device consists of three parts: the time when the bunch reaches the plane of the vacuum chamber where the probe is located, the time when the electromagnetic field excited by the beam reaches the probe, and the time when the probe signal is transmitted in the cable. Only the second part will change with the transverse position of the beam. Due to the different positions, the distance from the beam to the electrode also varies, and the speed of electromagnetic field propagation in the vacuum chamber is a constant speed of light. This means that the resolution of the scheme is not affected by whether the bunch is in the linear region, and there is always the same conversion coefficient within the vacuum chamber range. In the existing BPM based beam diagnosis schemes, when using cross-correlation method to extract arrival time, it has sub picosecond resolution [6]. At this time, using arrival time to extract the corresponding transverse position has a resolution of hundreds of micrometres, which can cover the measurement range of the transverse position of the beam outside the linear region. When the beam passes through the centre of the vacuum chamber, the signals obtained by the probes on both sides are relatively close, which is more suitable for extracting the transverse position from the amplitude; When the bunch passes through one side of the vacuum chamber, a larger signal will be generated on the probe closer to the beam, and the signal-to-noise ratio of amplitude information on the probe farther away from the beam will be greatly reduced. This paper achieves the fusion of two schemes by optimizing the corresponding algorithms and combining them with the actual parameters of the bipolar magnet, so that the beam can obtain high-resolution lateral position information at any position in the vacuum chamber.

BEM Based on Arrival Time Measurement of Beam

It is difficult to accurately measure the flight time of a bunch moving at near the speed of light between two BPMs, as the energy difference between the beam clusters generates a femtosecond difference in flight time at the laboratory scale, temporarily exceeding the resolution of BPM based beam arrival time measurements. However, when the beam passes through the dipole magnet, this distribution will be amplified due to the difference in flight distance between the beam clusters. According to the magnetic stiffness formula, a one percent energy difference between the beam clusters will result in an arrival time difference of about picoseconds. The resolution capability of existing beam arrival time measurement schemes can distinguish this difference.

The difference from the beam energy measurement based on the lateral position measurement of the beam mentioned above is that the measurement of the beam arrival time here refers to the measurement of the time difference between the arrival of the beam cluster and the vacuum chamber plane where the two sets of BPM probes are located. In the previous scheme, the measurement for converting the beam arrival time into position information is the measurement of the time difference between the arrival of the beam signal at different electrodes in the same set of BPM probes.

The above two methods are independent of each other and applicable under different conditions. They can be mutually verified.

EXPERIMENT

The FELiChEM is an experimental facility under construction at the University of Science and Technology of China (USTC) [7]. Each electronic macro pulse in the device contains several microelectronic pulses with a repetition frequency of 59.5 MHz or 119 MHz, known as electron bunch. The length of the electronic macro pulse is adjustable and lasts for 1-10 microseconds. Due to the different relative positions of electron beam clusters in the macro pulse, the electromagnetic environment for obtaining energy and generating laser will also vary. Therefore, the parameters (centre wavelength, intensity) of laser pulses generated by different electron beam clusters are slightly different.

The device has a BM section with some dipole magnet structure that meets the above conditions. The parameters of the dipole magnet at this location are as Table 1.

As shown in the Fig. 2, at the entrance of the BM and the location with the highest dispersion, four electrode BPM probes are equipped. The upgraded BPM system now has the ability to measure bunch-by-bunch. It can synchronously obtain and store position data at two BPM points in real time. Data analysis is carried out according to the above measurement principle.

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Table 1: Parameters of the FELiChEM Dipole Magnet

Parameter	Valve	Unit
Length	200	mm
Radius	254.648	mm
Angle	45	degree
Gap	45	mm
B_max	0.7926	T

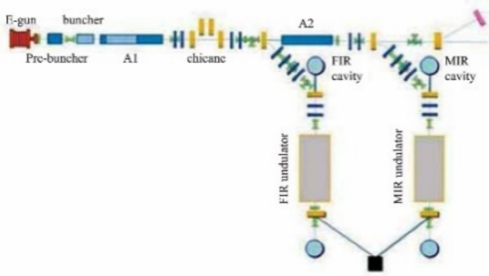

Figure 2: Layout of the FELiChEM.

Based on the parameters in the Table 1, the energy distribution inside the bunch string during the operation of the device is obtained.

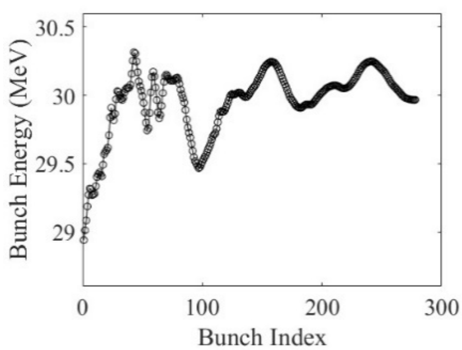

Figure 3: Beam energy distribution in the FELiChEM based on transverse position measurement.

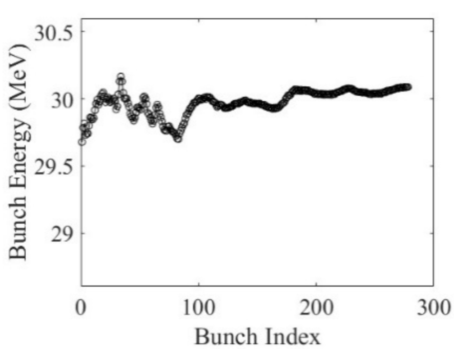

Figure 4: Beam energy distribution in the FELiChEM based on arrival time measurement.

As shown in the Figs. 3 and 4, when the FELiChEM operates with general parameters, there is a significant difference in energy inside the beam cluster string, with a clear distribution within the string. The head energy of the bunch is much lower than the design value and cannot participate in laser emission, which is consistent with the laser supply results (the number of laser pulses is always about 100 fewer than the number of electron bunch micro pulses). Which has better energy consistency and is considered the main source of luminescence, is considered the middle and rear part of the "beam core". It means this device has room for optimization.

The energy distribution trends obtained from the two schemes are similar, but there are differences in details. The reason is quite complex, as the influence of beam incidence angle and vertical distribution has not been excluded in the calculation. In further work, the influence of the above factors will be gradually eliminated. The existing work can already provide assistance for optimizing the operation of the device. Partial experiments have already been conducted. The results indicate that changes in the operating parameters of the device can alter the consistency of beam energy, and exhibit the same trend in both calculation methods.

CONCLUSION

This paper comprehensively achieves non-interceptive energy measurement of high repetition frequency free electron laser devices based on existing BPM systems through two methods: time-of-flight and position measurement. The relative resolution reaches 0.01 %, which can solve the problem of difficult real-time acquisition of beam energy during the operation of such devices without affecting the quality of light supply.

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