MANIPULATING THE FEL GAIN PROCESS WITH AN IN-CAVITY APERTURE SYSTEM*

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Abstract

The 53.73 meters long free-electron laser (FEL) resonator at Duke University consists of two concave mirrors with the similar radius of curvature. The downstream mirror receives not only the fundamental but also higher order harmonic radiation (typically in the UV and VUV range) emitted by relativistic electrons in the magnetic field of wigglers. The power load of wiggler radiation on this mirror can thermally deform and permanently damage the multi-layer coating of the mirror, therefore, limiting the maximum power of the FEL operation and reducing the mirror lifetime. To mitigate these problems, a water-cooled aperture system has been installed inside the FEL resonator. This aperture system has been used to prevent most of off-axis helical wiggler radiation from reaching the downstream FEL mirror. It has also been used to manipulate the FEL gain process by increasing the FEL beam diffraction loss inside the resonator. In principle, this aperture system can be used as an independent FEL gain control device for FEL operation. This paper reports our preliminary study of the FEL operation using the in-cavity apertures to manipulate the FEL gain process.

INTRODUCTION

The Duke free-electron laser (FEL) is the photon driver for the High Intensity Gamma-ray Source (HIGS) [1]. By colliding FEL photons with electrons at the center of the FEL resonator, an intense, highly polarized, nearly monochromatic γ-ray beam is generated. The γ-beam flux is determined by the intracavity FEL power and electron beam current. At the HIGS, the energy spread of the electron beam determines the minimal energy spread of the γ-ray beam. However, there are some limitations on the γ-ray beam production using a storage ring oscillator FEL. First, the wiggler harmonic radiation (typically in the UV and VUV range) can thermally deform and permanently damage the multi-layer coating of the downstream mirror, limiting the maximum power of the FEL and reducing the mirror lifetime. To mitigate these problems, a water-cooled aperture system has been installed inside the FEL resonator [2]. This aperture system has been used successfully to block most of off-axis radiation from the helical wigglers. Secondly, the FEL induced energy spread increase of the electron beam will reduce the γ-ray beam energy resolution. Sacrificing the γ-ray beam flux, this problem can be solved by operating two uneven electron bunches. The large bunch with a substantial amount of charge will produce a high intensity FEL beam, while the other bunch (the small one) with a small amount of charge will see no increase of its energy spread as it is below the threshold of lasing. For a high reflectivity optical resonator, the non-lasing small bunch typically has an averaged beam current of few mA. Because the gamma-ray photons are generated by colliding FEL photons produced by the large bunch and electrons in the small bunch, the above uneven two-bunch beam can produce a gamma-ray beam with a small energy spread, but with a substantially low γ-ray beam flux. To increase the gamma flux, we can inject more charge into the small bunch without bringing it to lasing. This can be realized by reducing the net FEL gain via an increase of the cavity loss using the in-cavity water-cooled apertures.

The FEL gain is proportional to the electron beam peak current. At the beginning stage of the FEL gain process, the electron bunch length is short; a higher peak current beam produces a higher FEL gain. With the growth of the FEL power inside the cavity, the FEL induced energy spread increases, resulting in a lengthened electron bunch and subsequently a lower FEL gain. When the FEL gain is reduced to a level of the total cavity loss, the FEL process reaches saturation.

This paper reports the study of FEL operation while manipulating the gain process by closing the in-cavity apertures.

THE DUKE FEL RESONATOR

The 53.73 meters long Duke FEL resonator cavity consists of two concave mirrors with a similar radius of curvature. At present time, two planar OK-4 wigglers and two helical OK-5 wigglers are used in various FEL configurations [4] (see Fig. 1). In Table 1, a set of key parameters for FEL operation are listed.

The water-cooled aperture system is installed about 22.3 meters downstream from the center of the FEL cavity. It is comprised of four individually movable copper aperture poles; H1 and H2 poles are horizontal, and V1 and V2 poles are vertical as shown in Fig. 1. Each pole has a built-in water cooling channel to dissipate the heat. In the present configuration, the maximum and minimum opening (full gap) of the aperture system is 48 mm and 10 mm, respec-

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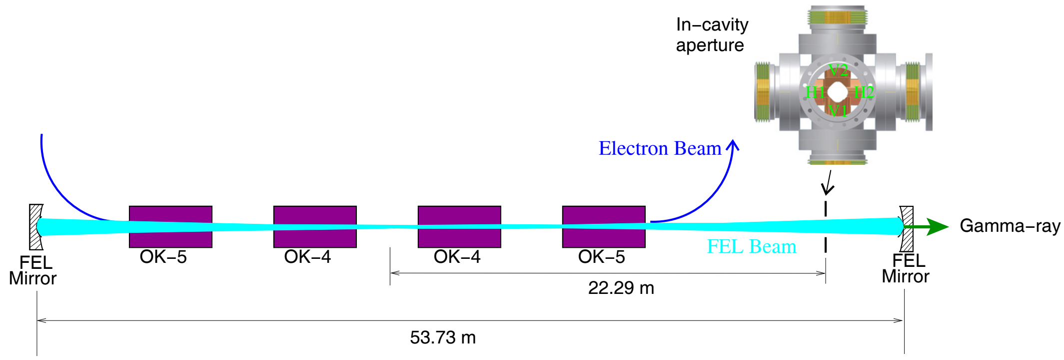

Figure 1: The layout of the FEL wigglers and optical resonator.

Table 1: A Set of Key Parameters for the Duke FEL

	OK-4 FEL	OK-5 FEL
No. of Wiggles	2	2
Wiggler Period	0.1	0.12
No. of Period	34	33
Max. B Field (T)	0.536	0.286
Wiggler Gap (mm)	25	40×40
Lasing Wavelength (μm)	0.19–1.06	0.19–1.06

tively, in the horizontal and vertical directions. The aperture system is developed to protect the downstream FEL mirror from off-axis high-order harmonic wiggler radiation. When the aperture is closed to a size comparable with the FEL beam size, it can substantially increase the FEL beam loss.

REPRODUCIBILITY OF THE APERTURE POLE SCANNING

The aperture poles are driven by stepping motors via a remote control. It is necessary to test the reproducibility of the pole scanning in order to produce consistent experimental data.

During the test, each pole was scanned inward from a position at 9 mm to 5 mm (the stop position). The other three poles are parked at the 9 mm position where they do not affect the FEL beam. The FEL out-coupled power was recorded during the scanning. Figure 2 shows the results of three scans using one of the horizontal aperture poles, H2. These scans show a very good reproducibility, indicating the FEL mode structure is well reproduced at the same aperture size during the interval of a scan. The results of scanning other three poles show similar reproducibility.

FEL BEAM SIZE AT THE LOCATION OF THE IN-CAVITY APERTURE

If there is no transverse physical limitation, the FEL beam in the optical resonator can be described by a fundamental Gaussian mode with a waist size given by

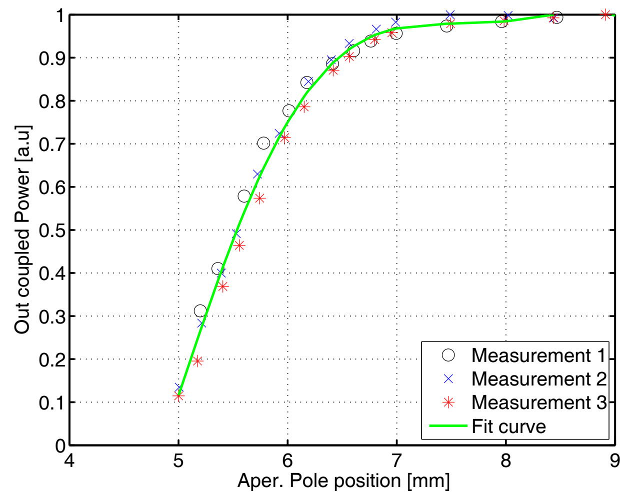

Figure 2: Reproducibility of scanning the aperture pole H2. The FEL is operated at 345 nm with two OK-4 wigglers. All other three poles are parked at 9 mm, a position where they do not affect the FEL beam.

$$w_o = \sqrt{\frac{\lambda}{\pi} Z_R}, \quad (1)$$

where λ is the laser wavelength , and

$$Z_R = \sqrt{\frac{L}{2}(R_m - \frac{L}{2})} \quad (2)$$

is the Rayleigh range of the laser beam, R_m is the radius of curvature of the cavity mirrors. When the aperture is closed to a size a few times of the laser mode size, it will start to increase the diffraction loss and reduce the FEL power. For cavity mirrors with a radius of curvature of 27.8 meters, the Rayleigh range of the laser beam is 5.01 meters (Eq.2). From Eq. 1, the Gaussian waist w_0 of a 345 nm FEL beam is 0.74 mm. The beam size at the location of the aperture is $w_0\sqrt{1+(\frac{z}{Z_R})^2} = 3.38$ mm. When H1 and H2 poles are closed to 5 mm, the FEL power is reduced to about 20% and 10%, respectively. The range of the pole motion is more than adequate for controlling the FEL power.

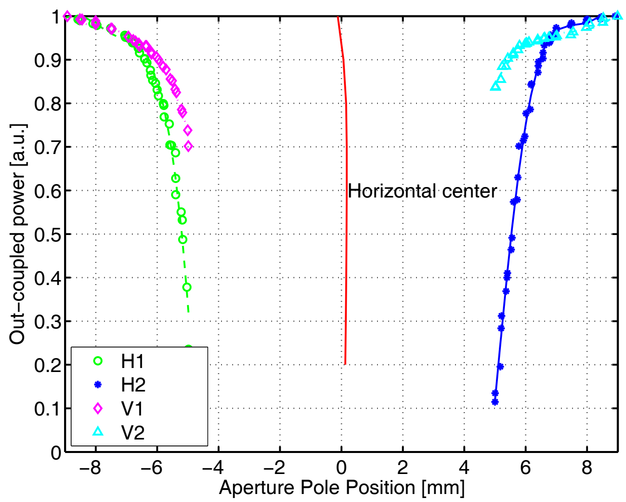

Figure 3: The FEL power as a function of the position of the scanning pole while keeping other three poles parked at 9 mm.

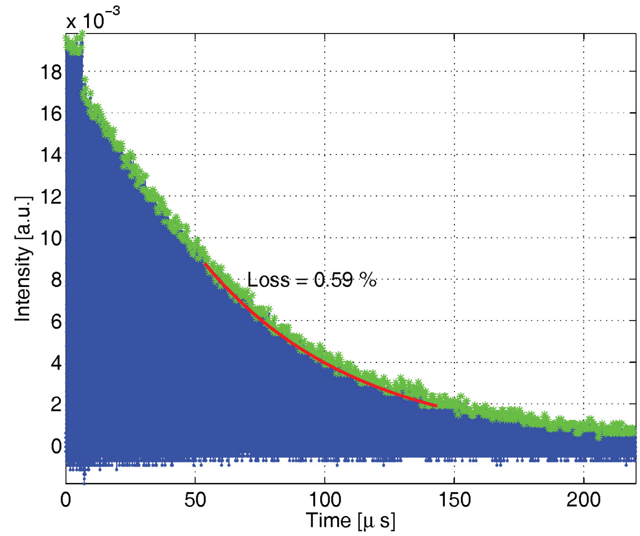

Figure 4: The FEL ring-down curve measured with H2 at the 7 mm position.

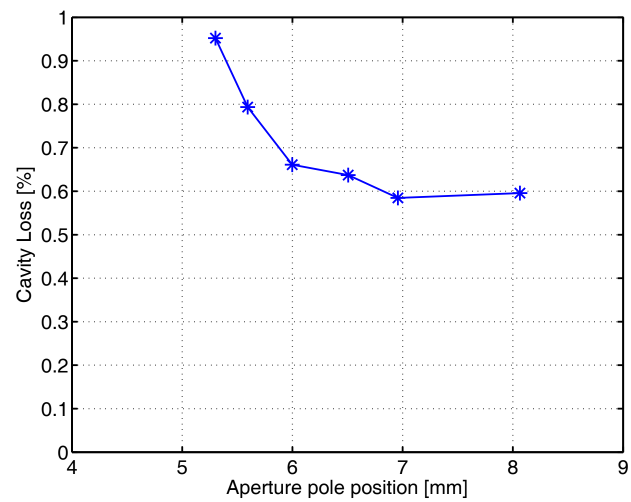

Figure 5: The single-pass cavity loss as a function of the H2 pole position. The other three aperture poles are parked at the 9 mm position.

In Fig. 3, the FEL power is shown as a function of the position of the scanning pole while keeping the other three poles parked at 9 mm. It is clearly seen that at a fixed relative FEL power level, for example, 85% of the full power, the vertical poles need to be brought to closer to the optical axis than the horizontal ones. This is a strong indication that the FEL mode is not a round Gaussian mode due to an overall smaller opening in the vertical direction than the horizontal due to the arrangement of vacuum chambers. This laser mode has a smaller vertical size at the location of the aperture than the horizontal direction.

CAVITY LOSS AT DIFFERENT APERTURE OPENINGS

To effectively manipulate the FEL operation, one of the horizontal aperture poles, H2, is used as a knob to control the cavity loss. Other poles are parked at the 9 mm position where they have no impact on FEL lasing. To determine the FEL cavity loss, the FEL optical pulse was measured using a photon multiplier tub (PMT). The ring-down process of the captured FEL power is initiated by knocking out the stored electron beam. Figure 4 shows a ring-down curve of the FEL power signal measured with H2 at the 7 mm position.

Figure 5 shows the cavity loss measured with H2 pole at positions between 8 and 5 mm. The single-pass cavity loss is increased from 0.6% at the 7 mm position to 9.6% at the 5.3 mm, an increase of the cavity loss of about 60%.

SUMMARY

The in-cavity aperture system have been used to manipulate the FEL gain process. This system can be used to increase the gamma-beam flux in the high resolution γ-ray beam production. It can also be used to independently control the FEL spectrum bandwidth for a fixed electron beam current, an area remains to be explored.

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