FEL TRANSVERSE MODE MANIPULATION USING AN IN-CAVITY APERTURE SYSTEM*

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Abstract

The Duke free-electron laser (FEL) is a storage ring based oscillator FEL (SRFEL). It has been used as the photon source for the High Intensity γ-ray Source (HIγS) at Duke University. The 54 m long FEL cavity consists of two concave mirrors with the same radius of curvature. The downstream mirror receives not only the fundamental radiation but also higher harmonic radiation emitted by relativistic electrons in the wiggler magnetic field. The ultraviolet (UV) and vacuum-ultraviolet (VUV) power load of harmonic radiation on this mirror can deform or even seriously damage multi-layer coating of the mirror, and hence limit the maximum power for FEL operation. To mitigate these problems, a water-cooled aperture system has been installed inside the cavity. This aperture system can also be used to manipulate transverse modes of the FEL beam. In particular, they can be used to reduce the wiggler radiation power in the fundamental mode, thus as an independent FEL gain control device. This paper reports our preliminary study of the FEL beam modes manipulation using the water-cooled in-cavity apertures.

INTRODUCTION

The Duke free-electron laser (FEL) is a storage ring based oscillator FEL (SRFEL). It has been used as the photon source for the High Intensity Gamma-ray Source (HIγS) at Duke University [1]. The 54 m long FEL cavity consists of two concave mirrors with the same radius of curvature. The downstream mirror receives not only the fundamental radiation but also higher harmonic radiation emitted by relativistic electrons in the wiggler magnetic field. The ultraviolet (UV) and vacuum-ultraviolet (VUV) power load of the harmonic radiation on this mirror can deform or even seriously damage multi-layer coating of the mirror, and hence limit the maximum power for FEL operation. To mitigate this problem, a motorized, water-cooled, aperture system has been installed inside the FEL cavity to block off-axis radiation. This aperture system has been used to effectively reduce harmonic radiation power load on the downstream mirror by two orders of magnitude or more, with a small attenuation, a factor of three to five, of the fundamental power by cutting off its off-axis power distribution. This large reduction of high harmonic power load on the FEL downstream mirror can be realized without having significant impact on the FEL operation [2, 3]. The in-cavity aperture system has made it possible to have high intra-cavity power FEL operation in the UV/VUV region with a large electron beam current at the Duke FEL laboratory (DFELL).

Traditionally, in-cavity apertures have been used to control the growth of higher-order transverse modes of a conventional laser [4]. At the DFELL, the in-cavity apertures can also be used to manipulate transverse modes of the FEL beam. In particular, they can be used to reduce the wiggler radiation power in the fundamental mode, thus as an independent FEL gain control device. The following sections report our preliminary study of the FEL beam modes manipulation using the water-cooled, in-cavity apertures.

FEL BEAM TRANSVERSE MODE CONTROL

The SRFEL is usually tuned to operate in the lowest-order Gaussian mode for high performance. The FEL beam power intensity distribution can be described by [4]

$$I(r,z) = \frac{2P}{\pi w(z)^2} e^{-2r^2/w(z)^2}, \tag{1}$$

where P is the total power of the laser beam, $w(z)$ is the beam size at a longitudinal location z, and r is the displacement from the optical axis in the polar coordinate system. The beam waist, located at $z = 0$, has a size of w_0,

$$w_0 = \sqrt{\frac{\lambda z_R}{\pi}}, \tag{2}$$

and the beam size at z is

$$w(z) = w_0 \sqrt{1 + (\frac{z}{z_R})^2}, \tag{3}$$

where λ is the wavelength of the laser beam, and z_R is the Rayleigh range. For a symmetric optical resonator with two mirrors of the same radius of curvature R, the Rayleigh range of the resonator is given by

$$z_R = \sqrt{\frac{L}{2}(R - \frac{L}{2})}, \tag{4}$$

where L is the cavity length.

For a circular aperture with a radius a located at z, ignoring the diffraction effect, the power transmission is given by

$$T = 1 - e^{-2a^2/w(z)^2}. \tag{5}$$

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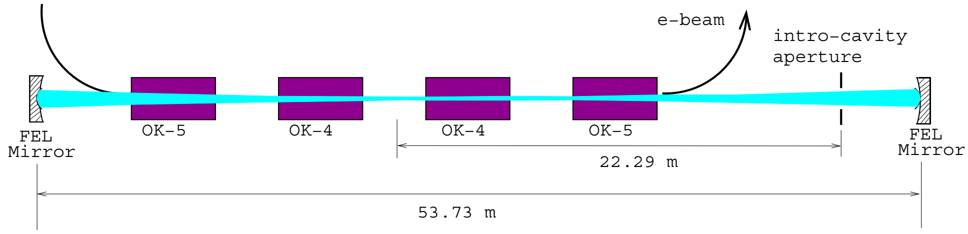


Figure 1: The layout of the Duke FEL oscillator cavity.

Table 1: Gaussian Beam Transmission Through a Round Aperture and Induced Near-Field Diffraction Ripple

	a	T	Ripple
Top hat	$\frac{\sqrt{2}}{2}w$	0.632	
$1/e$	w	0.865	
99**%**	$\frac{\pi}{2}w$	0.993	$\pm17\%$
1**% ripple**	$2.3w$	$1-2.54\times10^{-5}$	$\pm1\%$
	πw	$1-2.68\times10^{-9}$	

Besides reducing the transmitted power, the aperture also causes diffraction ripples in both near- and far-field regions. Table 1 lists the transmission and near-field diffraction ripple with apertures of different sizes. As the aperture size reduces, we expect the transverse modes to start to deviate from the ideal Gaussian mode, as the result of mode shaping. In the meantime, both transmission loss and diffraction loss can reduce the net gain of the laser cavity.

IN-CAVITY APERTURES FOR FEL GAIN CONTROL

The net gain of an SRFEL oscillator is determined by the gain of the FEL interaction and various loss mechanisms. To start the FEL lasing process, the gain has to be larger than the total loss of the optical resonator. As the FEL power grows, the electron beam energy spread increases, lengthening the electron bunch. Consequently, the FEL gain is reduced due to a lower peak electron beam current and the FEL oscillator reaches saturation when the net gain approaches zero.

A higher extracted FEL power can be produced by increasing the induced electron beam energy spread via FEL interaction. With an increased cavity loss, FEL saturation will be reached sooner, resulting in a smaller induced energy spread of the electron beam and yielding a lower extracted FEL power. The total round-trip cavity loss is the result of mirror transmission and various loss mechanisms, including mirror absorption, mirror surface scattering, and diffraction loss. The in-cavity aperture system introduces a new loss mechanism to the optical resonator. By varying the aperture size, we will be able to independently control the net gain of the FEL oscillator, allowing us to manipulate the extracted FEL power level.

The layout of the DFELL oscillator cavity is shown in Fig. 1. At the present time, two planar OK-4 wigglers and two helical OK-5 wigglers are installed in the storage ring FEL straight section. Depending on the need of an experiment, these wigglers can be set up in various configurations. For example, we can operate the OK-4 or OK-5 FEL as a conventional FEL with only one wiggler or as an optical klystron with two wigglers. Operating two OK-4 and two OK-5 wigglers simultaneously, a higher gain distributed optical klystron FEL was realized in 2005 [5].

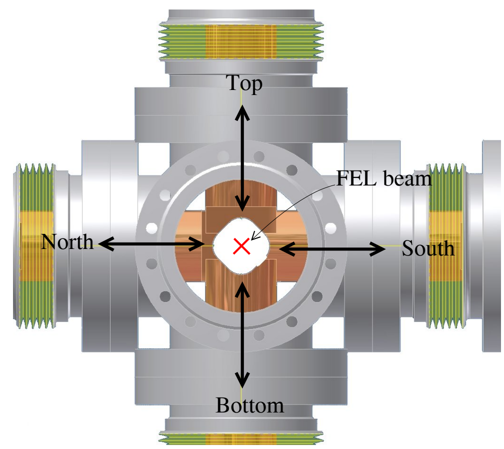


Figure 2: The front view of the water-cooled in-cavity aperture system.

The in-cavity aperture system is located at 22.29 m downstream from the center of the FEL resonator. It consists of four copper poles as shown in Fig. 2. There is a built-in water cooling channel in each pole to dissipate the heat generated by radiation emitted by electrons in the wigglers. Driven by a step motor, each pole can be moved independently. The maximum and minimum opening (full width) of these two apertures are 48 mm and 10 mm respectively in both horizontal and vertical directions. Because the opening of the aperture is not exactly circular, the intensity attenuation and diffraction effect will be different from a round aperture as discussed in the previous section.

FEL LASING TUNING USING APERTURE

The effect of the aperture system on FEL lasing is first studied via the measurement of the extracted FEL power and the electron bunch length. Direct studies on the FEL transverse mode distribution will be performed with a laser beam profile measurement system under development.

The extracted FEL power was studied as a function of

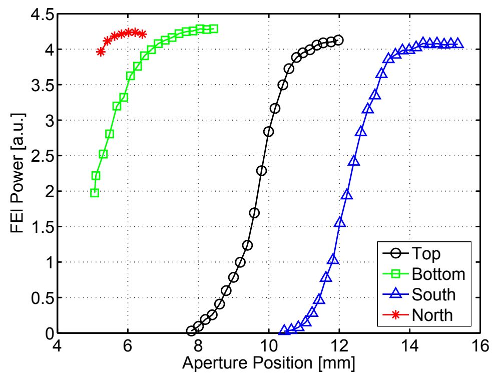


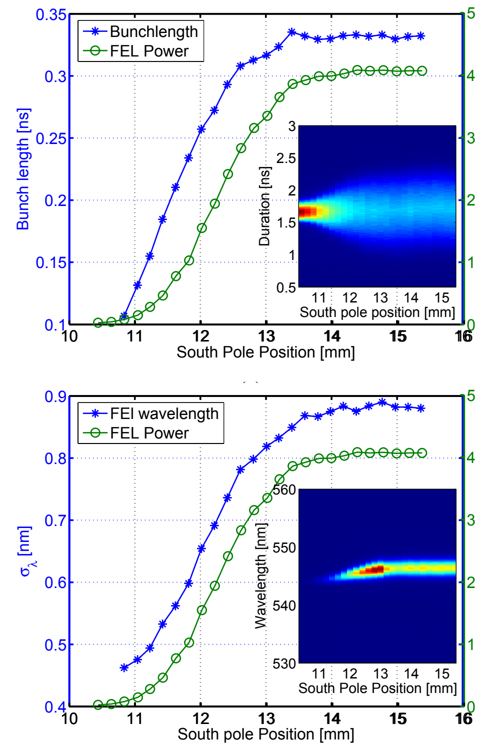
Figure 3: The extracted FEL power during the scanning of the aperture poles. The two-wiggler OK-5 FEL is lasing at 545 nm with a single-bunch current of 20 mA and an electron beam energy of 435 MeV.

the aperture pole position in both horizontal and vertical directions. Initially, all four aperture poles were fully opened so that they did not impact the FEL lasing. Then, one aperture pole was scanned at a time with all other three poles remained parked. The recorded FEL power is plotted in Fig. 3 for independent scans of four aperture poles. This figure shows that the extracted power begins to drop when the pole reaches a certain position at which the pole begins to cause substantial loss compared with the other cavity losses via reduced transmission and diffraction. The measured radius of curvature of the cavity mirrors is about 27.80 m, the cavity length is 53.73 m, from Eq. 3, the beam width at the location of the aperture system, $z = 22.29$ m, is about $w = 4.27$ mm. Figure 3 shows that the FEL power begins to reduce when the aperture opening is around 19 mm, about $4.5w$, in both horizontal and vertical directions. This is close to the 1% ripple criteria. From this preliminary data, it seems to indicate that the diffraction loss associated with the aperture closing is the dominant effect.

The energy spread of the electron beam is closely related to its bunch length. Therefore, we can study the bunch lengthening effect as the aperture closes. The electron beam bunch length was measured using a dissector [6]. Figure 4(a) shows the bunch length evolution as one of the aperture poles is scanned. As the aperture pole closes, both the extracted FEL power and electron beam bunch length are reduced. This is consistent with the expected reduction of the electron beam energy spread due to an increased FEL resonator loss. A related observation is, as shown in Fig. 4(b), the FEL bandwidth becomes narrower and the peak shifts to the shorter wavelength end as the result of reducing the beam energy spread.

SUMMARY

The in-cavity, water-cooled aperture system can be used not only to reduce the wiggler harmonic power load on the downstream FEL cavity mirror, but also to manipulate the FEL transverse mode. The mode modification increases



(b)

Figure 4: (a) The bunch length and FEL power as a function of the south pole position; (b) The FEL bandwidth and FEL power as a function of the south poles position. All other three poles are parked in the fully open positions. The FEL and electron beam parameters are the same as in Fig. 3. In the insets, the bunch longitudinal profiles and FEL lasing spectra are re-plotted as intensity plots.

the FEL cavity loss, and hence lower the maximum intracavity power via a reduction of the induced electron beam energy spread. This provides an effective way of improving the energy resolution of the HIγS Compton γ-ray which is produced by colliding the electron beam in the storage ring with the FEL beam. The authors would like to thank B. Jia and C. Sun at the DFELL for their help of this study.

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