CONTROLLING WIGGLER HARMONIC RADIATION TO REDUCE DAMAGE TO FEL CAVITY MIRRORS*

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Abstract

In an oscillator FEL, higher-order harmonic radiation from wigglers can cause serious damage to the downstream FEL resonator mirror or limit the maximum electron beam current for FEL operation due to thermal overload. With a helical wiggler, higher-order harmonic radiation is peaked off-axis. By blocking the off-axis wiggler harmonic power, the radiation damage to the FEL resonator mirror can be reduced. In this paper, we report a recently developed scheme to control the off-axis harmonic radiation from helical FEL wigglers using a set of motorized, water-cooled, in-vacuum apertures. These apertures can reduce the harmonic power load on the downstream FEL resonator mirror by one order of magnitude. With these apertures, high power FEL operation with a high electron beam current will become feasible in the UV-VUV wavelength range with Duke storage ring FELs.

INTRODUCTION

Wiggler magnets emit both fundamental and harmonic radiation. For oscillator FELs, UV-VUV harmonic radiation can cause serious damage to the downstream mirror of the FEL cavity. Compared to a planar wiggler, harmonic radiation from a helical wiggler is peaked off-axis and much improved mirror lifetime was expected by changing from a planar wiggler to a helical wiggler [1]. However, the off-axis harmonic radiation from helical wigglers can still reach the downstream mirror which has a finite size and can cause mirror damage or limit the maximum electron beam current for FEL operation due to UV-VUV power loading on the mirror. At Duke Free-Electron Laser Laboratory (DFELL), we have developed a mechanism to control the off-axis harmonic radiation from the helical wigglers by using a set of motorized, water-cooled, in-vacuum apertures. These apertures can reduce the harmonic radiation power load on the downstream mirror by one order of magnitude. With these apertures, high power FEL operation with a high electron beam current will become feasible in the UV-VUV wavelength range and with a reasonable lifetime of the FEL mirrors.

In this paper, we first describe the basic features of spatial distributions of helical wiggler radiation. We then move on to a brief introduction of the DFELL FEL wiggler configurations and provide a short description of the newly fabricated in-vacuum apertures. After that we will report the effectiveness of the apertures in reducing the wiggler harmonic radiation under various operation conditions and for different configurations of the Duke FELs.

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WIGGLER RADIATION

Frequency-Integrated Radiation Power Distribution

For a planar wiggler, the angular distribution of frequency-integrated power is given by the following equation [2]:

$$\begin{pmatrix} dP_\sigma / d\Omega \\ dP_\pi / d\Omega \end{pmatrix} = \frac{2e^2}{c} \cdot N_w K_w{}^2 \gamma^4 \cdot \frac{I_e}{e} \cdot \frac{1}{\pi} \int_{-\pi}^{\pi} d\xi \frac{\sin^2 \xi}{D^5} \begin{pmatrix} \left(1 - X^2 + Y^2\right)^2 \\ 4X^2 Y^2 \end{pmatrix} \quad (1)$$

where $D=1+X^2+Y^2$, $X = \gamma\varphi - K_w \cos\xi$, $Y = \gamma\psi$, $\xi = K_w z$, σ and π denote the horizontal and vertical polarizations respectively; φ and ψ are the horizontal and vertical observation angles, N_w is the numbers of wiggler periods, K_w is the dimensionless wiggler magnetic field parameter, γ is the relativistic factor, and I_e is the electron beam current. Similarly, the angular distribution of frequency-integrated power for a helical wiggler can be expressed as

$$\begin{pmatrix} dP_\sigma / d\Omega \\ dP_\pi / d\Omega \end{pmatrix} = \frac{2e^2}{c} \cdot N_w K_w{}^2 \gamma^4 \cdot \frac{I_e}{e} \cdot \frac{1}{\pi} \int_{-\pi}^{\pi} \frac{d\xi}{D^5} \begin{pmatrix} \left(1 - X^2 + Y^2\right)\sin\xi - 2XY\cos\xi \\ \left(1 + X^2 - Y^2\right)\cos\xi - 2XY\sin\xi \end{pmatrix}^2 \quad (2)$$

where $D = 1 + X^2 + Y^2$, $X = \gamma\varphi - K_w \cos\xi$, $Y = \gamma\psi + K_w \sin\xi$ and $\xi = K_w z$.

As an example, we plot the spatial distribution of radiation power from a planar wiggler (as shown in Figure 1) and a helical wiggler (as shown in Figure 2). It is obvious that the radiation power density is peaked on-axis for the planar wiggler and off-axis for the helical wiggler.

Different from planar wigglers, electrons in a helical wiggler travel with a constant longitudinal velocity. As a result, all higher-order harmonics (second order and above) vanish on the axis, leaving only the fundamental harmonic radiation peaked on-axis. For wigglers with a larger K_w, higher-order harmonic radiation becomes stronger than the fundamental. As shown in Figure 2, the off-axis harmonic radiation dominates the overall power distribution with a $K_w = 3$.

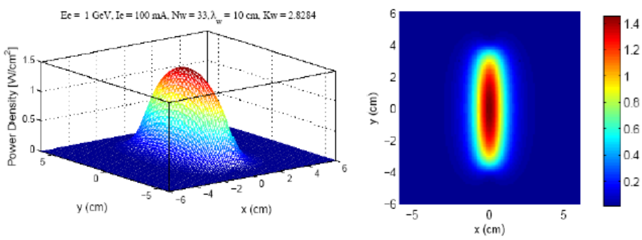

Figure 1: Spatial distribution of planar wiggler radiation power. Parameters for the calculation: E_e = 1 GeV, I_e = 100 mA, N_w = 33, λ_w = 10 cm, K_w = 2.8; the distance from the wiggler center to the screen is 27 m.

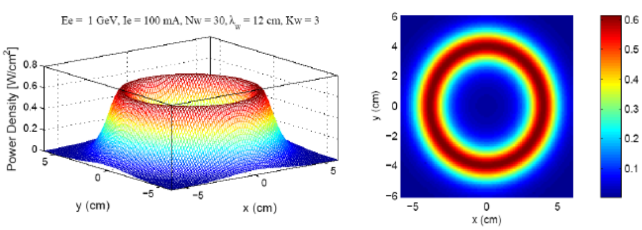

Figure 2: Spatial distribution of helical wiggler radiation power. Parameters for the calculation: E_e = 1 GeV, I_e = 100 mA, N_w = 30, λ_w = 12 cm, K_w = 3; the distance from the wiggler center to the screen is 27 m.

Harmonic Radiation Power Distribution

For a strong helical wiggler, the frequency-integrated n-th harmonic radiation power can be expressed as [3]

$$\frac{dP_n}{d\Omega} = P_t \gamma^{*2} [F_{n+}(\theta) + F_{n-}(\theta)] \qquad (3)$$

where $F_{n\pm}(\theta) = \dfrac{6n^2 \left(K_w^* J_{n\mp 1}(nc_w) - \gamma^* \theta J_n(nc_w)\right)^2}{2\pi K_w^{*2} \left(1+K_w^2\right)^2 \left(1+\gamma^{*2}\theta^2\right)^3}$,

$c_w = 2K_w^* \gamma^* \theta / (1+\gamma^{*2}\theta^2)$, $K_w^* = K_w / \sqrt{1+K_w^2}$, and $\gamma^* = \gamma / \sqrt{1+K_w^2}$, P_t is the total radiation power, and $\theta = \sqrt{\varphi^2 + \psi^2}$ is the polar angle from the z-axis (the longitudinal axis).

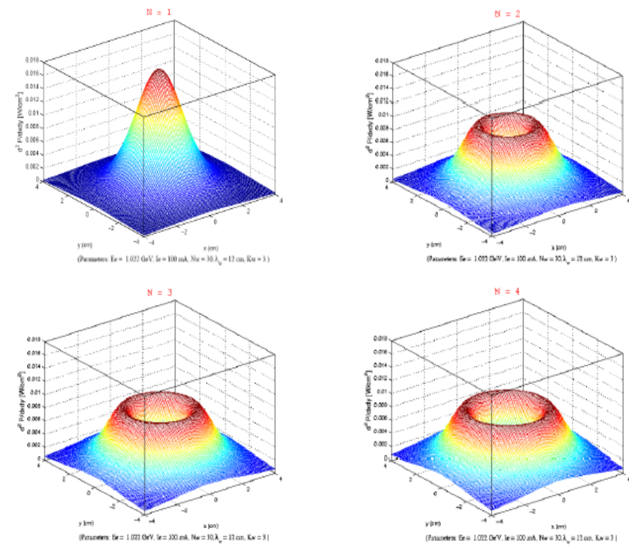

Figure 3: Spatial distribution of 1st, 2nd, 3rd, and 4th harmonic radiation power of a helical wiggler. Parameters for the calculation: E_e = 1 GeV, I_e = 100 mA, N_w = 30, λ_w = 12 cm, K_w = 3; the distance from the wiggler center to the screen is 27 m.

Figure 3 shows the plots of the power distribution of 1st (fundamental), 2nd, 3rd, and 4th harmonic radiation. Clearly, the fundamental radiation is peaked on-axis, while all the other higher-order harmonic radiation is peaked off-axis. The higher the harmonic order is, the further off-axis the peak is located.

IN-VACUUM WATER-COOLED APERTURES FOR OK-5 FEL

Setup of OK-5 Wigglers at the DFELL

On the Duke storage ring, two planar OK-4 wigglers and two helical OK-5 wigglers are installed in the 34 m long FEL straight section at the present time. In the near future two more helical OK-5 wigglers will be installed in the middle section of the straight section. A layout of four OK-5 wigglers is shown in Figure 4. The distances between each two wigglers are 6.72 m, while the distance between the fourth wiggler and the downstream FEL mirror is 16.54 m.

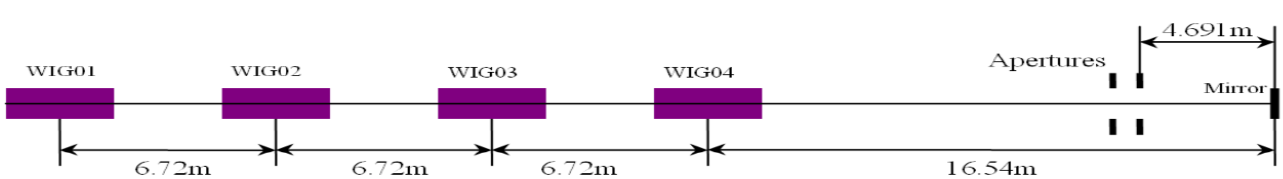

Figure 4: Layout of the OK-5 wigglers in Duke storage ring. Two of them have been installed at the ends of the south straight section of the ring; other two will be installed into the middle of the south straight section.

Control Harmonic Radiation with In-Vacuum Water-Cooled Apertures

Before 2006, the planar OK-4 FEL was typically operated with a relatively low beam current of less than 40 mA and with a low beam energy (< 600 MeV). Even with these less demanding beam parameters, we had to deal with the continuous degradation of FEL mirrors. Compared with the OK-4 wigglers, with the same beam parameters, the use of helical OK-5 wigglers significantly reduces the amount of higher-order harmonic radiation on the FEL mirror. However, as we move into the new FEL operation region with a much higher electron beam current (from 100 to 200 mA) and a high electron beam energy (600 MeV to 1.2 GeV), the higher-order harmonic radiation from helical wigglers can still pose a serious problem due to off-axis wiggler harmonic radiation on the FEL mirror with a 50 mm diameter.

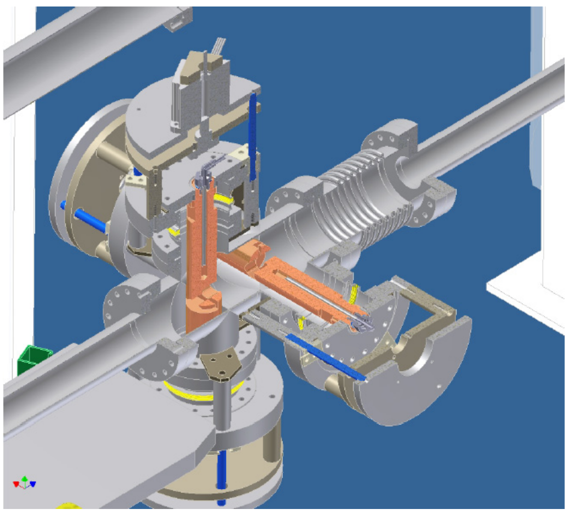

Figure 5: A cut-away view of the water cooled apertures.

To reduce the higher-order harmonic radiation power load on the downstream FEL mirror, we developed two apertures, one horizontal and the other vertical (as shown in Figure 5), to block the off-axis harmonic radiation from the OK-5 wigglers. Two apertures are formed using four independently motorized copper poles. The copper poles have built-in cooling channels to dissipate the heat generated by wiggler radiation. The aperture system is located 21.66 m downstream from the center of the FEL resonator and 4.69 m upstream from the downstream FEL mirror. The aperture size (full width) can be adjusted between 10 and 24 mm, making apertures useful for a variety of FEL operation conditions with different electron beam energies and lasing wavelengths.

An alternative method of reducing wiggler harmonic radiation loading on FEL mirrors is the use of smaller FEL mirrors. However compared with the use of apertures, this method has two major disadvantages. One is the cost and risk associated with developing a new line of FEL mirrors with a smaller size. Typically, it takes six to nine months for a vendor to make a batch of FEL mirrors which can meet the existing stringent specifications. Developing mirrors of a different size is time consuming with a projected development cycle of one to two years and risky for user operation when the funding for new mirrors is limited. We also have to modify or develop new in-house diagnostic systems used to characterize the mirrors. Furthermore, a set of new mirror holders have to be developed and tested for the FEL resonator. The second shortcoming is that in order to achieve the optimal effect of harmonic radiation reduction, various FEL operation configurations with different electron beam energies and lasing wavelengths require FEL mirrors of different sizes. This will further increase the cost and time for the mirror development. In contrast, the water-cooled apertures provide a solution which has a low risk and cost, is easy to implement, and yet very versatile.

Table 1: Fundamental/Harmonic Radiation Power without/with Apertures (with Four OK-5 Wigglers)

λ_R (nm)	E_e (MeV)	K_w	$R_{aperture}$ (mm)	Fund Rad Power On Mirror (W)		Harm Rad Power On Mirror (W)		Power Reduction Factor	
				w/o Apt	With Apt	w/o Apt	With Apt	Fund	Harm
245	600	2.15	8.24	0.2844	0.1645	1.8003	0.3175	1.73	5.67
	800	3.00	8.24	0.3067	0.1784	3.4606	0.4437	1.72	7.80
	1000	3.83	8.24	0.3168	0.1848	5.1107	0.5200	1.71	9.83
	1200	4.64	8.24	0.3222	0.1882	6.5753	0.5674	1.71	11.59
190	600	1.83	7.38	0.3871	0.2341	2.5370	0.5433	1.65	4.67
	800	2.60	7.38	0.4279	0.2608	6.3049	0.9022	1.64	6.99
	1000	3.34	7.38	0.4462	0.2730	11.7114	1.1616	1.63	10.08
	1200	4.06	7.38	0.4559	0.2795	18.5167	1.3417	1.63	13.80
175	600	1.74	7.12	0.4248	0.2606	2.7047	0.6272	1.63	4.31
	800	2.48	7.12	0.4744	0.2936	7.2211	1.1175	1.62	6.46
	1000	3.19	7.12	0.4965	0.3085	14.3508	1.5000	1.61	9.57
	1200	3.88	7.12	0.5083	0.3165	24.3351	1.7792	1.61	13.68

Table 2: Fundamental/Harmonic Radiation Power without/with Apertures (with Two Middle OK-5 Wigglers)

λ_R (nm)	E_e (MeV)	K_w	$R_{aperture}$ (mm)	Fund. Rad. Power On Mirror (W)		Harm. Rad. Power On Mirror (W)		Power Reduction Factor	
				w/o Apt	With Apt	w/o Apt	With Apt	Fund.	Harm.
245	600	2.15	8.24	0.1388	0.0708	0.4141	0.0518	1.96	7.99
	800	3.00	8.24	0.1500	0.0770	0.5894	0.0650	1.95	9.07
	1000	3.83	8.24	0.1551	0.0799	0.6977	0.0718	1.94	9.72
	1200	4.64	8.24	0.1578	0.0814	0.7660	0.0758	1.94	10.11
190	600	1.83	7.38	0.1910	0.1036	0.7010	0.0939	1.84	7.47
	800	2.60	7.38	0.2117	0.1160	1.2002	0.1297	1.83	9.25
	1000	3.34	7.38	0.2210	0.1217	1.5740	0.1496	1.82	10.52
	1200	4.06	7.38	0.2259	0.1247	1.8397	0.1613	1.81	11.41
175	600	1.74	7.12	0.2102	0.1164	0.8042	0.1120	1.81	7.18
	800	2.48	7.12	0.2354	0.1318	1.4846	0.1611	1.79	9.22
	1000	3.19	7.12	0.2466	0.1389	2.0372	0.1891	1.78	10.77
	1200	3.88	7.12	0.2526	0.1426	2.4537	0.2059	1.77	11.92

Table 1 and Table 2 summarize the calculation results for the fundamental and higher-order harmonic radiation power load on the downstream FEL mirror with and without apertures. The calculations were performed with various operation conditions and for different configurations of the Duke FELs. Two FEL configurations are presented - one with four OK-5 wigglers and the other with two OK-5 wigglers in the center of the FEL straight section. Several electron beam energies (600, 800, 1000, and 1200 MeV) and several UV-VUV lasing wavelengths (245, 190, 175 nm) are considered.

It is worth pointing out that at or above 1000 MeV, the apertures can reduce the power loading due to higher-order wiggler harmonic radiation by a factor of ten or more. The apertures also impact the fundamental radiation power, reducing it by a factor of less than two. Because of a conservative choice of the aperture size, the apertures do not have any practical impact on the build-up of the FEL lasing mode which is a fundamental Gaussian mode.

CONCLUSION

FEL mirrors can be damaged by high intensity harmonic radiation from wigglers, which poses a serious problem for the UV-VUV oscillator FELs. This problem can be mitigated by using helical wigglers which emit higher-order harmonic radiation off-axis. However, the off-axis harmonic radiation from helical wigglers can still cause serious damage to the downstream FEL mirror for high current FEL operation. The thermal load on the FEL mirror as a result of absorbing higher-order harmonic radiation can limit the maximum beam current for FEL operation.

We have developed a set of motorized, water-cooled, in-vacuum apertures to control the off-axis harmonic radiation from helical wigglers. Calculations indicate that these apertures can reduce the harmonic power load on the downstream mirror by one order of magnitude in the higher energy operation at and above 1 GeV. After installing these apertures in September, 2008, we will extend the high power FEL into the UV-VUV wavelength region using a high electron beam current. We also expect that these apertures will improve the stability of the FEL light sources by reducing the thermal heating effect of the FEL mirrors. This aperture idea can be adopted for high-power oscillator FELs driven by superconducting linac as they move toward UV operation with helical wigglers.

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