PROTECTION OF VUV FEL MIRRORS USING SOFT ORBIT BUMP AT DUKE FEL/HIγS FACILITY*

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Abstract

The Duke FEL and High Intensity Gamma-ray Source (HIγS) facility is operated with an electron beam from 0.24 to 1.2 GeV and a photon beam from 190 to 1060 nm. Presently, the energy range of the gamma-beam is from 1 MeV to about 100 MeV, with the maximum total gamma-flux of more then 10^{10} gammas per second around 10 MeV. Production of high intensity, high energy gamma-beams of 60 to 100 MeV, using UV-VUV mirrors of 240 to 190 nm, requires high energy, high current electron beams of 0.9 to 1.05 GeV. Synchrotron radiation damage to the FEL mirrors becomes crucial for VUV FEL operation at or below 190 nm. The edge radiation (ER) from the End-of-Arc (EOA) bending magnet, instead of the radiation of FEL wigglers, is the dominant cause of rapid degradation of the downstream FEL mirror. We describe here a further development of the "soft" orbit bump concept to significantly reduce the radiation exposure to the mirror from the EOA dipole magnet. The bump uses designated "soft" orbit correctors with magnetic field limited to produce radiation with a critical wavelength close to or longer than the FEL wavelength. A first experience of HIγS user runs with 192 nm mirrors utilizing the soft bump is also presented.

VUV FEL/HIγS OPERATIONS AT DUKE

The Duke storage ring is designed as a dedicated FEL driver and a host of several FEL wigglers in a thirty-four meter long FEL straight section. The main parameters of the Duke accelerators and FEL's are listed in Table 1.

Table 1: Parameters of Duke accelerators and FELs.

Accelerators	Storage ring	Booster injector
Operation energy [GeV]	0.24-1.2	0.16-1.2
Maximum current [mA]	125	15
Circumference [m]	107.46	31.902
Revolution frequency [MHz]	2.79	9.397
RF frequency [MHz]	178.55	
FELs	OK-4	OK-5
Polarization	Horizont.	Circular
No. of wigglers	2	4
No. of regular periods	33	30
Wiggler periods [cm]	10	12
Maximum peak field [kG]	5.36	3.17
Maximum K_w	5.00	3.53
Maximum current [kA]	3.0	3.5
FEL wavelength [nm]	190 - 1064	

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A planar optical-klystron FEL, the OK-4 FEL, consists of two planar wigglers sandwiching a buncher magnet. In 2005, operating with two OK-4 and two OK-5 wigglers simultaneously, we demonstrated lasing of the world's first distributed optical klystron FEL, the DOK-1 FEL, with a record FEL gain for storage ring based FELs [1].

The FEL straight section was recently upgraded to accommodate four OK-5 helical wigglers instead of two (see Fig. 1) [2]. In February and March of 2013, we had the fist user runs using 192 nm FEL mirrors at 1 GeV of electron beam energy to produce 87 MeV gamma ray beams [3].

Table 2 shows OK-5 VUV FEL/HIγS high energy operations. The number of the OK5 wigglers used in a particular VUV FEL/HIγS operation is determined by available FEL gain compared to the optical cavity loss and also chosen to optimize the intensity of the γ-beam without damaging downstream FEL mirror too rapidly. Extending the FEL operation to 192 nm and further down to 150 nm needs mirrors with increasing losses, and requires a higher FEL gain, and therefore more wigglers.

Table 2: OK-5 VUV FEL/HIγS high energy operations at Duke.

λ_{mirror} nm	$E_{e\ max}$ GeV	$E_{\gamma\ max}$ MeV	λ_c nm	No. of OK5 wigglers
250	0.925	60	1.5	2
192	1.050	97	1.0	2-3
150**	1.200	158	0.7	3-4

** – to be developped

CONCEPT OF SOFT ORBIT BUMP FOR VUV FEL OPERATION

Because of the degradation of UV/VUV mirrors (250, 190, and future 150 nm) caused by the off-axis higher-order VUV wiggler harmonic radiation, high-energy, high-flux HIγS γ-beam operation is possible only with the helical OK-5 FEL. Figure 1 shows the layout of the OK-5 FEL. The mirrors are protected from off-axis radiation by the in-vacuum mirror protection apertures [4].

In a production of gamma-beams with the energy above 60 MeV (the corresponding electron beam energy above 900 MeV), the corner bending magnets and other magnetic elements of the FEL straight section are also significant sources of radiation. For the VUV FEL operation we need to minimize all other sources of radiation harmful to the downstream FEL mirror. The most powerful hard photon source is the corner bending magnet nearest to the downstream mirror (E01B in Fig. 1). To reduce its radiation to the mirror, we developed an orbit bump using designated orbit correctors [5, 6].

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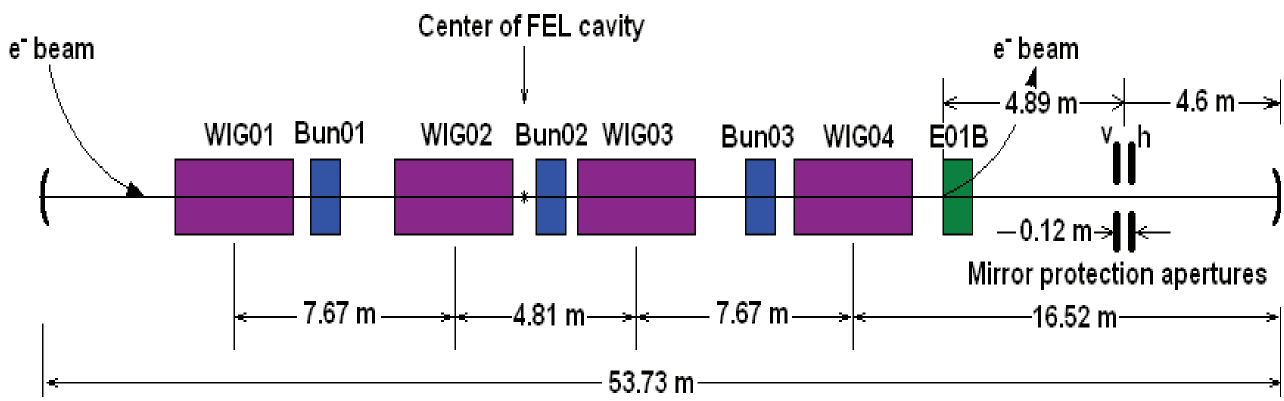

Figure 1: Configuration of the Duke FEL with helical OK5 wigglers.

In order not to introduce an additional source of radiation, the magnetic field of those correctors is limited to produce extremely soft radiation with a critical wavelength close to or longer than that of the FEL mirror ($\lambda_c \geq \lambda_{mirror}$).

The orbit bump deflects the beam orbit inwards at the entrance of E01B, therefore steering the dipole edge radiation away from the axis of the mirror (Fig. 2). Though we can not fully eliminate the dipole edge radiation, we can significantly reduce its power on the mirror. Initially, it was a three kicks bump with a maximum horizontal deflection angle of 1.2 mrad at Ee=1 GeV [5]. Recently it was modified to a six kicks bump, increasing the total angle up to 2 mrad while keeping the same constraints for the maximum magnitude of orbit change Δx (Fig. 3) [6].

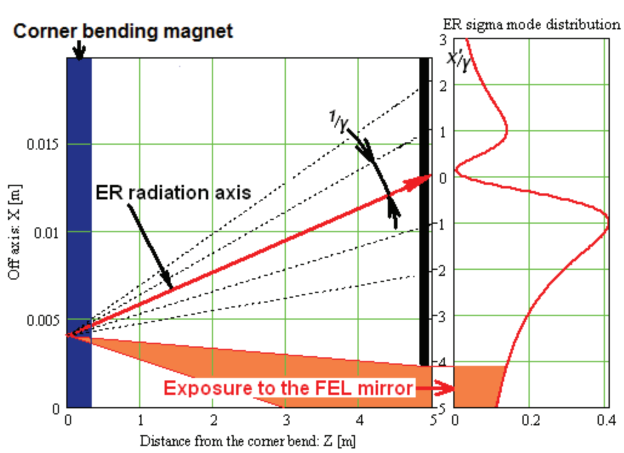

Figure 2: Concept of an orbit bump to protect the FEL mirror from radiation of the corner bending magnet.

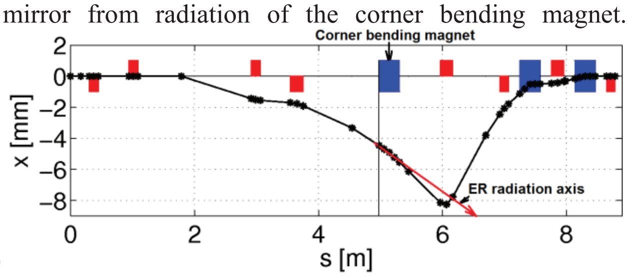

Figure 3: Six kicks orbit soft bump.

EDGE RADIATION FROM THE CORNER BENDING MAGNET

The properties of the edge radiation (ER) are fundamentally different from those of the classical synchrotron radiation (SR) from a uniform magnetic field [7]. For evaluation of the power of ER emitted from the magnet entrance we used a model with a step-function edge magnetic field. With this assumption, the spatial distribution of the ER does not depend on the wavelength for very long wavelengths $\lambda \gg \lambda_c$. Power density of the ER peaks for both σ and π modes at a horizontal and vertical angle 1/γ off the radiation axis. The ER σ mode (Fig. 2), asymmetrical with respect to the horizontal angle, is a dominating part of the total radiation power off axis [Fig. 4).

To experimentally evaluate the effect of the soft orbit bump on the ER radiation from the E01B bending magnet, we used VUV PMT Hamamatsu R7400-09 with spectral response limited between ~170nm and ~290nm [8]. All the calculations and measurements were performed for the opening of the mirror protection apertures typical for the real VUV FEL/HIγS high energy operation.

Figure 4 shows the power exposure to the downstream FEL mirror from the E01B ER in the spectral range of Δλ=170-290 nm, calculated as a function of the amplitude of the soft orbit bump. The numerical and experimental evaluation shows that, with the use of the soft orbit bump set at |X'cor|=2.1-2.8 mrad, the power of ER, and therefore the mirror damage effect, can be reduced by a factor of three to four.

Comparison of the mirror damage effect by wiggler radiation and by ER is not simple due to a tremendous difference in spectral and angular distribution. The ER is much broader in bandwidth and peaks around λ_c=1-1.5nm within the electron beam energy range of Ee=0.9-1.5 GeV (see in Table 2). This is much shorter than the wiggler radiation wavelength. The contribution of radiation at different wavelengths into the degradation of the FEL mirror is also not very clear.

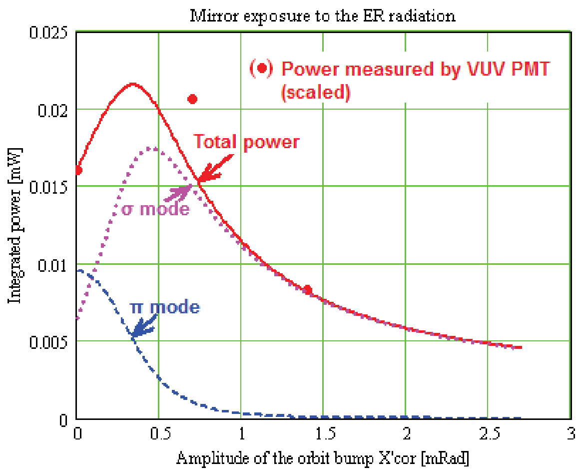

Figure 4: Power of the ER from corner bending magnet integrated in Δλ=170-290 nm for the three kicks bump [5]. E_e=926 MeV, I_e=5 mA. Amplitude of the soft orbit bump is measured as the total angular kick set for the designated correctors. The measured radiation power using VUV PMT is normalized to the calculated power for X'cor=0. The measurements for the new orbit bump will be performed and compared with the results of this old bump.

In a real VUV FEL/HIγS high energy operation, with normally closed in-vacuum protection apertures, the soft orbit bump allows us to reduce the radiation power on the FEL mirror from the E01B dipole down to at least a level of the same order of magnitude as or lower than that of the power of wiggler harmonics radiation. The estimations for the ER radiation are somewhat conservative, since the actual magnetic edge is "softer" than the step function.

THE FIRST EXPERIENCE OF HIGH GAMMA ENERGY USER OPERATION WITH 190 NM FEL MIRRORS

In the spring of 2013, we completed the first HIγS user runs using 190 nm FEL mirrors [2]. A high intensity 87 MeV gamma ray beam was produced with FEL lasing at 192 nm, using e-beam current of 90 mA in two bunches, at e-beam energy of 1 GeV. 165 hours of total gamma beam time were delivered. The three kicks soft orbit bump was successfully tested and used to protect the downstream FEL mirror.

These runs demonstrated a significant lifetime for the 190 nm FEL mirrors. Fig. 4 shows the degradation of the mirrors after about 165 hours of operation, or about 15 amp·hours of integrated e-beam exposure. The downstream mirror was near the end of its life by the end of the user runs. Therefore, the existing mirrors can be used for the high intensity gamma production up to approximately 200 hours.

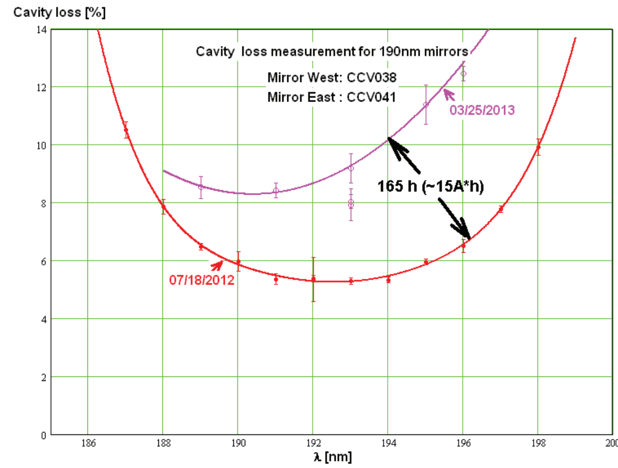

Figure 5: Degradation of VUV 190 nm mirrors during Eγ=87 MeV γ-production runs at Ee=1 GeV, 165 hours total run time, ~15 A·hr of e-beam exposure.

CONCLUSION

The soft orbit bump, with in-cavity protection apertures closed, allows us to reduce the radiation power on the FEL mirror from the corner bending magnet down to at least a level of the same order of magnitude as or lower than that of the power of wiggler harmonics radiation. It enables us to use the existing VUV FEL mirror for couple of hundreds of hour of operation. A new, more efficient bump has been recently designed, installed, and commissioned. The impact of the upgraded "soft" orbit bump will be evaluated with future VUV FEL operation.

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