SOFT ORBIT BUMP FOR DUKE STORAGE RING VUV FEL OPERATION*

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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 an FEL photon beam from 190 to 1060 nm. The energy range of the gamma-ray 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 the high-intensity, high energy gamma-beams of 60-158 MeV using UV-VUV mirrors of 250 - 150 nm requires high current and high energy electron beams (0.9-1.20 GeV). Radiation damage to the downstream FEL mirror becomes more severe for VUV FEL operation at 190 nm and below. At these VUV wavelengths with GeV electrons, the radiation from the end-of-arc (EOA) bending magnets, instead of the radiation from helical FEL wigglers, is the dominant cause of a rapid degradation of the downstream mirror. In this work, we propose a concept of a “soft” orbit bump using designated orbit correctors to significantly reduce the radiation from the EOA dipole toward the FEL mirror. The strength of magnetic field of these correctors is limited to produce a radiation with a critical wavelength close or below the FEL wavelength.

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. Main parameters of the Duke accelerators and FEL’s are listed in Table 1.

A planar optical-klystron FEL, the OK-4 FEL, consists of two planar wigglers sandwiching a buncher magnet. The FEL straight section is currently under an upgrade to accommodate four OK-5 helical wigglers instead of two (see Figure 1) [1]. In 2010, with only two OK-5 wigglers (WIG01 and WIG04 in Fig.1), a production of nearly 100 MeV γ-beams was demonstrated with a substantial γ-flux using 190 nm FEL mirrors [2]. Table 2 shows prospective OK-5 VUV FEL/HIγS high energy operations, the operation at 150 nm will be made possible by the upgrade. The number of the OK5 wigglers used in a particular VUV FEL/HIγS operation is determined by the 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 below 190 nm and furthermore down to 150 nm using mirrors with increasing loss, requires a high FEL gain and therefore more wigglers.

Table 1: Parameters of HIγS/FEL accelerators and FELs.

Accelerators	Storage ring	Booster injector
Operation energy [GeV]	0.24-1.2	0.18-1.2
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	

Table 2: Prospective OK-5 VUV FEL/HIγS high energy operations planned 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
190	1.060	100	1.0	2-3
150	1.200	158	0.7	3-4

CONCEPT OF SOFT ORBIT BUMP FOR VUV FEL OPERATION

Because of the degradation of UV/VUV mirrors (350, 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 OK-5 FEL. Figure 1 shows the layout of the OK-5 FEL. Such operation was made possible with the use of the in-vacuum mirror protection apertures [3].

Mirror Protection Apertures

There are two horizontal and two vertical apertures (Fig. 2), separately adjustable using stepping motors. Each aperture is a water cooled copper cylinder with profiled opening around the FEL optical axis. The purpose of the apertures is to intercept the off-axis harmonic radiation. The opening is tunable from about 5 mm (full gap) with fully inserted apertures to about 36 mm with apertures fully opened.

Soft Orbit Bump for VUV Operation

In a production of the gamma-beam with the energy above 55-60 MeV (the electron beam energy above 900 MeV), the corner bending magnets and other magnetic elements of the FEL straight section (bunchers, orbit trims, etc.) are also significant sources of radiation. For the VUV FEL operation we are trying to eliminate as much as possible all other sources of radiation harmful to the downstream FEL mirror. The most powerful hard

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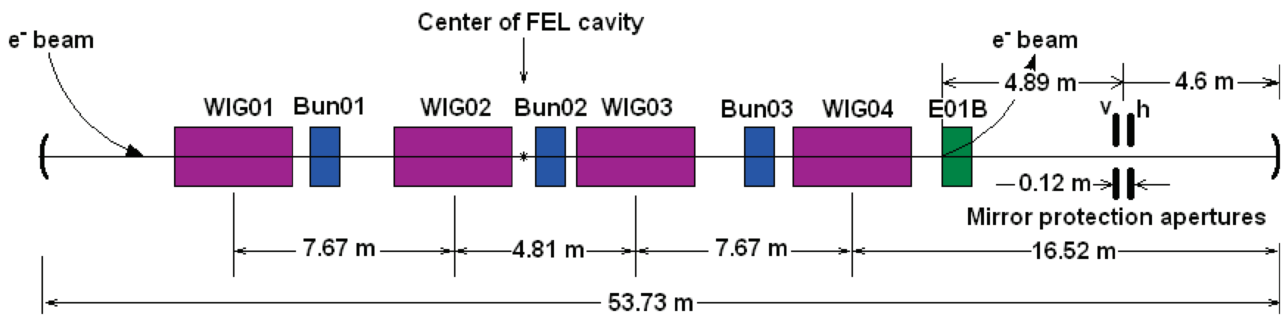

Figure 1: Configuration of the OK5 FEL.

photon source is the corner bending magnet nearest to the downstream mirror (E01B in Figure 1). To reduce its radiation to the mirror, we are developing an orbit bump using designated orbit correctors (Figure 3). In order not to introduce an additional source of radiation, the magnetic field of the correctors is limited to produce extremely soft radiation with a critical wavelength close or below that of the FEL mirror ($\lambda_c \leq \lambda_{mirror}$). The negative bump deflects the beam orbit at the entrance of E01B, therefore steering the dipole edge radiation away from the axis of the mirror (see Fig. 3). Though we can not fully eliminate the dipole edge radiation, we can significantly reduce its power.

PRELIMINARY RESULTS

The properties of the edge radiation (ER) are fundamentally different from those of the classical synchrotron radiation (SR) from a uniform magnetic field [4]. For example, there is no ER in the forward direction. 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 $\lambda >> \lambda_c$. Power density of the ER peaks for both σ and π modes at a horizontal and vertical angle $1/\gamma$ off the radiation axis. As oppose to the π mode, which is symmetrical with respect to the vertical angle, σ mode is asymmetrical (see in Fig. 3).

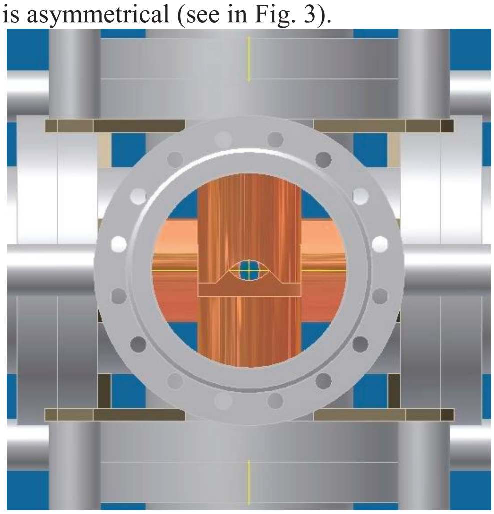

Figure 2: Mirror protection apertures with fully inserted positions.

The wiggler and non-wiggler related radiation was experimentally evaluated using a VUV PMT Hamamatsu R7400-09 with spectral response limited between ~170nm and ~290nm [5]. The experiment was performed at E_e=926 MeV, so that the PMT response was also a good match to measure the wiggler radiation around 190-250 nm for the conditions of producing 60 MeV gamma-rays (see in Table 1). A series of spectra were taken using an Ocean Optics Maya 2000 Pro spectrometer with a special grating for 172-310 nm wavelength range [6] (Figure 5). The purpose of those measurements was

- to evaluate the effect of the soft orbit bump for the non-wiggler radiation,
- to confirm that the dominant source of non-wiggler radiation is the ER from the E01B banding magnet and to verify that the simplified model used for the ER power calculation is adequate,
- to compare the non-wiggler related radiation with the wiggler radiation in the wavelength range of PMT.

All the calculations and measurements were performed for the opening of the mirror protection apertures at half gap of $\Delta X_{aper} \approx 2.5$ mm and $\Delta Y_{aper} \approx 4.5$ mm, typical for the real VUV FEL/HIγS high energy operation. Only one upstream OK-5 wiggler (WIG01 in Fig.1) was energized.

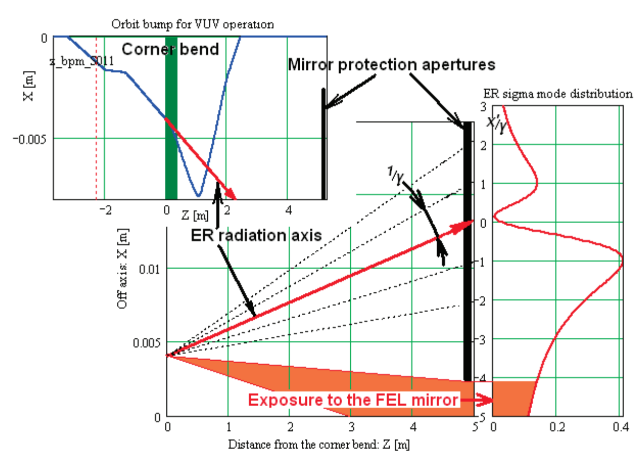

Figure 3: Using an orbit bump to protect the FEL mirror from radiation of the corner bending magnet. The amplitude of the bump is shown for the kick of the designated corrector set to X'cor=-1.4 mrad. The horizontal opening of the mirror protection aperture is 2.5 mm (half gap).

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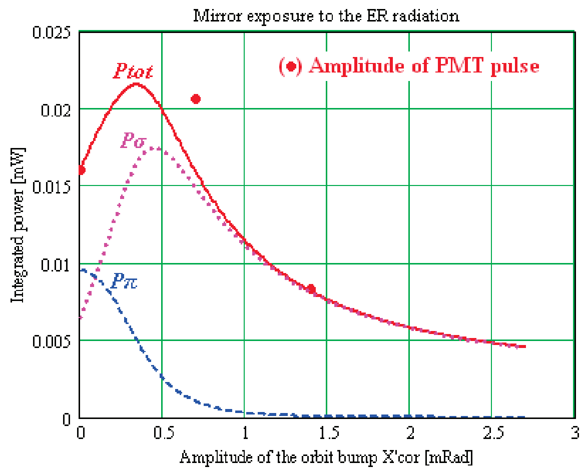

Figure 4: Power of the ER from corner bending magnet integrated in Δλ=170-290 nm. E_e=926 MeV, I_e=5 mA. Amplitude of the soft orbit bump is measured as the angular kick set for the designated corrector. PMT pulse is normalized to calculated power for X'cor=0.

Figure 4 shows the power of the E01B ER integrated over $\pm\Delta X_{aper}$, $\pm\Delta Y_{aper}$, and Δλ=170-290 nm, calculated as a function of the amplitude of the soft orbit bump. Besides the PMT response, there are other factors contributing to the spectral limitation of the VUV optical measurement, such as the cut-off of the low wavelengths by a 45 degree aluminum diagnostic mirror, CaF_2 optical view port, about 2 m long optical path through the atmosphere, VUV splitter, etc. The effect of the water vapor on the way of the VUV optical beam is clearly seen in the spectrum of the wiggler radiation taken at λ=195 nm (Fig. 5). As the ER peaks off the optical axis, the non-wiggler radiation power is maximum at non-zero orbit bump (Fig. 4). The PMT data qualitatively confirms this. 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 3-4.

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=1.5nm which is much shorter than the wiggler radiation wavelength. The total wiggler radiation power was also computed for the same openings of the mirror protection apertures. The ratio of the total power of the wiggler radiation at a central wavelength of 245 nm to the ER integrated within the PMT response was calculated to be about a factor of six. This ratio measured by the PMT was about factor three. This is a reasonable agreement considering a great number of assumptions and uncertainties in both the numerical calculations and the measurements.

For a typical operation energy of E_e=925 MeV, the total ER power integrated through the entire bandwidth is about factor 20, 4, and 2 greater than the total wiggler harmonics radiation using WIG01, WIG02+WIG03, and all four wigglers correspondingly. These estimates are made with the mirror protection apertures closed to about 7 mm (full gap). All the estimations for the ER radiation are somewhat conservative, since the actual magnetic edge is "softer" than the step function. Therefore, in a real VUV FEL/HIγS high energy operation, the soft orbit bump allows us to reduce the power of the ER from the E01B magnet down to at least about the same level as the total power of the wiggler harmonics radiation.

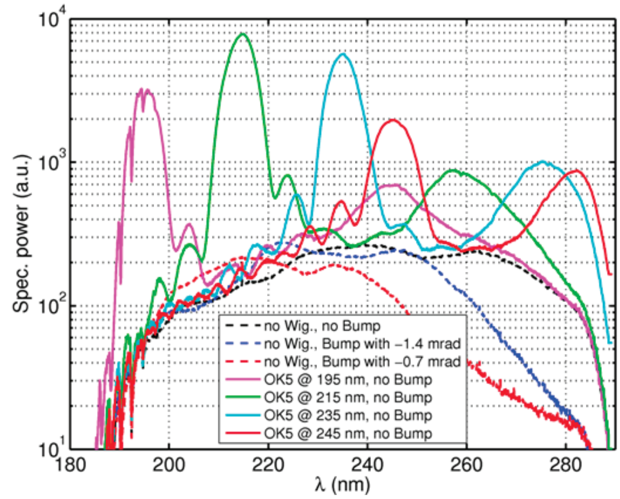

Figure 5: Spectra of the non-wiggler radiation and VUV wiggler radiation at λ=195, 215, 235, and 245 nm.

CONCLUSION

The preliminary design of soft orbit bump allows us to reduce the total power of the ER from the corner bending magnet to at least about the same level as the total power of the wiggler harmonics radiation. Additional development is planned to improve this soft bump scheme.

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