DESIGN OF A SOFT ORBIT BUMP FOR FEL MIRROR PROTECTION AT DUKE FEL/HIGS FACILITY*

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Abstract

In an oscillator Free-Electron Laser (FEL) with a high energy electron beam, it is critical to minimize harmful high-energy radiation on the downstream FEL mirror in order to increase its lifetime. At the High Intensity Gamma-ray Source (HIGS) facility at Duke University, effort has been devoted to developing a variety of techniques to reduce the amount of radiation on the FEL mirror. One of the most effective methods was the use of a set of adjustable in-vacuum apertures to block harmonic radiation from FEL wigglers. In recent studies, it was determined that the edge radiation from the end-of-the-arc bending magnet is a main source of EUV and soft x-ray radiation which causes mirror damage. To mitigate this effect, a soft orbit bump is designed to change the displacement and angle of the electron beam around the end-of-the-arc area. This soft orbit bump is developed using the multi-objective optimization technique. Calculation shows the soft orbit bump can significantly reduce the flux of high energy photons on the FEL mirror. Study will be performed to determine the impact of this orbit bump on the injection, beam lifetime, and the FEL and gamma-ray operation at HIGS facility.

INTRODUCTION

In an oscillator Free-Electron Laser (FEL) with a high energy electron beam, it is critical to protect mirrors from the damge caused by the high energy photons. These photons could be high order harmonic radiation from insertion devices, synchrotron radiation from buncher magnets and correctors, and radiation from bending magnets. One effective method of reducing radiation damage is using the adjustable aperture inside the FEL cavity to block the off-axis wiggler harmonic radiation. At High Intensity Gamma-ray Source (HIGS) [1], a water-cooled, in-cavity aperture has significantly improved the FEL mirror lifetime in the high-flux Compton gamma-ray production [2]. Due to the angular divergency of synchrotron radiation, the on-axis high energy synchrotron radiation photons from magnets far away from the FEL mirror does not contribute too much to the mirror damage. However, as shown in Figure 1, it can be seen that the first bending magnet of the east arc, E01B, can contribute significantly to the mirror damage due to its strong edge magnetic field radiation and short distance to the mirror.

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To further protect the mirrors from the damage of the E01B bending magnet edge radiation, it was proposed to use a local bump around this bending magnet [3], in which the edge field synchrotron radiation is directed away from the mirror. In the design of such a local bump, it is critical to reduce the harmful radiation from the bump correctors. Thus the correctors in this bump should have a weak magnetic field which can only produce low-energy radiation, making this local orbit bump a "soft" one. A soft orbit bump has been calculated and setup at the HIGS using the existing correctors near the E01B bending magnet [3]. Measurement results showed that, by using this soft orbit bump, the edge radiation power from E01B bending magnet on the mirror was significantly reduced. Although there is no direct measurement of the edge radiation damage on the mirror, the first successful high-flux gamma-ray operation at the HIGS with a high power VUV (192 nm) FEL beam has shown the effectiveness of extending the FEL mirror lifetime using such a soft orbit bump [5, 6]. However, the edge radiation power on the mirror cannot be further reduced for this soft orbit bump configuration due to the strength limitation of the correctors. Therefore, it is planned to setup a new soft orbit bump by installing additional correctors at appropriate locations to further reduce the edge radiation power.

ORBIT DESIGN

The characteristics of edge radiation is different from those of the synchrotron radiation produced by electrons in uniform magnetic field [4]. One significant difference is that the angular power distribution is not peaked at the tangent direction of the electron trajectory, but roughly at a $-1/\gamma$ angle with respect to the tangent direction, where γ is the relativistic factor of the electron and the minus sign means this angle is in the opposite direction to the bending direction. According to the magnet configuration shown in Figure 1, the electron beam angle at the entrance of the E01B bending magnet should be much more larger than $1/\gamma$ towards the inside of the ring. In our computation, the coordinate of the intersection point between the tangent line of the electron orbit at the E01B bending magnet entrance and the FEL protection aperture, $|x_{\text{aper}}| = |x_i + 4.89[\text{m}]x'_i|$, is used to characterize the effectiveness of the soft orbit bump, where 4.89 m is the distance between the magnet entrance and the aperture, x_i and x'_i are electron beam orbit horizontal coordinate and angle at the E01 bending magnet entrance, respectively. Only an $|x_{\text{aper}}|$ much larger than $4.89/\gamma$ could reduce the edge ra-

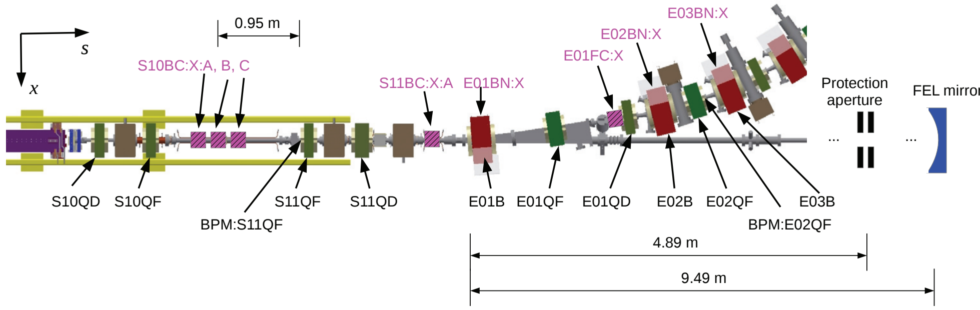


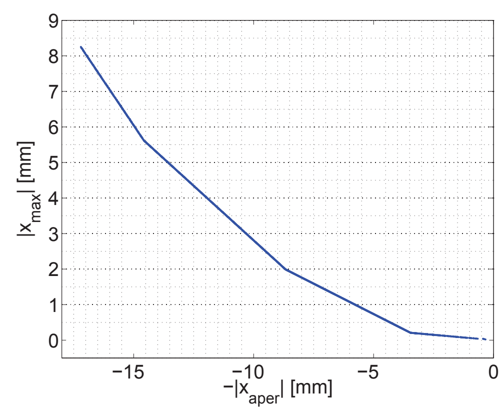
Figure 1: Layout of magnets at the end of the south straight section and the beginning of the east arc at Duke storage ring. The original soft orbit bump uses correctors S10BC:X:A, S10BC:X:C, E01BN:X and E02BN:X. The other correctors, S10BC:X:B, S11BC:X:A, E01FC:X are newly installed correctors. The existing E03BN:X is also used in the new soft orbit bump.

diation power on the FEL mirror. In the original soft bump design, the maximum $|x_{\rm aper}|$ is for 1 GeV electron beam is about 10 mm.

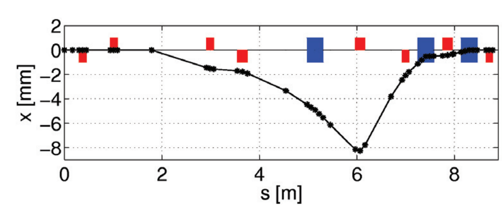
The quantity $|x_{\rm aper}|$ should be maximized for an effective soft orbit. This requirement usually conflicts with the desired maximum height of soft orbit bump $|x_{\rm max}|$, which should be as small as possible to preserve a good injection efficiency and a long beam lifetime. In the design of the new soft orbit bump, the multi-objective genetic algorithm (MOGA) [7] is used. This algorithm can efficiently find the optimized solutions for complicated problems with several independent variables, objectives and constraints, especially for those with trade-off objectives. Figure 1 shows the available locations for installing new correctors in the E01B bending magnet region. One additional corrector can be installed at S10 section to reduce the magnetic field of the two existing correctors. Another one can be installed upstream of the E01B bending magnet to increase the absolute value of x'_i. In the calculation, three S10BC:X correctors are treated as one effective corrector. Two correctors at the end of the bump are used to make the local bump closed. Thus there are four independent variables in this problem. Two trade-off variables, $-|x_{\rm aper}|$ and $|x_{\rm max}|$, are chosen to be the objectives to be optimized. For the constraints, the maximum strength of each S10 correctors is constrained within 0.4 mrad; and the S11BC:X:A corrector strength is set to be smaller than 0.8 mrad.

Figure 2a shows the calculated Pareto front of 10^4 random seeds evolving for 200 generations. The maximum $|x_{\rm aper}|$ could reach 17.2 mm within the constraints of correctors, much more larger than the value of the original soft orbit bump. The maximum soft orbit bump height $|x_{\rm max}|$ shown in Figure 2a is about 8.3 mm. Such a large soft orbit bump may reduce the injection efficiency and the beam lifetime, which need to be further studied experimentally. Several correctors have already reached their maximum values when $|x_{\rm aper}|$ is larger than 10 mm. To fully use these correctors, we chose to use the soft orbit bump configuration at the up-left end of the Pareto front. The calculated electron beam orbit for this bump configuration is shown in Figure 2b. It can be seen that the largest orbit offset is located at the E01QF quadrupole where the vacuum chamber has an extra clearance compared to regular quandrupoles. This large horizontal aperture is helpful in operating a large soft orbit bump.

IMPLEMENTATION AND MEASUREMENTS



(a) Pareto front of objectives at the 500th generation.



(b) Electron beam orbit of a soft orbit bump. This orbit corresponds to the up-left point in Figure 2a. The total strength of S10BC:X correctors is 1.28 mrad.

Figure 2: Computation results of the soft orbit bump using multi-objective genetic algorithm method.

To operate the new soft orbit bump, two BPMs inside the bump, BPM:S11QF and BPM:E02QF, are taken out of the orbit feedback to avoid the competition between the soft

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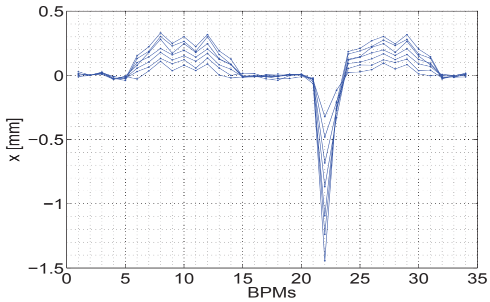
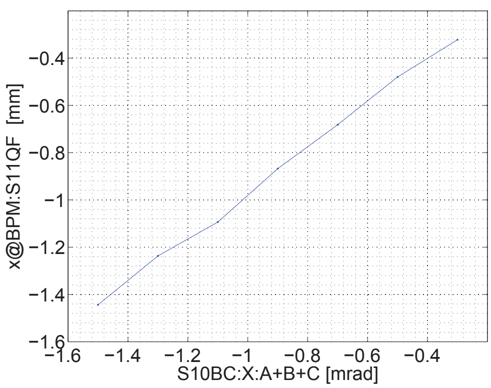


(a) The electron beam orbits in the storage ring for different soft orbit bump heights. The BPM:S11QF and BPM:E02QF are the 21st and the 22nd BPMs in the plot, respectively. Different orbits from high to low correspond to S10BC:X settings from -1.5 mrad to -0.3 mrad.



(b) Electron beam horizontal position at S11QF BPM for different S10BC:X corrector settings.

Figure 3: Measured orbits for different soft orbit bump settings.

orbit bump control and the global orbit feedback. The correctors used in the soft orbit bump are shared by the global orbit feedback by implementing extra soft control channels for these correctors.

In the experiment, the bump height can be linearly scaled by varying the strength of all correctors until one of them reaches the power supply limit or saturates. The soft orbit bump was set up and measured at the electron beam energy of 1 GeV. It was found that at this energy the soft orbit bump can be operated at a maximum height of -21.5 mm with the S10BC:X correctors set to 1.5 mrad. Figure 3a shows the measured orbits around the storage ring for different soft orbit bump heights. From this Figure it can be seen that there is an orbit leakage on the order of 30 μm in the straight sections. This orbit leakage can be further reduced by the fine adjustments of the correctors in the bump. As there was no RF frequency tunning in this experiment, the electron beam energy was changed due to the orbit length variation caused by the soft orbit bump. This energy change induces a non-zero orbit in the dispersive regions, as shown in Figure 3a. It can be estimated that there was a relative electron beam energy increase of about 0.13% for the largest soft orbit bump. At the HIGS, this amount of electron beam energy variation can cause a roughly 0.26% shift of the gamma photon beam center energy. This gamma photon energy change can be easily compensated by adjusting the FEL wavelength.

Located 0.95 m downstream from the S10BC:X correctors, the S11QF BPM is used as a monitor for the local bump. Figure 3b shows the S11QF BPM readings for varied strength of the first corrector in the soft orbit bump. It is clear that the S10BC:X correctors are still working in the linear region up to 1.5 mrad of total steering angle at 1 GeV. The fitted relation between the total angle of S10BC:X correctors and the S11QF BPM readings is $x_{\mathrm{S11QF}}[\mathrm{mm}] = -0.025 + 0.945\theta_{\mathrm{S10BC:X}}[\mathrm{mrad}]$, showing a 25 μm residual orbit which is comparable with the residual orbit in south straight section. The fitted distance between the BPM and the S10BC:X correctors center, 0.945 m, is close to the measured value of 0.95 m, indicating a good calibration for these three S10BC:X correctors. The other corrector, S11BC:X:A, is expected to work in the linear region in this measurement. Therefore, in this measurement, x_{aper}, the parameter which determines the edge radiation power on the mirror, should be close to the calculated value.

SUMMARY

At the HIGS, by installing additional correctors around the E01B bending magnet region, an improved soft orbit bump has been developed to further reduce the edge radiation power on the FEL mirror. Its effectiveness has been confirmed by the preliminary measurement results [6], showing a radiation power reduction on the FEL mirror. Future study should focus on the impact of this soft orbit bump on the injection and beam lifetime in real operation.

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