EXPERIENCE OF FEL MIRROR DEGRADATION AT THE DUKE FEL AND HIGS FACILITY*

S. F. Mikhailov[#], V. G. Popov, J. Li, Y. K. Wu
FEL Laboratory, Duke University, Durham, NC 27708, USA

Abstract

The Duke FEL and High Intensity Gamma-ray Source (HIγS) are operated with a wide range of electron beam energies (0.24 - 1.2 GeV) and photon beam wavelengths (190 - 1060 nm). Currently, the HIγS user operation is carried out in the gamma-beam energy range from 1 to 61 MeV [1]. Recently production of 70-100 MeV γ-rays was demonstrated with substantial γ-flux using 190 nm FEL mirrors [2]. The maximum total γ-flux produced at the HIγS facility is $2 \cdot 10^{10}$ or higher gammas per second around 10 MeV. Production of this high level gamma-ray flux requires a very high average FEL photon beam power inside the FEL resonator at one kilowatt or more. The high power FEL operation can cause significant degradation of the FEL mirrors due to higher-order wiggler harmonic radiation, especially when operating the FEL in the UV region at a high electron beam energy. This has limited the high-energy, high-flux HIγS gamma-beam operation mostly to circular polarization when UV mirrors are used, as higher-order harmonic radiation of helical wigglers is peaked off-axis. To ensure the predictability and stability of the HIγS operation for user research program, we have developed a comprehensive program to continuously monitor the performance of the FEL mirrors. This program has enabled us to use a particular set of FEL mirrors for many hundreds hours of high gamma-flux operation with predictable performance. In this work, we discuss sources and consequences of the mirror degradation for a variety of wavelengths. We also present our estimates of the mirror life time as a function of the FEL wavelength, gamma-ray polarization, and total gamma-flux.

DUKE FEL/HIγS FACILITY

The Duke Free-Electron Laser Laboratory (DFELL) operates accelerator based UV-VUV storage ring FEL and an FEL driven Compton gamma-ray source, the High Intensity Gamma-ray Source (HIγS). The DFELL accelerator facility includes three accelerators, the linear accelerator pre-injector (linac), a full-energy, top-off booster injector synchrotron, and a 0.24 – 1.2 GeV electron storage ring. Main parameters of the booster and storage ring are listed in Table 1.

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. A planar optical-klystron FEL, the OK-4 FEL, consists of two planar wigglers sandwiching a bunch magnet. A helical FEL, the OK-5 FEL, is comprised of two helical wigglers separated by more than 20 meters (Table 4). Recently, a production of nearly 100 MeV γ-beams was demonstrated with a substantial γ-flux using 190 nm FEL mirrors [2]. The Duke FEL/HIγS facility delivers nearly two thousand hours of beam time annually for HIγS users.

Table 1: Parameters of DFELL accelerators.

	Storage ring	Booster
Operatrion energy [GeV]	0.24-1.2	0.18-1.2
Injection energy [GeV]	0.24-1.2	0.18
Maxmum beam current [mA] single/multi-bunch	100/300	3/15
Circumference [m]	107.46	31.902
Revolution frequency [MHz]	2.79	9.397
RF frequency [MHz]	178.55	

Table 2: Parameters of Duke FEL wigglers.

	OK-4	OK-5
Polarization	Horizontal	Circular
No. of wigglers	2	2 installed
No. of regular periods	33	30
Wiggler periods [cm]	10	12
Peak field [kG @ 3kA]	5.36	2.86
FEL wavelength [nm]	190 - 1064	

To operate stably for many hundreds of hours, we need FEL mirrors capable of withstanding a high integrated dose of radiation without a significant degradation. Management of the FEL mirrors, including their continuous monitoring during operation, regular cavity loss measurements and mirror degradation tracking and evaluation, is crucial for realizing reliable and predictable gamma ray performance for user operation. This ongoing study of the degradation process for different kinds of the FEL mirrors from different vendors allows us to make reliable projection of the inventory needs for different wavelength mirrors years down the road.

FEL MIRRORS

To cover the gamma-beam energy range of 1-100 MeV, we use a variety of different mirrors listed in Table 3. So far, we have been using mirrors from two vendors: Laser Zentrum Hannover e.V. (LZH: [3]), and GSI Group Lumonics, General Optic, (formerly Wave Precision) (CCV: [4]). From both those vendors, we have mirrors based on thick fused silica substrates with radius curvature of $27.46^{+0.4/-0.2}$ m, with a multilayer oxide coating using ion beam sputtering deposition technique.

For each wavelength/gamma energy range, we have few mirror pairs in house. For every pair, we track degradation of the mirrors periodically measuring FEL cavity loss after substantial period of operation (Figures 1, 2). The initial measurement is always performed for the fresh mirrors before they are used in any operation.

---

* Supported in part by US DoE grant DE-FG02-971ER41033.
[#] smikhail@fel.duke.edu

Table 3: Production FEL mirrors at DFELL.

λ (spec)	#	Vendor(s)	Reflectivity (spec)
nm			%
1064	6	General Optics	> 99.95
780	6	General Optics	> 99.95
540	6	General Optics	> 99.95
450	2	Laser Zentrum Hannover	> 98.5 (old)
450	2	Waver Precision	> 99.95 (old)
450	5	Laser Zentrum Hannover	> 99.95
350	5	Laser Zentrum Hannover	> 99.95 (prototype)
350	4	Laser Zentrum Hannover	> 99.95
245	2	Laser Zentrum Hannover	> 98.5 (old)
240	6	Laser Zentrum Hannover	> 99.5
190	4	Laser Zentrum Hannover	> 98.5

TYPICAL MODES OF OPERATION OF DUKE HIγS/FEL

For the HIγS operation optimized to produce a maximum gamma ray flux, we usually store two equal charge electron bunches separated by a half circumference of the storage ring. In special cases, when the energy resolution of the gamma ray beam is more important rather than the gamma ray flux on target, we use an uneven bunch pattern in which the smaller bunch has a current below lasing threshold. This preserves its small energy spread which determines the minimum energy spread of the gamma ray beam.

With the low-loss mirror optical cavities (a round trip cavity loss below 0.6-0.8 %) we use a single OK4 wiggler to produce a linearly polarized gamma ray beam, or a single OK5 wiggler to produce circular polarized gammas. The use of a single wiggler enables us to store a much higher beam current while reducing the wiggler radiation power loading on the downstream mirror. The upstream wiggler, which is much further away from that mirror, is always used in that case in the single wiggler FEL mode. With a cavity loss above 0.6-0.8 % per pass, two OK4 or two OK5 wigglers are used in an optical klystron mode of FEL operation.

DEGRADATION OF THE FEL MIRRORS

From our experience, the following major sources of the mirror degradation are observed:

- Irreversible degradation of the downstream mirror caused by excessive exposure to high intensity/power from both direct wiggler radiation and FEL power in the optical resonator.
- Carbonization of the mirror surface, in our case it usually happens with the upstream mirror. The downstream mirror exposed to the direct wiggler radiation is less susceptible to the surface carbonization.
- Radiation damage due to the high-order wiggler harmonic UV/VUV radiation, especially when operating the FEL in UV region at a high electron beam energy. This is the dominant source of degradation for all the mirrors operating with OK-4 wiggler(s) in the linear polarization mode, and the UV mirrors (≤350 nm) operating with OK-5 wiggler(s) in the circular polarization mode.

Table 4 shows mirror pairs for which we have most representative degradation history.

Table 4: FEL optical cavity configurations (pairs of mirrors). $\Delta\lambda$ is the cavity loss bandwidth with twice of the minimal loss.

Optical cavity/pair of mirrors	CCV			LZH
Parameter	054-077	024-037	027-040	304/305-306
$\lambda_{\text{minimum loss}}$ initial [nm]	762	541	250	N/A
$\lambda_{\text{minimum loss}}$ present [nm]	766	543	250	454
Initial width $\Delta\lambda/\lambda$ [%]	12.2	13.2	12.4	N/A
Current width $\Delta\lambda/\lambda$ [%]	6.8	8.1	11.6	5.8
Initial minimum cavity loss [%]	0.11	0.21	1.21	N/A
Present minimum cavity loss [%]	0.33	0.59	1.21	1.38
Operation hours	550	1350	180	>950
$T*I_{\text{beam}}$ [amp*hours]	36.5	93.3	7.8	>50
Range of operational beam energy [MeV]	320-500	360-600	600-930	420-680

There are three main effects by which the degradation can be numerically characterized:

- (1) an increase of the minimum cavity loss at $\lambda_{\text{minimum\_loss}}$ (Figure 3);
- (2) a shift of the optimum wavelength $\lambda_{\text{minimum\_loss}}$ at which the loss is minimum, towards the higher wavelength;
- (3) a reduction of the bandwidth of the optical cavity (Figure 4).

To optimize the operation while extending mirror lifetime, the electron beam current is chosen to produce an adequate flux for a specific user experiment as requested by the user group.

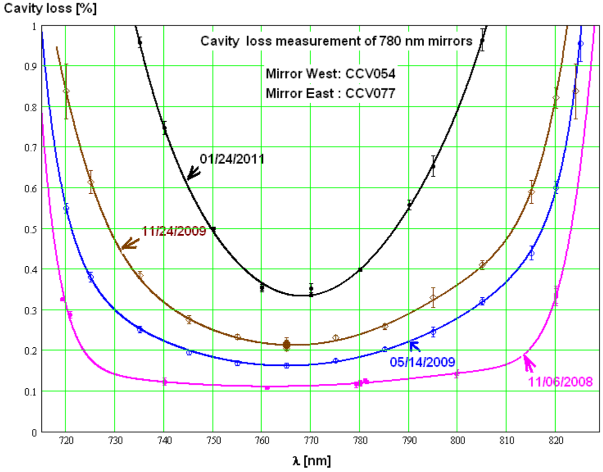

Figure 1: The measured FEL cavity loss for 780 nm mirrors CCV054 and CCV077.

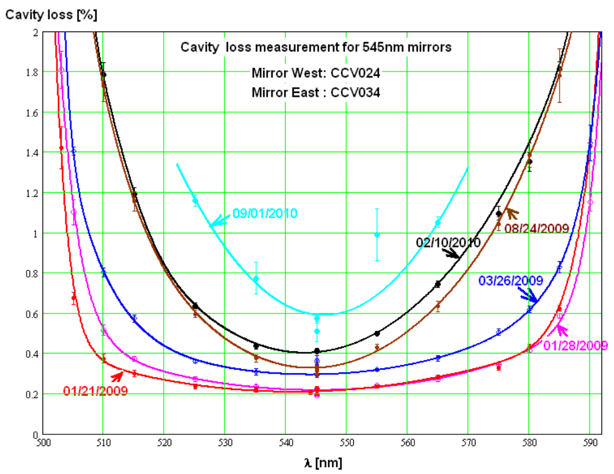

Figure 2: The measured FEL cavity loss for 540 nm mirrors CCV024 and CCV034.

The mirror degradation slowed down tremendously after installation of a mirror protection aperture with controllable openings for horizontal and vertical directions before the downstream FEL mirror [5]. The protection apertures are carefully adjusted for each FEL/HIγS run, so that they do not cause any significant additional diffraction loss. The aperture system is capable of blocking most of off-axis radiation, which is crucial for the high electron beam energy, high election beam current operation of the OK-5 FEL.

OPERATION WITH UV MIRRORS

The degradation of UV mirrors (350, 240 and 190 nm) caused by the off-axis higher-order UV/VUV wiggler harmonic radiation limits the high-energy, high-flux HIγS gamma-beam operation mostly to circular polarization. Such operation has not been possible or stable enough without the use of the in-vacuum protection apertures. 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.

To protect the downstream FEL mirror from the most harmful radiation from the nearest corner bending dipole, we are developing an orbit bump using a designated orbit corrector. The magnetic field in it is limited to produce extremely soft radiation with a critical wavelength close or below that of the FEL mirror ($\lambda_c \leq \lambda_{mirror}$) (Figure 5).

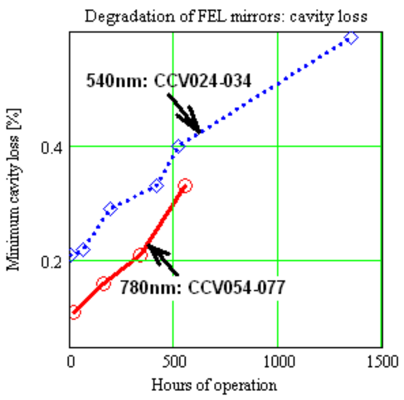

Figure 3: Degradation of FEL mirrors: increase of the minimum FEL cavity loss.

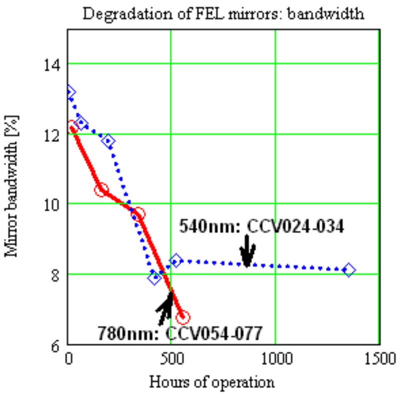

Figure 4: Degradation of FEL mirrors: reduction of the optical bandwidth of the FEL cavity. Bandwidth is defined as Δλ/λ [%], where Δλ is the cavity loss bandwidth with twice of the minimal loss.

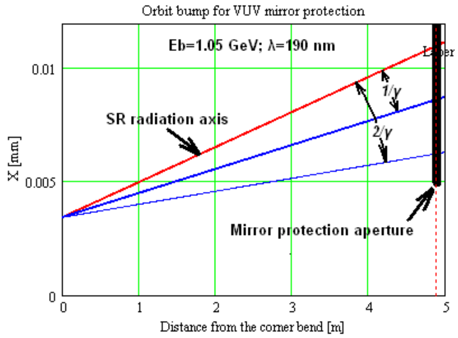

Figure 5: Orbit bump to protect VUV degradation mirror from radiation from the corner bending magnet.

CONCLUSION

The program to continuouly monitor and evaluate the FEL mirrors enables us to use a particular pair of mirrors for an extended period of high gamma-flux operation with predictable performance.

REFERENCES

[1] H. R. Weller, *et al.* "Research Opportunities at the Upgraded HIγS Facility", an invited review article for Prog. Part. Nucl. Phys. (2008).

[2] Y. K .Wu et.al "An VUV FEL for producing Circularly Polarized Compton Gamma-ray Beams in the 70 to 100 MeV Region", this Proceeding.

[3] http://www.lzh.de

[4] http://www.gsig.com

[5] S.Huang, J.Li, Y.K.~Wu, "Water Cooled, In-cavity Apertures for High Power Operation of FEL Oscillators" Nucl. Instr. Methods A, 606, pp. 762-769 (2009).