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

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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 about 65 MeV, with a near-future extension to about 100 MeV using 190 nm FEL mirrors. The maximum total gamma-flux produced at the HIγS facility is up to 10^{10} 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 a few 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.

DUKE FEL/HIγS FACILITY

The Duke Free-Electron Laser Laboratory (DFELL) operates several accelerator based photon sources including the UV-VUV storage ring FEL and an FEL driven Compton gamma-ray source, the High Intensity Gamma-ray Source (HIγS) [1]. The DFELL accelerator facility includes three accelerators, the linear accelerator pre-injector (linac), a full-energy, top-off booster synchrotron, and a 0.18 – 1.2 GeV electron storage ring. Main parameters of the booster and storage ring are listed in Table 1.

Designed as a dedicated FEL drive, the Duke storage ring hosts several free-electron lasers in a thirty-four meter long FEL straight section. A planar optical-klystron FEL, the OK-4 F EL, 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. Operating four wigglers together, two OK-4 and two OK-5 wigglers, we demonstrated in 2005 the lasing of world's first distributed optical klystron FEL, the DOK-1 FEL [2]. Now, Duke FEL/HIγS facility delivers thousand of hours of beam time annually for the HIγS users [1].

Table 1: Parameters of DFELL accelerators.

	Storage ring	Booster
Maximum energy [GeV]	1.2	
Injection energy [GeV]	0.18-1.2	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 routinely during hundreds of hours, we need state of art FEL mirrors capable of withstanding these hundreds hours of operation without a fatal degradation. Management of the FEL mirrors, including their permanent monitoring, regular cavity loss measurements and mirror degradation tracking and evaluation, is crucial to provide a predictable HIγS facility operation. This undergoing study of degradation processes for different kind of the FEL mirrors from different vendors allows us to reasonably predict their degradation months and years ahead.

FEL MIRRORS

To cover the gamma beam energy range of 1-100 MeV, we use a variety of different mirrors listed in Table 1. So far, we have been using mirrors from two vendors: Laser Zentrum Hannover e.V. (LZH: [3]), and GSI Group Lumonics, General Optic, former 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 SiO_2/HfO_2 coating using ion beam sputtering deposition technique.

For each mirror, radius curvature and optical transmission is measured [5]. Based upon these measurements, the mirrors are matched to make specific FEL cavity pairs (cavity configurations). After being in FEL/HIγS operation for a significant time, the FEL cavity loss is measured for each pair/cavity. For the

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measurement of the cavity loss we use pass-by-pass measurement technique described in [6].

Table 3: FEL mirrors currently in hand at Duke FELL.

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 with maximum required gamma ray flux we usually store two opposite electron bunches with an approximately equal current in each In special cases, when the energy resolution of the gamma ray beam is more important rather then the total gamma ray flux produced, we use asymmetrical bunch pattern with one bunch has a current below lasing threshold, so that the lasing does not induce the energy spread of that bunch.

With the low loss mirror optical cavities (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 much higher beam, current without an excessive wiggler radiation power loading of the downstream mirror (east mirror). The upstream (west) wiggler, whish is much further away from that mirror, is always used to utilize the natural collimation of SR radiation by the vacuum chamber. The higher loss optical cavity mirror configurations with cavity loss higher then 0.6-0.8 % usually require the use of two OK4 or two OK5 wigglers at a time.

DEGRADATION OF THE FEL MIRRORS

We learned the following major sources of the mirror degradation:

- Direct degradation of the downstream (East) mirror cased by excessive exposure 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 (west) mirror. The downstream (east) mirror exposed to the direct wiggler radiation is less susceptible to the surface carbonization. Figure 1 shows an example of a severely carbonized mirror.
- High-order wiggler harmonic (UV and DUV) radiation damage, especially when operating the FEL in UV region at a high electron beam energy. This is the dominant source of degradation for the UV mirrors ((350 nm and below).

The degradation of UV mirrors caused by the high-order wiggler harmonic radiation limits the high-energy, high-flux HIγS gamma-beam operation mostly to circular polarization, as higher-order harmonic radiation of helical wigglers is peaked off-axis.

Table 4 presents our most actively used cavity pairs for which we have the most representative mirror degradation history. Those are for 780, 540, 450 and 260 nm cavities. In the LZH 450 nm pair, the upstream mirror #304, which was severely carbonized, was replaced by the mirror #305, which allowed us to almost return this cavity to the original conditions.

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

- (1) increase of the minimum cavity loss at $\lambda_{minimum\_loss}$ (Figure 4);

Table 4: FEL optical cavity configurations (pairs of mirrors)

Optical cavity/pair of mirrors Parameter	CCV		LZH	
	054-077	024-037	303-302	304-305-306
$\lambda_{minimum\ loss}$ initial [nm]	762	541	N/A	N/A
$\lambda_{minimum\ loss}$ current [nm]	766	543	260	454
Initial width Δλ/λ [%]	12.2	13.2	N/A	N/A
Current width Δλ/λ [%]	9.7	8.4	11.5	5.8
Initial minimum cavity loss [%]	0.11	0.21	N/A	N/A
Current minimum cavity loss [%]	0.21	0.40	2.0	1.38
T operation [hours]	334	518	>250	>950
$T*I_{beam}$ [amp*hours]	20.4	33.3	>10	>50
Range of operational beam energy [MeV]	320-500	360-600	560-900	420-680

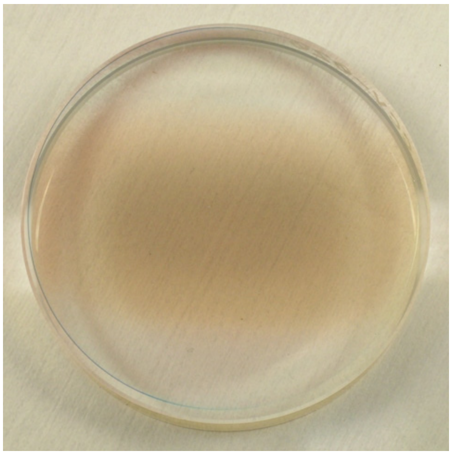

Figure 1: A carbonized West (upstream) mirror CCV020.

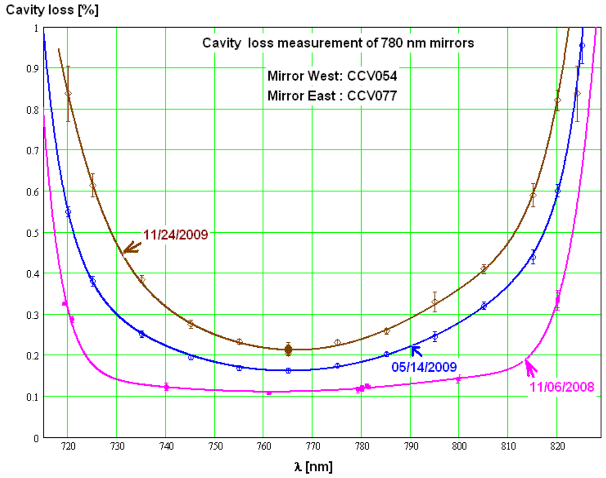

Figure 2: FEL cavity loss measurement data for 780 nm mirrors CCV054 and CCV077.

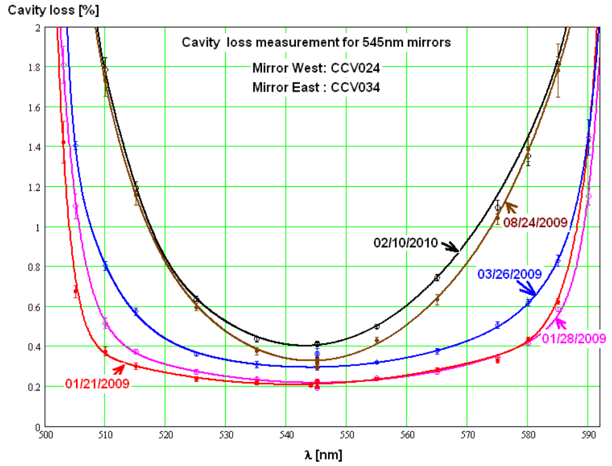

Figure 3: FEL cavity loss measurement data for 540 nm mirrors CCV024 and CCV034.

- (2) shift of the optimum wavelength $\lambda_{minimum\_loss}$ at which the loss is minimum, towards the higher wavelength;
- (3) reduction of the bandwidth of the optical cavity (Figure 5).

To increase the operation of each mirror pair to hundreds of hours, the beam current is limited to the minimum required to provide for a specific gamma-flux needed for a specific HIγS run.

The mirror degradation slowed down tremendously after installation of a mirror protection aperture with controllable openings for each horizontal and vertical direction between the downstream OK5 wiggler and downstream FEL mirror [7]. The protection aperture is carefully adjusted for each FEL/HIγS run, so that it does not cause any significant additional diffraction loss. Nevertheless, it reduces a great deal the total radiation exposure to the downstream (east) mirror. The most importantly, it cuts off the most damaging off-axis higher-order wiggler harmonic radiation. Some operations would not simply be possible without the protection aperture.

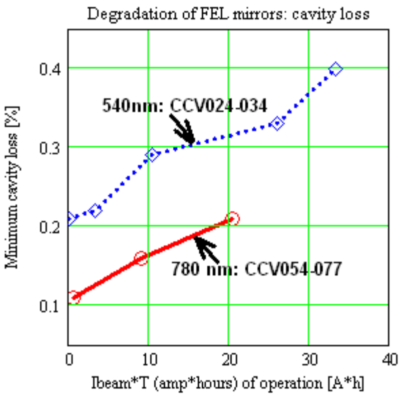

Figure 4: Degradation of FEL mirrors: increase of the minimum FEL cavity loss.

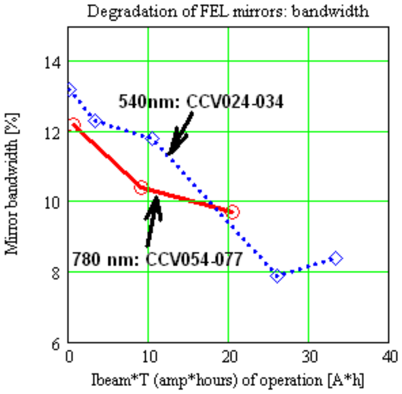

Figure 5 Degradation of FEL mirrors: reduction of the optical bandwidth of the FEL cavity. Bandwidth is defined as $\Delta\lambda/\lambda$ [%], where $\Delta\lambda=\lambda_2-\lambda_1$ is the wavelength width at which the cavity loss is factor two higher then the minimum loss: $loss(\lambda_2)=loss(\lambda_1)=2\ loss(\lambda_{minimum\ loss})$

CONCLUSION

The program of constant monitoring and evaluation of the FEL mirror cavities enables us to use particular pairs of FEL mirrors for a few hundreds hours of high gamma-flux operation with predictable performance.

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