Lasing Below 170 nm Using an Oscillator FEL

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The short wavelength operation of free-electron laser (FEL) oscillators is limited by the availability of high-reflectivity, thermally stable, and radiation-resistant FEL mirrors in the VUV wavelength. We report our recent work to extend the shortest lasing wavelength of the oscillator FEL to 168.6 nm using a storage ring FEL. This progress has been made possible by developing a new FEL configuration with substantially reduced undulator harmonic radiation on the FEL mirror, a thermally stable FEL optical cavity, and a new type of high-reflectivity fluoride-based multilayer coating with a protective capping layer. Using these fluoride-based mirrors, we have demonstrated storage ring FEL lasing from 168.6 to 179.7 nm with excellent beam stability. Employing this VUV FEL in Compton scattering, we have produced the first 120 MeV gamma rays at the High Intensity Gamma-ray Source (HIGS). Operating the HIGS in this new high-energy region will create many new opportunities for photonuclear physics research, in particular, the low-energy QCD research.

I. INTRODUCTION

Conventional masers or lasers have been developed to operate at wavelengths from microwave, to infrared (IR), to visible, and to ultraviolet (UV) and vacuum UV (VUV)[1]. The photon energy of the laser beam is determined by the energy difference between the electronically excited high-energy state and low-energy state of the laser medium which takes one of three forms of conventional matter: gas, liquid, or solid. The conventional lasers operating in deep UV and VUV are excimer lasers, including KrF lasers (248 nm), ArF lasers (193 nm), Xe_2 lasers (172 and 175 nm), and F_2 lasers (157 nm). With no dependence on the bound states of conventional matter, the free-electron laser (FEL)[2,3] employs free electrons in a charged particle accelerator as the laser medium (i.e. a plasma medium), which enables the FEL to operate in a much wider spectrum range from microwave to hard x-ray. In principle, the FEL is wavelength tunable, with its tunability limited by the capabilities of the accelerator and/or optical system used.

Since the early 1970s, several generations of the FELs have been developed utilizing different accelerator technologies. The first generation FELs are laser oscillators driven by a linear accelerator to operate in the infrared region[3,4]. The second generation FELs are also oscillators but driven by a storage ring[5] to reach shorter wavelengths from visible to VUV. The third generation FELs driven by advanced linear accelerators are single-pass FELs, which can operate from extreme UV (EUV) to x-ray. In such an FEL, the electron beam can produce coherent radiation through two different mechanisms: (1) via the interaction of the electron beam with its spontaneous radiation in a process called self-amplified spontaneous emission (SASE)[6–8], or (2) with the electron beam modulated, bunched, and amplified with an external optical beam in a seeded FEL operation[9,10]. The operation of single-pass FELs does not require a laser resonator, and therefore, can reach extremely short wavelengths such as hard x-ray[11].

Before the era of the SASE FELs, the push for the short wavelength laser operation was spearheaded with the development of the storage ring FEL oscillators. The first deep UV lasing around 240 nm was realized with the VEPP-3 storage ring FEL at Budker Institute of Nuclear Physics[12,13]. FEL operation in the deep UV spectrum of 226–256 nm was demonstrated using the storage ring FEL at Duke University in 1998[14]. This was followed by the first FEL operation into the VUV region, 193.7–209.8 nm, with the Duke FEL in 1999[15]. Around that time, other new storage ring FELs also demonstrated short-wavelength lasing, including 212 nm lasing with the NIJI-IV FEL in Japan[16] and 189.7 nm lasing with the European storage ring FEL at ELETTRA[17]. Eventually, the European storage ring FEL set the shortest FEL lasing record at 176.4 nm around 2005[18,19]. All these advances into the deep UV and VUV were made possible due to the parallel technological development of high-reflectivity multilayer mirror coatings. Since the mid-2000s, the lack of progress in developing robust VUV coatings suitable for the radiation environment of accelerators has prevented the storage ring FEL from reaching deeper into the VUV spectrum.

To generate high-energy photons in the gamma-ray region, a well-established technology is Compton scattering in which a relativistic electron beam collides with a laser beam[20]. The wide wavelength tunability of the FEL makes the oscillator FEL a highly versatile photon drive for a Compton gamma-ray source. For example, by colliding the electron beam in the Duke storage ring with the FEL beam generated by the same electron beam, high-intensity, polarized, and nearly monochromatic gamma-ray beams can be produced at the

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High Intensity Gamma-ray Source (HIGS) facility[20–22]. The gamma-ray beam energy can be changed by more than two orders of magnitude, from 1 MeV to 110 MeV, by varying both the electron beam energy (240 MeV to 1.1 GeV) and FEL lasing wavelength (1060 nm to 190 nm).

Operating this Compton source to produce gamma rays above 110 MeV will enable a new class of nuclear physics experiments to measure electromagnetic and spin polarizabilities of nucleons, a critical part of the low-energy QCD research program at the HIGS[22–24]. Reaching this higher energy region requires the Duke FEL to operate reliably at 175 nm or shorter wavelengths, a new VUV region for oscillator FELs. The scientific research program at the HIGS facility provided the primary motivation for us to resume the VUV FEL research. In the following sections, we will report recent successes in this area by using a new approach to develop FEL configurations and suitable VUV mirrors.

II. DEVELOPMENT OF VUV MIRRORS AND DUKE FEL

A. Review of UV and VUV Coating Development for FEL

Extending the storage ring FEL operation into short wavelengths critically depended on the advancement of the mirror technology. From the late 1990s to the early 2000s, researchers around the world worked on developing deep UV and VUV multilayer coatings suitable for the harsh synchrotron radiation environment of the storage ring. The goals were to develop high-reflectivity, low-loss, thermally and mechanically stable UV and VUV mirrors which were radiation resistant for a long useful lifetime. A range of coating technologies using either oxides or fluorides were investigated and compared, including thermal evaporation (TE) methods (e-beam and boat evaporation), TE-related ion-assisted deposition (IAD) and plasma ion-assisted deposition (PIAD), as well as ion beam sputter deposition (IBS)[18,19,25–29]. These studies showed that to achieve high reflectivity, oxides multilayer coatings were suitable for the deep UV spectrum (down to 190 nm) due to their reasonably large band gaps. The coatings using fluorides with even larger band gaps were required for the VUV wavelengths (below 190 nm). With proper control of substrate temperatures and using reactive gas during the deposition, thermal evaporation produced high-quality coatings with a reasonable packing density, good stability, and high reflectivity in the UV-VUV region[26]. However, among the aforementioned thin-film deposition methods, because of the use of an atomic beam with a high kinetic energy, IBS produced the most durable oxides-based coatings with lower porosity, higher density, and superior thermal and structural stability. The oxides-based IBS multilayer coatings have been highly successful for the storage ring FEL operation.

For example, IBS coated HfO_2 (high index of refraction) and SiO_2 (low index of refraction) multilayer mirrors have been found to be radiation robust, and thermally and mechanically stable for FEL operation from infrared (1060 nm) to deep UV (240 nm)[14]. However, the FEL mirror's reflectivity decreases at shorter wavelengths due to the increased absorption in the coating layers; a drastic increase of absorption in HfO_2 limits the use of such mirrors below about 220 nm. At longer wavelengths (240 to 1060 nm) the IBS coated HfO_2/SiO_2 FEL mirrors have been shown to be highly reliable for high-power storage ring FEL operation with extended durations at the HIGS. Based on operation data from 2008 to 2021, the useful lifetime of these IBS mirrors varies from a few hundred hours to more than one thousand hours, depending on the FEL wavelength and the amount of the irradiation dose on the mirrors.

To reach below 200 nm, the nontransparent HfO_2 can be replaced by Al_2O_3. This led to the development of the IBS coated Al_2O_3/SiO_2 multilayer thin-film for the FEL mirrors. This type of mirrors helped the Duke FEL reach lasing at 193.7 nm (with a low electron beam current) in 1999[15]. However, both oxides, but in particular Al_2O_3, suffers from a rapid increase of absorption below 190 nm[30], making this type of FEL mirror coating unsuitable to the shorter wavelength VUV region.

To achieve high reflectivity below 190 nm, the appropriate materials are a variety of fluorides, in particular, LaF_3 (high index of refraction) and MgF_2 (low index of refraction). Fluoride coatings are commonly applied using the thermal evaporation technique, and the resultant thin films are less dense, and therefore not suitable in the radiation environment of charged particle accelerators. Researchers at Laser Zentrum Hannover e.V. (LZH), Germany found a single layer SiO_2 IBS coating only suffered from a weak degradation under harsh irradiation treatment using undulator radiation (110 nm) produced by a 2 GeV electron beam[28]. This led to the development of VUV FEL mirrors with a multilayer fluoride coating protected by a SiO_2 IBS coating top layer[18]. These mirrors were used at ELETTRA FEL[31] to enable the FEL to operate in a new wavelength region, lasing at 176.4 nm with a 750 MeV electron beam and a maximum current of 23.6 mA[18,19]. However, the downstream/front mirror was rapidly damaged by synchrotron radiation when the electron beam energy was increased to 1.5 GeV during an attempt to produce the FEL lasing. The mirror degradation was permanent—the performance of the damaged FEL mirror could not be restored using a UV cleaning process and a heat treatment[18]. While successfully demonstrating the high-reflectivity of the SiO_2 protected fluoride multilayer mirrors around 176 nm, the work at ELETTRA FEL fell short of showing a long useful lifetime of these FEL mirrors.

By the mid-2000s, the push to develop shorter wavelength VUV optics was abandoned in both the optics industry and the FEL community. The lithography technology used to manufacture integrated circuits had moved away from 157 nm lithography due to optical material challenges associated with the increasingly shorter wavelength. Instead, the industry adopted 193 nm immersion lithography[32] as the solution to reach a higher spatial resolution. In parallel, the FEL community turned its focus toward the development of single-pass FELs without the need for an optical cavity to reach a wide range of wavelengths[33–35], extending the FEL operation into the EUV and x-ray spectral regimes.

B. Duke FEL Development for VUV Operation

At the HIGS, we have continued storage ring FEL research toward the shorter VUV wavelengths in order to produce higher energy Compton gamma rays for nuclear physics research. For example, to generate gamma rays in a new high-energy region of 110 to 130 MeV, we would need to operate the Duke FEL at 175 nm or a shorter wavelength. Recognizing that the main obstacles for VUV FEL operation are mirror damage and durability, since 2005 we have adopted a new strategy to deal with the root cause of these problems using the two different means: (1) using a different type of undulators and reducing the amount of radiation, especially the high-energy photon flux, on the mirror; and (2) improving the thermal and mechanical stability of the FEL mirrors and the laser cavity.

The commonly used planar undulator magnets produce higher-order harmonic radiation on axis[36], which is the main source of harmful radiation impinging on the FEL mirror. The harmonic radiation on the mirror can be substantially reduced by using helical undulators which produce harmonic radiation off-axis[36]. From 2005 to 2007, four helical electromagnetic undulators (the OK-5 undulators) were installed on the Duke storage ring[37] (see Fig. 1.(a)). To further limit harmonic undulator radiation incident on the mirror, a water-cooled, in-cavity aperture system (see Fig. 1.(b)) was deployed to block the off-axis OK-5 radiation, typically in the UV to EUV region. This system is capable of reducing the amount of harmonic radiation incident on the front FEL mirror by as much as two orders of magnitude[38]. In the meantime, by allowing the on-axis fundamental radiation from the OK-5 undulator to pass freely, the aperture system has little adverse impact on FEL lasing. With these developments, we were able to operate the FEL in a wide range of wavelengths (1060–350 nm) with a high electron beam current (100–120 mA) while maintaining excellent stability of the FEL beam.

When operating around 190 nm with a high electron beam current, the FEL suffered from a certain type of rapid instability. This was caused by a temperature gradient across the mirror surface due to poor thermal conductivity of the fused silica mirror substrate, inadequate thermal contact between the substrate and its holder, and the lack of active cooling of the mirror mount. To improve substrate's thermal performance, sapphire was selected as the new substrate material for VUV mirrors because of its excellent thermal conductivity. Sapphire's exceptional hardness also helped improve the mechanical stability of the FEL mirror. In addition, two new FEL mirror mount systems (see Fig. 1.(c)) were developed with increased overall thermal conductivity. The thermal contact between the FEL mirror and its holder was improved by greatly increasing the contact areas on the side, front, and back of the mirror. The heat was then effectively conducted outside of the vacuum system using a holder made of a large copper (or aluminum) disk. The mirror mount assembly was actively cooled from outside using a compressed air vortex chiller.

By eliminating most of the intense and energetic synchrotron radiation from undulators and improving the thermal performance of the FEL mirrors, we have largely succeeded in creating an operating environment for the FEL which is similar to that for a conventional excimer laser. This has led to stable, high-power FEL operation around 190 nm with a high electron beam current (up to 120 mA). This decade-long development of the Duke FEL also paved the way for attempting VUV lasing below 190 nm.

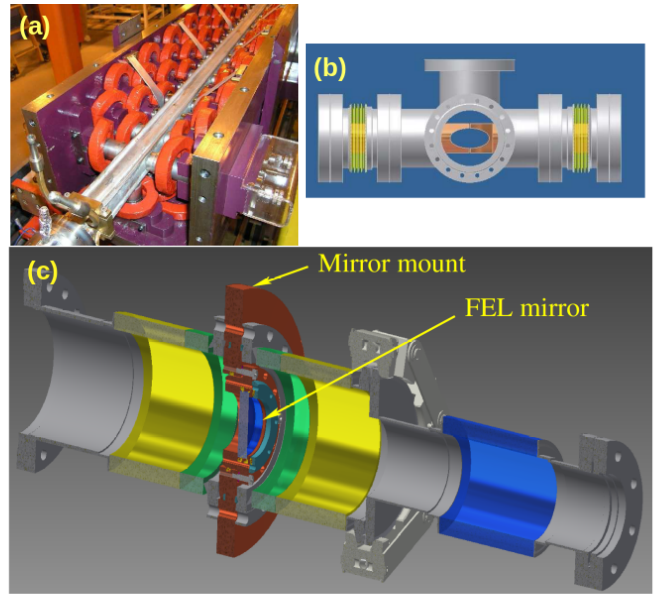

FIG. 1. (a) A picture showing one end of a helical OK-5 undulator with its top plate removed. (b) A design drawing depicting the water-cooled, in-vacuum horizontal aperture in the open position. The vertical aperture is not shown. (c) A schematic of the new mirror holder and mount system for the downstream FEL mirror with improved overall thermal conductivity to allow higher power FEL operation in VUV. The mirror mount is actively cooled from the outside using a compressed air vortex chiller.

C. New 175 nm Coatings for FEL Mirrors

More recently, we (the Duke and LZH groups) started a multi-year research project to develop fluoride-based 175 nm coatings, with an ultimate goal of producing high-reflectivity, robust 175 nm mirrors suitable for FEL operation. We aimed at developing three fluoride multilayer coatings: (1) an evaporated fluoride coating with an IBS SiO_2 protective top layer; this is a further optimized coating similar to the one used to establish 176.4 nm lasting at ELETTRA[18,19]; (2) a new evaporated fluoride coating with an atomic layer deposition (ALD) capping layer; and (3) a new IBS fluoride coating with or without a protective layer. While the research and testing of the latter two types of coatings is still ongoing, we have achieved our development goals using the first type of fluoride coating. The detailed descriptions of related coating technologies and parameters, coating processes and treatments, radiation tests of sample coatings, and optical characterization and post-irradiation analyses will be published elsewhere. In the following sections, we will report our FEL research results using three test fluoride mirrors deposited with the first type of the coating.

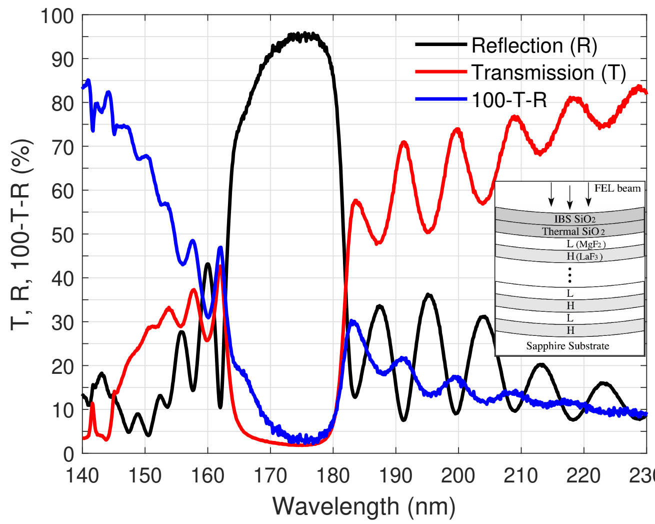

FIG. 2. Optical performance of a new VUV FEL mirror (serial number SAP-110), including the mirror reflectivity (black curve), transmission (red curve), and loss (blue curve) as a function of wavelength. Optical measurements are carried out using the LZH VUV spectrometer.

The measured optical performance of the newly developed 175 nm FEL mirror is shown in Fig. 2. The reflectivity is peaked around 175 nm with the highest value reaching 96%. In the high-reflectivity region, a 5 nm spectral area has high reflectivity over 94%, with a corresponding transmission of 1.8% to 2.6%. This allows a sizable fraction of the laser beam to be extracted for measurements and real-time monitoring. All three test mirrors show a similar optical performance.

III. OSCILLATOR FEL LASING IN NEW VUV RANGE

A. Configuration of Storage Ring FEL

To test the new 175 nm FEL mirrors, the Duke FEL was configured to use three helical OK-5 undulators (see Fig. 3). The intense off-axis harmonic radiation from the undulators is mostly blocked by the water-cooled aperture system[38] downstream from the undulators to protect the FEL mirror further downstream. The FEL beam extracted from the upstream/back FEL mirror is transported to the FEL diagnostic system to measure the laser beam power, transverse profile, spectrum, etc., all within a nitrogen-purged enclosure.

The VUV FEL diagnostics are comprised of a set of essential measurement instruments inside a nitrogen-purged box (see Fig. 3). The FEL VUV instruments include: (1) a VUV spectrometer (Maya 2000 Pro from Ocean Optics) covering 142–289 nm with the corresponding resolution varying from 0.078 nm to 0.067 nm; (2) a solar-blind VUV photomultiplier tube (Hamamatsu R7400U-09) with a spectral response limited to 170–290 nm to measure the FEL temporal structure;

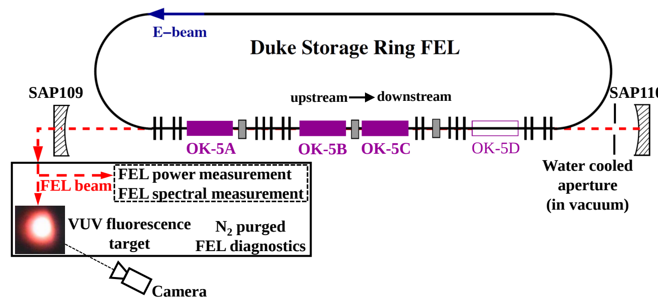

FIG. 3. Experimental setup for testing 175 nm VUV mirrors. Three OK-5 helical undulators (OK-5A, B, C) are powered to enhance the FEL gain. A water-cooled, in-vacuum aperture system downstream the undulators is used to block most off-axis higher harmonic radiation. For the FEL cavity, mirror SAP109 is used as the back mirror (upstream), and mirror SAP110 or SAP107 is used as the front mirror (downstream). An optical diagnostic system enclosed in a nitrogen-purged box is used to characterize the VUV FEL beam.

(3) a broadband optical power meter (Melles Griot 13PEM001 with a thermopile sensor head) to measure the FEL power; and (4) a VUV fluorescent screen to monitor the FEL transverse profile. All optical elements used in the nitrogen-purged box, including beamsplitters, focusing lenses, a flat mirror, and neutral-density filters, are rated for VUV operation down to about 160 nm.

B. VUV FEL Lasing Down to 168.6 nm

Two 175 nm mirrors were installed in the FEL cavity with mirror SAP110 installed downstream of the cavity as the front mirror and mirror SAP109 installed upstream of the cavity as the back mirror. The downstream/front mirror (SAP110) was vacuum-conditioned in a process which started with a low-current and low-energy electron beam (at 533 MeV) to expose the mirror to "soft" undulator spontaneous radiation. The beam current was gradually increased from 0.1 mA to 0.4, 0.8, and finally to 2.5 mA. During the conditioning, radiation-induced degassing of the mirror surface elevated the vacuum around the mirror holder. As gas molecules were pumped out, the vacuum recovered slowly and eventually settled down to an slightly elevated level with a steady 2.5 mA beam.

The initial attempt to achieve VUV lasing was carried out using an electron beam with an intermediate energy of 683 MeV. When the FEL is not lasing, the beam image of reflected spontaneous undulator radiation is shown in Fig. 4(a). With careful tuning, we achieved the first FEL lasing with the new mirrors at 177 nm. A recorded FEL beam image on a VUV fluorescence screen is shown in Fig. 4(b). Clearly, the FEL beam image on the fluorescence screen is highly saturated due to the high laser intensity.

The high-reflectivity bandwidth of the laser cavity was explored by tuning the FEL operation to scan the lasing wavelength. Using the 683 MeV electron beam, we were able to achieve FEL lasing in a reasonably large tuning range, from 168.6 nm to 179.7 nm. Figure 4(c) shows the measured spec-

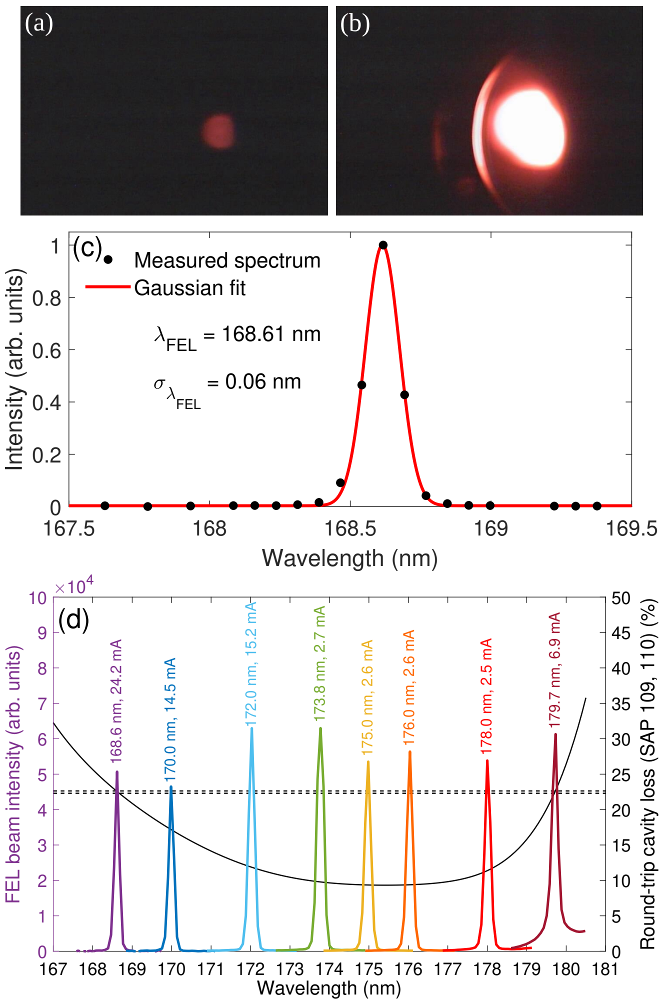

FIG. 4. Optical beam images on a VUV fluorescence screen: (a) the FEL lasing is off, (b) the lasing is on. The FEL lasing can be turned off/on by inserting/removing a screen with a small hole to block the optical path. With this screen inserted, the image shows the undulator radiation reflected by the downstream mirror through the hole in the screen. (c) Measured spectrum of 168.6 nm FEL lasing. Intensity is normalized to the peak value. (d) Wavelength scanning of VUV FEL lasing. The solid black curve shows the cavity round-trip loss, and two almost overlapping dashed black lines mark the losses for the shortest/longest lasing wavelength. All lasing spectra are measured using a 683 MeV electron beam.

trum around 168.6 nm with a fitted relative rms spectral width of about 4×10^{-4}. This work has set a new shortest lasing wavelength for oscillator FELs at 168.6 nm.

The FEL beam spectra were measured using the VUV spectrometer with a relative rms spectral resolution of 4×10^{-4} at around 170 nm. A few selected lasing spectra are shown in Fig. 4(d). The round-trip loss of the FEL cavity was estimated based on the measured reflectivity curve of the two mirrors, with one such curve shown in Fig. 2 for SAP110. The round-trip cavity loss was relatively flat around the minimum loss point, 9.3% at 175.4 nm. At this wavelength, FEL lasing was possible with a low electron beam current of about 1.5 mA in a single bunch. When the lasing was tuned away from this flat region, a higher beam current was necessary to compensate for the increasing cavity loss. Overall, the demonstrated wavelength range is consistent with the cavity round-trip loss for this pair of FEL mirrors (see the black curve in Fig. 4(d)). The maximum round-trip losses associated with the lasing lines at two spectral ends (168.6 nm and 179.7 nm, respectively) are about the same, at about 22%. Therefore, the FEL gain at these two wavelengths is expected to be more than 22% per pass.

C. Mirror Lifetime Test

The lifetime tests for the VUV mirrors were carried out while producing Compton gamma rays for a nuclear physics experiment. As the first step, we demonstrated the gamma-ray production in a new energy region.

Using the same pair of mirrors (SAP109 and SAP110) for the first FEL test, we proceeded to generate circularly polarized gamma rays. By varying the electron beam energy, we produced gamma rays with peak energies around 45, 60, and 120 MeV. The gamma-ray spectra, measured using a NaI detector, are shown in Fig. 5. The related beam parameters for gamma-ray production are summarized in Table I. Due to the use of a collimator with a large opening aperture (half angle 0.3 mrad)[39], the highest energy gamma-ray spectrum is peaked around 110 MeV with a relatively large energy spread. The measured total gamma-ray flux is about 3.1×10^7 γ/s with a 30 mA beam current. With this test, we established a new record for the highest energy gamma-ray production around 120 MeV for the HIGS facility.

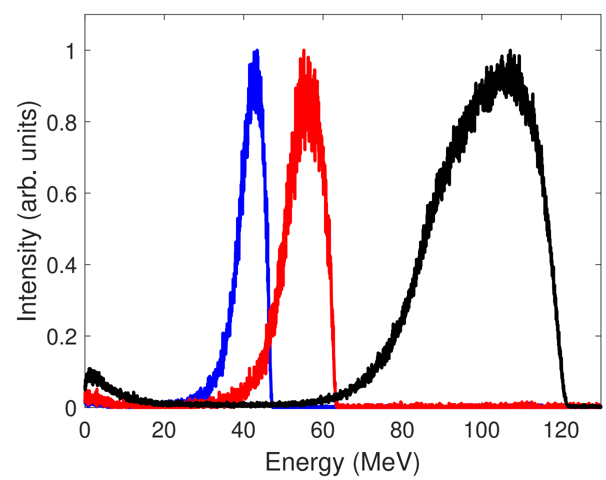

FIG. 5. Measured gamma-ray spectra with maximum energies around 45 MeV, 60 MeV, and 120 MeV using an electron beam of 683 MeV, 793 MeV, and 1110 MeV, respectively, with FEL lasing between 173 and 174 nm.

We conducted the FEL mirror lifetime test using the second pair of mirrors: a new front mirror (SAP107) and a used back/upstream mirror (SAP109). The same back mirror was

Electron beam energy (MeV)	E-beam current (mA)	FEL wavelength (nm)	Max. gamma-ray energy (MeV)
683	30	174	45
793	25–30	174	60
1110	30	173	120

TABLE I. Operational parameters for the gamma-ray beams produced for spectrum measurements shown in Fig. 5.

used because it was expected to have a much longer lifetime than the front mirror as it was not subject to intense undulator harmonic radiation. The lifetime test was combined with an experimental test run using a ^{12}C target and a NaI detector. This test was aimed at gaining a better understanding of the detector energy resolution and determining how to produce a high-resolution gamma-ray beam for the nucleon electromagnetic polarizability measurements at the HIGS. We produced circularly polarized gamma rays at two energies, around 86 MeV and 120 MeV using electron beams at 936 MeV and 1.11 GeV, respectively. The radiation exposure time for the mirrors was accumulated mostly during the following activities: (1) the setup of FEL operation and gamma-ray production; (2) gamma-ray production for the ^{12}C Compton scattering data run; and (3) additional gamma-ray beam production for equipment calibration and test.

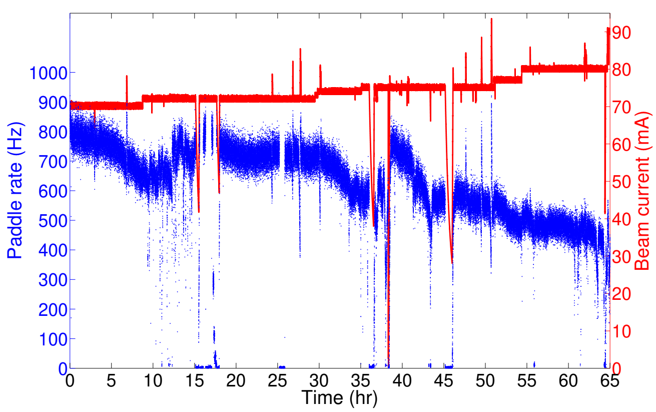

FIG. 6. Electron beam current (red) and gamma-ray flux (blue) recorded during 65 hours of continuous operation as part of the mirror lifetime test. The electron beam energy was kept constant at 936 MeV and the two-bunch electron beam current was increased in small steps from 70 mA to about 80 mA to compensate for gradual flux reduction. The (relative) gamma-ray flux was measured using a single-paddle system. The occasional drops of the flux and downward spikes in the beam current were caused by interruptions of the gamma-ray production when researchers accessed the target room to make adjustments to their experimental setup.

The majority of beamtime was accumulated during the research run using an 86 MeV gamma-ray beam, reaching a total of about 71 hours. The measured electron beam current and gamma-ray flux are shown in Fig. 6 during a continuous three-day operation including two overnight shifts. It can be seen in the figure, as the mirrors degraded, the gamma-ray flux gradually decreased. To help compensate for the flux loss, the electron beam current was raised slowly from 70 mA to 80 mA. Toward the end of this run, the gamma-ray flux decreased to about one-half of the initial value. A total of 83 hours of beamtime were produced using this set of mirrors for the two highest electron energies, 938 MeV and 1.11 GeV, with integrated radiation exposure of 5985 mA-hr. Normalized for a steady operation with a constant beam current of 75 mA, the effective total beamtime is about 80 hours. From this test, we can conclude that the useful lifetime for these 175 nm mirrors (when used as the front FEL mirror) is 80 hours or longer, exceeding the lifetime goal of 50 hours set for this mirror development program. During this test run, the extracted FEL power was monitored continuously. For example, at the beginning of the run, the measured extracted FEL power was about 60 mW with a 60 mA of electron beam (in two bunches) at 1.10 GeV. Based on the measured Compton gamma-ray flux at 86 and 120 MeV gamma production, the estimated intracvity FEL power ranged from 12 to 15 W.

IV. POST-LASING MIRROR CHARACTERIZATION

The first pair of 175 nm FEL mirrors (SAP109 and SAP110) was used for the FEL lasing test and the initial test to generate Compton gamma rays. They were used for 20 hours of production of a high-flux 120 MeV gamma-ray beam.

At the end of these tests, this pair of FEL mirrors were taken out of the cavity and visually inspected. The back mirror (SAP109) exposed to only FEL radiation shows no visible change (see Fig. 7(a)). On the front mirror (SAP110), three ring-shaped darker regions are clearly visible (see Fig. 7(a)). These are caused by the mirror's exposure to the off-axis harmonic radiation from each of the three helical undulators after passing through the partially closed water-cooled aperture system as described in Section II B. The edges of the dark regions track the shape of the protective aperture. The darkest region on the surface is a small spot located halfway from the mirror center at the four o'clock direction (see Fig. 7(b)). This region was irradiated by high-energy synchrotron radiation from the end-of-the-arc dipole magnet which bends the electron beam to exit the FEL cavity. Finally, a circular region around the mirror center which reflects the FEL beam is observed with good transparency without visible damage.

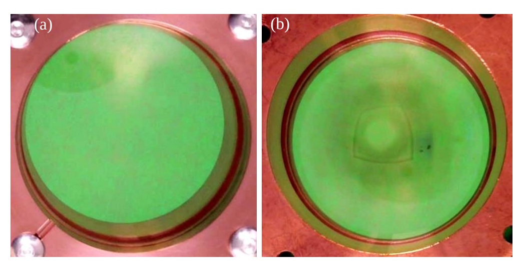

FIG. 7. The mirror images after the FEL lasing test: (a) the image of the back FEL mirror (SAP109), and (b) the image of the front FEL mirror (SAP110) exposed to undulator harmonic radiation. The diameter of the mirror surface shown in each photo is 44.45 mm.

Both mirrors are examined further using a Nomarski microscope at LZH. For the front mirror (SAP110), the microscope images confirm observed results in Fig. 7(b) and provide more details about various damage regions. The possible causes of mirror damage include material deposition on the surface (e.g. carbon deposition) and/or material changes in the coating. The darkest region irradiated by the dipole radiation is likely damaged by local melting of the coating.

The most important optical properties of the mirrors, reflectivity and transmission, are also measured. For the back mirror (SAP109), the reflectivity remains unchanged for the longer wavelength region (172–180 nm) when compared with the measured reflectivity before irradiation. Reflectivity in the shorter wavelength region (165–172 nm) is found to be reduced at locations close to the mirror center where the FEL beam has the highest intensity. The transmission across the high-reflectivity band is increased uniformly across the mirror surface, almost doubling the minimum transmission around 175 nm. The above results are consistent with the observations based on microscope images, indicating a high possibility that increased absorption takes place in the SiO_2 protective layer and/or the top layers of the fluoride coating.

For the front mirror (SAP110), the measurements show more significant overall reflectivity reduction across a broader wavelength range (163–180 nm) as compared with the back mirror (SAP109). The largest reflectivity decrease takes place in the coating regions exposed to undulator harmonic radiation. The measured transmission shows varying degrees of increase in the high-reflectivity spectral region. However, around the mirror center, the mirror loss remains roughly the same for 167–176 nm, compared to the level of loss before irradiation. These observations indicate a likely degradation of mirror material over the entire stack of the front mirror (SAP110), which is very different from the likely degradation of the top layers in the back mirror (SAP109).

One of the important findings is that for both the front and back mirrors, the measured reflectivity in the region close to the mirror center remains largely unchanged for the wavelength in a narrow high-reflectivity band (i.e. 172–176 nm) after more than 20 hours of exposure to intense FEL and/or synchrotron radiation. This result indicates that the mirror degradation due to FEL radiation alone is mild and builds up slowly, which is consistent with the observed long mirror lifetime.

The pair of mirrors used for the lifetime tests (SAP107 and SAP109) is still under investigation. In addition to optical characterization, the front mirror (SAP107) will also be subjected to heat and UV treatments to determine whether the coating damage can be partially reversed. The related results will be published elsewhere.

V. SUMMARY

We have successfully developed high-reflectivity, thermally stable, radiation-resistive 175 nm FEL mirrors. The mirror coating is an evaporated fluoride multilayer protected by a SiO_2 top layer. Using these mirrors, we have extended the Duke FEL operation to a deeper VUV wavelength range from 168.6 to 179.7 nm, setting a new short-wavelength record for FEL oscillators at 168.6 nm. We have also produced circularly polarized gamma rays up to 120 MeV, extending the HIGS operation into a new high-energy region. To test their durability, the FEL mirrors were used to produce high-flux, circularly polarized gamma-ray beams at 86 MeV and 120 MeV for a nuclear physics experiment. This test has demonstrated that these 175 nm FEL mirrors have a useful life of more than 80 hours. Finally, the post-lasing analysis reveals a mild degradation of the back mirror and a more severe degradation of the front mirror which is subject to intense synchrotron radiation.

For the low-energy QCD research program at the HIGS, the next high-energy range is from 130 to 150 MeV. A high-intensity gamma-ray beam in this energy range will create new opportunities for nucleon spin-polarizability research and photo-pion production research at the HIGS. This will require even shorter wavelength FEL mirrors with durable, high-reflectivity coatings around 155 nm. The development of such a coating is expected to benefit from the lessons learned and experience gained in this research. We will explore multiple new technical solutions to develop the radiation-resistive and thermally stable fluoride-based coating around 150 nm, where coatings will suffer from more optical losses. The exploration will include IBS or ALD coated fluoride multilayer coatings, new types of protective layer for the fluoride coatings, and other types of materials for the multilayer coating.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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