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PRODUCTION OF 120 MeV GAMMA-RAY BEAMS AT DUKE FEL AND HIGS FACILITY*

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Abstract

In this paper we report extension of the operational energy of the gamma-ray beams produced at Duke High Intensity Gamma-ray Source (HIGS) up to ~120 MeV, opening up a new high energy region of gamma-rays for photonuclear physics research. This achievement is based upon development of radiation robust, thermally stable, high-reflectivity fluoride (LaF3/MgF2) multilayer VUV FEL mirrors, enabling us to maintain stable high intensity FEL lasing at the wavelengths of around 175 nm. We discuss the challenges of HIGS operation at high gamma-ray and high electron beam energies with the downstream FEL mirror exposed to extremely hush radiation. The experience of the first HIGS user operation with high intensity, high gamma-ray beams energies (~86 MeV and ~120 MeV) using these new mirrors is also discussed.

DUKE FEL/HIGS FACILITY

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. The 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. A circular optical-klystron FEL employs up four OK-5 helical wigglers; two of them in the middle of the straight section are switchable with two planer OK-4 wigglers.

Table 1: Parameters of Duke Accelerators and FELs

Accelerators	**Storage Ring**	**Booster Injector**
Operation energy [GeV]	0.24-1.2	0.16-1.2
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]	5.90	3.25
Maximum K_w	5.51	3.61
Maximum current [kA]	3.65	3.65
FEL wavelength [nm]	175 - 1100	

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DEVELOPMENT OF 175 nm VUV MIRRORS

Since 2012, HIGS routinely produced gamma-ray beams of 1 MeV to 100 MeV, using FEL mirrors from 1060 nm to 190 nm [1]. In order to conduct nucleon eletromagnetic polarizability experiments in a new high-energy region, gamma-ray beams of energy higher than 100 MeV are required. To extend the energy, we needed mirrors of a wavelength shorter than 190 nm. The development of such VUV mirrors has been undertaken by our collaborators at Laser Zentrum Hannover (LZH), Germany. LZH researchers in collaboration with TUNL have developed radiation robust, thermally stable, high-reflectivity fluoride (LaF3/MgF2) multilayer VUV FEL mirrors, enabling high intra-cavity FEL lasing at the wavelengths of around 175 nm. New mirror R&D started in 2018. A variety of coating materials and techniques were tested in the real radiation environment at Duke FEL/HIGS facility. Figure 1 shows measured properties of the mirror that has been used at the downstream side of the optical FEL cavity for the first 120 MeV user HIGS run. Sapphire substrates are used to provide for thermal stability and efficient cooling.

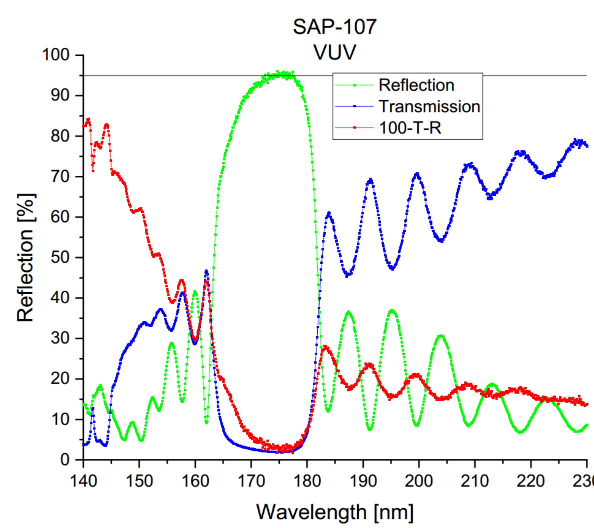

Figure 1: Measured reflectivity and transmission of a new 175 nm fluoride FEL mirror (serial number SAP-107) used at the downstream side of the optical FEL cavity during the first 120 MeV HIGS user run.

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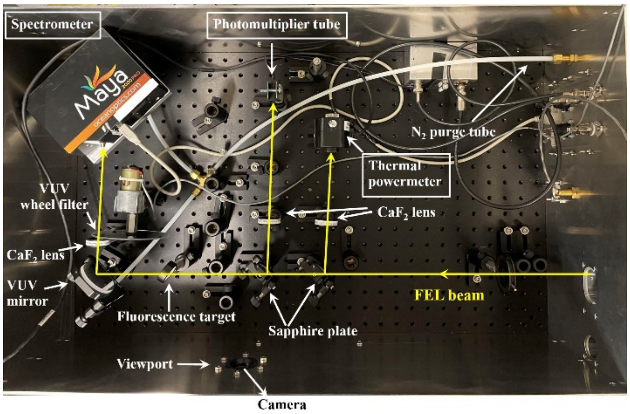

Figure 2: VUV optical diagnostics board.

VUV FEL DIAGNOSTICS

For the FEL operation at the wavelengths of about 195 nm and below, all the elements of VUV FEL diagnostics are located in a nitrogen purged diagnostics box (Fig. 2, [2]).

The FEL VUV diagnostics includes the following key elements:

- Ocean Optics Maya 2000 Pro spectrometer with a special grating covering 142 - 289 nm wavelength range;
- Hamamatsu R7400U-09 VUV solar bind PMT with a spectral response limited to the range of ~170-~290 nm to measure the FEL temporal structure;
- Melles Griot 13PEM001 broad band optical power meter with a thermopile sensor head to measure the FEL power;
- VUV fluorescent target to monitor the FEL profile.

The other elements, such as sapphire plate splitters, CaF_2 focusing lenses, VUV enhanced Al mirror and OD 4.0 neutral density filter, are all rated for deep VUV down to ~160 nm.

CRITICAL HARDWARE ENABLING VUV FEL OPERATION

Because of a rapid degradation of 175 nm mirrors caused by the on-axis higher order harmonic radiation, 175 nm operation is not possible with planar OK-4 FEL, i.e. with linearly polarized FEL beams. It can be run only with helical OK-5 wigglers, with the production of only circularly polarized FEL and gamma-ray beams. However, due to substantial power absorption of the FEL beam power and of wiggler off-axis harmonic radiation in the downstream FEL mirror, even with OK-5 FEL, the following hardware is necessary to enable high-energy, high FEL power, and high gamma flux HIGS operation:

- A copper mirror holder and mount for downstream FEL mirror actively cooled from outside using a compressed air vortex chiller (Fig. 3);
- In-vacuum mirror protection water-cooled horizontal and vertical apertures blocking most of the damaging higher order harmonics off-axis radiation incident on the downstream FEL mirror (Fig. 4, [3]).

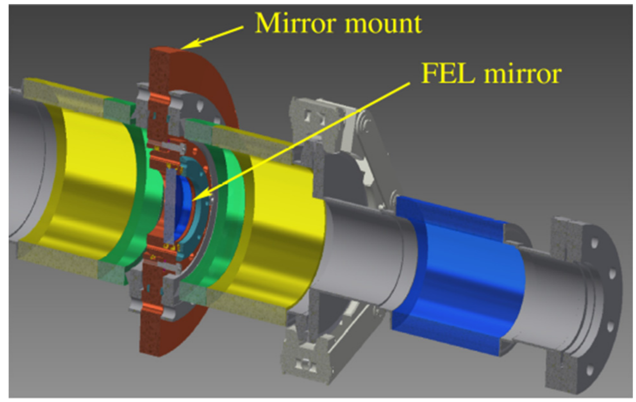

Figure 3: Copper mirror holder and mount for downstream FEL mirror.

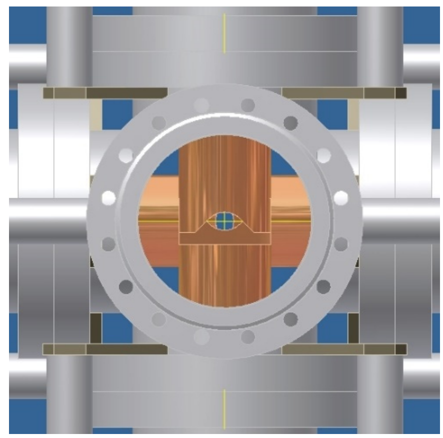

Figure 4: In-vacuum mirror protection water-cooled horizontal and vertical apertures in fully inserted position.

The air-cooling of the downstream mirror allows evacuating up to a few watts of power dissipated in the mirror. The properly tuned opening of the mirror protection apertures is absolutely critical to achieve a substantial life time of the downstream FEL mirror.

120 MeV GAMMA-RAY PRODUCTION

The production of 120 MeV gamma-ray beams at HIGS was first demonstrated in July 2021, along with the first lasing at the record low wavelengths within a range of 168.6 – 179.7 nm.

120 MeV gamma-ray beams for users were first produced at HIGS in February 2021, for an experimental test run using a ^{12}C target, as a part of the electromagnetic polarizability research program. Compton scattering spectra were measured using NaI detector. With a large cross section, Compton scattering from ^{12}C provides much higher count rates without using a cryogenic target. It enables a precise measurement of the cross section for ^{12}C inelastic Compton scattering, which is poorly known at the present time.

The FEL system was configured to use the three upstream helical wigglers, OK-5A, B, and C (Fig. 5). We produced circularly polarized gamma rays at two energies, around 86 MeV and 120 MeV, using electron beam energies of 0.936 GeV and 1.11 GeV, respectively.

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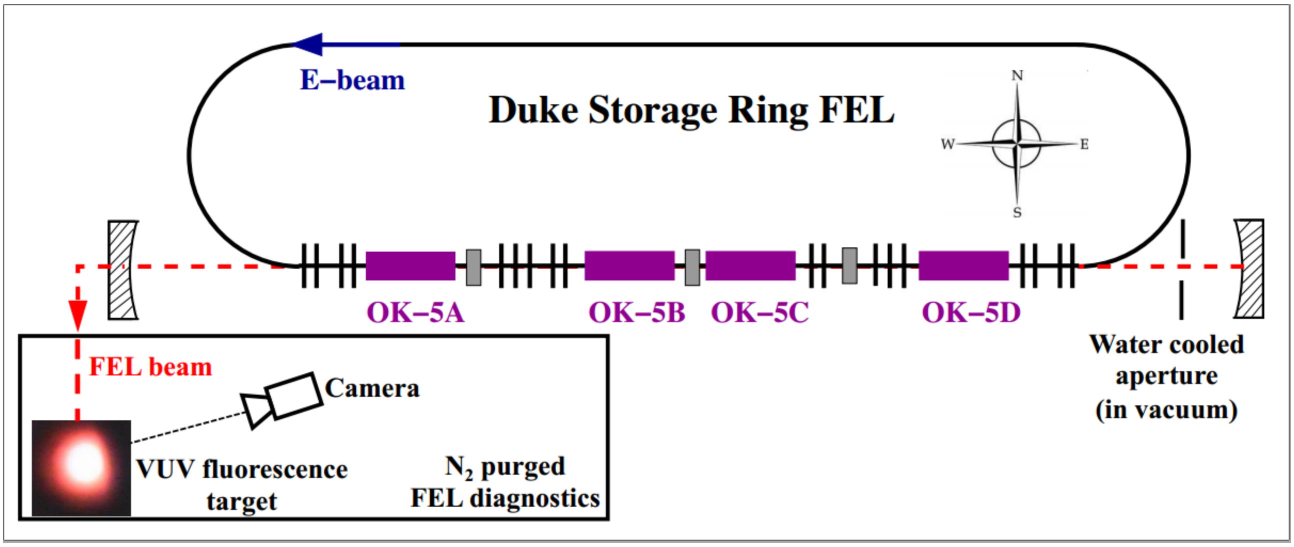

Figure 5: Configuration of the OK-5 FEL for production of high energy gamma-ray beams using VUV mirrors. OK-5A, OK-5B, and OK5-C were energized for the 86 MeV and 120 MeV gamma-ray beam production using 175 nm mirrors.

Figure 6 shows measured spectra for these energies, with the gamma-ray beams passing through a 9 mm diameter lead collimator. The maximum intensity of the gamma-ray beams at the target (after collimation) was measured at 2.3×10^6 γ/s and 2.7×10^6 γ/s at 86 MeV and 120 MeV, respectively. The maximum total gamma-ray flux produced was ~10^8 γ/s for both energies.

The total time of gamma-ray beam production for this run was about 70 hours at 86 MeV, and about three hours at 120 MeV, respectively. To partially compensate the effect of mirror degradation, the wavelength of the FEL beam during the run was gradually reduced from ~175 nm at the beginning of the run down to ~173 nm at the end of the run.

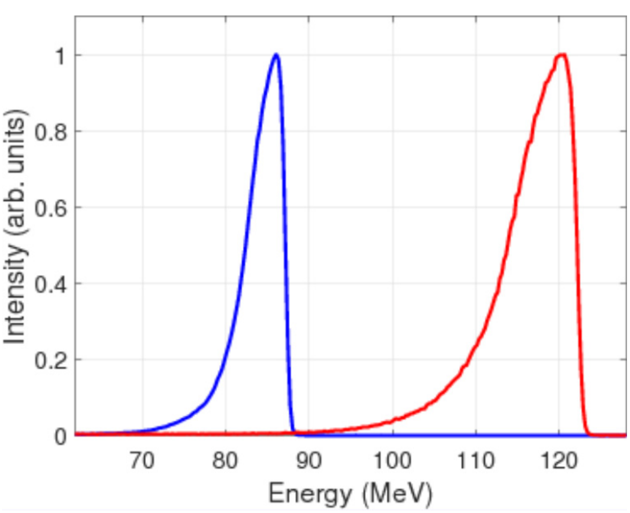

Figure 6: Energy spectra of 86 MeV and 120 MeV gamma-ray beams produced using 0.936 GeV and 1.11 GeV electron beams. The gamma-ray spectra are measured using a high-resolution NaI detector, and normalized to their respective peak intensity.

CONCLUSION

With an additional modification of the power supply system supplying OK-5 wigglers, using 175 nm high intensity FEL, we can further extend HIGS operation from 100 MeV up to 130 MeV, making it possible to conduct nucleon eletromagnetic polarizability experiments in a new high-energy region at the HIGS facility. This significant progress with the gamma-ray source development will have a long lasting impact on the low-energy QCD research program at the HIGS. The next interesting higher energy range is from 130 MeV to 150 MeV, which will create new opportunities for nucleon spin-polarizability measurements at the HIGS. This will require even shorter wavelength FEL mirrors with high-reflectivity, durable coatings around 155 nm.

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