ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG20

VUV DIAGNOSTICS FOR OSCILLATOR FEL OPERATION FROM 200 nm TO 155 nm*

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Abstract

Powered by a storage ring with energies ranging from 240 MeV to 1.2 GeV, the Duke Free-Electron Laser (DFEL) has demonstrated operation across a broad wavelength spectrum from infrared (IR) to vacuum ultraviolet (VUV): 1100 nm to 170 nm. This FEL serves as a photon source for the High Intensity Gamma-ray Source (HIGS), producing polarized, near-monochromatic, and high-flux Compton gamma-ray beams in an extensive energy range from 1 to 120 MeV, with the highest flux recorded at 3.5e10 ph/s (total) around 10 MeV. To generate high-energy gamma-ray beams above 80 MeV, the FEL must operate in the VUV region from 195 nm to 155 nm. This work describes the development and operation of VUV beam diagnostics within a nitrogen-purged enclosure, with increased difficulty as the wavelength shortens towards 155 nm. We will discuss the challenges encountered and the solutions found for VUV beam diagnostics, leading to the successful FEL lasing in the VUV region.

DUKE FEL/HIGS FACILITY

The Duke Storage ring is designed as a dedicated FEL driver and a host of several FEL wigglers in a 34 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.

VUV FEL OPERATION AT HIGS

Since 2012, HIGS routinely produced gamma-ray beams of 1 MeV to 100 MeV, using FEL mirrors from 1060 nm to 190 nm. In order to conduct nucleon electromagnetic 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. For the VUV FEL operation, we commonly use VUV mirrors developed and fabricated by Laser Zentrum Hannover (LZH), Germany. In 2019, in collaboration with TUNL, LZH developed radiation robust, thermally stable, high-reflectivity 175 nm mirrors, tested at Duke in July 2020, showing FEL in the range of 168-178nm [1].

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]	175	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	Horizontal	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	

In January 2021, using these mirrors, 120 MeV high intensity gamma ray production was demonstrated at HIGS [2]. Currently, 155 nm mirrors are under development. First experimental batch of such mirrors was tested at Duke in January 2024. FEL was demonstrated in the range of 155-159 nm for a very short period of time of about one hour as mirrors rapidly degraded.

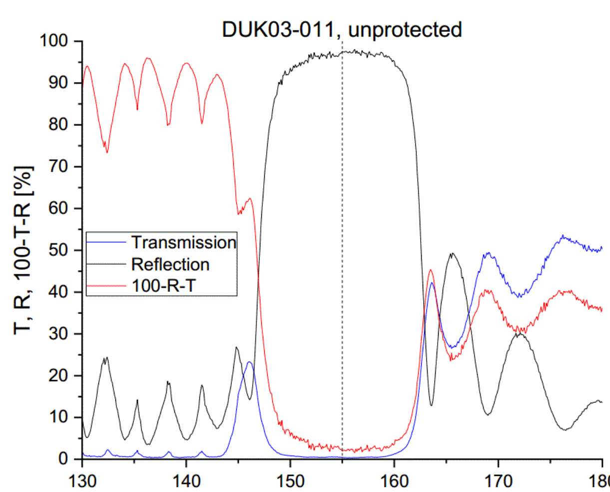

Figure 1: Measured reflectivity and transmission of an experimental 155 nm FEL mirror (serial number DUK003-011) used for the FEL diagnostics set-up and first FEL demonstration in the range of 155-159nm.

*Supported in part by US DoE grant DE-FG02-971ER41033.
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ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG20

Figure 1 shows measured properties of the experimental mirror that has been used at the upstream side of the optical FEL cavity for the first lasing demonstration down to 155nm. Sapphire substrates are used to provide for thermal stability and efficient cooling. With 155 nm mirrors in hand, we can reach energy of gamma rays of ~150 MeV approaching photo-pion physics research at HIGS. This also required a further development of VUV diagnostics for the wavelength down to 155 nm.

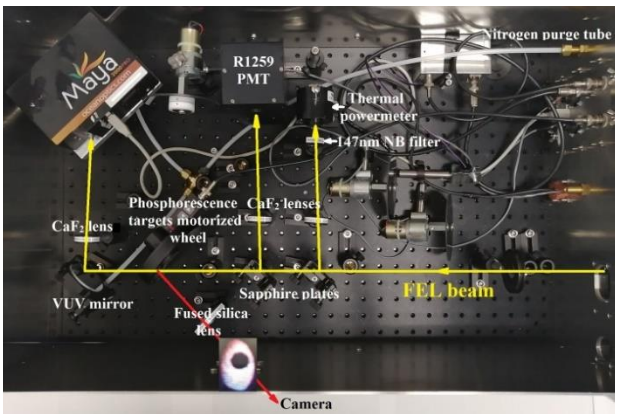

Figure 2: VUV optical diagnostics board configured for 155 nm FEL/HIGS operation.

VUV FEL DIAGNOSTICS

For the FEL operation at the wavelengths of below 200 nm, all the elements of VUV FEL diagnostics are located in a nitrogen purged diagnostics box (Fig. 2). The light reflected by the downstream mirror of the FEL cavity is out-coming through the upstream FEL mirror, then through the CaF_2 viewport of the vacuum chamber, and enters the diagnostics box.

The FEL VUV diagnostics includes the following key elements common for any VUV operation of below 195 nm:

- Ocean Optics Maya 2000 Pro spectrometer with a special grating covering 142 - 289 nm wavelength range;
- Melles Griot 13PEM001 broad band optical power meter with a thermopile sensor head to measure the FEL power;
- VUV phosphorescence targets to monitor the FEL profile;
- Edmund Optics VUV enhanced Al mirror (Fig.3);

The other elements, such as sapphire plate splitters, CaF_2 focusing lenses, are all rated for deep VUV down to ~140 nm.

The light coming through the sapphire plate splitters illuminates the target and a portion of it goes through the hole in the target to the spectrometer after being reflected by the VUV mirror and focused by the CaF_2 lens.

For the VUV phosphorescence targets we use phosphor powders originally developed for Cathodic Ray Tubes (CRT). Those are chemical compounds which are luminescent when exposed to the light of shorter wavelength absorbing the photon energy and reemitting it at a longer wavelength. For our targets, we used Y2O2S:Eu compound re-emitting in a bright red color. This compound has shown sufficient sensitivity down to 155 nm wavelength both for initial stage of establishing of the FEL and during the FEL operation.

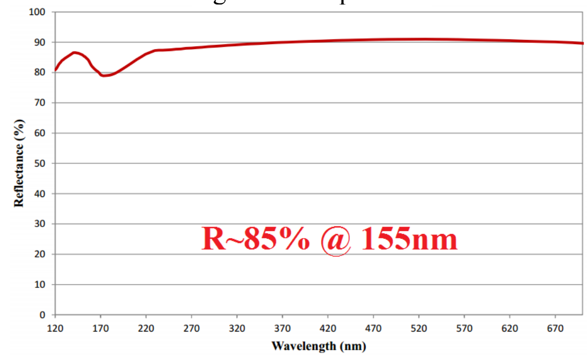

Figure 3: Edmund Optics VUV enhanced Al mirror reflectivity @ 0^0 AOI.

DIAGNOSTICS FOR 195-170 nm FEL/HIGS OPERATION

For the FEL operation down to 170 nm we use some elements rated only down to ~160 nm, in particular, a fused silica neutral density filter wheel (motorized) with OD variable from 0 to 4.0. To measure the FEL temporal structure, we use Hamamatsu R7400U-09 VUV solar bind PMT with a spectral response limited to the range of ~170 - ~290 nm (Fig. 4 left). The spectral limitation of the radiant sensitivity and quantum efficiency of the PMT by ~150-310 nm is extremely useful as it provides with a considerable selectivity and makes it almost insensitive to a background optical radiation at longer wavelengths. The latter significantly increase signal/noise ratio of the temporal structure signal. One should realize that transmission of the FEL mirrors within the high reflectivity range is very low, for the VUV mirror it is ~0.3%, while at the wavelengths beyond that range it is order of 10-50% (see, Fig. 1, for example). Therefore, the contribution of the parasitic background radiation may become dominant without suppression by the PMT spectral response. Such selectivity is even more important for the 155 nm FEL operation (see the following section). This is especially critical for an initial establishment and tune-up of the FEL.

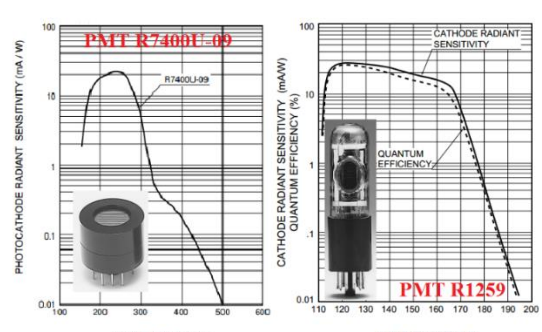

Figure 4: Characteristics of Hamamatsu R7400U-09 and R1259 PMTs.

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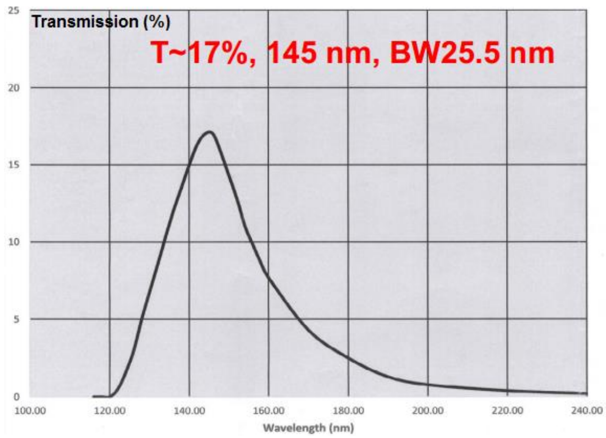

Figure 5: Transmission of eSource Optics 25147FNB 147 nm Narrow Band filter.

DIAGNOSTICS FOR 155 nm FEL/HIGS OPERATION

The VUV diagnostics for establishing and maintaining FEL operation around 155 nm is significantly more challenging.

- Sensitivity of Maya 2000 Pro spectrometer below 160 nm drops, abruptly falling down below 147 nm.
- For 155 nm FEL, we will use Hamamatsu R1259 PMT (Fig.4 right) This PMT, due to the special cathode material, has a radiant sensitivity and quantum efficiency hard limited by ~190 nm, which provides an excellent selectivity to the wavelengths of interest of 150-160nm.
- For additional selectivity, we use 25147FNB 147 nm Narrow Band filter (Fig. 5). For the real FEL operation, it is installed in front of the power meter in order to reduce a dominant contribution of the parasitic optical radiation above 160nm. At the stage of establishing of the FEL it is beneficial to use it in front of the PMT to bust its selectivity even further. The power meter is of no use at this stage due to extremely low power. The sapphire plate splitter in the power meter line (see Fig. 3) is removed to increase the power coming to the other elements.

We do not out-pump the air out of the diagnostics box, the box is just naturally purged by the constantly flowing high purity dry nitrogen, gradually replacing air. The most significant component of the air to eliminate is the water vapor, the presence of which is clearly seen in the absorption lines of the spectrum until the diagnostics box is completely purged. In order not to allow any water vapor back to the box, the nitrogen inside it holds some positive excessive pressure, provided by the permanent flow and sufficiently tight sealing. The nitrogen purge takes ~4-6 hours to fully eliminate any additional absorption down to below 150 nm.

For the 155 nm FEL operation, we use a motorized target wheel, with four thin aluminum targets mount in it. Each target has a hole in the middle with diameter of 1/4" (6.35nnm), 1/8" (~3.2mm), 1/16" (~1.6mm), and 1/32" (~0.8mm) consequently. At the beginning of the FEL set-up the target with the maximum opening is used, to let sufficient amount of light enter the spectrometer.

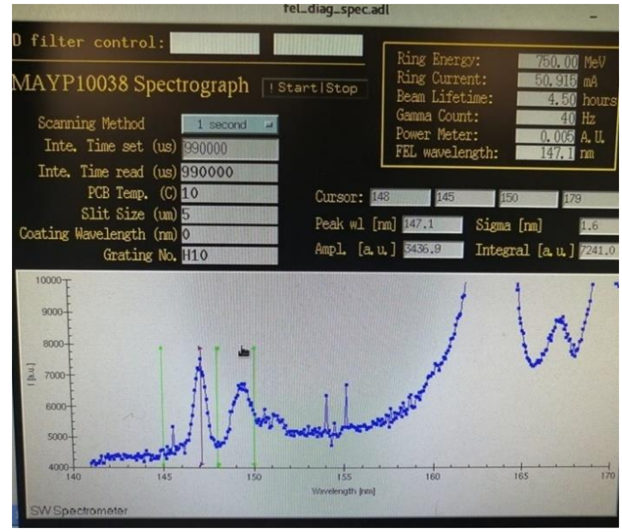

Figure 6: The lowest wavelength of the wiggler radiation measured by Ocean Optics Maya 2000 Pro spectrometer.

With that opening, the lowest wavelength of the wiggler radiation measured by the Maya 2000 Pro spectrometer is 147 nm (Fig. 6). After establishing an initial low power lasing, the targets with the smaller openings must be used not to saturate the spectrometer. At the high power FEL operation, the smallest opening is used.

CONCLUSION

With successful development of 155 nm high intensity FEL, we can further extend HIGS operation from ~130 MeV up to ~150 MeV, making it possible to conduct nucleon electromagnetic spin-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. Successful development of FEL in this new VUV wavelength range will be advancement in the FEL optical cavity technology used in Compton gamma-ray production for energies approaching the threshold of pion-photo-production. This new capability will allow physicists of HIGS Compton-scattering Collaboration to evaluate strategies for producing gamma rays at HIGS above 150 MeV as required for photo-pion physics research.

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