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CHARACTERIZATION OF FEL MIRRORS WITH LONG ROCs*

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Abstract

A challenge for the Duke storage ring, featuring a nearly concentric 53.73-meter-long FEL cavity, is the characterization of the FEL mirrors with a long radius of curvature (ROC). The Duke FEL serves as the laser driver for the High Intensity Gamma-ray Source (HIGS). As we extend the energy coverage of the gamma-ray beam from 1 to 120 MeV, the FEL operation wavelength has expanded from infrared (1,060 nm) to VUV (170 nm). We report the improvements made to a wire-diffraction system to measure long ROCs ($R > 25$ m), including new data from a completely different method validating the results of this ROC measurement apparatus. This system has been used to characterize two types of substrates and FEL mirrors with ROCs ranging from about 27 to 29 m. The recent ROC measurement results are presented in this work.

INTRODUCTION

The High Intensity Gamma-ray Source (HIGS) [1, 2] at Triangle Universities Nuclear Laboratory (TUNL) is the world's premier real photon facility for photonuclear research. The facility produces polarized Compton gamma-ray beams [3, 4], both linear and circular, in a wide energy range from 1 to 120 MeV with the highest flux of about 3.5×10^{10} γ/s and a maximum spectral flux of more than 10^3 γ/s/eV around 10 MeV. The wide energy range and high flux are realized by colliding a MHz storage-ring electron beam of large bunch charge with a free-electron laser (FEL) beam of high intracavity laser power. The operation energy of the storage ring ranges from 240 MeV to 1.2 GeV, and the FEL is operated between infrared (about 1060 nm) and the vacuum UV (VUV) wavelengths (about 175 nm).

For a two-mirror FEL stable resonator (see Fig. 1), the need to separate the FEL beam from the electron beam at mirror locations limits its cavity length (L) to half of the storage ring circumference, $L = 53.73$ m. To optimize the FEL gain [5], the Rayleigh range (z_R) of the cavity should be chosen to be close to the beta function of the electron beam in the interaction region ($\beta_0 = 3$–6 m). We typically choose $z_R = 4.0$–4.5 m, much less than the cavity length L. Therefore, the optimal FEL cavity is a nearly concentric two-mirror cavity, with radius $R > L/2 = 26.865$ m.

One of many challenges associated with this resonator is to work with mirrors of a very long radius of curvature (ROC), in particular, to develop a reliable and robust measurement system for measuring long ROCs.

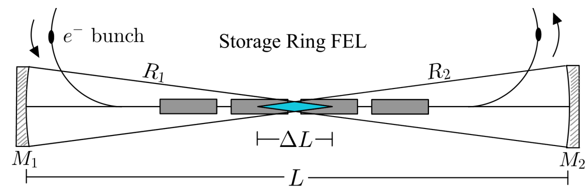

Figure 1: Layout of the storage ring FEL oscillator with a nearly concentric FEL cavity. The spherical mirrors M_1 and M_2 have radii of curvature $R_1 \approx R_2 = \frac{1}{2}(L + \Delta L)$ ($\Delta L \ll L$). The overlap of the spheres' centers is highlighted in blue, indicating a stable resonator.

IMPROVING ROC MEASUREMENTS

The FEL mirror substrates need to satisfy multiple stringent specifications, including surface quality, surface roughness (super-polished), and an extended radius of curvature ($R > 27$ m). In the late 1990s, only a handful of optics companies were capable of and interested in producing high-quality, custom substrates, particularly for occasional small orders. Fortunately, we initiated and sustained a long-term relationship with an optical company (currently part of Gooch & Housego, LLC [6]). Like typical optics companies, they did not have expensive equipment to measure the substrates with ROC longer than 10 m. This motivated us to develop a simple, inexpensive long ROC measurement system on-site. Such a system was developed in the early 2000s by combining geometric imaging and single-wire diffraction with the preliminary results reported in [7].

The schematic layout of the ROC measurement system is shown in Fig. 2. The setup resembles a simple single-lens imaging system, with the lens replaced by the curved substrate to reflect back the beam. An intense coherent light source, a He-Ne laser, is used so that an uncoated substrate or a coated FEL mirror can reflect sufficient light for measurement. A straight wire of a chosen size is positioned in the beam path as the target object, and the resulting image is captured by a CCD camera. The wire target and camera are moved together along the beam direction using a motion stage while the beam images are recorded.

Since the initial report of this work, several important improvements have been made:

- The combination of an analog camera and a frame grabber has been replaced by a high-quality CCD camera;
- The operation of the measurement system now utilizes a combination of MATLAB [8] and EPICS [9]; and
- The image analysis software has been significantly improved over time.

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The improvement in image analysis has stemmed from physics insights about the ROC system. The substrate (or FEL mirror) under measurement acts as a spatial filter due to its finite size. For instance, a very large optic can reflect multiple diffraction fringes, providing enough information to form an image of the wire target and thus allowing its width to be measured. However, our substrates and FEL mirrors have a 2-inch diameter, which reflects the diffraction beam around the 0th-order (see Fig. 2i), resulting in the inability to form a sharp image due to a significant loss of optical information. However, we found that we could leverage the diffraction patterns in the image by measuring the separation of the two dominant ripples around the region where the wire image would be (see Fig. 3c). This separation is smallest at the location where the geometric image would be formed.

When the system was not well aligned or when the ROC of the optic under measurement exceeded the travel range of the motion stage, multiple pronounced diffraction ripples would appear in the image. Incorrect identification would prevent us from making proper adjustments to bring the optic into the measurement range. The analysis software was further improved to make it more robust in identifying the intended diffraction ripples in the measured images.

RECENT MEASUREMENTS

Since 2004, this measurement system has been used to characterize the ROC of both new substrates and coated FEL mirrors. When a batch of substrates was made by the optics company, they determined the substrate's ROC using a relative method by comparing it with a 4-inch reference optic via an interferometry method, essentially an extended Newton's ring method [10] using a curved reference surface. Therefore, this method critically depended on the accurate knowledge of the absolute ROC of the reference optic, which was characterized with our ROC measurement system soon after it was developed. After the COVID-19 pandemic, while rebuilding its internal expertise in measuring the substrate ROC, the company sent this optic for calibration by a third party using a coordinate-measuring machine (CMM) [11]. In Table 1, the ROC values measured using CMM and wire-diffraction are compared. The absolute difference (ΔR = 0.112 m) is about one standard deviation. Considering the resolutions of these two measurements and the fact that they were carried out 19 years apart, they agree remarkably well.

Table 1: Comparison of the measured ROC of the 4-inch reference optic using two different methods.

Measurement System	**ROC result**	**Year**
Duke ROC system	$R_1 = 27.493 \pm 0.080$ m	2004
Third-party CMM	$R_2 = 27.605 \pm 0.100$ m	2023

The Duke FEL has been operated in a wide wavelength range, from infrared (1060 nm or even longer) to VUV wavelengths, with a recent success in reaching 168.6 nm,

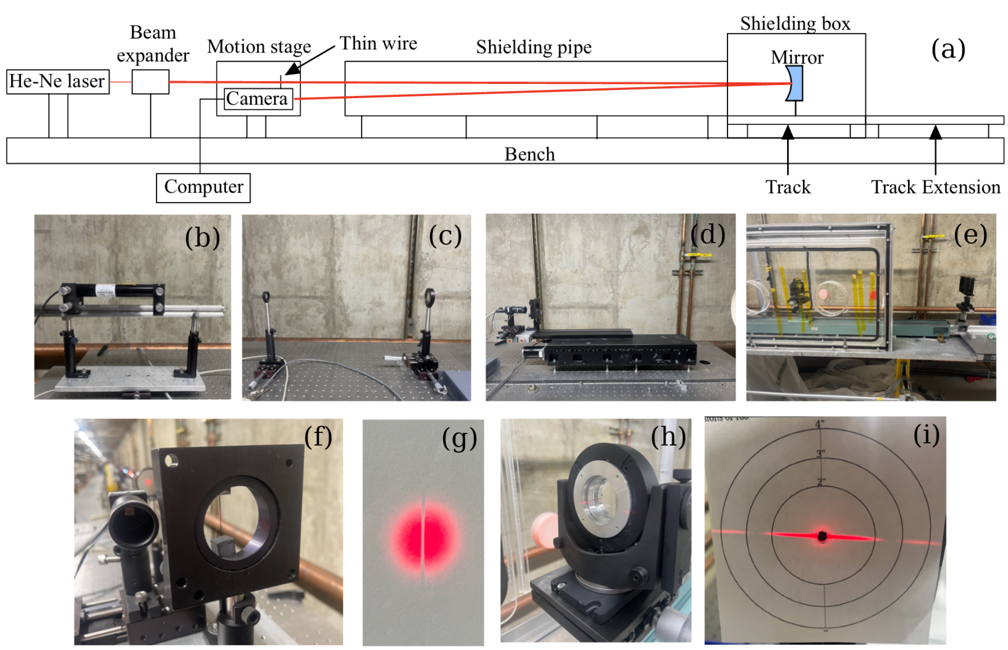

Figure 2: (a) A schematic layout of the wire diffraction ROC measurement apparatus. From (b) to (i), a series of photos are used to illustrate various parts of the system: (b) the He-Ne laser; (c) the beam expander comprising two lenses; (d) the motion stage; (e) the substrate and its holder in a sealed glass box; (f) the thin wire target (width 0.56 mm) and camera installed on the motion stage; (g) the "wire image" displayed on a paper target in front of the camera, used for visual inspection; (h) the holder for the substrate; and (i) the diffraction pattern displayed on a paper target in front of the substrate, used for visual inspection. The inner circle, with a radius of 2 inches, captures most of the 0th-order diffraction fringe. The outer circle, with a radius of 4 inches, captures the entire 0th-order and much of the 1st-order diffraction fringe.

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the shortest lasing wavelength for oscillator FELs [12]. At longer wavelengths (1060–240 nm), the FEL mirrors use SiO_2 substrates. The related ROC specification is $R = 27.46^{+0.4}_{-0.2}$ m, with a corresponding nominal Rayleigh range of $z_R = 4.00$ m.

A few years ago, working with the same optics company, we tried to explore the use of ultra-low expansion glass (ULE) for substrates with identical ROC specifications as the SiO_2 substrates. However, the ROC of the first two ULE substrates was found to be about 1 meter longer than the specifications. After having their 4-inch reference optic calibrated (mentioned above), the company also developed a set of more resilient procedures to measure the substrate ROC using a relative method. In the meantime, we provided them with a spare uncoated substrate and a used FEL mirror with known ROC values as additional references.

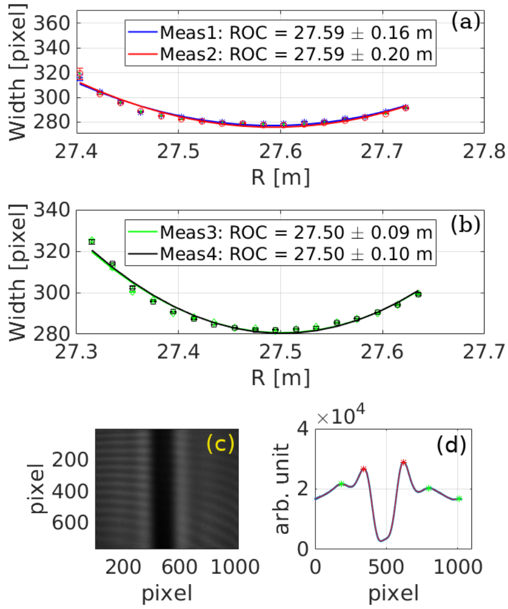

Figure 3: (a) and (b) ROC measurement results of a ULE substrate in two mutually perpendicular directions. (c) Diffraction-dominated "wire image" near where the geometric image would be formed. (d) 1-D projection of relative intensity profile from (c).

The new ULE substrates are measured with the ROC measurement system at Duke. As shown in Fig. 3(a) and (b), the measured ROC of the ULE substrate along two mutually perpendicular directions are very close, with $R_1 = 27.59$ m and $R_2 = 27.50$ m, respectively. Fig. 3(c) shows the measured "wire image" dominated by diffraction ripples and the related projection of the image intensity is shown in Fig. 3(d). The distance between two peaks around the central valley (where the wire image would be) is measured as the translation stage is moved. The location where the minimum distance is found determines the ROC of the substrate.

The operation of the Duke FEL in the VUV wavelengths is limited by thermal instability due to significantly increased heat load. This results from the absorption of short wavelength radiation from undulators (both fundamental and harmonic) and the end-of-the-arc dipole, which increases rapidly as the electron beam energy is raised. To implement external cooling, we redesigned the FEL cavity mount and mirror holder and worked with the optics company to develop new substrates using sapphire, which has an order of magnitude higher thermal conductivity compared to SiO_2. For FEL operation below 200 nm, the specified ROC is increased to $R = 27.66^{+0.8}_{-0.2}$ m to enlarge the FEL beam size for a better match with the electron beam. This helps improve the FEL gain without adversely impacting Compton gamma-ray production, as the flux at higher gamma-ray energies (above 20 MeV) is mainly limited by the rate of injection to replace the lost electrons in Compton scattering.

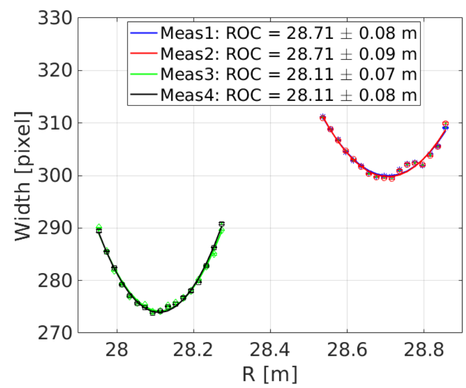

Figure 4: ROC measurement results of a sapphire substrate in two mutually perpendicular directions.

Figure 4 shows the measured ROC of a typical sapphire substrate. Compared to SiO_2 or ULE substrates, there is a relatively large discrepancy in the measured ROC values in two mutually perpendicular directions, $R_1 = 28.71$ m and $R_2 = 28.11$ m. This was likely caused by the extremely high hardness of sapphire, making it difficult to form a perfect spherical surface. Further work will be needed to improve the surface curvature of sapphire substrates. Meanwhile, the sapphire substrates have been used to produce mirrors for successful FEL operations in the wavelengths around 190 and 175 nm, demonstrating improved thermal stabilities.

SUMMARY

Over the years, we have made substantial improvements to the wire diffraction ROC measurement system developed for long ROCs ($R > 25$ m). Recent improvements include automated control, simplified data acquisition, and robust data analysis. Its results have been recently validated using a CMM technique. This cost-effective ROC measurement system has been used to characterize all substrates and FEL mirrors used for FEL operation and gamma-ray production.

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