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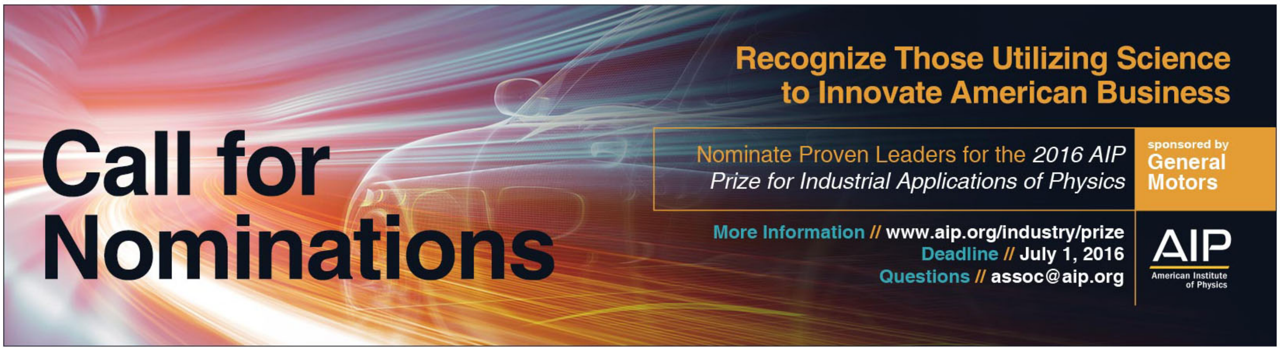

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REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 051901 (2016)

Large aperture Fizeau interferometer commissioning and preliminary measurements of a long x-ray mirror at European X-ray Free Electron Laser

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The European XFEL (X-ray Free Electron Laser) is a large facility under construction in Hamburg, Germany. It will provide a transversally fully coherent x-ray radiation with outstanding characteristics: high repetition rate (up to 2700 pulses with a 0.6 ms long pulse train at 10 Hz), short wavelength (down to 0.05 nm), short pulse (in the femtoseconds scale), and high average brilliance ($1.6 \cdot 10^{25}$ (photons s^{-1} mm^{-2} $mrad^{-2}$)/0.1% bandwidth). The beam has very high pulse energy; therefore, it has to be spread out on a relatively long mirror (about 1 m). Due to the very short wavelength, the mirrors need to have a high quality surface on their entire length, and this is considered very challenging even with the most advanced polishing methods. In order to measure the mirrors and to characterize their interaction with the mechanical mount, we equipped a metrology laboratory with a large aperture Fizeau interferometer. The system is a classical 100 mm diameter commercial Fizeau, with an additional expander providing a 300 mm diameter beam. Despite the commercial nature of the system, special care has been taken in the polishing of the reference flats and in the expander quality. We report the first commissioning of the instrument, its calibration, and performance characterization, together with some preliminary results with the measurement of a 950 mm silicon substrate. The intended application is to characterize the final XFEL mirrors with nanometer accuracy. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4949005]

I. INTRODUCTION

Starting operation at the end of 2016, European XFEL is an X-ray Free Electron Laser facility in Hamburg, Germany.[1,2] A 1700 m long, pulsed, superconducting linear accelerator (LINAC) accelerates the electron bunches up to 17.5 GeV.[1] At the end of the LINAC, the individual electron bunches are selectively distributed in the three undulator chains (SASE1, SASE2, and SASE3). After that, a beam composed by many thousand X-ray pulses of mJ-power and fs-durations is produced. The photon transport system is then responsible to deliver the photon beam from the undulators to the experiments, preserving its unique characteristics in terms of transversal coherence and short pulse length.

The basic setup of the three "beamlines" is conceptually similar. First of all, we have an optical chicane composed by two mirrors, to displace the beam and to separate it from higher energy background radiation. Then, we have a third mirror to distribute the beam along two experimental stations. More beamlines and experimental stations are foreseen in the future; in that case, the number of optical elements would increase. One of the main characteristics of these mirrors is that they are very long (almost 1 m) and the specified polishing quality is very challenging: the error of the surface, when compared to the best-fitting sphere, should be less than 2 nm Peak-to-Valley (P-V), and the sphere itself should have a radius of curvature longer than 6300 km. This curvature corresponds to a sag of 20 nm on a 1 m long mirror, which is very challenging to be measured but theoretically possible through interferometry or high precision deflectometry. The characteristics of such surface are studied using Zernike polynomials or classical polynomial functions.[3] The high accuracy flatness is required to preserve the wavefront quality of the beam, and the extreme long radius of the residual sphere is intended to avoid the focusing of the beam during the propagation, which in some cases is up to almost 1 km. Both the parameters are difficult to obtain with current polishing methods,[4] but even more difficult is to preserve such an accurate shape inside the mechanical mount. A particular mechanical mount is designed to move the mirror inside several degrees of freedom, for initial alignment and during the operation, and also to support the mirror cooling.

To allow a proper characterization of the optics, to check if they are complying with the specifications, to study their interactions with the mechanical mounts, and to do a proper installation, we decided to equip a metrology lab[5] with a large aperture Fizeau, reaching an expanded beam diameter up to 12 in. (300 mm). The requirements and commissioning of the instrument are here reported, with particular detail on the repeatability of the measurements and its relative calibration, and a practical example of a mirror measurement. The final goal is to investigate the ultimate accuracy that we can obtain from such a system when it is used to characterize the XFEL mirrors.

II. LARGE APERTURE FIZEAU INTERFEROMETER

Considering the intended usage of the instrument, we had tight requirements for the desired measuring system in terms of repeatability and relative accuracy. Additional value was to allow flexibility for future slightly curved mirrors and to have a

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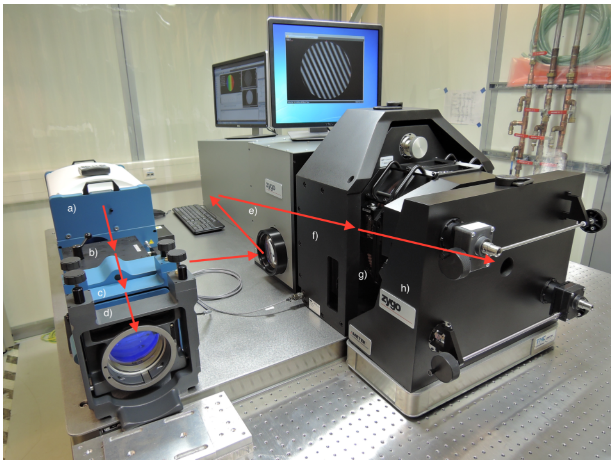


FIG. 1. The large aperture Fizeau interferometer installed on the table with the following components: Dynafiz 4 in. Fizeau (a), foldable mirror (b), 4 in. transmission flat (c), 4 in. reference flat (d), beam expander (e), piezoelectric phase-shifter (f), 12 in. transmission flat (g), 12 in. reference flat (h). The laser beam optical path is depicted in red.

relatively fast system for quick inspection and characterization of the several mirrors required for the European XFEL project. The chosen system has been a commercial Fizeau interferometer[6] with 12 in. beam diameter created with a separate beam expander and with two reference flats (a transmission flat (TF) and a reference flat (RF)) to create the cavity for grazing incidence setup measurements. The initial intent is to use such a system to test flat mirrors, but K-B mirrors could be measured using RADSI method.[7]

A. Fizeau system requirements and commissioning

The system has been installed on an anti-vibrational optical table (Fig. 1), inside a clean tent to reduce particle contamination. Special thermal stabilization is not yet implemented, but it is foreseen for the final lab, 0.1 °C over 24 h. To allow flexibility, it is possible to switch the beam between a directly provided 4 in. beam and an expanded 12 in. beam. The choice between the two options is done using a foldable mirror. The nominal system specifications are reported in Table I.

The optical setup used to test the long mirrors is called "grazing incidence setup," a variation of the "skip-flat test"[8] used for big optical flats in the optical shops.[9,10] First of all, a long optical cavity is prepared with two auxiliary optical flats: a transmission flat (TF) and a reference flat (RF). The cavity is calibrated doing a measurement with the Fizeau. Then, we insert the x-ray mirror inside the cavity and we realign it, taking a second measurement. Because the contribution of RF is flipped horizontally when the second setup is created, we cannot completely correct the second measurement using the first one: as depicted in Fig. 2, the RF is reflecting different light rays in the two setups. If we subtract the second measurement with the first one, we can correct the measurement by the symmetrical part of the errors. After that, the x-ray mirror final map is corrected for the grazing incidence angle used. This setup is able to work out a measurement map of the entire x-ray mirror and therefore it is one of the useful methods to test the European XFEL mirrors inside their mechanics, before the final installation (Fig. 2).

TABLE I. Measuring system nominal specifications.

Large aperture Fizeau	
Measuring principle	Phase shift interferometry
Diameter aperture	4 in. and 12 in.
Laser source	Stabilized He-Ne laser
Resolution	$\lambda/12000$ (high resolution mode)
Camera size	1200 pixels × 1200 pixels
Digitization	10 bit
Repeatability (nominal)	<0.25 nm (2σ)
Optical flats	
Clear aperture	4 in. and 12 in.
Nominal quality	$\lambda/20$
Material	Fused silica

We performed some measurements to assess the instrument repeatability. The first measurement has been done creating an optical cavity with the two big flats, the transmission flat (TF) and the reference flat (RF), separated by few mms of air. In this way, we minimize the vibrations and the air fluctuations and we can expect to have a very stable setup. We performed a high number of measurements (400) in these conditions, and we analyzed the data to work out the average and the sigma, pixel-by-pixel. The error map is showed, without removing the best tilt and piston because it is a measurement of the sigma error and not a real surface figure (Fig. 3(a)). We can see that we had a repeatability map with an average standard deviation of 0.18 nm, with a higher peak in the center. The measurement was then repeated with a 1 m long cavity (Fig. 3(b)).

The peak of error in the center is due to the catadioptric reflections in the cavity: it is localized in a small region so it has no big impact on the measurement and can be masked. We can also see that, even with the air disturbances correlated

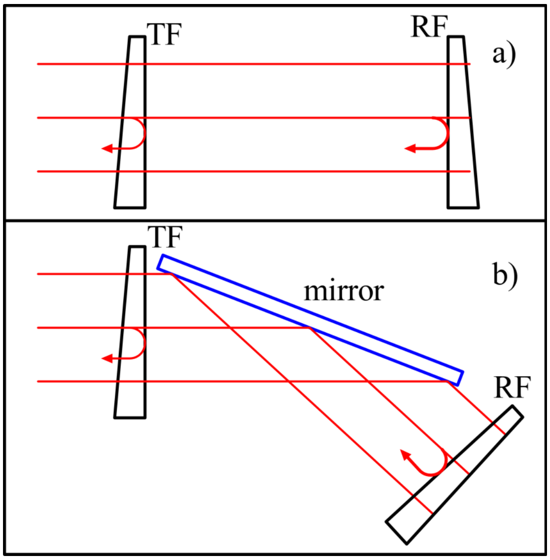


FIG. 2. Schematic of the grazing incidence setup to be used for measuring long mirrors (top-view). Cavity measurement (a) and test mirror measurement (b). In the second setup, the optical beam is flipped horizontally by the test optic, so the influence of the second flat (RF) on the measurement is different.

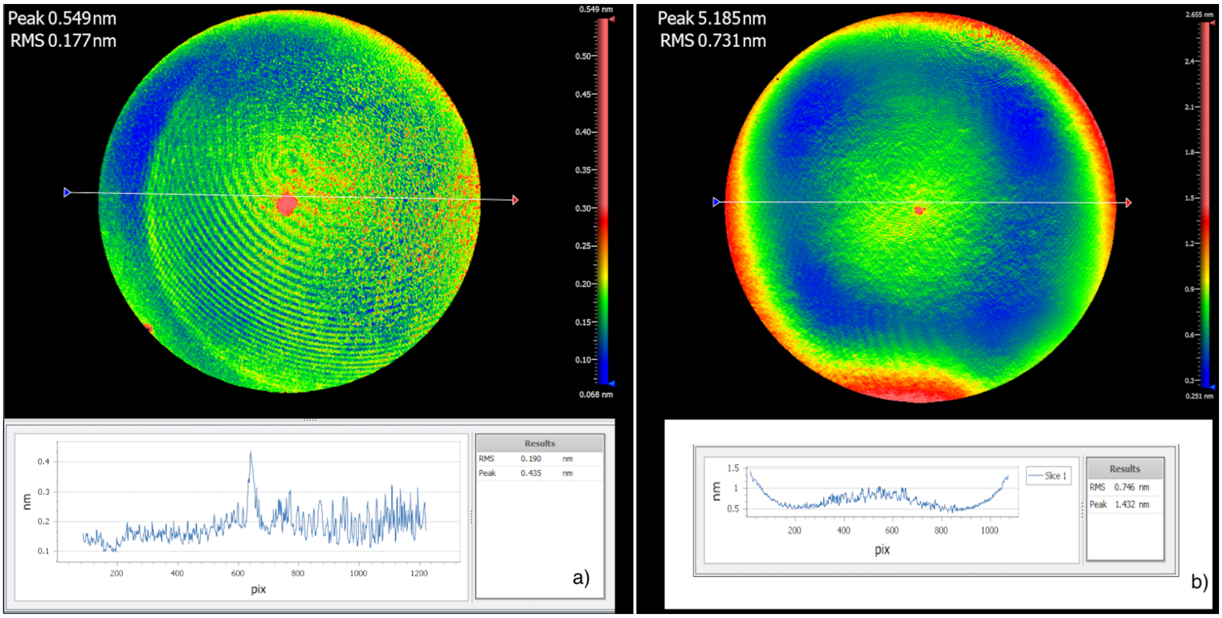


FIG. 3. Error map of repeatability test for the 12 in. clear aperture, with the two flats creating an optical cavity with few mms of separation (a) and with 1 m (b).

with a long cavity, the average standard deviation is still in sub-nanometer (0.7 nm in this example). So, the conclusion of the commissioning phase was that the instrument is capable to carry out a sub-nm accurate measurement, from the repeatability point of view.

Another important point is the quality of the expander which is used to deliver the 12 in. beam. The beam expander is in the common path of the optical interferometer, before the wavefront splitting, so its quality is in general not critical. The situation changes when we have a big misalignment between the reference and the test beam or when we are testing a slightly curved optics against a flat reference or a cavity built with flats. In this case, the error increases, because the two beams are travelling inside the expander in slightly different paths, resulting in an additional systematic error that is very difficult to calibrate because it depends on the amount of misalignment. In order to increase flexibility of our instrument, we asked for a high quality beam expander. To have a quantitative measurement of the beam expander quality, we placed a high quality flat (4 in.) in the optical path, in between the foldable mirror and the expander, so between (b) and (e) in Fig. 1, and one of the 12 in. flats at the end of the beam expander (f). The measurement obtained is the transmission quality of the expander, if the influence of the flats on the measurement is considered negligible as in this case (Fig. 4).

B. Quasi-absolute calibration of the system

In order to deliver better measurements, we need to calibrate the system to correct for the systematic errors introduced by the transmission and reference flats. This is in general done with some variants of the three flats method,[11,12] and it is not possible with only two flats. An easy way is to ask for calibration data of the two flats from the provider. Unfortunately the flats are then dismounted for shipping and remounted in slightly different conditions. To check how much the surfaces were changed, we simulated the expected cavity using the producer calibration files, and we compared the result with the one measured during the commissioning. We found a discrepancy of 20.5 nm P-V on the 12 in. clear aperture, and of 8 nm P-V on the central profile (Fig. 5).

We are currently using these data to correct all the measurements done with the interferometer. We understand that this is not enough and further development of the method would be needed. It is now under study the possibility to have a calibration of one of the flats, with the collaboration of the official metrology institute in Germany PTB, but the problem of mounting and dismounting reproducibility could be a strong limitation. Alternatively, the implementation of the three-flat test with a third flat directly on the XFEL site could be a more effective solution.

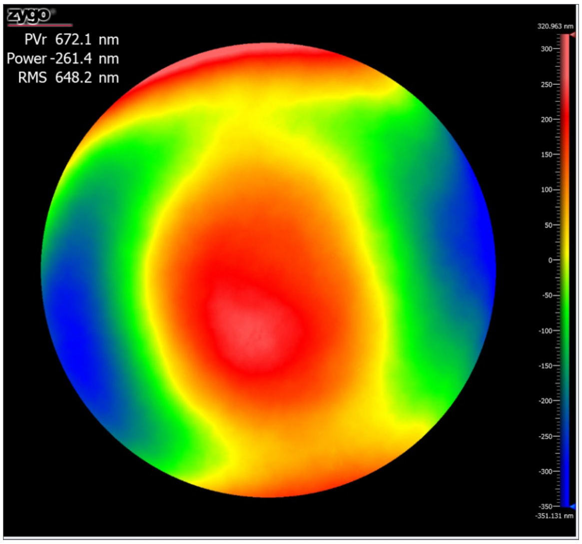
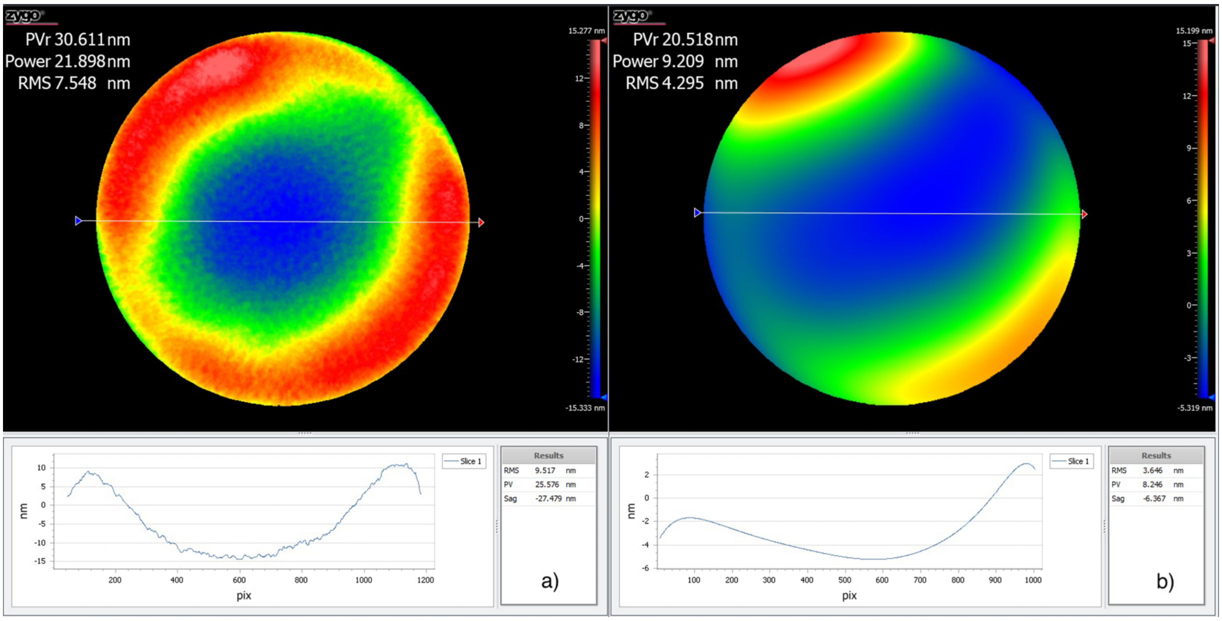


FIG. 4. Transmission quality of the beam expander.



PVr 30.611nm
Power 21.898nm
RMS 7.548 nm

Results
RMS 9.517 nm
PV 25.576 nm
Sag -27.479 nm

PVr 20.518nm
Power 9.209 nm
RMS 4.295 nm

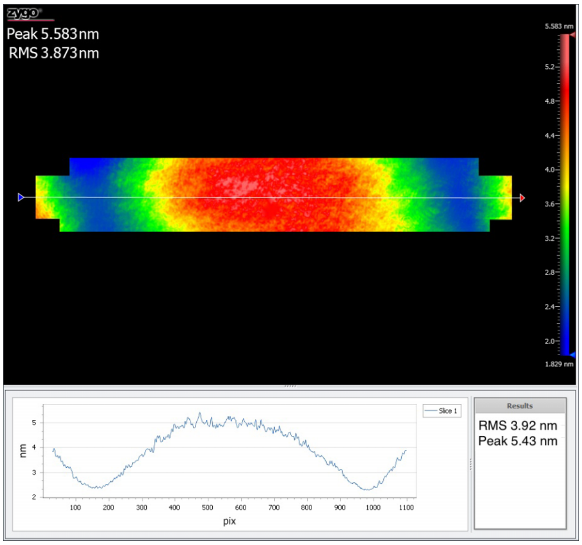
Results
RMS 3.646 nm
PV 8.246 nm
Sag -6.367 nm

FIG. 5. Measured optical cavity quality (a). Difference between the measurement and the simulation (b).

III. FIRST RESULTS ON A LONG MIRROR

We did a preliminary measurement of a long silicon substrate, traditionally polished, on the entire clear aperture 950 mm long and 52 mm wide. We did a similar statistical study, also with 400 measurements, ending with the sigma map of the measurements (Fig. 6). This is calculated without taking into account the grazing incidence correction factor, to have it comparable with the previous maps.

We can easily see that the rms of the sigma map increased: comparing the Fig. 6 with Fig. 3, it is 5 times higher, meaning that the measurements variability increased. We think that this is coming by the test mirror, probably because of higher vibration and sensitivity to environment effects. This information means to us that the actual limits of this method are coming from the environment and not from the instrument. The instrument will be moved in a cleanroom end of 2017, where better temperature control and vibration isolation will allow better measurements. The measurements presented here will be very useful as a reference to judge the future situation



Peak 5.583nm
RMS 3.873nm

Results
RMS 3.92 nm
Peak 5.43 nm

FIG. 6. Sigma map of the measurement of a long mirror substrate. The missing corners are because of some parts of the mechanical holder casting a shadow on the mirror.

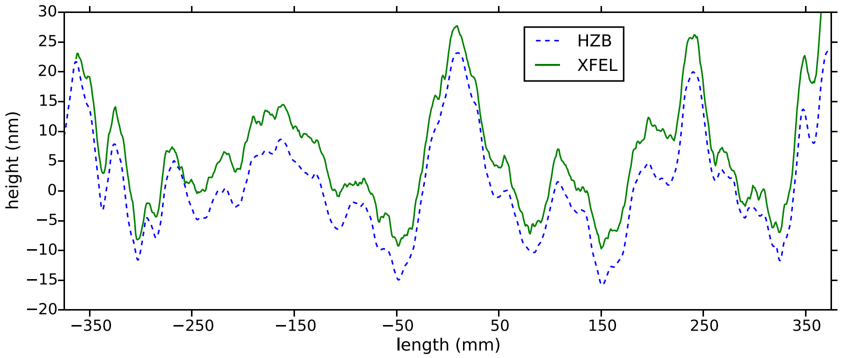


FIG. 7. Comparison between HZB and XFEL measurements of the central profile of one long mirror. The two profiles have been offset vertically for demonstration purposes.

in order to tune it and to check the instrument after the "second commissioning."

We also compared the central profile of the average map obtained with a previous measurement of the same mirror performed at HZB (Berlin), after removing of the fourth power polynomial to reduce the influences from the two flats. We can see that the two profiles are quite close: if we calculate the difference in the central part, we obtain 1.7 nm rms and 9.8 nm peak-to-valley (Fig. 7). This is of course only a preliminary result: we will improve the result in the future using a three-flat test approach and round-robin comparisons with other metrology labs. The result indicates that, apart from a long spatial wavelength contribution coming from the flats shape, removed with the fourth power polynomial fitting, the two instruments are very close. Further efforts in the flats calibration will probably reduce the actual gap.

IV. CONCLUSIONS

We have shown a large aperture Fizeau interferometer commissioned for the XFEL future metrology lab. The performances of the instruments are quite good in repeatability, well below the nm level. When a cavity of 1 m is built, the repeatability is much worse, indicating a need to improve the environment control. This improvement will be done in a future cleanroom, enhancing temperature and vibration stability.

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