Progress of multi-beam long trace-profiler development

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ABSTRACT

The multi-beam long trace profiler (LTP) under development at NASA's Marshall Space Flight Center[1] is designed to increase the efficiency of metrology of replicated X-ray optics. The traditional LTP operates on a single laser beam that scans along the test surface to detect the slope errors. While capable of exceptional surface slope accuracy, the LTP single beam scanning has slow measuring speed. As metrology constitutes a significant fraction of the time spent in optics production, an increase in the efficiency of metrology helps in decreasing the cost of fabrication of the x-ray optics and in improving their quality. Metrology efficiency can be increased by replacing the single laser beam with multiple beams that can scan a section of the test surface at a single instance. The increase in speed with such a system would be almost proportional to the number of laser beams. A collaborative feasibility study has been made and specifications were fixed for a multi-beam long trace profiler. The progress made in the development of this metrology system is presented.

Keywords: Long trace profiler, optical metrology, x-ray optics metrology, multi-beam profiler, surface profile measurement, Grazing incidence X-ray optics, X-ray mandrel metrology

1. INTRODUCTION

Future x-ray astrophysical missions require sub-arc-second x-ray optics with few meters effective area, thus necessitating the fabrication of square meters of precisely figured and superpolished optical surfaces. Such fabrication requires fast sub-micro-radian accuracy figure metrology. The long trace profiler (LTP) is a slope-measuring instrument widely used for figure metrology of grazing incidence X-ray optics and it fulfills the metrology accuracy requirement, but because it scans the surface under the test by single laser beam the measuring speed of this instrument is slow.

MSFC uses a vertical LTP[2],[3],[4], to measure the surface slope profiles of x-ray optics. The LTP uses a single laser beam to scan along the test surface, which on reflection gets focused on the detector by a Fourier Transform (FT) lens. The position of this beam on the detector with respect to the reference beam position gives the mirror surface slope at each scan point. These slope data provide the measure of the optical quality of the test surface. The slope data can then be converted to height data which is usually required for the fabrication purposes. Spatial wavelengths from 1 mm to several 100's of mm can be measured using the LTP. The slope resolution possible with this system is <1 μrad, which is adequate for 1-2 arc second class astronomical x-ray optics. But, the time taken to measure a surface of ~300 mm length is approximately 5 minutes and, to average the noise errors due to environment, multiple measurements are needed. Thus a feasibility study is underway at MSFC to study a multi-beam LTP approach in order to increase the measurement speed of the LTP.

2. MULTI-BEAM LTP

By replacing point-by-point measurement done with the single beam LTP, the multi-beam LTP (MBLTP) would provide a significant improvement in the measurement rate, almost proportional to the number of the beams used. Figure 1 shows a schematic of the metrology approach using multiple laser beams.
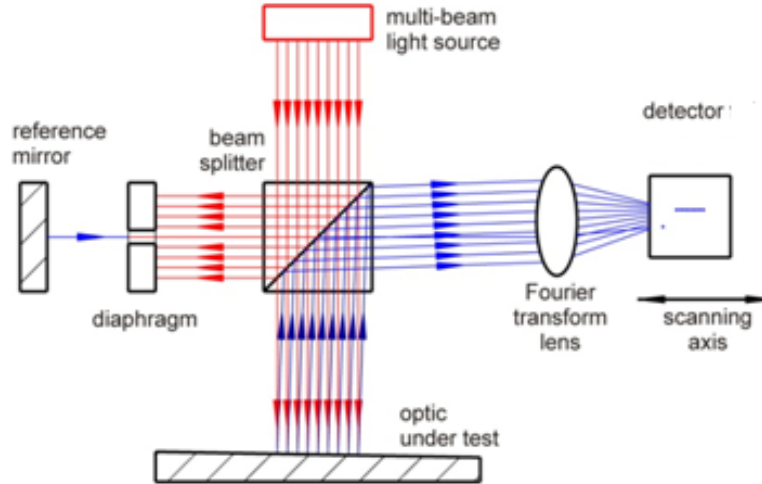
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Figure 1: Schematic of a multi-beam LTP. Multiple beams, exiting the beam splitter, are focused on a 2-D detector through a Fourier transform lens. The scanning axis on the detector can either be parallel or perpendicular to the plane of the beam.

A laser beam is split into multiple almost equal intensity beams which are divided into two segments by a polarizing beam splitter. One of these is directed towards a non-movable reference mirror and the other to the test surface. The reference mirror helps to correct for the angular errors caused due to the movable parts of the system and pointing instability of the light source. Different polarization is maintained between the beams of the two segments using waveplates. Optical beams reflected off each of these two segments are then focused onto a 2D detector using a Fourier-Transform/F-Theta (FT) lens. The scanning axis on the detector can be along the plane of the beams or perpendicular to the plane of beams. Table 1 shows the requirements formulated for the multiple optical beam system.

Table 1. Requirements for the multi-beam light source.

Parameter	Value
Spatial separation of adjacent beams	2.4 mm
Single beam spot size (Gaussian)	2.1 mm
Single beam divergence	0.2 mrad
Single beam pointing stability	0.1 μrad
Number of (Gaussian) beams	10
Angular separation of adjacent beams	0.25 mrad
Stability of angular separations	0.1 μrad
Max-min variation of intensities	$\pm 0.05\, I_0$

3.   WEDGED ETALON SPLITTER

One of the technical challenges in the multi-beam LTP development is the generation of multiple optical beams of about equal intensity. These beams also need to have a defined angular and spatial beam separation. Desired

parameters of the multibeam light source are shown in Table 1. A wedged etalon beamsplitter is an ideal candidate for the task. Such beam splitters have been used for wafer curvature measurements[5], for strain monitoring in thin films[6], as well as to produce multiple, equal-intensity beams for two-dimensional beam steering[7] and for a galvanometric scanner of a confocal scanning microscope[8].

The initial design of the wedged etalon beam splitter, and results of a study to analyze the possible geometrical layouts and technical specifications, have been described earlier[1]. The schematic of the beamsplitter is shown in figure 2. The spatial separation of the beams is defined by the thickness of the etalon while the angular beam separation defines the wedge angle. The angular beam separation sets the initial positions of the

Figure 2. Geometrical layout of the multiple-beam-generating etalon. One side of the etalon has a customized gradually transmitting coating while the central region of other side has 100% reflective coating.

beams on the LTP detector and the change in position of a beam during the LTP scan will signal the change in the slope of the surface under the test between the scan points. The etalon has a gradually transmitting coating on one of the surfaces to obtain almost equal intensity in the outgoing beams. The central region of the other surface of the etalon has a coating with zero transmission and the outer region has an antireflection coating, enabling 100% beam input into the etalon. The etalon is designed to have 50 mm x 50 mm dimension with a thickness of 3 mm and a wedge angle (γ) of 60 µradian. The etalon beam splitter is designed to produce ten beams.
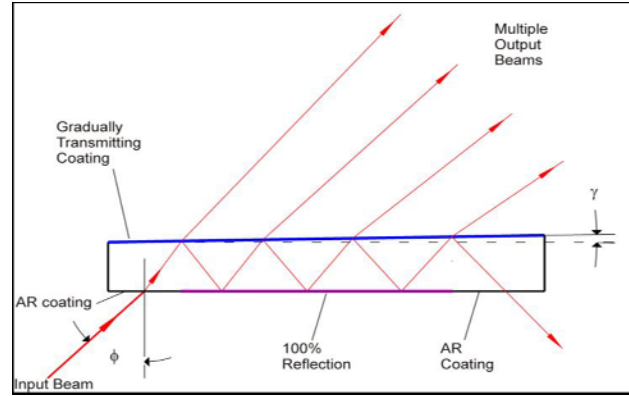
Two approaches for the design of the gradually transmitting coating have been considered. One is to produce the coating with optical transmission changing in steps. This method, if realized, is capable of providing beams with
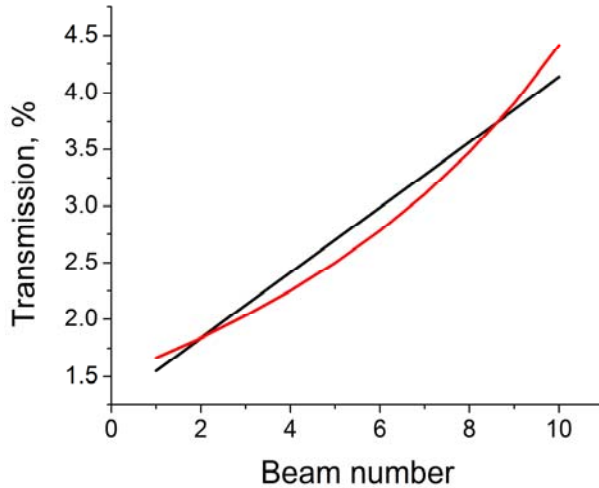

Figure 3: Ideal and linear approximation calculated transmission curves for the 10 beam etalon beams splitter
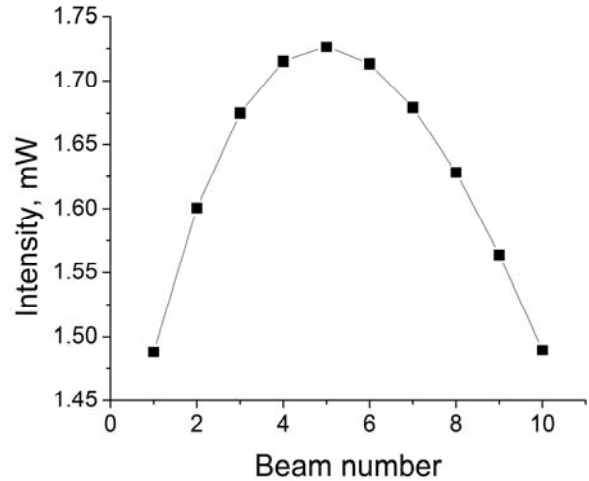

Figure 4: Intensities of the laser beams exiting the etalon with linear approximation transmission curve (assuming 100 mW of incident intensity)

exactly the same intensity. On other hand, precise fabrication of such the coating can be challenging. Another technique is to fabricate coating with transmission continuously changing from one side to another side of the etalon. In this case the beam intensities are bound to fluctuate depending on the etalon alignment, but the fabrication is relatively easier compared to the fabrication of the coating with optical transmission changing in steps. To simplify the fabrication process, the continuously changing transmission along the wedged surface of the etalon has been chosen.
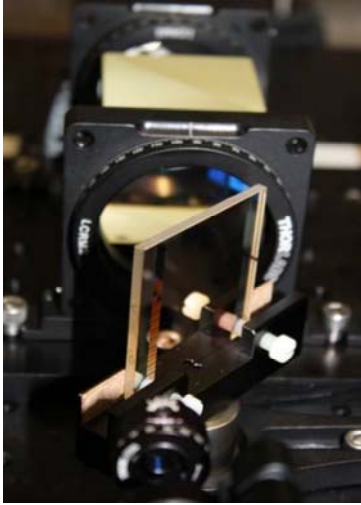
Figure 5: Etalon beam splitter installed on the multi-beam LTP breadboard.

Two options were considered for the materials for the gradually changing transmission and the zero transmission coatings: a multilayer coating optimized for 670 nm wavelength and a silver coating. The multilayer is an ideal choice since the absorption at each reflection is negligible so the design of the gradually transmitting coating is straightforward. In the case of the silver coating the accurate transmission profile design requires precise knowledge of the absorption value at each reflection. Because the fabrication of a multilayer coating with gradually changing transmission is rather complicated and, hence, expensive, the silver coating option has been chosen. The ideal transmission profile calculated with an assumption that the absorption at each reflection is exactly 4%, and with the goal of equal intensity of all beams, is shown in Figure 3. Analysis has been done to study the linear approximation to ideal transmission gradient. Such an approximation is acceptable since it limits the variation of the beam intensities below 10%. The intensities of the output beams calculated for the 4% absorption silver coating etalon with the linear approximation of the transmission curve, are shown in Figure 4. The etalons with the linear transmission approximation were fabricated by Reynard Corporation [9]. A sample without wedge had been used to calibrate the coating process in order to achieve minimal variation of the beam intensities. Then, a few samples of the wedged etalon were coated and the intensities of the beams produced by the etalon coupled with a 670 nm laser were measured using a light power-meter. The results are summarized in the Table 2. Sample #1 installed into the MBLTP optical board described below is shown in Figure 5.

Table 2. Measured average intensities of the beams produced by the wedged etalons. The incoming beam intensity was measured to be 289 µW.

Sample #	1	2	3	4	5	6
Average intensity, µW	7.65	6.84	7.54	7.57	5.53	6.69
Standard deviation, µW	0.33	0.67	0.66	0.49	0.36	0.36

4. INITIAL TESTS OF THE MBLTP

For initial tests a breadboard of the multi-beam LTP optical board shown in Figure 6 was assembled. The tests were carried out with the optical board assembled on a manual mechanical stage. The reference mirror was installed outside of the breadboard to permit corrections on the optical board rotation during the scans. Prior to the calibration measurements the detector was installed in place of the surface under test and the angular and spatial separation of the beams were measured. The angular separation was found to be around 250 micro-radians and the spatial beam separation was 2.55±0.03 mm. Then, the detector was installed after the FT lens and its position relative to the lens was optimized by minimizing the beam sizes at the detector.
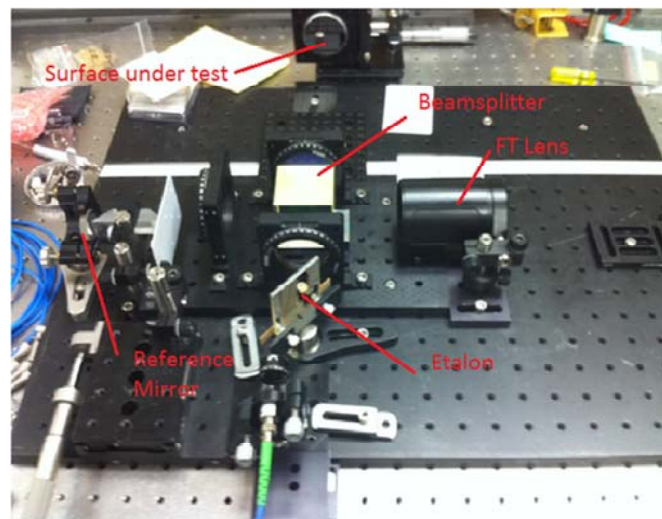

Figure 6: The optical board installed on the mechanical stage (not shown.) The reference mirror is shown on left, the detector (not shown) is on right.

To speed up the development process, Lawrence Berkeley National Laboratories provided the LabView[TM] based LTP control software which can accommodate three laser beams. This was then modified at MSFC for the chosen detector (JAI AM 1600 GE camera manufactured by 1st Vision Inc.[10] which has 7.4 µm pixel size with 36.1 mm x 24 mm of active area) and to accommodate eleven optical beams. Tests to check the speed of the readout and processing have been made. The multi-beam LTP shows a speed of 0.5 fps for a full frame of 4872x3248 pixels but this can be increased by partial frame readout. The slope measurements presented here have been made with a speed of 1.5 fps for a partial frame readout of 4872x800 pixels.
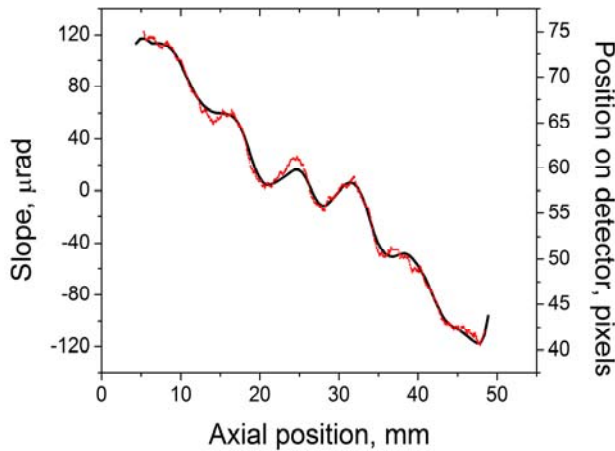
Figure 7: The slope profile of a curved mirror measured with the MBLTP (black line) compared to the slope profile measured with the ZYGO interferometer (red dots).
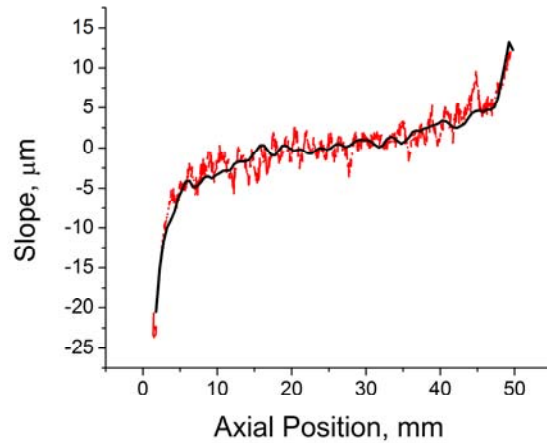
Figure 8: The slope profile of the flat mirror measured with the calibrated MBLTP (black line) and the Zygo interferometer (red dots).

To calibrate the multi-beam LTP a central strip of a curved 50 mm diameter sample has been measured. The optical board was moved in 1 mm steps during the measurements and the software tracked and recorded the positions of each beam, in fractions of a pixel, on the detector during the scan. Then, the data collected for each beam were stitched together and compared to the slope profile of the curved mirror measured using the ZYGO interferometer. The calibration factor converting the pixel size into the surface slope was varied to achieve the best fit between the data collected by the LTP and the interferometer. The best fit was obtained at 7.47 micro-radians per pixel. The slope profiles of the curved mirror measured with the LTP and the interferometer are shown in figure 7.

For the proof-of-concept demonstration a central strip of a flat 50 mm diameter sample has been measured. The optical board was moved in 1 mm steps during the measurements and the software tracked and recorded the positions of each beam on the detector during the scan in micro-radians. The data collected for each beam were stitched together in accordance with the angular and spatial beam separation measured previously and compared to the slope profile of the curved mirror measured using the ZYGO interferometer. The slope profiles of the flat mirror measured with the LTP and the interferometer are shown in figure 8. Note, most of the slope profile of the flat mirror measured with the LTP represents an average of ten scans by individual beams.

5. CONCLUSIONS

A multi-beam LTP is under development at MSFC in collaboration with Lawrence Berkeley National laboratory and Brookhaven National Laboratory. This equipment, unlike the conventional single beam LTP, uses multiple beams to make simultaneous measurements in a single instance axis of scan of the test surface. This leads to a significant increase in the rate at which surface profile metrology of grazing incidence optics can be done.

Proof-of-concept tests have demonstrated viability of the multi-beam LTP approach. Incorporation of an air-bearing stage with the multi-beam LTP optical board is planned. Experiments to estimate the accuracy of the slope measurements by the MBLTP and the possible measurement rate will be performed after that.

This proof of concept study forms the groundwork for a future modular metrology approach where-in an entire length of a test surface can be measured in a single instance using multiple optical beams and also multiple frequencies can also simultaneously be measured.

6. ACKNOWLEDGEMENTS

7. REFERENCES

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[1]NASA Marshall Space Flight Center
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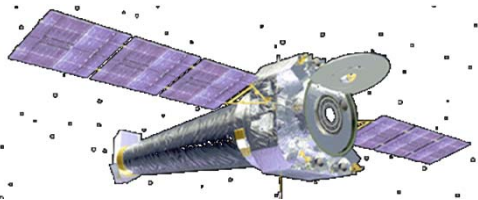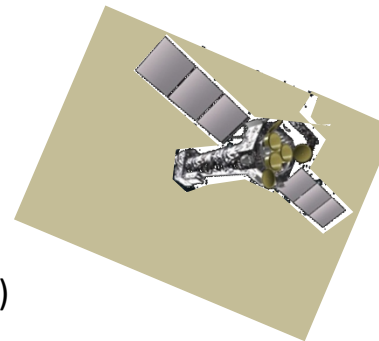[3]Brookhaven National Laboratory

Future Challenges

Einstein Observatory (1978-1981)
HPD =10″, A = 0.04 m^2 (f = 3.3 m)

ROSAT (1990-1999)
HPD = 5″, A = 0.10 m^2 (f = 2.4 m)

XMM-Newton (1999-?)
HPD = 14″, A = 0.43 m^2 (f = 7.5 m)

Chandra X-ray Observatory (1999-?)
HPD = 0.6″, A = 0.11 m^2 (f = 10 m)

Need for sub-arcsecond resolution and few meters of effective area
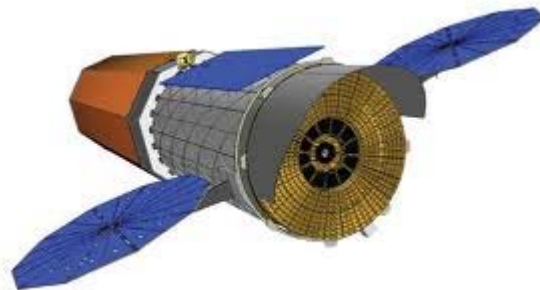
SMART-X (2030)
HPD = 0.5″, A ~ 2.3 m^2 (f = 10 m)

Fast figure metrology with sub microradian resolution

Long Trace Profiler
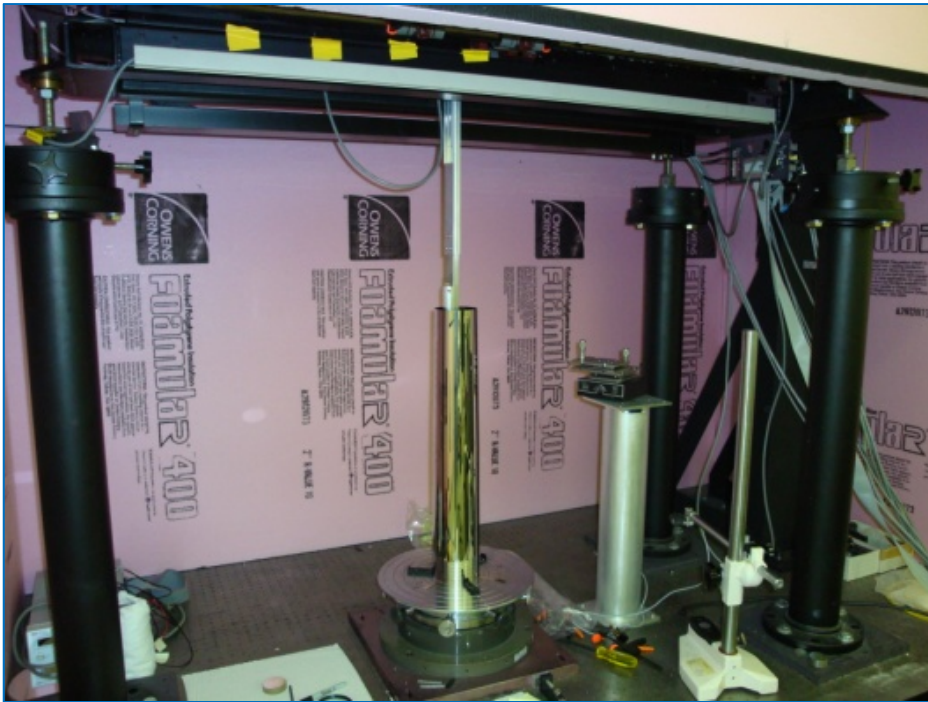
☹Time taken to measure is about 5 mins for 300 mm sample length

- Pencil beam interferometry

- Measure spatial wavelengths starting from 1 mm upto several 100's of mm

- Laser beam scans point-by-point - slope data

- Position of the beam at the detector – direct measure of the slope

- Accuracies possible <1 urad

- Multiple measurements – 2D topography

Multi-beam long trace-profiler
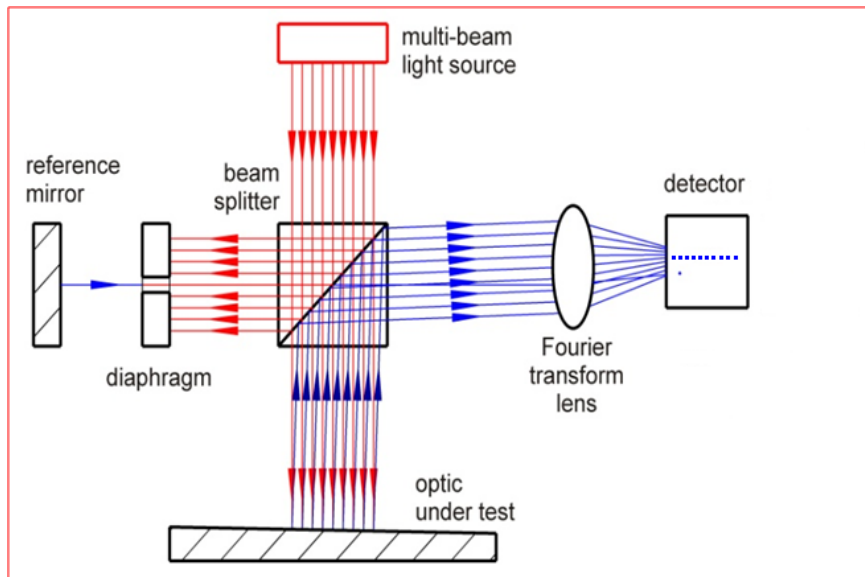

Further improvements:

- Make use of advanced technology

- Higher resolution and faster 2D detectors

- Stable optical sources

- Increase the speed & accuracies of

  measurements - **Multiple beams**

Internal funding, so approach is to order off-shelf optics for
proof-of-concept. Then, select the best and define the goals
for optical elements quality improvements

Etalon, designed in collaboration with Valeriy V. Yashchuk [LBNL] :
- Number of beams –10; almost equal intensity
- Spatial and angular separation of beams – 2.4 mm and 250 μrad
- Dimension – 50 x 50 x 3 mm
- Wedge – 60 μrad
- 11 fabricated, 8 usable, 2 best (intensity uniformity)

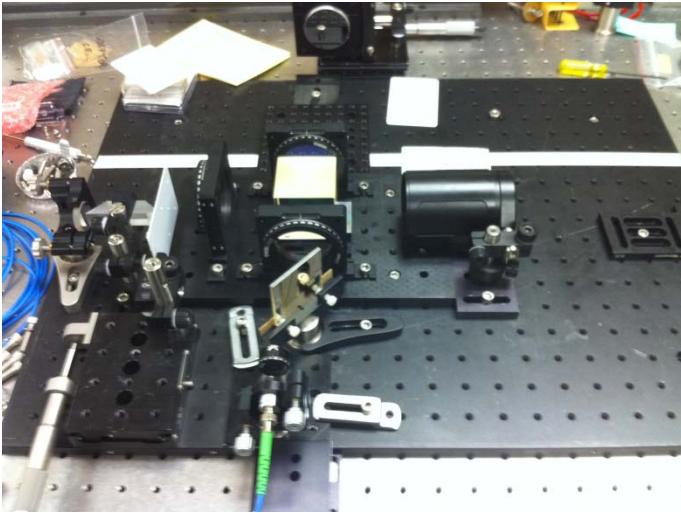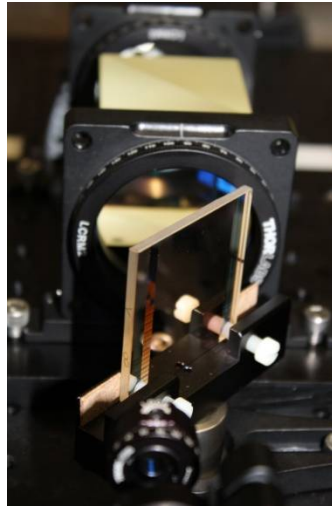# Wedged Etalon Multi-Beam Splitter with gradually transmitting coating
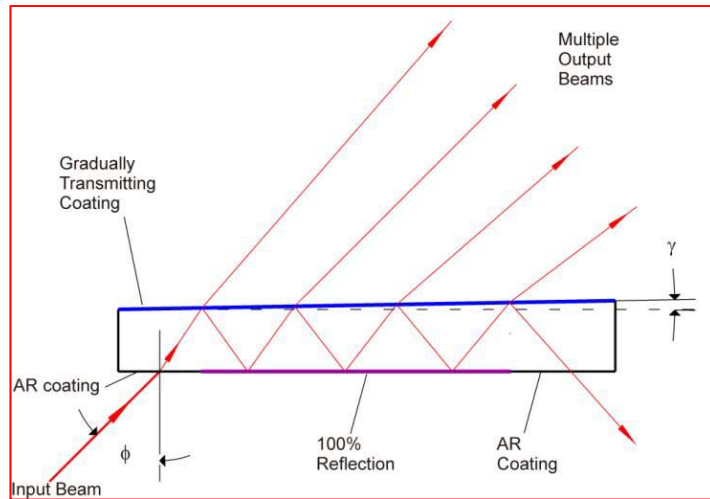
Etalon Schematic
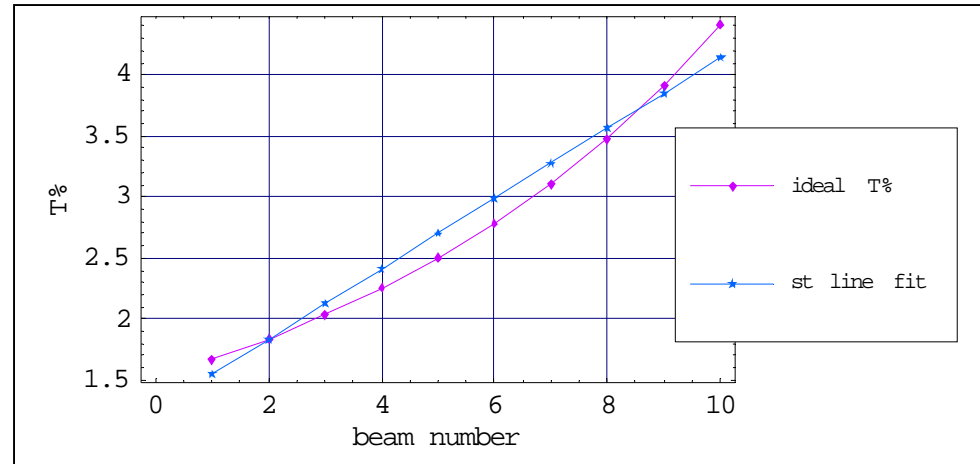
Ideal and straight line estimated transmittance curves of the 10 beam exiting the etalon.

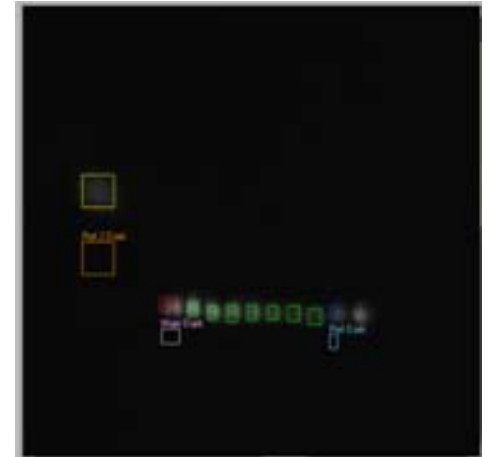| Sample #	1	2	3	4	5	6
Average intensity, uW	7.65	6.84	7.54	7.57	5.53	6.69
Standard deviation, uW	0.33	0.67	0.66	0.49	0.36	0.36

MBLTP breadboard

MBLTP breadboard, the detector is not shown (on right)


Etalon beamsplitter (left), ten signal beams and reference beam focused on the detector (right)

Screenshot of the detector window. Reference beam is on top left.

- Detector -36 mm x 24 mm area, 7.4 x 7.4 μm pixel size, 1.3 fps for partial frame of 4872x800
- Custom designed FT lens (Peter Z. Takacs [BNL]!) – air-spaced doublet lens, 500 mm focal length, 50 mm diameter, Low distortion – to minimize the effects of lens on systematic errors, three sets fabricated. Working with Peter to define the metrology to detect the best combination
- The system resolution due to the detector-lens pair is estimated to be ~ 0.23 microrad.
- Breadboard is assembled, preliminary testing is being done using regular detector; UV version (no front cover) was procured.
- Berkeley National Labs (Valeriy) has provided software code, we have adapted it

  for new detector and ten beams
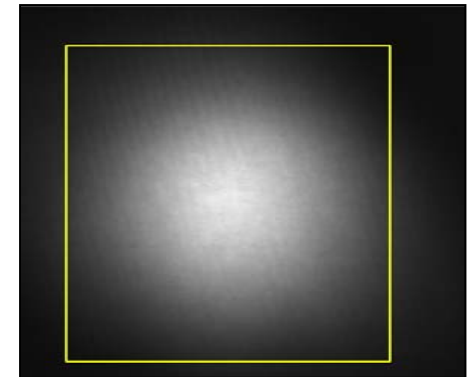
Reference beam on detector, secondary interference fringe pattern is due to the cover plate on the detector

Future plans

Tune the FT lens doublet

Incorporate the windowless detector

Incorporate the air-bearing stage

Build the optical board

Conclusions

A multi-beam LTP is under development at MSFC in collaboration with Lawrence Berkeley National laboratory and Brookhaven National Laboratory.

The components are fabricated, tested individually and assembled into breadboard.

This proof of concept study is believed to form a basis of future modular metrology approach where-in an entire length of the test surface can be measured in a single instance using multiple optical beams.