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The Measurement of the Optical Cavity Length for the Infrared Free Electron Laser.[*]

OR: How a combination of surplused equipment and old fashioned techniques can be applied to a state of the art FEL facility.

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ABSTRACT

One of the final tasks involved in the alignment of the newly constructed Free Electron Laser at the Thomas Jefferson National Accelerator Facility was to accurately measure the length between two mirrors which make up the optical cavity.

This presentation examines the survey techniques and equipment assembled in order to complete these measurements, together with the possible sources of error, and the accuracy achieved.

1. INTRODUCTION

Construction work for a 1 kW infrared Free Electron Laser at the Thomas Jefferson National Accelerator Facility was started in June 1996. Almost exactly two years after ground breaking, the new machine had already delivered first light at a record 150 watts [1]. One year later, the machine had exceeded its design goal by reaching 1.72 kW, making it the most powerful IR FEL in the world. The facility is intended to demonstrate the potential scientific and commercial uses of high powered lasers for research, defense and industrial purposes.

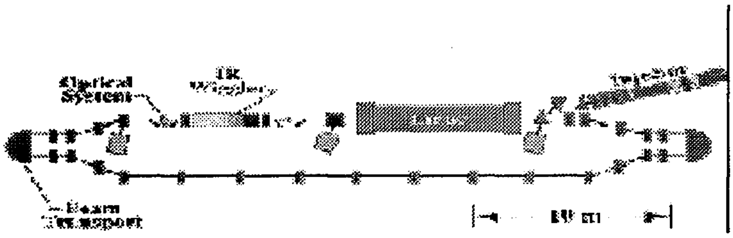

Figure 1 – FEL Schematic

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[*] Work supported by Office of Naval Research, by Navy/DOE Interagency Agreement 1846-J053A1, and by Department of Energy under contract number DE-AC05-84ER40150

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The machine consists of an injector, a single cryomodule forming a linac, an optical cavity/wiggler section, and beam transport elements for recirculation (Figure 1). It extends for just under 50 meters from one end to the other. General transverse alignment tolerances for components have been defined as 0.5mm rms for quadrupoles, and 1.0mm rms for dipoles. Linearity of entrance and exit quads to the wiggler magnet is 0.1mm.

The optical cavity is where the electron beam is converted into light. Beam oscillations caused by a wiggler magnet generate light which is then reflected back and forth between two mirrors located upstream and downstream of the wiggler. In order for the FEL to lase, the cavity length must equal a specific value. This value is determined by the round trip travel time for photons which must match the arrival time for electrons [2]. For a cavity of 8 meters in length, as in this case, the range over which it will lase is approximately 5 microns. In practice, the final value is arrived at by scanning the cavity length until lasing occurs. This must be accomplished slowly and therefore can be very time consuming. Also a risk of serious mirror misalignment exists if large displacements from their original positions are involved. For these reasons, it was considered necessary to achieve an initial accuracy for the cavity length of less than 100 microns.

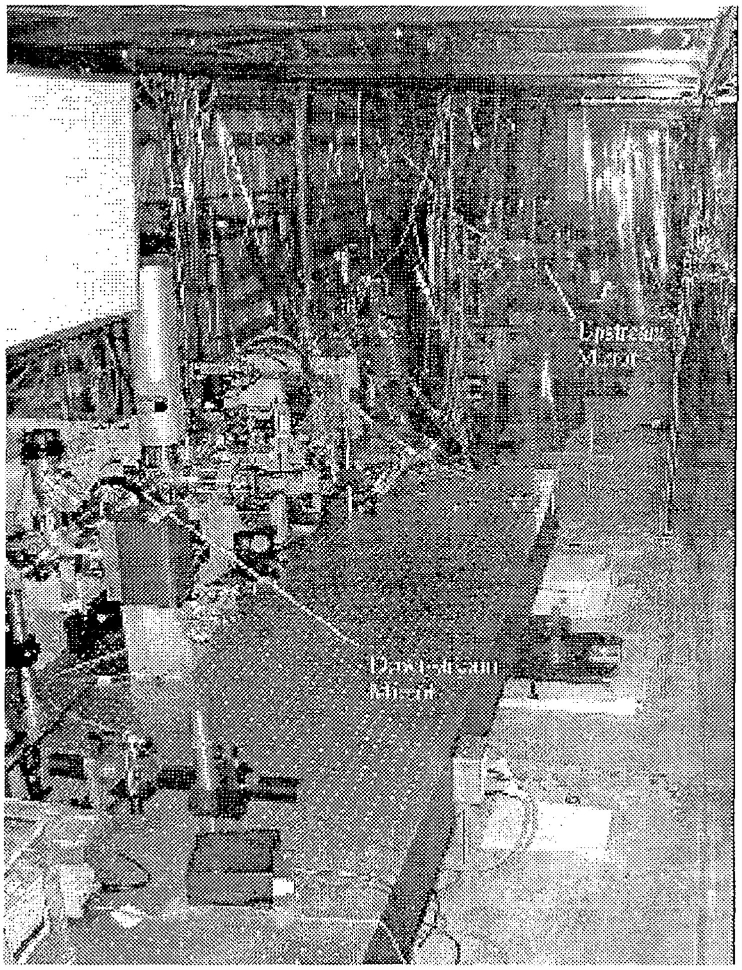

Figure 2 – FEL Optical Cavity

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2. SURVEY CONSIDERATIONS

When first asked to assist in setting the cavity length, the alignment group considered several approaches. Clearly, a laser tracker would have been well suited to the task, had one been available. Since this was not the case, an alternative was needed. It was initially thought that the Mekometer ME5000 could be used. With a stated standard deviation of 200 microns, and a calibrated standard deviation of around 70 microns, the accuracy of the instrument would be at the limit of what was required. A HP interferometer was also available. This would obviously fulfill the accuracy requirements, but the physical constraints associated with its use (i.e. smooth transportation of the prism) would need to be resolved. Indeed, with each of these approaches, the problem of fixturing arose.

The mirrors would be mounted in the beamline on a gimbaled mount allowing for rotation on two axes (pitch and yaw). This complicated any fidicialization of the supports. No matter how we decided to measure the distance, we had first to develop references which not only could be accurately related to the mirror surface, but also serve as a reference for distance measurement.

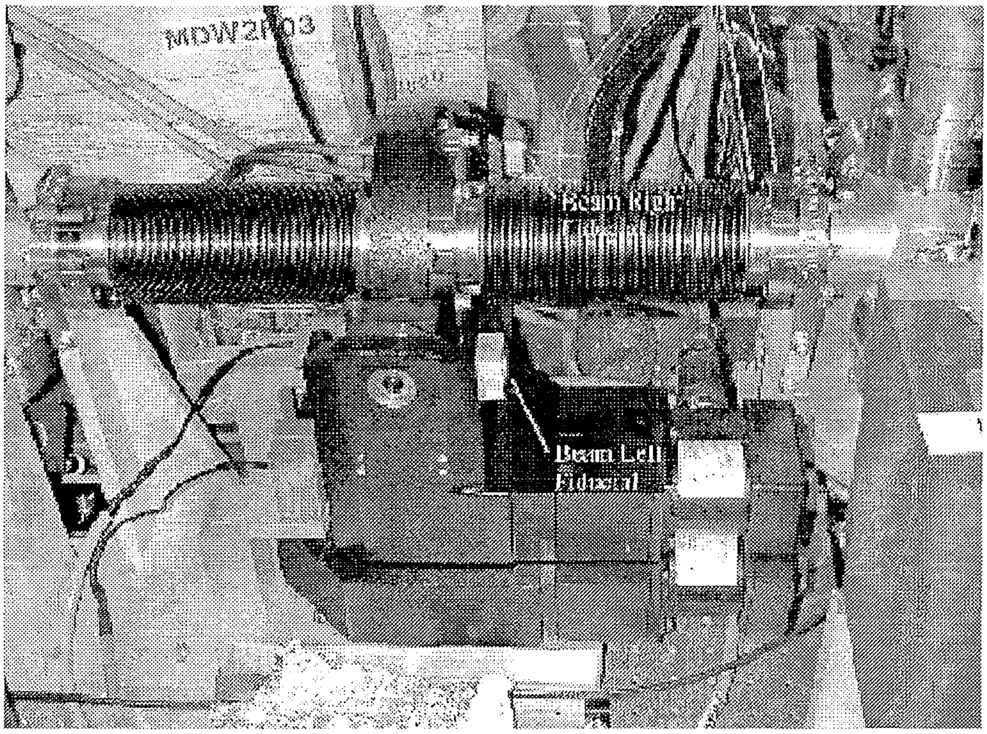

Figure 3 – FEL Mirror Mount

3. FIDUCIALIZATION

The fiducialization of the mirror mounts was carried out in two stages. The initial fiducialization used two ¼ inch bushings attached to either side of the gimbaled mirror mount (Figure 3). The bushings were placed equi-distant from the Z-axis and at the vertical center of

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the pivot in order to reduce any cosine error resulting from pitch. Each of these bushings would accept a survey target for sighting. The locations of the targets were measured relative to the mirror face using a Mytutoyo model 710 CMM. These beam left (BL) and beam right (BR) targets were used in the first set of measurements taken in the FEL.

The second fiducialization utilized a custom made target. This "dummy mirror" consisted of an aluminum cylinder with a ¼ inch hole at the center of the exposed end. A tooling ball target was placed in the hole for sighting. The opposite end of the dummy mirror registered against the same surface in the gimbal mount that the actual mirror was later mounted to. The length of the dummy mirror was measured on the CMM and the target length was measured on a microscope. The target was attached to the dummy mirror with epoxy prior to measuring to eliminate error due to fitup tolerances.

4. SURVEY METHOD

Given the complications of the fiducialization, it became clear that the extra accuracy of the interferometer would be essential. A rail would have to be set up in order to transport the prism. It was thought that optical tooling bars might work satisfactorily for this purpose, provided we could link together the four bars that we had obtained from surplus. Fortunately the total length of the bars was 29 feet (2x10ft, 1x6ft, 1x3ft) or 8.839m which was just the right size for measuring the cavity. This also combined well with using optical tooling transits to sight the fiducials on the mirror mounts.

A scheme was developed whereby the interferometer prism was epoxied onto the instrument carriage of the tooling bar, just in front of a jig transit (Figure 4). Measurements were made using the interferometer in order to gain familiarity with the instrument which had been unused for several years. Linking plates were fabricated and tests were carried out to see if the interferometer beam could be transferred across the joints between the tooling bars. These proved to be successful. With this knowledge, it was possible to proceed with this method.

The initial measurements in the FEL took place over three days in early March 1998. The tooling bars were linked together and supported by two optical tables and one other stand. These were then leveled and aligned parallel to the beamline, at an offset of 0.8m. The interferometer was mounted separately, at one end of the tooling bars. Behind this, a transit was set up which served as a control scope for the moving transit on the carriage. At each mirror mount location a sighting was made on the beam left and beam right fiducials. The sighting scope was autocollimated with the control scope to ensure the line of sight was perpendicular to the reference line. The transit was moved into coincidence with the fiducials using the slow motion screw on the instrument carriage rather than using the micrometer. Interferometer measurements were then made to the prism attached to the instrument carriage. Five different operators were used during the measurement process in order to reduce systematic error.

After several sets of measurements, it was clear that the repeatability of the results was not as expected. In some cases millimeter differences were observed. Given the inexperience with this interferometer, it was decided to add the Mekometer to the measurements as a "gross" check. The Mekometer was set up behind the control scope and a prism was epoxied onto the base of

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the moving transit. Measurements were then repeated with Mekometer distances measured at each fiducial sighting. Although this slowed down the procedure considerably, it did provide a valuable check on the interferometer.

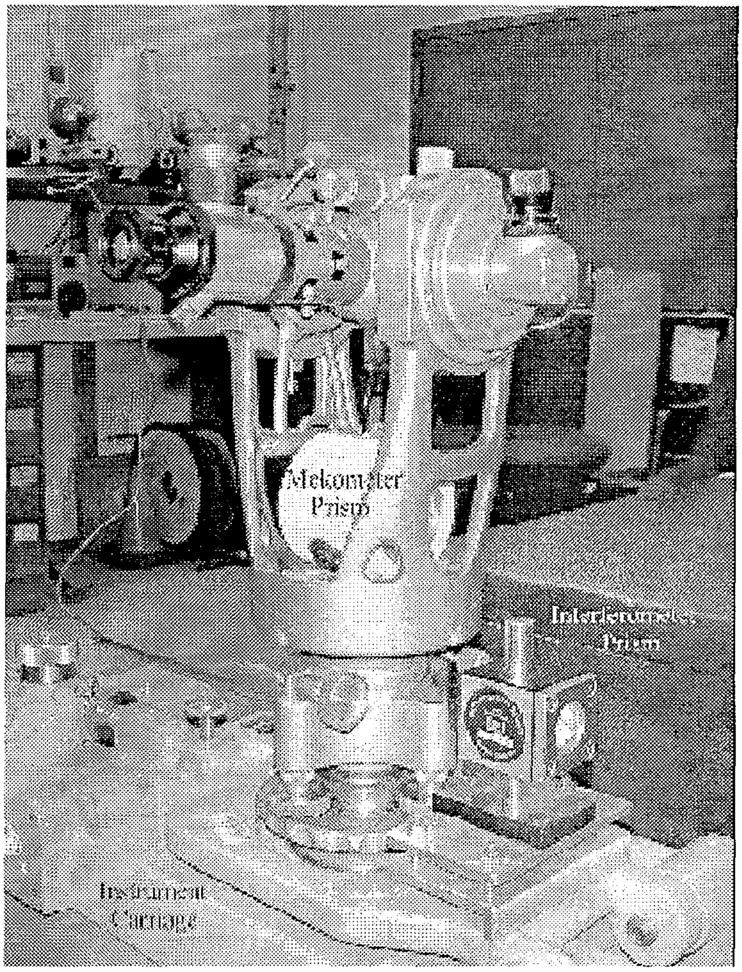

Figure 4 – Transit on Instrument carriage and tooling bar.

5. RESULTS

During the first three days eleven measurements were made. Due to poor repeatability, six of these were rejected. The FEL was then closed up and the mirror mounts were moved and returned close to their original position. Four further measurements were made (Mar 9), all of which were satisfactory. The results seen in Table 1 show a good agreement between the interferometer and the Mekometer, and served to prove the method [3]. These were not, however, the final results used to set the cavity distance.

At the end of March a second set of distance measurements was made between the mirror mounts in the FEL [4]. During this time the mirror mounts were moved closer to the ideal value by approximately 2mm. On this occasion, in addition to the left and right fiducials, the center

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target was used. A total of five full sets of measurements were made, each by a different operator (Table 2). This included interferometer measurements between the beam left, beam right and center targets, as well as Mekometer measurements between the center targets. Two further interferometer measurements were then made using just the center targets. All measurement sets were used in the final results.

Table 1 – Initial Results

Date	Interferometer	Mekometer	Std dev
Mar 4-6	8004.753	8004.728	0.013
Mar 9	8004.835	8004.830	0.009

Once again the Mekometer results agreed well with the interferometer. What was disturbing was the significant difference between the two interferometer distances i.e. the center and the mean left/right distances which totaled almost 100 microns. As the fiducialization procedure for the targets had improved since we started this process, and given that the offset location of the BL/BR targets could lead to larger geometric errors if the mirror mount assembly was pitched and yawed, then the better distance was thought to be derived from the center targets.

Table 2– Final Results

Observer	Station	Interferometer	v	Mekometer	Diff
JCD	BL	8006.539	0.008		
	BR	8006.712	0.028		
	CTR	8006.686	-0.020	8006.635	-0.051
CJC	BL	8006.536	0.005		
	BR	8006.686	0.002		
	CTR	8006.717	0.011	8006.715	-0.002
RGS	BL	8006.517	-0.014		
	BR	8006.667	-0.017		
	CTR	8006.679	-0.027	8006.655	-0.024
CG	BL	8006.528	-0.003		
	BR	8006.688	0.004		
	CTR	8006.709	0.003	8006.685	-0.024
SEH	BL	8006.534	0.003		
	BR	8006.665	-0.019		
	CTR	8006.685	-0.021	8006.675	-0.010
CJC	CTR	8006.742	0.036		
JCD	CTR	8006.726	0.020		
	Mean BL:	**8006.531**	$\sigma = .009$	**8006.673**	**Mean**
	Mean BR:	**8006.684**	$\sigma = .019$		
	Mean CTR:	**8006.706**	$\sigma = .024$		

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6. ERRORS

The point to point interferometer distances were calculated to have a standard deviation of almost 20 microns. Based on instrumental accuracy of 1 second, the transfer from the transit on each sighting was estimated at 6 microns. The fiducialization on the CMM was estimated at ±10 microns for each mirror mount. Similarly, the accuracy of the mirror mounted to the reference surface was set on the CMM at ±10 microns each. Systematic effects such as the temperature of the mirror mounts would also play a part. The total error estimate (RMS) would therefore be in the order of ±30 microns at one sigma.

7. CONCLUSION

The wiggler magnet was installed in the machine on 13th June 1998 in preparation for FEL commissioning. On Monday 15th June, after five hours of effort, the FEL lased for the first time [5]. The distance between the mirrors at which lasing occurred was recorded as 8006.646 mm. This is 60 microns shorter than the center target distance, which is just within the 2 sigma level. With hindsight, if the average of all three measurements had been taken then a value just 16 microns away from the final lasing distance would have been used. The technique described above proved effective in setting the cavity distance. It also made good use of some aging equipment which may otherwise have continued to collect dust.

For the future, an upgrade to a larger infrared machine as well as an ultraviolet machine is planned. This would involve measuring two much longer optical cavities. The new IR cavity would be 32 m long, whereas the UV cavity would stretch for 64m. These distances would no longer be suitable for measurement with an interferometer; however, the Mekometer results indicate that it could produce acceptable results provided care is taken on the fiducialization.

References

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[3] Curtis C.J., Jefferson Lab Alignment Group Data Transmittal #415, 10 Mar 1998.
[4] Curtis C.J., Jefferson Lab Alignment Group Data Transmittal #423, 31 Mar 1998.
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