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ALIGNMENT OF THE VISA UNDULATOR*

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Abstract

The Visible-Infrared SASE Amplifier (VISA) undulator [1] consists of four 99cm long segments. Each undulator segment is set up on a pulsed-wire bench, to characterize the magnetic properties and to locate the magnetic axis of the FODO array [2]. Subsequently, the location of the magnetic axis, as defined by the wire, is referenced to tooling balls on each magnet segment by means of a straightness interferometer. After installation in the vacuum chamber, the four magnet segments are aligned with respect to themselves and globally to the beam line reference laser. A specially designed alignment fixture is used to mount one straightness interferometer each in the horizontal and vertical plane of the beam. The goal of these procedures is to keep the combined rms trajectory error, due to magnetic and alignment errors, to 50µm.

1 INTRODUCTION

The four-meter long undulator consisting of four 99cm long segments is supported on a strongback. The undulator system needs to be aligned to 50µm so that maximum Self-Amplified Spontaneous Emission (SASE) gain can be attained. Each magnet must be aligned with respect to each other and, at the same time, with respect to the global beam line coordinate system. In addition, the beam of a laser (**R**eference **L**aser **B**eam - RLB) defines the global position of the undulator's centerline in the beam line coordinate system.

The extremely tight alignment tolerance precludes the application of traditional high precision optical alignment methods, including laser tracker based procedures. However, because of the straight-line geometry and the relatively short length, interferometric straightness measurement techniques can be used. A standard HP straightness interferometer in "long distance" mode (0.5m - 30m) will provide a straightness resolution of 0.8µm with 5µm accuracy over the length of the undulator, and a straightness measurement range of ±1.5mm. This method is one dimensional, i.e. horizontal and vertical positioning will be accomplished using two independent straightness interferometer systems.

The final alignment residuals should be less than 50µm. However, the total alignment tolerance also includes the fiducialization error, which in itself consists of two contributions. The first part is related to the precision with which the true magnetic centerline can be

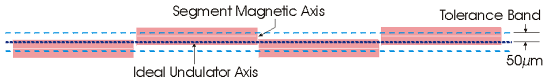

Fig. 1 Visa Alignment Tolerance

determined. The second on how the centerline can be transferred onto mechanical fiducials. Each undulator has an error budget as shown in the following table.

Table 1: Alignment Error Budget	*[µm]*
Magnetic Centerline Determination	20
Transfer onto Fiducials	23
Reference Undulators to RLB	29
Positioning	28
Total (added in quadrature)	51

2 ALIGNMENT CONCEPT

2.1 Fiducialization (Magnetic Measurements)

The first step in fiducialization of the undulator magnets involves determining the magnetic centerline yielding a wire that is physically positioned along the magnetic centerline of the undulator [3].

Next the wire position is measured with respect to the **W**ire **F**inder's (WF) reference tooling ball. One WF is positioned on each the upstream and downstream sides of an undulator segment to detect the wire position in the horizontal orientation only. To avoid wire sag effects that would bias the vertical measurements, the vertical positioning will be accomplished by rolling the undulator segment by 90° creating another horizontal measurement.

Now with the WF tooling balls positioned relative to the magnetic centerline, a straightness interferometer setup can be used to measure the undulator tooling balls relative to the WF tooling balls. These steps are all repeated with the undulator segment rolled each time by 90°. After correcting for the non-parallelity effect between the wire and the interferometer axes, adding the fiducialization values of the two tooling balls in both the horizontal and vertical plane should equal the spatial distance between the respective two tooling balls. This value is compared against a previous measurement on a high accuracy Coordinate Measurement Machine (CMM).

2.2 Installation Alignment

Conventional alignment methods will be used to for mechanical installation achieving about 200µm accuracy.

2.3 Fine Alignment

Positioning the Alignment Jig

The absolute distance between the Laser Finder (LF) tooling ball and the Straightness Interferometer (SI) reference line is unknown, all SI measurements are only relative. Theoretically, the SI reference line must be

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precisely parallel to the RLB in order to avoid applying corrections to each undulator tooling ball measurement.

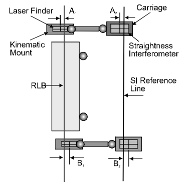

Fig. 2 Alignment jig

Using the same constant length offset bar for the "A" and "B" measurements, parallelity is achieved when A1 + A2 equals B1 + B2. However, tests have shown that it is difficult and time-consuming to achieve this condition. On the other hand, a parallelity of about 0.5 mm can be achieved quickly by adjusting the pointing of the interferometer laser. Therefore, the effects of the remaining skewness of the straightness interferometer axis with respect to the LF line will be taken out numerically by applying a similarity transformation.

<u>*Detect RLB Position with Laser Finders-Reference to SI*</u>

A kinematic mount will be installed on both the upstream and downstream sides of the undulator assembly (fig. 2). This is necessary, since only one Laser Finder will be used to detect the RLB in order to avoid systematic errors. First, the LF is set into the downstream mount, and the RLB position is measured with respect to the horizontal and vertical tooling balls of the LF. Second, these tooling balls are referenced against the respective SIs integrated into the alignment jig. Last, these two steps are repeated for the upstream LF position.

<u>*Measure Positions of Undulator Segments With SI*</u>

It should be stressed again that the SI is only a relative alignment tool. The capability to position the undulators to an absolute position is only gained through the absolute calibration of the LF. The absolute calibration of the LF yields a metric measurement of the horizontal and vertical projected distances between the RLB and the LF tooling balls in the horizontal and vertical planes, respectively. The subsequent SI measurements let us relate the unknown undulator segment fiducial positions to the known LF positions. To create an accurate snap shot of an undulator segment's position, the horizontal and vertical SI readings are taken simultaneously.

<u>*Position Undulators*</u>

Before the position correction values can be calculated, the SI readings need to be corrected for the non-parallelity of the RLB and SI coordinate systems. A similarity transformation (fig. 3) is used to compute the corrected SI readings. The basic similarity transformation can be written as:

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} t_x \\ t_y \end{pmatrix} + \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix}$$

The three unknowns: t_x, t_y, θ can be determined by substituting the coordinates of two points known in both systems into a set of four equations. Because the coordinate systems are almost parallel, only approximations for x and u are required. Subsequently, the solution of the equation yields the unknown offset value of an undulator fiducial from the RLB axis. This offset reduced by the fiducial's fiducialization value (FV) gives the position adjustment value (ΔP). The undulator's position is then adjusted under the control of the SI.

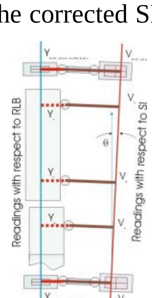

Fig.3 SI Position

<u>*Quality Control*</u>

After all adjustments are applied, the undulator fiducial positions are recorded. Due to the geometry and construction of the supports, a slight coupling between the adjustment axes is to be expected. This might require iterating the last two steps.

$$\Delta P_i = RLB + \overline{SI}_{RLB} - FV_i - \overline{SI}_i$$

3 IMPLEMENTATION

3.1 Fiducials

Fiducials are measured independently and considered as such for both horizontal and vertical coordinates. The single dimensionality does not, however, represent a limitation. To obtain micron type results, great care must be taken to avoid any kind of first order errors. Hence, in high precision industrial metrology, measurements are always taken in the principal plane, i.e. horizontal measurements are carried out in the horizontal plane and vertical measurements in the vertical plane, respectively. Consequently, the undulator is designed to have the horizontal fiducials on the side and the vertical fiducials on the top. For redundancy reasons tooling balls are also placed on the opposing sides (fig. 4).

3.2 Straightness Measurements

The SI is not much different from a typical distance measurement interferometer. The Michelson interferometer is replaced by a Wollaston prism and the retro reflector by a straightness reflector. To measure straightness, however, the reflector is held fixed, and the Wollaston prism moves along the to be measured object.

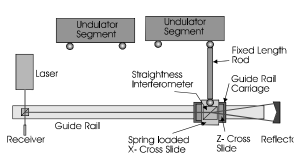

Fig. 4 Interferometer

Since the interferometer counts fringes, the beam signal must never be interrupted, e.g. due to a deviation of the prism from the beam or by blocking off the beam transport, since this would cause the interferometer to loose count. To prevent a possible deviation of the prism from the beam path and to also maintain maximum measurement range to both sides, i.e. to keep the prism centered on the beam, the prism is usually mounted to a carriage riding on a precision guide rail. Because the rail moves the prism parallel to the measurement object, an interface between the prism and the fiducials is needed such as a constant distance rod. Whenever the prism is near a fiducial, the rod is inserted between the prism and the fiducial. To facilitate the insertion and to provide constant measurement conditions,

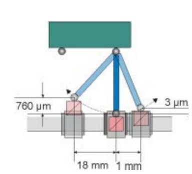

Fig. 5 Arcing

the prism is mounted on a spring loaded cross slide (fig. 4). This implementation does not provide any indication when the rod is truly perpendicular to the measurement interferometer beam. Fortunately, this is not a new and unique problem being typical to optical tooling measurements. To overcome this, the rod is arced while the scale is read. At the smallest value, the scale is perpendicular to the line of sight. Scale arcing can be implemented in this set up by moving the prism in the Z direction while watching the SI read-out (fig. 5). A motor driven stage is added between the carriage and the X cross slide and moved by hand near the measurement point. Then the Z stage drive is engaged, which moves the prism across the unknown measurement point. A computer interfaced to the drive readout and the interferometer readout records coordinate pairs (z, x) over this distance. Subsequently, a simple circle fit not only solves for the true measurement point and thus for the shortest distance, but also improves the significance of the solution by fitting many readings.

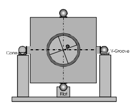

Fig. 6 Quad.

3.3 RLB Laser Finder

A laser beam cannot be picked up accurately by standard alignment instrumentation. A tool needs to be developed which references an optical beam to mechanical fiducials.

Detector fixture design

The proposed **L**aser **F**inder (LF) consists of a frame, which carries four tooling balls in the same geometry and dimensions as they are mounted to the end of an undulator. A quadrant detector is mounted to the center of the frame within a few hundred microns (fig. 6) giving the beam position in its own coordinate system.

Two distinct methods are employed to detect the laser position. The first works on the principle of a slit that allows the laser light to pass through. Thus, even if the laser cross section is not uniform in intensity, the slit is immune to this since only a profile of the laser light that passes through the slit is used to determine the beam position. This method will not be able to average out atmospheric effects or other effects due to vibrations. The other method is based on using the quadrant detector by summing the laser intensity readings on each of the two halves of the sensitive surface and then comparing the two. The arrangement is automatically rotated 90º to measure the other dimension. Tooling ball and detector coordinate systems need to be related via a calibration.

Detector fixture calibration

The positions of the four tooling balls are first measured accurately on a coordinate measurement machine. Then the frame is set up on the same calibration stand as the WF (fig. 6). An X, Y reading of the beam spot is taken. Rolling the frame 180º allows a second reading. The depiction in fig. 7 combines the geometric relationship from both readings. A simple vector algebra operation will produce the unknown calibration offsets with D being the laser beam position vector and *C* being the electrical center position vector, both expressed in a Cartesian coordinate system with its datum located with respect to the symmetry axes of the two horizontal tooling balls.

$$\bar{D} = \frac{1}{2}(\bar{A}_I + \bar{A}_{II})$$

$$\bar{C} = \frac{1}{2}(\bar{A}_{II} - \bar{A}_I)$$

This procedure does not solve for the rotation between the tooling ball coordinate system and the quadrant detector system. While the procedure could be expanded to include this, it is believed not to be required as long as the quadrant detector is carefully aligned with respect to the tooling balls.

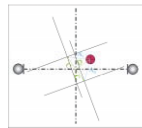

Fig. 7 Relating Readings

3.4 Finding the Wire

Wire finder design

The wire position on either side of an undulator segment is measured with WFs. The position measurement is carried out in one plane at a time with one device on either side of the undulator. A laser avoids wire contact. This consists of a laser emitter mounted so that the emerging beam will pass through a slit across the wire to a receiver on the other side (fig. 8). After measuring the intensity of the signal received, a computation based on the signal profile will provide an accurate determination of the wire position. A mechanical WF is also used which touches both sides of the wire to determine its position. Assuming the wire has an ideal round profile, the average of both measurements gives the wire position in the WF's "arbitrary" coordinate system.

Fig. 8 Laser finder on calibration fixture

Wire finder calibration

Next, the wire position measurements need to be related to the tooling balls on the WF frame. Since the device measures only in one dimension the wire measurement is made a second time with the fixture yawed by 180º. A calibration mount is required to retain the position (analogous to fig. 7). The kinematic mount can be realized by a combination of the standard cone, V-groove, and flat mounts. The distance between the tooling balls needs to be measured accurately.

Reference wire finder fiducials to undulator fiducials

Lastly, the WF tooling ball positions are referenced to the tooling balls on the undulator following the procedure already described in chapter 2.1.

4 CONCLUSION

Alignment will begin in April/May of 1999 and the first beam is expected in June.

5 REFERENCES

[1] R. Carr et al.: The VISA Free Electron Laser

[2] G. Rakowsky et al., Measurement and Optimization of the VISA Undulator

[3] G. Rakowsky, ibid.