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# VISA Undulator Fiducialization and Alignment

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# VISA Undulator Fiducialization and Alignment♦

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Abstract

As part of the R&D program towards a fourth generation light source, a Self-Amplified Spontaneous Emission (SASE) demonstration is being prepared. The Visible-Infrared SASE Amplifier (VISA) undulator will be installed at Brookhaven National Laboratory by the end of the year. The VISA undulator is an in-vacuum, 4-meter long, 1.8 cm period, pure-permanent magnet device, with a novel, strong focusing, permanent magnet FODO array included within the fixed, 6 mm undulator gap. The undulator is constructed of 99 cm long segments. To attain maximum SASE gain requires establishing overlap of electron and photon beams to within 50 µm rms. This imposes challenging tolerances on mechanical fabrication and magnetic field quality, and necessitates use of laser straightness interferometry for calibration and alignment of the magnetic axes of the undulator segments. This paper describes the magnetic centerline determination, and the fiducialization and alignment processes which were performed to meet the tolerance goal.

## 1 Introduction

The four-meter long undulator consisting of four 99 cm long segments is supported on a strongback and mounted inside a vacuum vessel. The undulator design was described in detail by Libkind[1]. The undulator segments need to be aligned to 50 µm with respect to each other so that maximum **S**elf-**A**mplified **S**pontaneous **E**mission (SASE) gain can be attained[2].

To accomplish successful alignment[3] three major tasks need to be completed: firstly, the undulator segments need to be fiducialized, secondly, the segments need to be aligned, at first conventionally with respect to the global beam line coordinate system and then interferometrically with respect to their common axis, and lastly, the beam of a laser (**R**eference **L**aser **B**eam - RLB), which will provide the reference for the diagnostic pop-in monitors[4], has to be pointed such that it becomes collinear to the undulator axis.

## 2 Error Budget

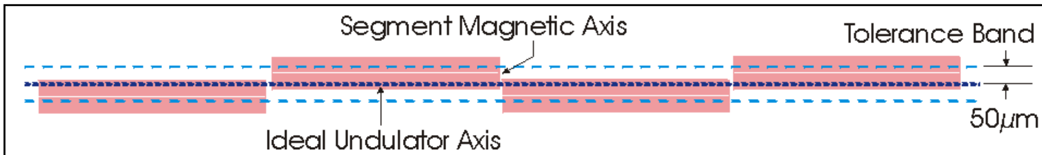


*Fig. 1 Visa Alignment Tolerance*

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The fiducialization and alignment residuals have to be kept to less than 50 µm (see fig. 1). The first two entries in the total budget come from the fiducialization process, positioning and RLB alignment being the remaining contributions. Their associated projected errors are shown in the Table 1 and, added in quadrature, come very close to the desired final residual of 50 µm.

*Table 1: Tolerance Budget*

| ***Alignment Error Budget*** | ***projected*** | ***achieved*** |
|---|---|---|
| | *[*µm*]* | *[*µm*]* |
| ***Magnetic Centerline Determination*** | 20 | 10 |
| ***Transfer onto Fiducials*** | 23 | 8 |
| ***Positioning*** | 28 | |
| ***Setup RLB with respect to Undulators*** | 29 | |
| ***Total (added in quadrature)*** | 51 | 42 |

# 3 General Approaches

## 3.1 Fiducials

Fiducials are measured independently and are 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 other sides (see fig. 2).

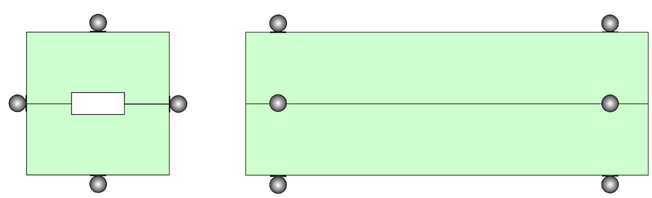


*Fig. 2 Undulator fiducials*

## 3.2 Determining the Magnetic Centerline

The high tolerances preclude the traditional mechanical approach to locate the centerline. Instead, it is necessary to determine the true centerline based on magnetic properties. Because of the limited aperture, a pulsed wire system was chosen as the primary measurement tool[5]. Since wire sag would affect measurements in the vertical plane, vertical plane measurements are transformed into horizontal plane measurements by rotating the segments by 90°. It should also be noted that earth's field effects need to be compensated for by enclosing the setup in a Helmholtz coil.

### 3.3 Straightness Measurements

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 0.8 µm with 5 µm accuracy over the length of the undulator, and a straightness measurement range of ±1.5 mm. This method is one dimensional, i.e. horizontal and vertical positioning is accomplished using two independent straightness interferometer systems.

## 4 Instrumentation

### 4.1 Pulsed Wire System

To measure and correct trajectory errors, and to determine the magnetic centerline, a pulsed wire system[6] was chosen as the primary measurement tool.

Two undulator segments are set up on a granite table for stability. The segments are supported the same way as in their final installation. Smaller granite blocks sit atop the ends of the table, supporting the 4 m long wire, the oil bath damper, one Wire Finder each at both ends of an undulator segment pair, and the wire pulse detector. The setup is shown in Figure 3. The wire is threaded through the undulator segments, fixed at one end, and then tensioned by a weight at the other end after being deflected over a pulley. A High Voltage Pulser sends a current pulse through the wire. The Lorentz force of the transverse field of the undulator segment's quadrupoles induces a mechanical transverse impulse, which causes a displacement wave to propagate down the wire. The wire pulse detector sees the signal as a displacement of the wire. The pulse's timing resolution provides the longitudinal parameter. The distorted pulses are displayed on an oscilloscope (see fig. 4) and provide an instant image of the trajectory thus becoming an excellent null-finding indicator for locating the magnetic axis.

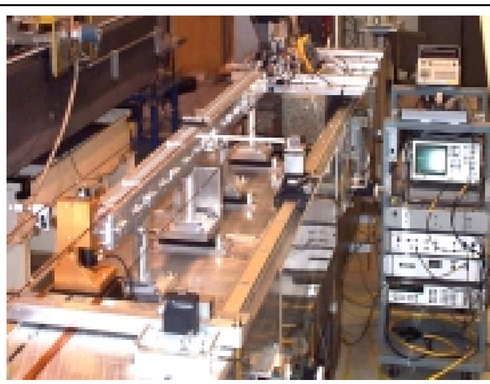


*Fig. 3 Pulsed Wire Bench Setup*

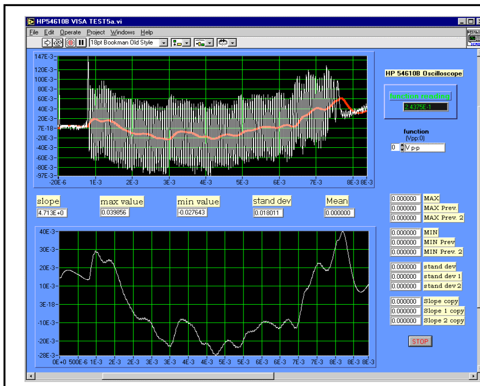



*Fig. 4 Pulsed Wire Signal Display*

## *4.2 Measuring Straightness Offsets*

### Straightness Interferometer

A straightness interferometer 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 object being measured. Since the interferometer counts fringes, the beam signal must never be interrupted, e.g. due to a deviation of the Wollaston prism from the beam or by blocking off the beam transport, since this would cause the interferometer to lose count. To prevent a possible deviation of the Wollaston 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 Wollaston prism is usually mounted to a carriage riding on a precision guide rail. Because the guide rail moves the Wollaston prism parallel to the measurement object, an interface between the prism and the fiducials is needed. A constant distance rod can realize such an interface. Whenever the prism is in the longitudinal vicinity of a fiducial, the rod is inserted between the Wollaston prism and the fiducial. To facilitate the insertion of the rod and to provide constant measurement conditions, the Wollaston prism is mounted on a cross slide. In addition, to ease the placement of the rod, both ends have a sleeve, which fits loosely over the tooling ball on the undulator as well as the one on the prism (see fig. 5, sleeves are not shown). However, this implementation does not provide any indication of when the rod is truly perpendicular to the measurement interferometer beam. Fortunately, this is not a new and unique problem, being also a condition typical to optical tooling measurements.

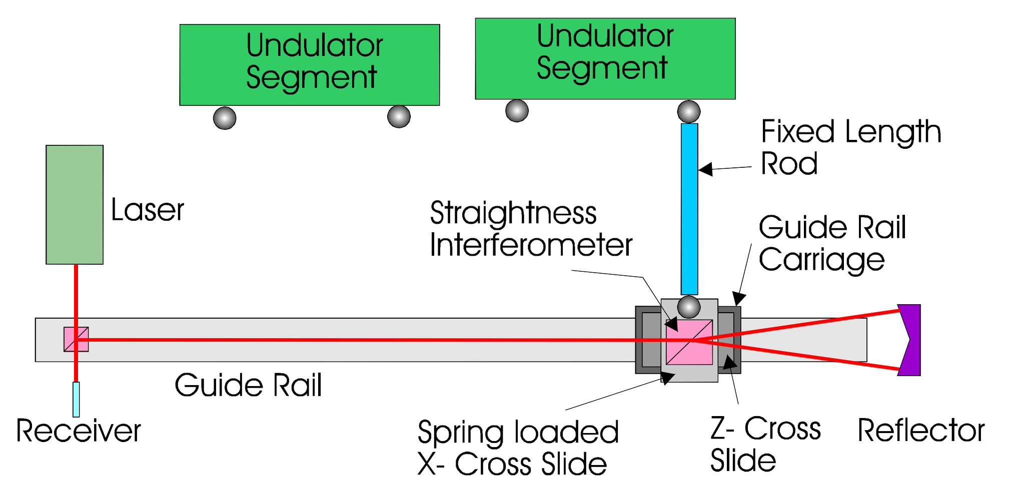



*Fig. 5 Interferometer implementation*

### Arcing

To overcome the problem, the instrument operator instructs the rod man to arc the scale while he is constantly reading the scale. He knows that when he observes the smallest scale value, the scale must be perpendicular to the line of sight. This arcing can be implemented in this set up by slowly moving the Wollaston prism in the Z direction while watching the straightness interferometer read-out (see fig. 6). Since it proved less accurate to manually move the carriage at a constant speed across a measurement point, an additional motor driven stage was added between the carriage and the X cross slide. In this configuration, the carriage is moved by hand to a position of about an inch before a measurement point (see fig. 7). Then the Z stage drive is engaged, which moves the Wollaston prism across the unknown measurement point (see fig. 8). A computer interfaced to the drive read-out 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[7].

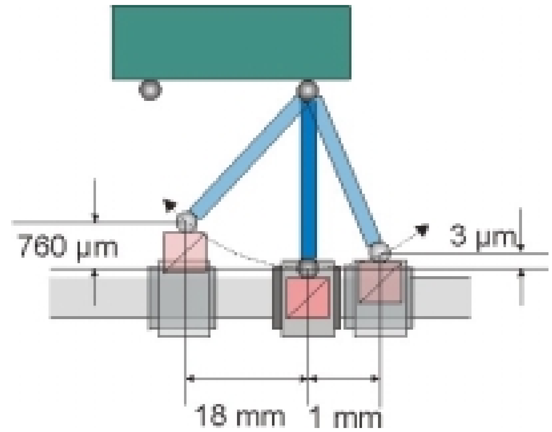


*Fig. 6 Effect of Arcing*


*Fig. 7 Arcing drive and stop*

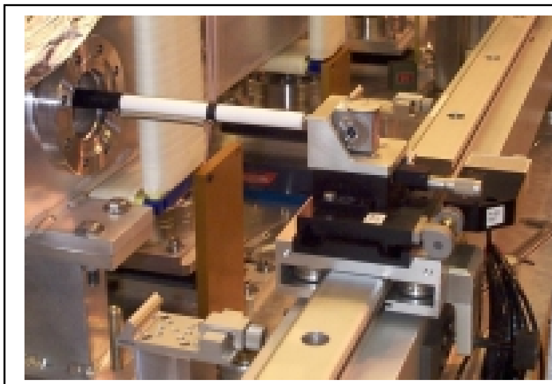


*Fig. 8 Arcing rod attached to cross slide*

## 4.3 Locating the Wire Position

### Wire Finder Design

As described above, a “pulsed-wire” bench is used to determine the magnetic centerline. The wire position on either side of an undulator pair will be detected with Wire Finders (see fig. 9). The position measurement is carried out in one plane at a time with one device on either side of the undulator. Each wire finder is

*Fig. 9  Laser based Wire Finder*

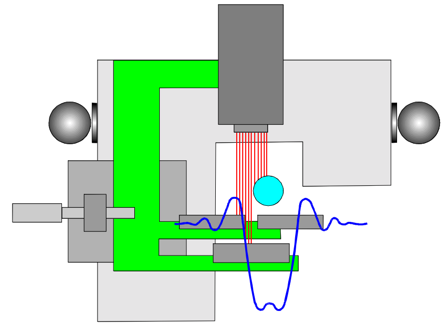


*Fig. 10  Wire Finder Schematic*

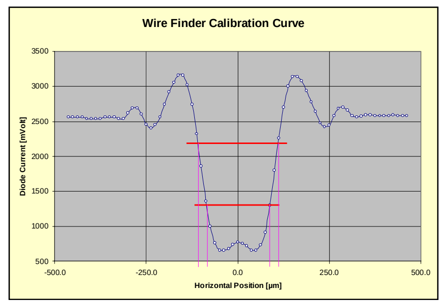



*Fig. 11  Wire Position Determination*

a frame, which sits perpendicular to beam direction on the undulator support plate during magnetic measurements. Each frame carries two tooling balls in the measurement plane in the same geometry as the tooling balls on the undulator. A laser-based design allows detecting the wire position without touching it (see fig. 10). The device 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. After measuring the intensity of the signal received, a computation based on the signal profile will provide an accurate determination of the wire position (see fig. 11).[8]

## Wire Finder Calibration

The wire position measurements need to be related to the reference-tooling ball on the wire finder frame. Since the device measures only in one dimension at a time, a calibration can be simply achieved by determining the lateral offset of the wire finder's coordinate system with respect to one of the tooling balls. This is accomplished by performing the wire measurement a second time, this time however with the fixture yawed by 180º (fig. 12, 13). To retain the fixture in the same transverse position during both measurements, a calibration mount is required where the fixture rests on its tooling balls in a kinematic mount. The kinematic mount can be realized by a combination of the standard cone, V-groove, and flat mounts. One tooling ball sits in a cone shaped mount, the second one sits in a V-groove with the V-groove oriented perpendicular to beam direction. The remaining degree of freedom restraint consists just of a dowel pin stopping the plate from flipping around its pitch axis. To complete the calibration,

*Fig. 12 Wire Finder in Calibration Stand, zero° yaw position*

*Fig. 13 Wire Finder in Calibration Stand, 180° yaw position*

the distance between the tooling balls needs to be measured accurately. Hence, the wire position with respect to one tooling ball in the first position will be half of the tooling ball distance plus the lateral offset plus the micrometer reading. This value is referred to as the wire offset and is vital in completing the fiducialization of the magnets.

### Wire position measurement

The actual wire position measurement is carried out by driving the detector assembly across the wire profile. The micrometer readings are recorded at two defined detector voltage output levels on either side of the wire. The mean of the micrometer readings yields the wire center position (see fig. 11).

## *4.4 RLB Laser Finder*

A laser beam cannot be picked up accurately by standard mechanical alignment instrumentation. Therefore, a tool was needed that would reference an optical beam to mechanical fiducials[9].

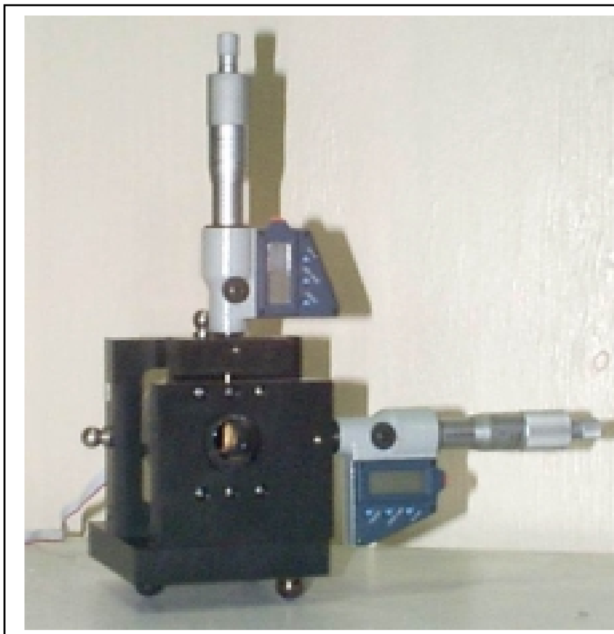


*Fig. 14 Laser Finder Implementation*

### Detector Fixture Design

The **L**aser **F**inder (LF) (see fig. 14) consists of a frame, which carries four tooling balls in the same geometry and dimensions as they are when mounted to the end of an undulator. A quadrant detector is mounted to the center of the frame within a few hundred µm. The quadrant detector will give a read-out of the beam position in the quadrant detector's coordinate system.

The Laser Finder is built as a nulling device. The quadrant detector is mounted on a two-dimensional cross slide. The position of the quadrant detector can be adjusted by micrometers horizontally and vertically. The quadrant detector sums the laser intensity readings on each of the two halves of the sensitive surface and then compares the two. This arrangement is subsequently electronically rotated 90º to measure the other dimension. The detector's coordinate system needs to be related to the tooling ball coordinate system through calibration measurements.

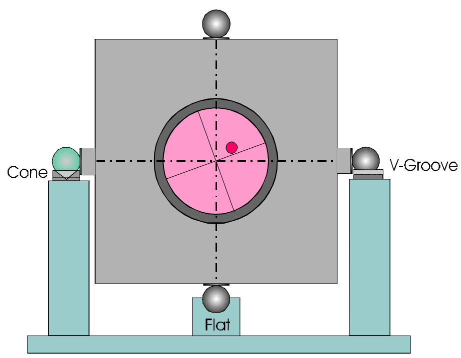



*Fig. 15 Laser Finder in calibration fixture*

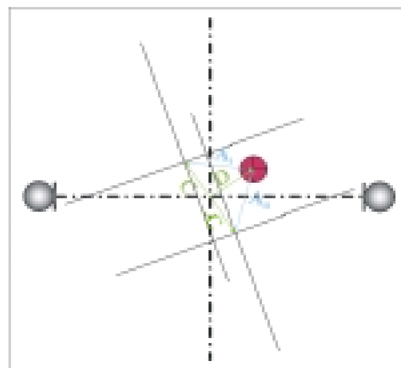


*Fig. 16 Relating both measurements*

## Laser Finder Calibration

Firstly, the positions of the four tooling balls are measured accurately on a coordinate measurement machine. Secondly, the frame is set up on a calibration stand similar to the Wire Finder (see fig. 15). An X, Y reading of the beam spot is taken. Subsequently, the frame is rolled by 180º and a second reading is taken. The depiction in Figure 16 combines the geometric relationship from both readings. Figures 17 and 18 show the Laser Finder during calibration. A simple

*Fig. 17 LF in calibration stand, Position 1*

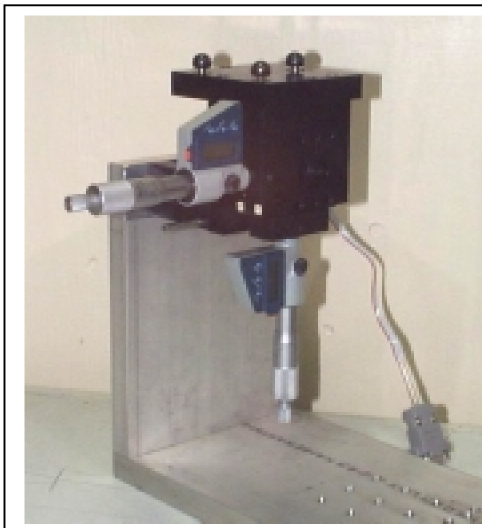


*Fig. 18 LF in calibration stand, Position 2*

vector algebra operation will produce the unknown calibration offsets D and, C, both expressed in a Cartesian coordinate system with its datum located with respect to the symmetry axes of the two horizontal tooling balls.

It should be pointed out that this procedure does not solve for a parameter representing the rotation between the tooling ball coordinate system and the quadrant detector coordinate system. While the procedure could be expanded to include this parameter, it is believed not to be required as long as the quadrant detector is carefully aligned with respect to the tooling balls.

# 5 Fiducialization Process

The fiducialization measurements are carried out in one dimension (plus length) at a time (fig. 19). It consists of six-steps, which are subsequently repeated for the other dimension and additionally for closure checks in the 180° and 270° roll positions:

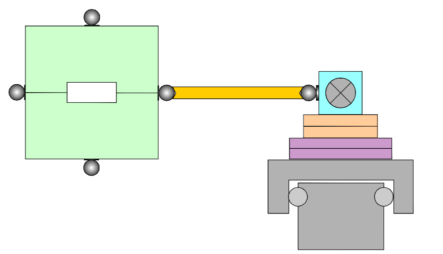


*Fig. 19 One dimensional measurement*

## 5.1 Find Magnetic Centerline

The first step in the fiducialization of the undulator magnets involves determining the magnetic centerline. This step will yield a wire that is physically positioned along the magnetic centerline of an undulator pair[10].

## 5.2 Detect Wire Position

Two Wire Finders, one positioned on each the upstream and downstream sides of a pair of undulator segments (see fig. 3), are used to detect the wire position and relate it to the Wire Finders' reference tooling balls. By combining the wire position information and the relationship of the detector zero to the reference tooling ball which is known from calibration, the position of the Wire Finder reference tooling ball is known with respect to the magnetic axis.

## 5.3 Map Fiducial Positions with Respect to a Straight Line

Next a straightness interferometer setup is used to measure the position of the undulator tooling balls relative to the Wire Finder reference tooling balls.

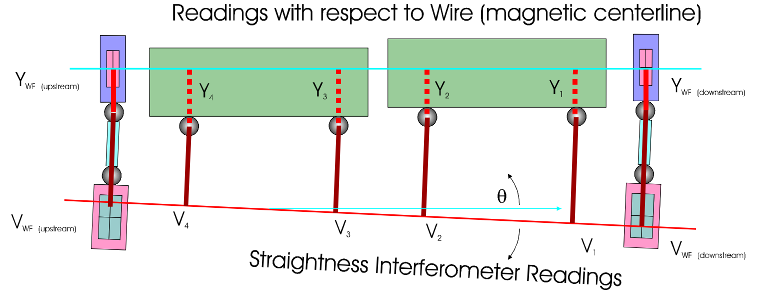



*Fig. 20 Fiducialization Geometry*

### 5.4 Calculate Fiducial Offsets

After correcting for the non-parallelity effect between the wire and the interferometer axes, the perpendicular distance of the tooling balls from the magnetic axis is obtained (fig. 20).

### 5.5 Repeat for Other Dimensions

To avoid wire sag effects that would bias the vertical position measurements and to carry out all measurements in the principle plane of each tooling ball, the fiducialization process is designed to be one-dimensional (plus z distance) only. The vertical positioning will be accomplished by rolling the undulator segment by 90° thus creating another horizontal measurement.

### 5.6 Closure Check

The above steps are all repeated by rolling the undulator segment into the 180° and 270° positions. Adding the fiducialization values of two opposite tooling balls in both the horizontal and vertical plane yields the spatial distance between the respective two tooling balls. Comparing this value against a previous measurement on a high accuracy Coordinate Measurement Machine (CMM) provides a valuable check against measurement and systematic errors (fig. 21).

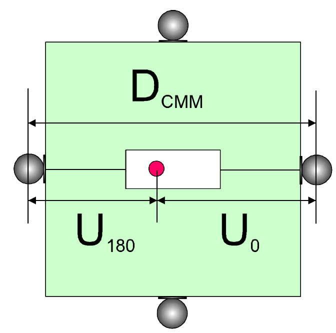



*Fig. 21 Closure dimensions*

## 6 Alignment Process

A six step process was designed to accomplish the alignment goal.

### 6.1 Installation Alignment

Conventional alignment methods will be used to support mechanical installation. This step will align the undulator with respect to the global beam line coordinate system and with respect to the common axis with an accuracy of about 150 – 200 µm.

### 6.2 Map Undulator Fiducials

The technique underlying the fine alignment is analogous to the fiducialization process as it is based on the use of straightness interferometry. A dual straightness interferometer setup is used to measure the position of the undulator tooling balls relative to the arbitrary straightness interferometer reference line. Since test measurements had shown that it was necessary to control the alignment process in both the vertical and horizontal plane simultaneously, two straightness interferometers are set up, one in the horizontal plane and one in the vertical plane. A special alignment jig was designed to facilitate the setup and alignment of both straightness interferometers (see fig. 22). Figures 23 through 26 show details of the arcing and interface rod implementation.

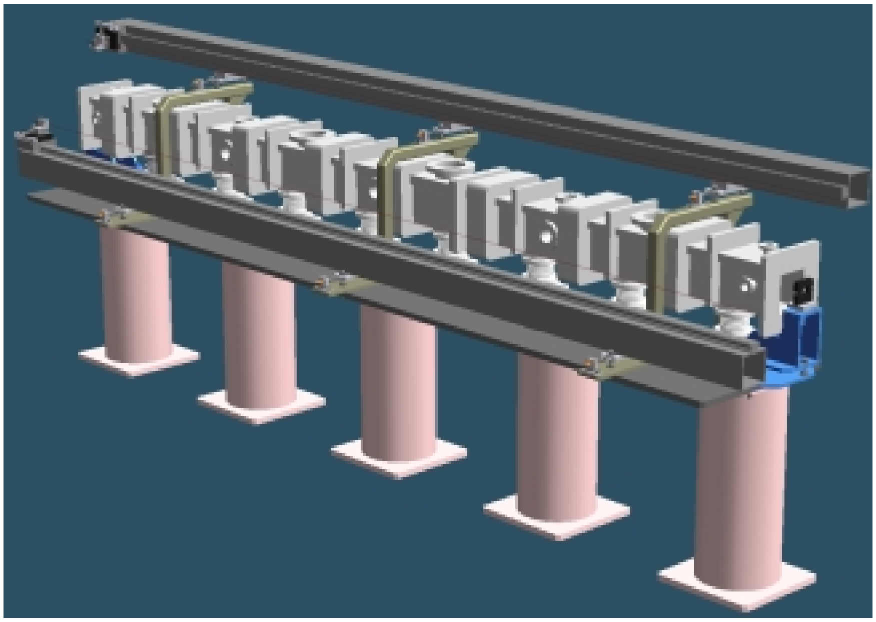


*Fig. 22 Interferometer jig installed around VISA vacuum vessel*

*Fig. 23 VISA test installation with jig*

*Fig. 24 VISA test installation with jig*

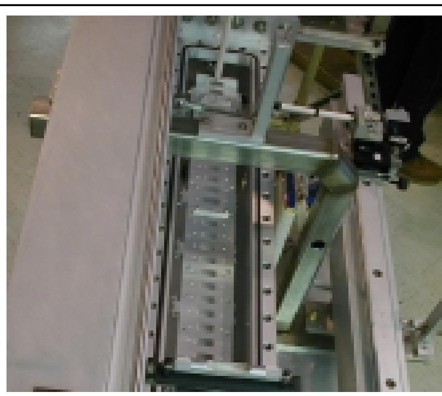


*Fig. 25 Undulator segment in vessel*

*Fig. 26 Alignment jig with SI lasers*

To create an accurate snap shot of an undulator segment’s position, the horizontal and vertical straightness interferometer readings are taken simultaneously. It should be stressed again that the straightness interferometer is only a relative measurement tool. The capability to align the undulators to an absolute position is only provided through conventional alignment.

### *6.3 Mathematically Align Coordinate Systems*

The raw measurements are taken in different coordinate systems, which have different datums: the SI coordinate system, the undulator segment fiducialization coordinate system, and the undulator common axis coordinate system.

#### Align SI Readings to À Priori Undulator Axis

In a first step the straightness interferometer readings need to be corrected for the non-parallelity of the à priori undulator axis and straightness interferometer coordinate systems. A similarity transformation is used to compute the corrected straightness interferometer readings (see fig. 27).

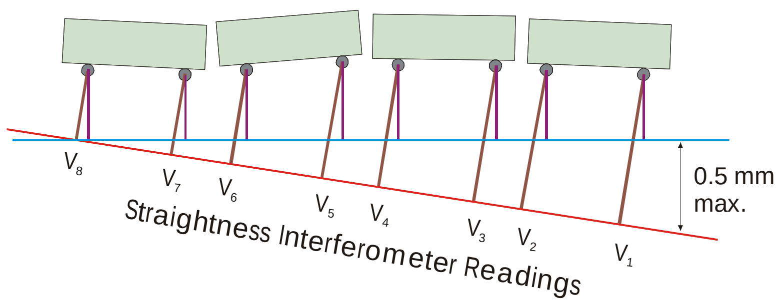



*Fig. 27 Align SI readings to à priori undulator axis*

#### Transform Undulator Segment Fiducialization Offsets Into À Priori Axis System

The fiducialization offsets were determined in a coordinate system whose axis is aligned to the individual segment’s centerline. Since at this stage the individual segments are potentially yawed and pitched with respect to each other, the nominal fiducial offsets need to be transformed into the à priori axis system (see fig. 28).

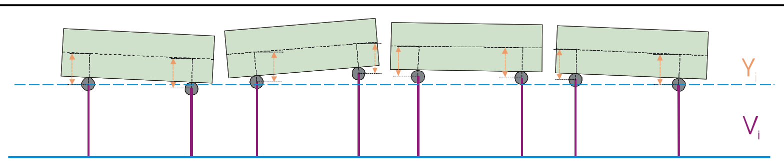
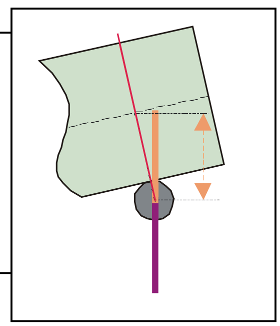



*Fig. 28 Transform undulator segment fiducial offsets to à priori undulator axis orientation*



#### Combine transformed offsets and readings

After transformation of the SI readings and the nominal fiducialization offsets into a common coordinate system, the two values can be combined and represent the actual offset from the undulator segment's magnetic centerline at the tooling balls position with respect to the à priori common undulator axis (fig. 28).

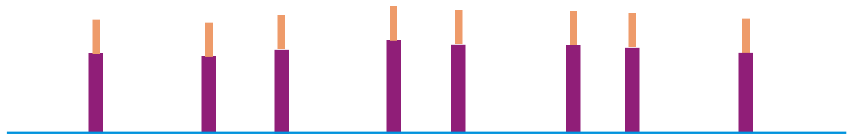


*Fig. 29 Combined offsets*

### 6.4 Fit Straight Line to Data

From these measurements position corrections for the undulator magnets can be calculated. To minimize necessary movements a line fit is applied to the data (fig. 30). The resulting offsets from the fitted line (fig. 31) represent the corrections, which need to be applied to align the undulator segments to a common straight line.

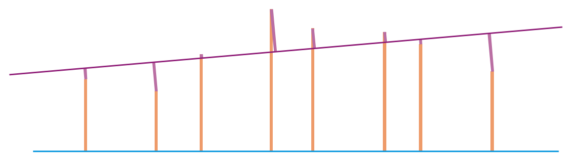


*Fig. 30 Straight line fit through offsets*

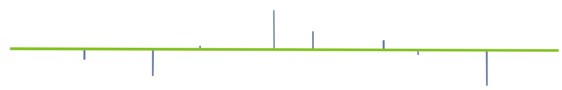


*Fig. 31 Computed position corrections*

### 6.5 Apply position corrections

The above computed position corrections are applied under the control of the dual axis straightness interferometer system. For ease of operation, the corrections are translated into fractions of rotation of the respective screws controlling the positioning device (fig. 32)[11].

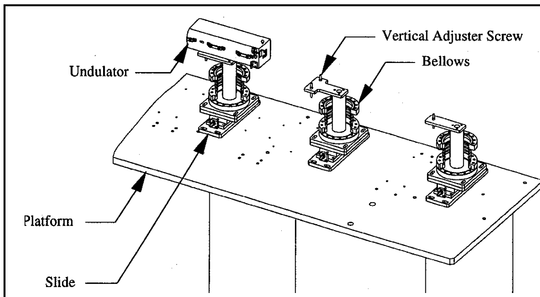
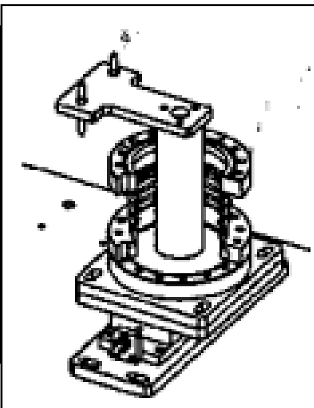



*Fig. 32 Mechanical Adjustment arrangement*



### 6.6 Quality Control Map

After all adjustments are applied, the undulator fiducial positions are again 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. After the positioning goal is achieved, a final map including the fiducials of the Laser Finder in both the upstream and downstream position is recorded and processed.

# 7 Measurement Results

## *7.1 Wire Finder Calibration*

The results of a repeatability test of the Wire Finder calibration are shown in Figure 33. The calibration was carried out before the Wire finder was used on the fiducialization bench and afterwards at the end of the day. Both calibration sets consisted of four individual measurements. The small differences between individual measurements and between the two sets demonstrate the accuracy and reliability of the device. The calculated Standard Deviation projects that the contribution of the Wire Finders to the total error budget will be negligible.

**Laser Finder Calibration Comparison**

| **Golden Fixture** | | | | **Black Fixture** | | | |
|---|---|---|---|---|---|---|---|
| before | Δ | after | Δ | before | Δ | after | Δ |
| 43.2745 | -0.003 | 43.2742 | 0.000 | 43.4017 | 0.000 | 43.4038 | 0.000 |
| 43.2698 | 0.002 | 43.2752 | -0.001 | 43.4035 | -0.002 | 43.4057 | -0.002 |
| 43.2713 | 0.001 | 43.2729 | 0.002 | 43.4006 | 0.001 | 43.4025 | 0.001 |
| 43.2724 | 0.000 | 43.2758 | -0.001 | 43.4016 | 0.000 | 43.4038 | 0.000 |
| 43.272 | | 43.275 | | 43.402 | | 43.404 | |
| | -0.003 | | | | -0.002 | | |
| **StD.** | **1.5** | **µm** | | **StD.** | **1.2** | **µm** | |

*Fig. 34 Laser finder Calibration Comparison*

## *7.2 Fiducialization Repeatability*

Four sets of measurements were taken which began with centering the pulsed wire on the magnetic axis, measuring the wire position, and then taking interferometer readings of the tooling balls (see fig. 34, 35). After each set, the magnets as well as the interferometer were moved to guarantee independent measurements. The measurements of each set were first reduced by taking out the skewness between the reference lines and then used to project the perpendicular offset of the tooling balls from the magnetic center line. The measurement data is presented in figure 36. Fig. 37 shows the results of the data reduction. All but two of the independent measurements agree to within two µm, the worst data point is 6 µm off. The standard deviation of all measurements is 2.3 µm.

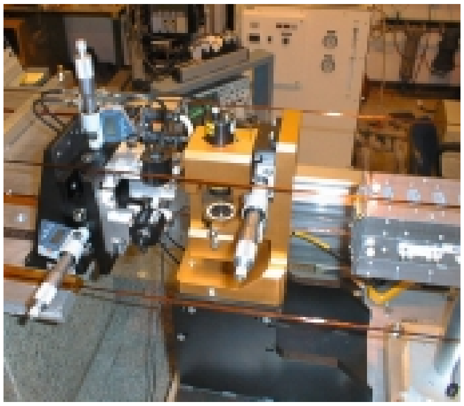


*Fig. 34 Pulsed wire detector and Wire Finder*

*Fig. 35 Bench with undulator magnet and interferometer set-up*

| | | Wire (Magnetic Axis) | | Interferometer Readings | |
|---|---|---|---|---|---|
| | | z | y | u | v |
| Measurement Set 1 | WF_G | 0 | 50.533 | 0 | 0.298 |
| | WF_B | 2223 | 50.503 | 2223 | 0.9293 |
| | M1_TB4 | | | 169 | 0.351 |
| | M1_TB8 | | | 1134 | 0.7418 |
| | M2_TB4 | | | 1162 | 0.6367 |
| | M2_TB8 | | | 2129 | 0.9225 |
| Measurement Set 2 | WF_G | 0 | 50.532 | 0 | -0.3343 |
| | WF_B | 2223 | 50.501 | 2223 | 0.2683 |
| | M1_TB4 | | | 169 | -0.281 |
| | M1_TB8 | | | 1134 | 0.0551 |
| | M2_TB4 | | | 1162 | -0.0073 |
| | M2_TB8 | | | 2129 | 0.2639 |
| Measurement Set 3 | WF_G | 0 | 50.534 | 0 | 1.9019 |
| | WF_B | 2223 | 50.504 | 2223 | 2.5144 |
| | M1_TB4 | | | 169 | 1.9518 |
| | M1_TB8 | | | 1134 | 2.3371 |
| | M2_TB4 | | | 1162 | 2.2279 |
| | M2_TB8 | | | 2129 | 2.5051 |
| Measurement Set 4 | WF_G | 0 | 50.532 | 0 | -0.0784 |
| | WF_B | 2223 | 50.501 | 2223 | 0.5409 |
| | M1_TB4 | | | 169 | -0.0226 |
| | M1_TB8 | | | 1134 | 0.3654 |
| | M2_TB4 | | | 1162 | 0.2553 |
| | M2_TB8 | | | 2129 | 0.5368 |

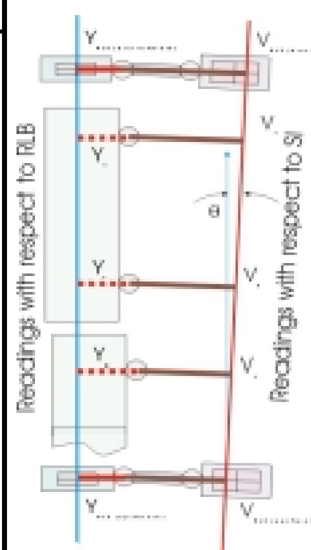



*Fig. 36 Fiducialization Rpeatability*

| | Measurement 1 | Measurement 2 | Measurement 3 | Measurement 4 | Average |
|---|---|---|---|---|---|
| M1_TB4 | 50.536 | 50.537 | 50.535 | 50.538 | 50.537 |
| M1_TB8 | 50.639 | 50.650 | 50.641 | 50.644 | 50.644 |
| M2_TB4 | 50.526 | 50.528 | 50.524 | 50.526 | 50.526 |
| M2_TB8 | 50.524 | 50.523 | 50.522 | 50.524 | 50.523 |
| | Δ | Δ | Δ | Δ | |
| M1_TB4 | 0.84 | -0.56 | 1.51 | -1.79 | |
| M1_TB8 | 4.29 | -6.26 | 2.30 | -0.33 | |
| M2_TB4 | -0.09 | -1.87 | 1.79 | 0.16 | |
| M2_TB8 | -0.71 | 0.06 | 1.59 | -0.94 | |

*Fig. 37 Fiducialization test analysis*

## 8 Conclusion

Initial fiducialization measurements confirm that the “Magnetic Centerline Determination” and “Transfer onto Fiducials” tolerances cannot only be met, but at least cut in half. The alignment jig has been assembled in the “test assembly” area and successfully tested. Presently, the fine alignment is scheduled for the end of the year[12].

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