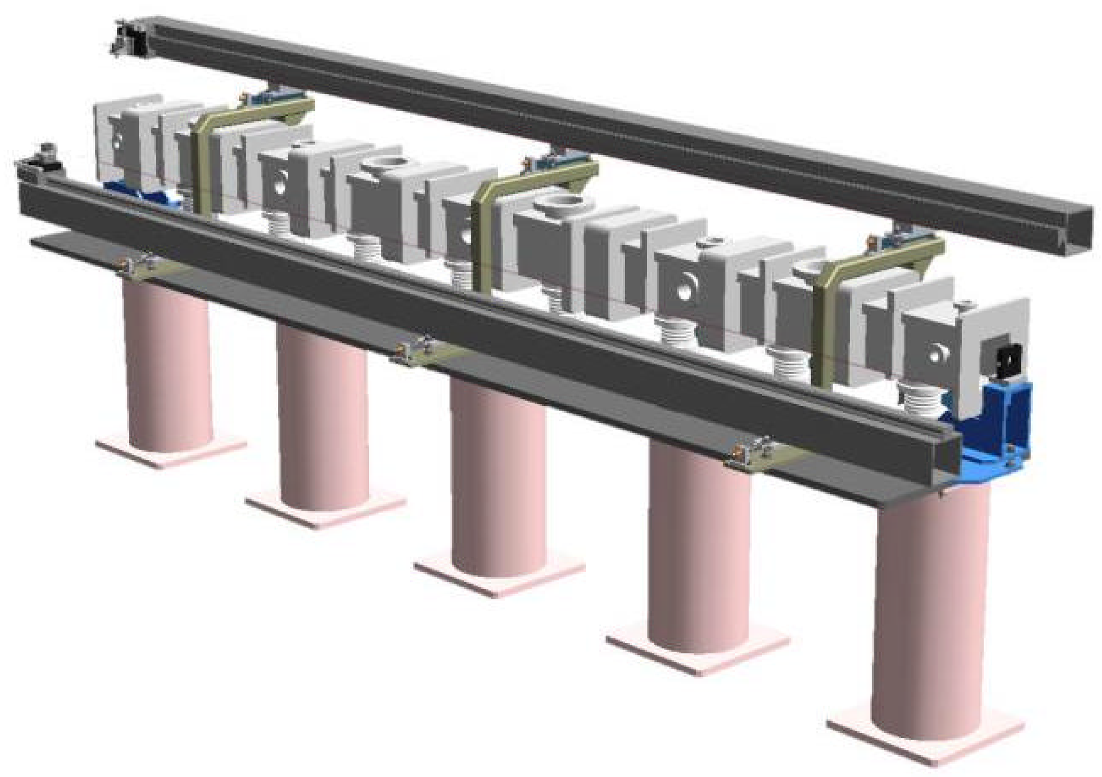
Stanford Linear Accelerator Center
established 1962

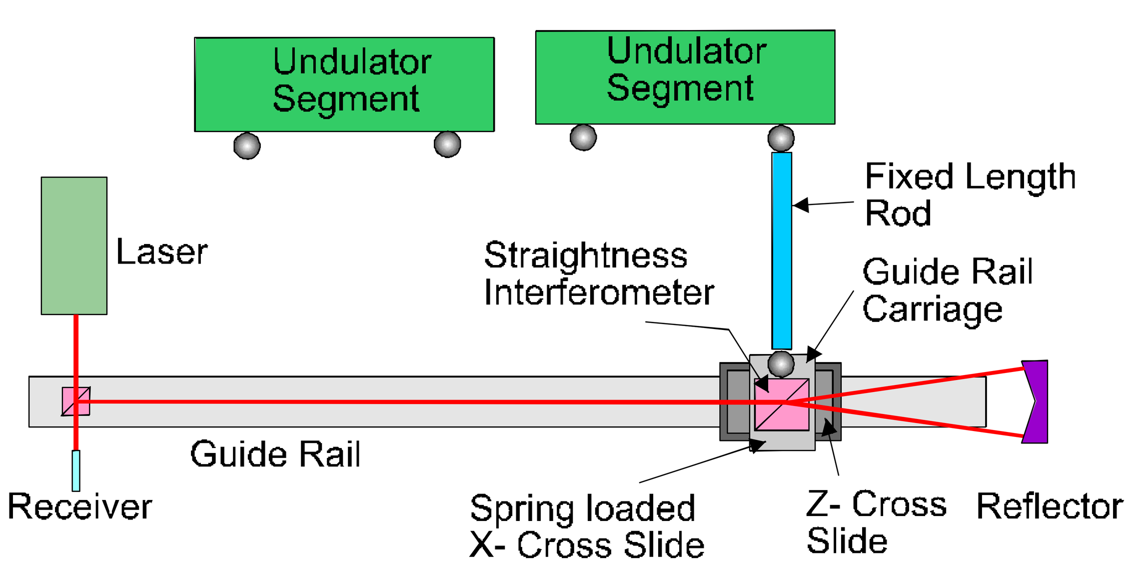
Very High Precision Alignment of Undulator Magnets in a Vacuum Chamber

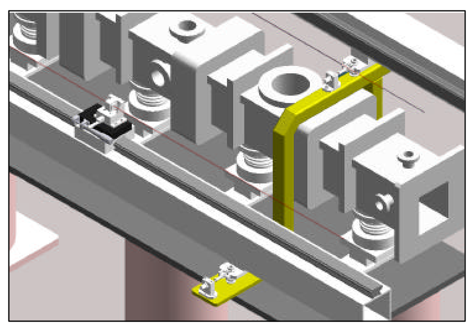
Overview

A four meter long Visible-Infrared SASE Amplifier (VISA) undulator is being prepared as part of a R&D program towards a fourth generation light source. It consists of four 99cm long magnets enclosed in a vacuum chamber. Successful positioning will be attained when the magnetic centerline of all four undulators is aligned to within 50µm so that maximum Self-Amplified Spontaneous Emission (SASE) gain can be achieved. The assembly will be installed at Brookhaven National Laboratory by the end of the year.

This presentation focuses on the procedural, mechanical and geometrical problems associated with the chosen method for very precise straightness alignment. Some hardware and software details are presented. Testing has so far suggested very favorable results.







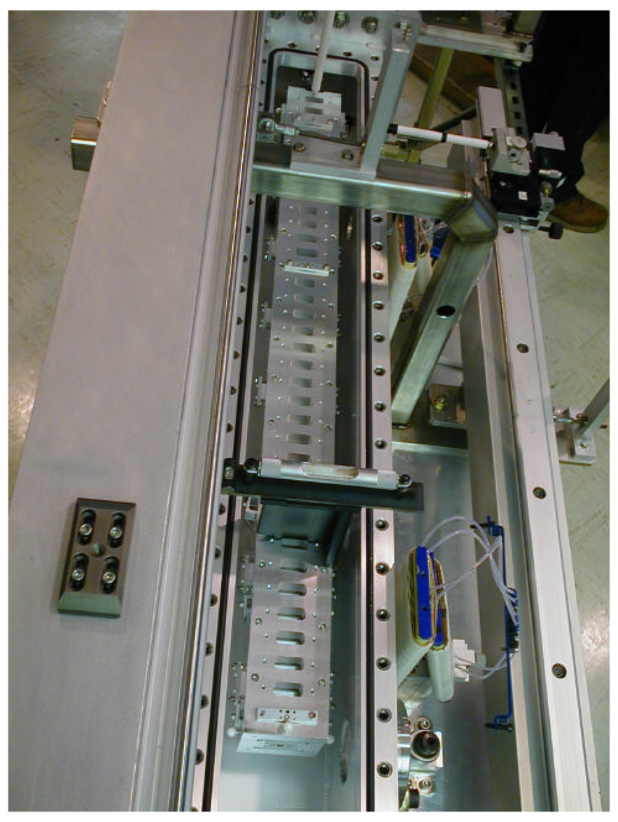
Alignment Error Budget	*[µm]*
Magnetic Centerline Determination	20
Transfer onto Fiducials	23
Positioning	28
Setup RLB with respect to Undulators	29
Total (added in quadrature)	51

Alignment Procedure

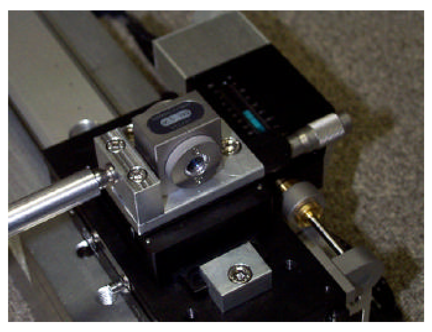
The four undulator magnets are installed inside the vacuum chamber. Conventional alignment methods are used for mechanical installation providing about 150 to 200 µm accuracy. Since the goal is to align the undulator magnets to at least 50 µm, straightness interferometry was chosen for the fine alignment. Two independent laser systems are positioned horizontally and vertically relative to the magnets (see figure above). Fiducialized tooling balls on the magnets are accessable through portholes on the side and top of the vacuum chamber as shown in the detailed view above. Measurements are made by inserting a rod between the interferometer and a fiducialized tooling ball on each magnet end [3,4]. The raw data consists of a series of readings taken as the rod is arced so that a distance perpendicular to the laser line can be obtained (see *Circle Fit* figures on next panel).

Since the fiducialized magnets and the laser system have different coordinate systems with different datums, a similarity transformation is used to translate laser interferometer readings into magnet readings. Once this is accomplished, and using the fiducialization values of the magnets, a line fit is used to determine what movements will be necessary to align the magnetic centerlines to within the specified tolerance. (see *Alignment Software Procedure* on the next panel for further details.) This line is defined by a Reference Laser Beam that represents the desired path of the particle beam. Measurements to the particle beam are possible by using a Laser Finder device placed at either end of the vacuum chamber [5].

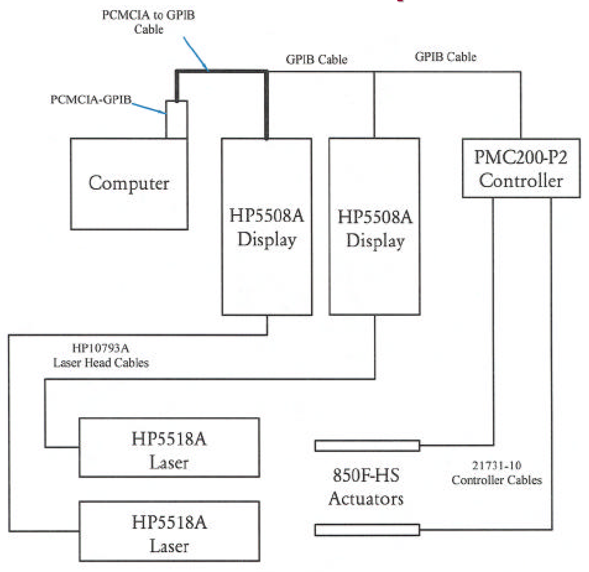
Undulator Segment in Vacuum Chamber With Both Rods Measuring Far End of Magnet



Interferometer on Sliding Stage With Actuator



Measurement and Control Hardware Profile



Alignment Hardware

Two separate rails mounted on beam supports are shown in the photos on the left. Moving along the rail is a carriage with two cross-slide stages and an interferometer mounted on top. Positions perpendicular to the laser beam are found at each tooling ball on each magnet (via a circle fit).

A flowchart of the measurement and control hardware necessary to automate this process is also shown. The arcing of the rod and all actuator and interferometer measurements (both horizontal and vertical) are automatically generated and recorded .

The rod is designed so that no net force is applied to the magnets. This is accomplished with a spring system connecting the magnet to the interferometer while the rod is in place. The rod has a conical end that is designed to avoid slippage on the tooling balls as it is arced. The weight of the rod and interferometer assembly were neutralized by using a counter-weight system for vertical measurements. [4]

As mentioned, access to the undulator tooling balls is limited to openings on the top and one side of the vacuum chamber. One horizontal rod and one vertical are carefully inserted into the portholes while trying to avoid breaking the interferometer beam. Once in place and ready to arc, actuator positional feedback is necessary to carefully avoid over-arcing the rod and possibly touching the side of the porthole.

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Alignment Software Procedure

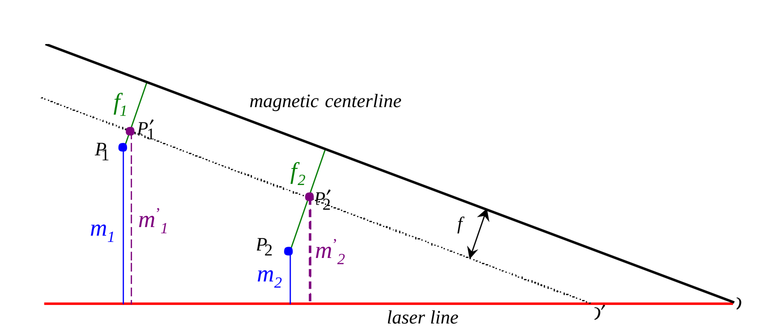
Preliminary Alignment

- measure the horizontal and vertical position of all four magnets and two Laser Finders (LF) using best-fit circles
- correct sign according to magnet position (being left or right of interferometer beam) and interferometer setting
- transform interferometer measurements into magnetic measurements using similarity transformation. Note: The angle of rotation is computed by knowing the *y* and *v* values at each LF (see figure)
- align magnets according to computed results

Refinement

- measure all magnets and LFs again and correct for magnet position and interferometer setting
- line fit
- similarity transformation to position best-fit line to LF centers
- align all magnets and read final values

Line Fit of Magnetic Center Line



Using the average fiducialization value for all magnets $\bar{f}$, at point P' (P'_1 or P'_2) connecting to the measured interferometer values (m_1 and m_2), the projected pseudo measurements m' (m'_1 or m'_2) are found for each magnet's a by,

$$m' = m + \cos a\,(f - \bar{f})$$

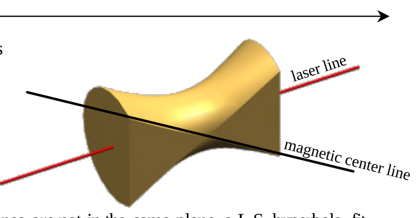
where

$$\sin a = \frac{m'_1}{O'P'_1} = \frac{m'_2}{O'P'_2} = \frac{|m'_2 - m'_1|}{\|P'_1 P'_2\|} \cong \frac{|m_2 + f_2 - m_1 - f_1|}{\|P_1 P_2\|}$$

For small a's a simple L.S. line is computed as

$$x = x_c + \frac{x_i}{z_i} z$$

where x_c is the x-intercept



If a is determined to be large enough and the lines are not in the same plane, a L.S. hyperbola fit represents the relationship between the laser and best-fit magnet lines (see figure), where

$$x = x_c \pm \sqrt{a^2 + q^2 (z - z_i)^2}$$

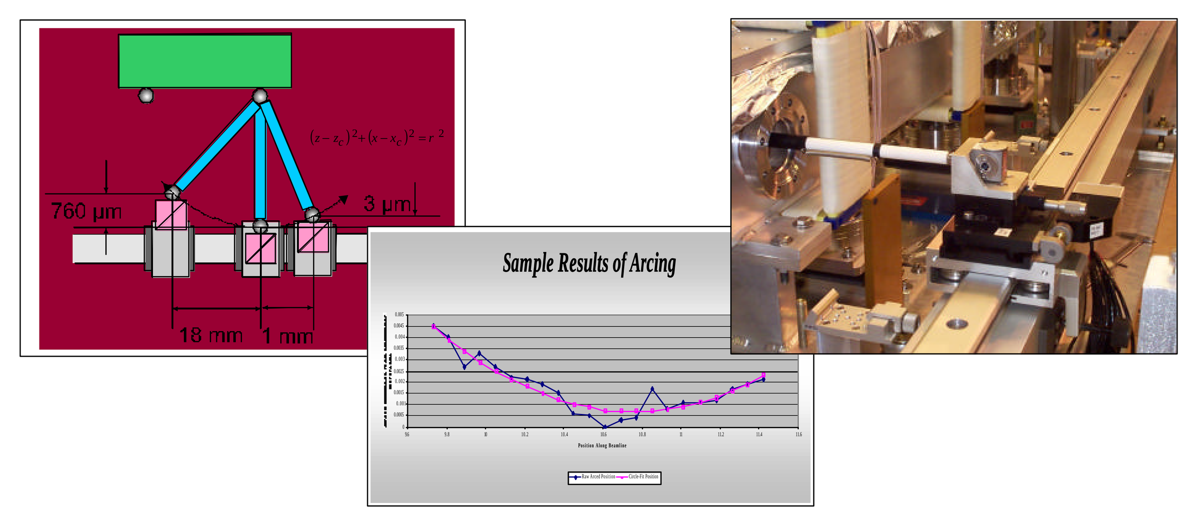
The vertex is positioned by the first two unknowns z_i and x_c and the asymptotes are characterized by the last two unknowns a and $q = a/b$

Test Results

Relative Position of Tooling Balls on Each Undulator (without fiducialization data)

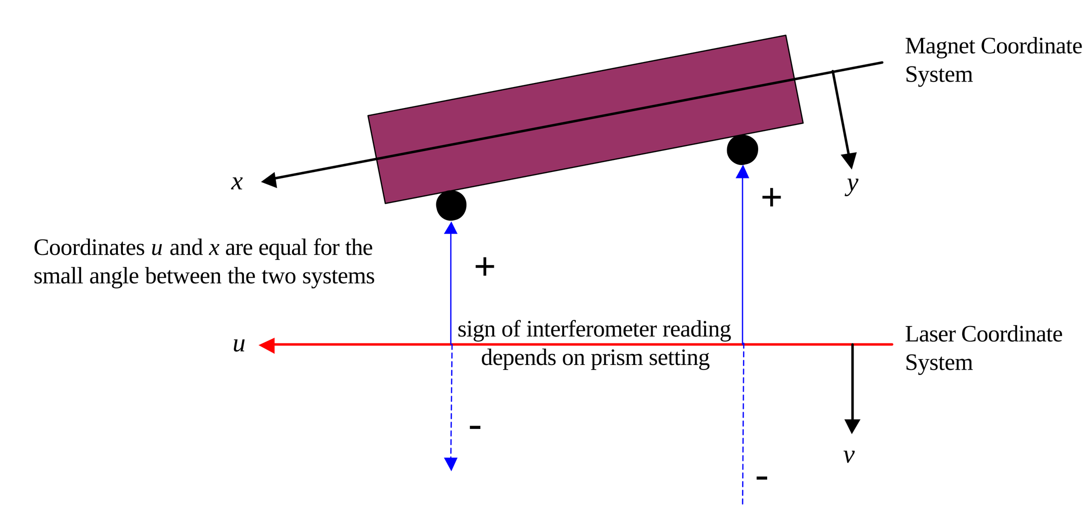
	Horizontal Position (µm)	Vertical Position (µm)
Magnet 1	9.0	3.6
	13.9	-15.8
Magnet 2	12.3	12.1
	-85.5	-9.1
Magnet 3	12.5	1.3
	16.8	0.2
Magnet 4	15.3	13.0
	5.6	-5.3

Circle Fit to Measure Relative Magnet Positions



A best-fit circle is used to determine the extreme position of the interferometer (perpendicular to the laser beam). Discrete readings are automatically gathered where the dependant variable *z* (position along the axis of the laser beam) is actually considered an observable instead of the usual known value. This gives a better solution (unbiased) by allowing slightly less accurate "along the beam" values to be used. The circle fit is used to smooth the data, not to find the distance (radius) from the interferometer to the magnet's tooling ball. (Only about 0.5% of the perimeter of the circle is actually measured.)

Coordinate System and Similarity Transformation



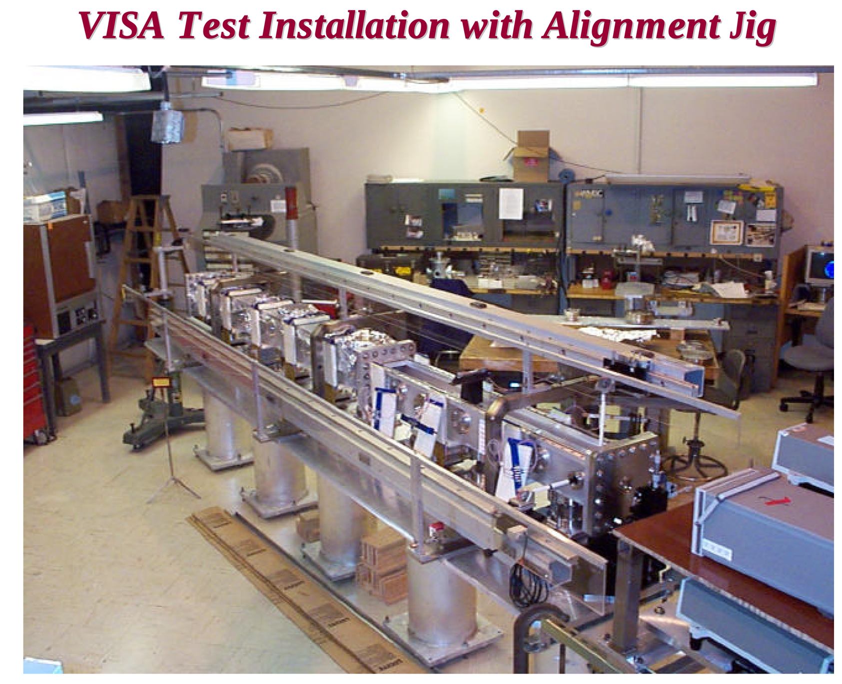
The position of the magnets relative to the laser coordinate system and the setting on the interferometer are both considered to correctly define a consistent RH coordinate system.

A position *y* in the magnet coordinate system is found by the similarity transformation:

$$y = t_y - \sin a\, u + \cos a\, v$$

where a = the rotation between the coordinate systems

VISA Test Installation with Alignment Jig



Summary and Status

This presentation covered some of the details on various hardware and software considerations necessary for better than 50µm accuracy. Testing continues on the VISA assembly in Brookhaven and fine alignment is scheduled for the end of 1999.

References

[1]R. Carr et al., *The VISA FEL Undulator*, Proceedings of the 20th International FEL Conference (FEL98), Williamsburg, VA, August 1998.

[2]M. Libkind et al., *Mechanical Design of the VISA Undulator*, Proceedings of the 1999 Particle Accelerator Conference (PAC99), New York City, NY, March/April 1999.

[3]G. Rakowsky et al., *Measurement and Optimization of the VISA Undulator*, Proceedings of the 1999 Particle Accelerator Conference (PAC99), New York City, NY, March/April 1999.

[4]R. Ruland et al., *Alignment of the VISA Undulator*, Proceedings of the 1999 Particle Accelerator Conference (PAC99), New York City, NY, March/April 1999, SLAC Pub. 8086.

[5]Z. Wolf et al., *Alignment Tools Used to Locate a Wire and a Laser Beam in the VISA Undulator Project*, to be published in Proceedings of the Sixth International Workshop on Accelerator Alignment at ESRF, Grenoble, France, 1999

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