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ENGINEERING SUMMER SCHOOL

Part VI
Alignment

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OUTLINE

- Deformation
- Alignment instruments
- Pre-analysis
- Re-alignment

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ALIGNMENT

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Deformation

COVERED IN THIS SECTION

Objective

Understand that good alignment is temporary.

Key points

- Beam lines are attached to buildings, and buildings move over time.
  - Settlement, compression
  - Diurnal motion
- Vacuum can move guides
- Partial remediation by scheduling final alignment activities after most of deformation has occurred.
- Periodic realignment might be necessary.
- Feedback systems and automated realignment might be possible.

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EXAMPLES: SETTLEMENT AND COMPRESSION

- ORNL – SNS accelerator tunnel
  - Final part of tunnel was constructed on compacted fill: side slope from excavation for target building basement.
  - Accumulated settlement now exceeds 200 mm.
  - Current rate ~ 1 mm/year: frequent realignment required.
  - Elsewhere only 10 mm to 50 mm.
- GOOD: Swiss Light Source
  - Floor of ring is physically isolated from exterior walls and central support column.
  - 0.9-mm tilt across ring in a decade, with seasonal changes.

Target building excavation showing typical side slopes

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SETTLEMENT AND COMPRESSION

- ORNL SNS Target monolith: 5 mm during initial construction
- Elevation for each new beam line determined by its measured position, not original design value.
- Construction of adjacent beam line next to an existing one can cause additional deformation.

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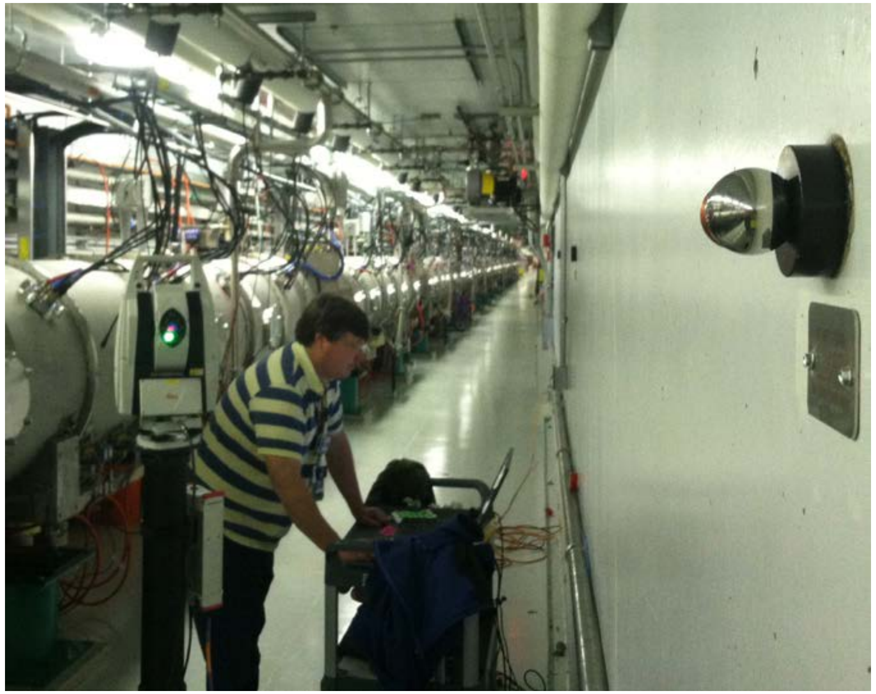
WALLS

- More vulnerable to both vertical and horizonal motion.
- Importance: survey monuments can be mounted on walls, even if the beam line isn't.
- Avoid exterior building walls for survey monument placement because of diurnal motion from sunlight.



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THE WALLS ARE CLOSING IN

At 2-m ht, wall-to-wall distance: -0.77 mm

At 1-m ht, wall-to-wall distance: -0.66 mm

At floor, wall-to-wall distance: -0.38 mm

- Accumulated deformation over ten years is an order of magnitude larger than the desired alignment precision in the cave.

THE WALLS ARE SPREADING APART

+1 mm
width
typical

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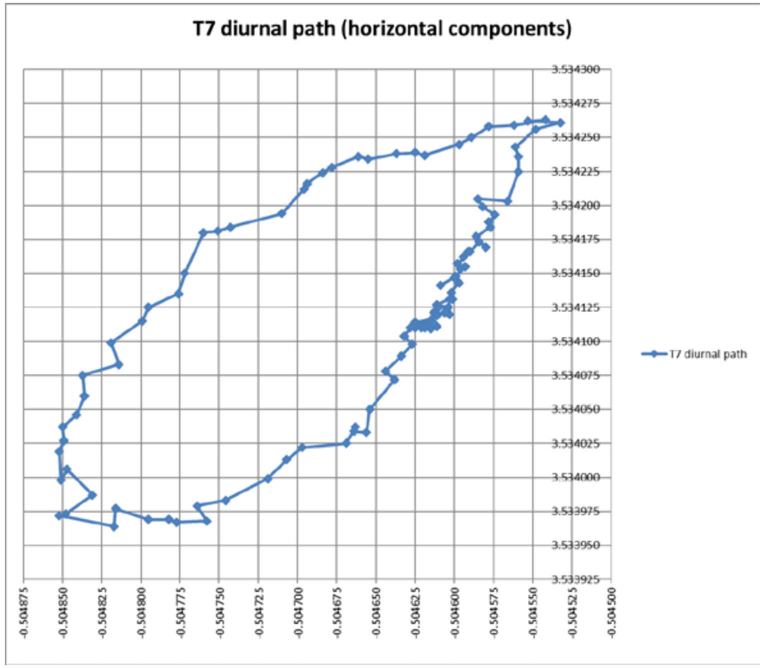
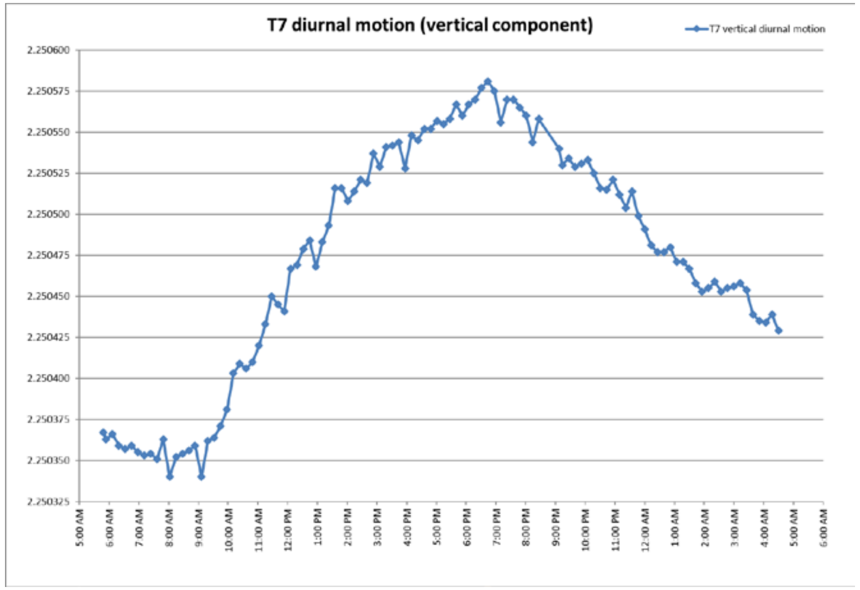
DIURNAL MOTION





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TEMPERATURE EXAMPLES

- HVAC vent pointed at critical component.
- Scale changes to initial survey control network on SNS instrument hall floor. Same with SINQ.
- Air temperature stability needed for accurate results from laser tracker (scintillation).
- Signal conditioning (temp control in racks).

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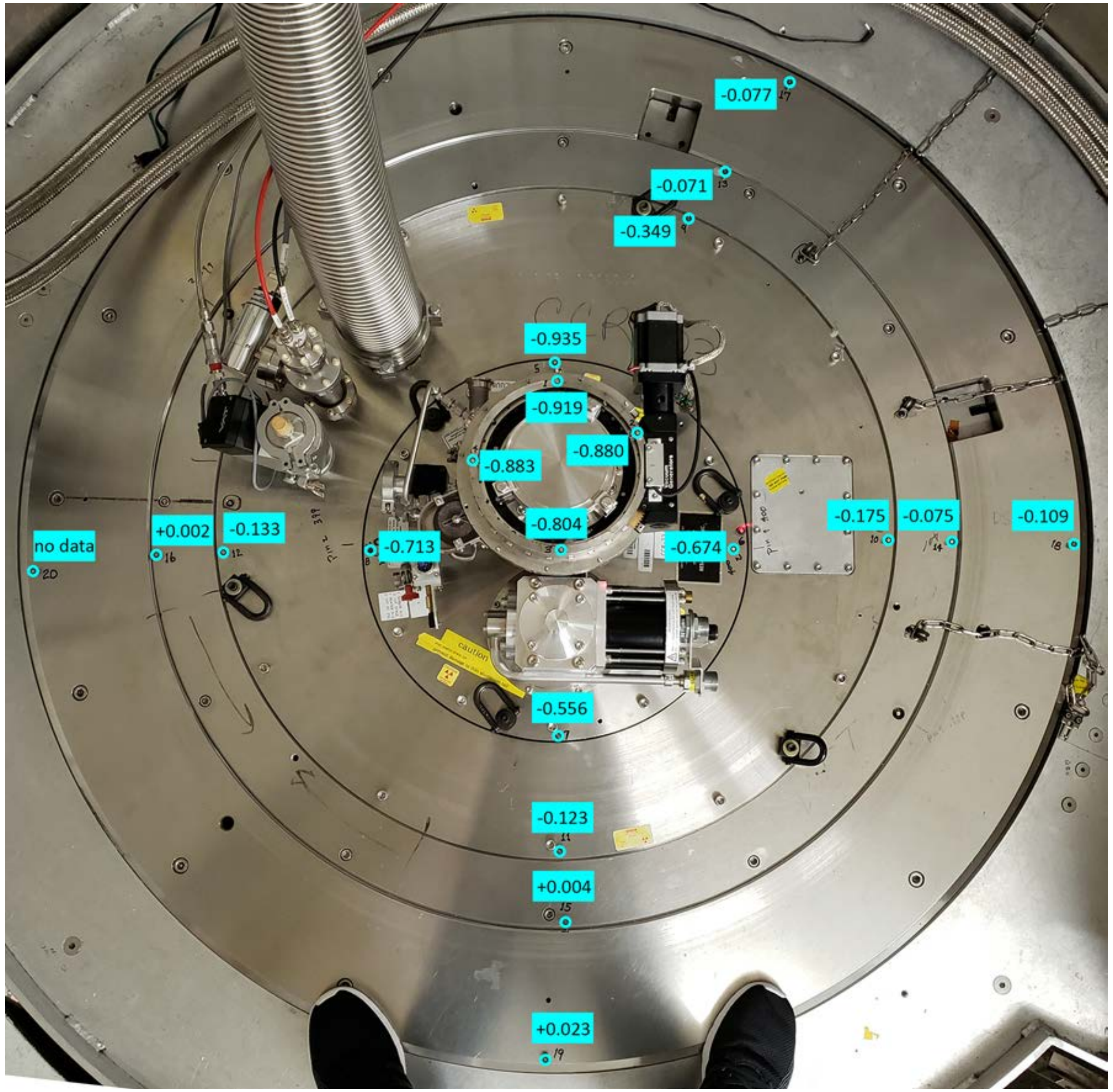
VACUUM EXAMPLE

- Deformation of sample tank under vacuum (problem if sample hangs from stick beneath top flange).
- Vacuum systems have the potential to apply force to guides and cause misalignment.
- Bellows between adjoining housings should not transmit force.
- Sometimes it is possible to do final alignment after vacuum.



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Alignment & Metrology Instruments

COVERED IN THIS SECTION

Objective

Review the instruments commonly used in alignment and metrology

Key points

- Most widely used instrument for industrial alignment is the laser tracker.
- Coordinate measurement machines (CMMs) can provide sub-micron results in small volumes.
- Theodolites used for measuring angles, and autocollimation.

LASER TRACKERS

- Measures slope distance, horizontal angle, and vertical angle (the three components of a point in a spherical coordinate system).
- Target is the center of a spherically mounted retroreflector.
- Motors keep the tracker aimed at the retroreflector as it is moved.
- Originally developed here at NIST.

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RETROREFLECTORS AND NESTS

- Retroreflector
  - Three mutually perpendicular mirrors have the property of reflecting light back parallel to incoming ray.
  - Precisely mounted at center of high-precision sphere.
- Nest
  - Conical bearing surface for sphere.
  - Intent is for center of reflector to remain fixed in one location, regardless of how the sphere is oriented in the cone.
  - Magnet holds reflector to nest, but magnet does not contact reflector.

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MORE RETROREFLECTORS AND NESTS

Nests for 0.5-inch reflector.
Shank degrades repeatability.

Non-shank
fiducial nest

Floor monument

Inexpensive washers for
conical-head screws
(horizontal surface only).

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BEST PRACTICES WITH LASER TRACKER

- Laser tracker accuracy degrades with distance.
  - Tracker should be positioned close to the component being aligned.
  - Transform into network coordinate system using monuments closely surrounding the component.
- Environmental factors
  - Stable temperature.
  - No vibration.
  - Exclude other workers to the extent possible.

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COORDINATE MEASUREMENT MACHINE (CMM)

- Measures coordinates directly in a Cartesian coordinate system by moving a probe along three mutually perpendicular axes.
- Some CMMs can measure to sub-micron precision over small volumes.
- Higher-precision CMMs are usually restricted to smaller measurement volumes.
- Useful for fiducializing neutron guides, among other things.

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CMM ARM

- Measures angles with rotary encoders at a series of joints between known-length segments.
- CMM arm is less expensive.
- But isn't comparable to the accuracy of high-precision CMM.

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THEODOLITE

- Measures horizontal angles and vertical angles with precision similar to laser tracker.
- If it measures distances, too, then it's called a total station. (distances inferior to laser tracker)

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ALIGNMENT

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Alignment plan and pre-analysis

COVERED IN THIS SECTION

Objective

Demonstrate that your alignment plan meets the scientist's alignment requirements

Introduce criteria for survey network design

Introduce criteria for positioning fiducial points

Understand the two main approaches to alignment pre-analysis

Key points

- Pre-analysis: estimating suitability of schemes for attaining alignment goals.
- Must propagate uncertainty from measured network of angles and distances into the resulting coordinates.
- Typically this is a trial-and-error process, using specialized software.
- Handle deformation separately.

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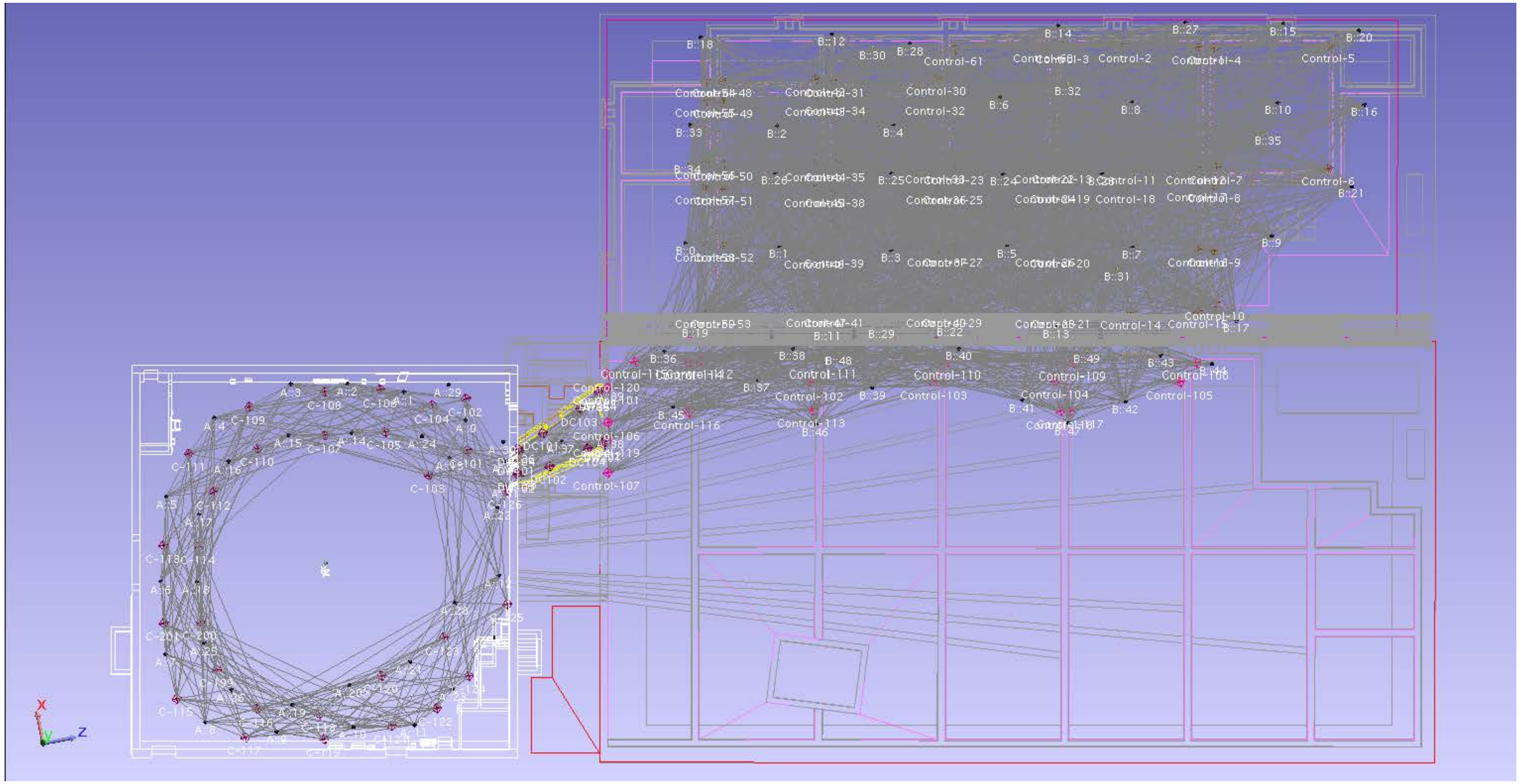
PRE-ANALYSIS OF AN ALIGNMENT PLAN

- Survey network design
  - Where to place monuments?
  - What instruments to use?
  - Connectivity?
- Fiducialization of neutron guides
  - Where to place fiducial points?
  - Or use glass surface directly?
- Physically aligning the guides
  - What instruments to use?
  - Which monuments to tie?
  - Where to set up instruments?



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SURVEY NETWORK DESIGN - MONUMENTS

- Where to place survey monuments (for trackers)?
  - Closely surrounding each component to be aligned, in 3D, if possible.
  - In positions that will remain unobstructed.
  - Attached to unmoving objects and surfaces.
  - Also in locations needed for network strength.
- Assume that you will lose monuments to obstructions and set more than minimum needed.

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SURVEY NETWORK DESIGN: INSTRUMENTS

- Which instrument(s) should be used to measure network?
  - Don't need differential levelling due to improvements in gravity orientation of laser trackers.
- Where to place instruments to make network measurements?

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FIDUCIALIZATION CONSIDERATIONS

- Where to place fiducial points?
  - Preferably near the outside corners of the component.
  - Preferably some immediately adjacent to adjustment mechanisms.
  - Visible from the side where the laser tracker will be (downstream? side?)
  - Still visible for later realignment?
- How many fiducial points?
  - Geometric minimum is three non-collinear points, but always assume that some will be obstructed or destroyed.

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TWO APPROACHES TO PRE-ANALYSIS

- Purpose is to propagate uncertainty from network of measured distances and angles into derived coordinates.
- Variance-covariance propagation
  - Classical formula based on least squares
  - Handles only uncertainty, not bias
- Monte Carlo simulation
  - Can handle bias, but would require custom programming
- Both are trial-and-error processes of modifying the parameters of the network until the goal is achieved.

$$(A^T \Sigma^{-1} A)^{-1}$$

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IMPLEMENTATION SUMMARY

1. Create survey control network
   - Place survey control monuments where needed.
   - Tie them together into a beam line coordinate system with laser tracker.
2. Fiducialize beam guides and transform them into the beam line coordinate system.
3. Align components in field with laser tracker.

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ALIGNMENT

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Re-alignment

COVERED IN THIS SECTION

Objective

Introduce ways to detect misalignment and fix it.

Key points

- Misalignment can be detected by performing periodic re-observation campaigns.
- Automated systems to detect misalignment have been used in the accelerator world (hydrostatic levels, taut wire, LVDTs).
- Physical realignment of neutron beam lines has always been manual?
- Automated realignment systems exist in the accelerator world.

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MANUALLY DETECTING MISALIGNMENT

- You left accessible fiducial points on the outside of housings for re-measurement, right?
- Deformation also affects the survey control network, so the network must be re-observed, too.
- Identify a group of points that didn't move – if possible – and transform new points onto old for comparison.
  - L-1 norm estimation
  - Successive de-weighting schemes
  - Trial-and-error, informed by knowledge of likely deformation processes
- Network datum might have to be re-defined using critical interfaces, instead.

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AUTOMATED MISALIGNMENT DETECTION

- Hydrostatic levels mounted to girders
  - Ridiculously precise (detect tides).
  - See papers published on the Swiss Light Source system.
  - Streaming path?
  - Neutron radiation effects?
- Linear variable displacement transformers (LVDTs).
- Taut-wire with capacitive sensors.
  - See effort underway for CLIC.
  - Streaming path?
- Provides insight into what happens when shielding is added.

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MANUAL REALIGNMENT

- First, do the scientists want you to do it?
  - Risk of damaging something
- Second, do you want to do it?
  - Activation
- Third, *can* you do it?
  - If initial alignment was done by sighting upstream inside guide, do you have to remove everything to realign?

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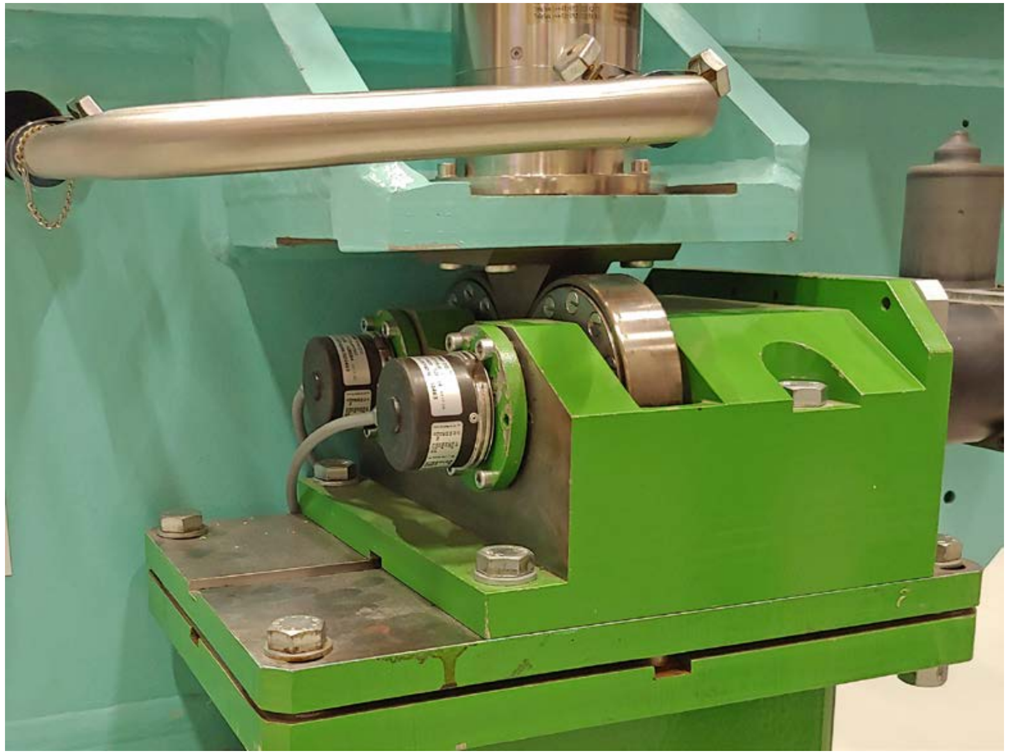
AUTOMATED REALIGNMENT

- Cam-roller system
  - See papers by Swiss Light Source.
- Wedge system
  - Contemplated by both SLS and CLIC.
- Keep an eye on ESTIA.



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QUESTIONS

Thanks for participating

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