Updating the CLS Storage Ring Reference Network
Presented by David M. Smith
2022-11-03
On behalf of the CLS SA&V Team
Background

- The Canadian Light Source (CLS) is Canada’s only Synchrotron
- Storage Ring constructed in 2003, first light December 2003
- CLS was built upon the infrastructure of the Saskatchewan Accelerator Laboratory, which was built in the early 1960’s

CLS LINAC, the same location, just sixty years apart!

Vacuum chambers being installed in February 2003
Background

• 3rd Generation Synchrotron
  • 171 m circumference
  • 2.9 GeV, 220 mA top-up
  • 22 operating beamlines
• Recently completed Phase III (2019), completed suite of operational beamlines*
• Facility is focusing on the following:
  • Renovation of older beamlines,
  • New experimental methods and expanding user base, and
  • Improving machine performance (2 RF cavities).
• Canadians love talking about our weather, typically goes from -30°C to +30°C each year

*there is room for one more insertion device beamline, but no construction plans at this time
Background

- CLS Storage Ring girders remained untouched since installation, considered OK given low alignment demands and high emittance ($\epsilon_x = 18.1$ nm-rad).

- Large Beam Position Monitor (BPM) offsets were used to steer the electron beam (150 – 500 µm) to align SR beam.

- Machine alignment became a larger concern when 1) an in-vacuum insertion device was damaged, and 2) some BPM offsets seemed to restrict top-up mode from working.

In-vacuum wiggler’s foil damaged due to missteer + orbit correction thresholds, large BPM offset and improper orbit control thresholds

Radiation indicator result 12 m downstream of insertion device. Dipoles completely misaligned from theory (black tick marks)

CLS double bend achromat layout. Orbit correction steers the beam to BPM centers plus any offsets. Not easy to move or shim individual magnets or BPMs
Background

- Before considering alignment work in SR, the reference network needs to be addressed
  
- Combination of concrete curing (seen at many new synchrotrons), equipment drift, and original network formation methods has led to a poor network (high error, poor locates)
  
  - Locate to SR Network $\geq 0.50$ mm RMS error, $\geq 1.00$ mm MAX error typical
  
  - Locate to SR Quads $\geq 0.25$ mm RMS error

- Locate error dominates any survey or alignment performed in the SR

- CLS Survey, Alignment, and Vibration (SA&V) pursued updating the network in the SR in 2021
The SA&V Team

- The SA&V team was formed in 2019 in anticipation of upcoming alignment work and
- Not a “department”, but an inter-departmental task force and research team, spend 10% - 20% of their time on SA&V work
- Glad to be back at IWAA!

**Team Mandate**

1) Develop of SA&V protocols
2) Conduct SA&V tasks
3) Maintain software, equipment, and methodologies
4) Advance knowledge
Methodology

- During the Spring of 2021, SA&V team did complete resurvey of the SR including monuments and components
- Included two beamlines, BXDS and CMCF (monuments only)
- 642 monuments, took two months due to a COVID-19 outbreak at the facility

Multiple SMR’s allowed for quick capture using auto-measure features of SA

SA&V team uses a Leica AT960-LR for survey measurements

All setups and shots shown for network creation shown in SA
Methodology

• General rules for collecting the data
  • Each point captured minimum 4 times,
  • Minimum one opposed measurement from another viewing angle. The more view angles, the better
  • Tracker is located to the original network via 3 points (Nominal Points method)

Laser tracker setups chosen to overlap to make sure each point is captured a minimum of four time. Usually each point is captured at least twice from each side.

AT960-LR can capture multiple retroreflectors quickly using Auto-Measure
Methodology

• First level of trimming outliers (data cleaning) occurred daily either on the floor or afterward when reviewing the data by best fitting shots to the original network.

• Test locates were performed through the process (every few days) to temporary USMN’s to ensure consistency

• Further trimming done in SpatialAnalyzer’s (SA) Unified Spatial Metrology Network ranking feature (USMN)
Methodology

• Goal of trimming outliers:
  • Maximum ranking of 100% (or as close as reasonably possible), and
  • Minimize the number of measurements removed, less than 10%.

• “the percentage of the expected 3-sigma envelope consumed by the maximum measurement residual […] points with smaller rankings are more tightly clustered around the optimal value” [1].

• Max IV Survey, Alignment and Mechanical Stability team provide excellent discussion of how the ranking works for outlier removal [2]. We followed many of the procedures outlined in their paper.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Step</th>
<th>Ranking [%]</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 4 measurements for point</td>
<td>1</td>
<td>&gt;150</td>
<td>Single measurement set to 0</td>
</tr>
<tr>
<td>2</td>
<td>100 &lt; x &lt; 150</td>
<td>Single measurement set to 0.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>&gt;100</td>
<td>Single measurement set to 0.25</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Ranking analysis guideline for point weighting.

Methodology

- Boundary conditions used to minimize alignment at key transition area (sensitive beamlines, Booster Ring to SR interface). Boundary conditions brought in as mini-USMNs (USMN with points)

- These areas are perturbed less than the other point groups at the cost of a residual error

- Added benefit, helps minimize alignment at sensitive transition areas, where alignment could affect machine performance

<table>
<thead>
<tr>
<th>Boundary Condition</th>
<th>Weight</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical Reference Network</td>
<td>0.1</td>
<td>Original machine alignment</td>
</tr>
<tr>
<td>BXDS Focusing Region</td>
<td>2.0</td>
<td>USMN included 4 instruments</td>
</tr>
<tr>
<td>CMCF Focusing Region</td>
<td>2.0</td>
<td>USMN included 6 instruments</td>
</tr>
<tr>
<td>BTS + SR Interface</td>
<td>3.0</td>
<td>USMN included 4 instruments</td>
</tr>
</tbody>
</table>

Table 2: Final weighting of boundary conditions.
Methodology

• Network uncertainty calculated to 99.7% confidence interval (3σ), 500 samples (analysis takes ≈4.5 hours)

• End goal for final network:
  • Average network error ≤ 0.100 mm,
  • Average network uncertainty ≤ 0.050 mm
Results

• Cleaning guidelines applied to data

• After cleaning the data, 8% of original points were removed, mostly control points from the Historical Reference Network

• We were able to reach ranking of 100%, but noticed diminishing returns on final network result around 110%

• About 14 different USMN iterations were completed

<table>
<thead>
<tr>
<th>Table 3: Outlier results before and after cleaning</th>
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</thead>
<tbody>
<tr>
<td>Before-Cleaning</td>
</tr>
<tr>
<td>Number of Stations</td>
</tr>
<tr>
<td>Number of Points</td>
</tr>
<tr>
<td>Number of Measurements</td>
</tr>
<tr>
<td>Max Ranking</td>
</tr>
<tr>
<td>RMSE of network (mm)</td>
</tr>
</tbody>
</table>
Results

• Significant change in some areas from original network

<table>
<thead>
<tr>
<th>Error (mm)</th>
<th>Ux (mm)</th>
<th>Uy (mm)</th>
<th>Uz (mm)</th>
<th>Umag (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.094</td>
<td>0.045</td>
<td>0.048</td>
<td>0.131*</td>
</tr>
<tr>
<td>RMS</td>
<td>0.127</td>
<td>0.056</td>
<td>0.056</td>
<td>0.198</td>
</tr>
</tbody>
</table>

* did not meet our goal criterion

Table 4: Network statistical results

Graphical displace showing magnitude change from original network to the new network. Minimum change captured in blue (min = 0.04 mm), max change in red (max = 5.18 mm)

• Did not meet uncertainty goal in Z axis, but we did in the X and Y axes (horizontal)

• Average error < 0.100 mm
Conclusion

• Overall the creation of the new network was successful

• New locates averaging less than 0.080 mm RMS error
  
  • Not surprising it’s better given the method of capture, but does it describe reality?

  • Significant deviation from original network, how much is 20 years of shifting concrete and components, how much from other factors

  • Future work reviewing residual error in the boundary condition areas, compare against beamline alignment

  • Desire to continue with epochs of measurement once we’re confident in path forward
Conclusion

- New network has since been used for girder adjustments in the Storage Ring, “quasi-alignment”
- Girder moves were to eliminate large BPM offsets, moving girder to BPM position, remove stress on orbit control
- Further work, analysis needed before pursuing SR alignment (diagnostic tools, simulations, quad centers)
Future Work

• Further study of new network ongoing, continuing to survey other machine areas in the meantime

• Booster Ring (BR) next area of interest
  • BR has always had major alignment issues (poor energy acceptance, high dispersion)
  • Goal is to update network in BR, measure components
  • Evaluate magnet positions and work with physicists to simulate alignment changes
  • Develop our diagnostic tools (magnet fiducialization, corrector current measurements)

• Plan is to first develop a methodology to align (smooth) the BR. If successful (proof of concept), this will be applied to further alignment in the Storage Ring.
Acknowledgments

• Only one member of a larger team!

• Special thanks to those from other facilities who met with our team for discussions on our alignment work:
  • Behrouz Afzali Far and MAX IV SAM team
  • Rodrigo Junqueira Leao, GSI Helmholtz Centre for Heavy Ion Research

• Special thanks to IWAA International and Local organizing committees