SLS 2.0 HIGH-PRECISON ALIGNMENT OF THE UPGRADED STORAGE RING USING THE ELECTRON BEAM

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1. SUMMARY

The Swiss Light Source, SLS, is an electron accelerator and storage ring, built to use the emitted synchrotron light to conduct groundbreaking research in biomedicine, engineering and natural sciences. The storage ring has been rebuilt as SLS2.0 to improve brightness and reduce horizontal emittance from 5 nm to about 150 pm. This decrease in beam size makes the machine not only more capable, but way more sensitive to a correct alignment.

The base is a solid reference network, which consists of 727 reference points distributed around the building. Using Laser trackers, vibrating and moving wires and precise manual adjustment mechanics like wedges and differential screws, the roughly 1000 magnets along the 288-meter circumference ring were aligned with a precision of 30 µm RMS Element to Element. This allowed to store an electron beam in the ring, whose initial orbit was only 0.5mm off the target of 288m.

To further improve the performance of the machine, one must go beyond the capabilities of geodetic devices like laser trackers and theodolites. Using the electron beam as measurement device, exact locations of misalignment can be determined by the feedback pattern of the corrector magnets. The realignment can then be conducted live, with stored electrons flying through the machine at lightspeed, by using remotely driven, small step motors to correct for values in the Micrometer region.

Freeing up the magnetic correction of the electron beam by performing a precise Alignment makes the Lightsource much more capable and competitive, laying the foundation to more pioneering discoveries.

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2. PSI AND THE SWISS LIGHT SOURCE

The Paul Scherrer Institute (PSI) is the largest research center for the natural sciences and engineering in Switzerland, hosting large-research facilities for neutron, proton, muon, and photon science. PSI conducts research covering the three pillars of fields of future technologies and materials, energy and the environment, and human health. Since the turn of the 21st century, a central tool in achieving ground-breaking science in these fields has been the Swiss Light Source synchrotron facility (SLS), which began operation in early 2001. Users and the in-house scientific staff have driven scientific endeavors as diverse as bioimaging, molecular biology, novel electronic materials, nano magnetism, catalysis and energy research, and cultural heritage, to name just some examples. Indeed, two recent Nobel prizes were awarded for discoveries in part enabled by experimental data obtained at the SLS. The SLS has attracted users worldwide and has proved to be such a highly sought-after research tool for two primary reasons. The excellent performance of the underpinning electron accelerator and storage ring, including its high-performance reliability and stability, made the SLS the benchmark in synchrotron machine performance until well into the second decade of this century. [1]

3. SLS 2.0 UPGRADE AND ALIGNMENT REQUIREMENTS

With the advent of novel technologies in accelerator physics and the consequent emergence of the next generation of storage-ring facilities known as diffraction-limited storage rings (DLSRs), it became clear a decade ago that an upgrade of the SLS in like manner was pressing [24]. Planning of the upgrade began in 2014 with the submission of a Letter of Intent to the Swiss State Secretary for Education, Research, and Innovation. After a preparatory period stretching over 9 years, the last photon to be produced by the original SLS machine was at 8:00 am on 30th September 2023. DLSRs offer a quantum-leap improvement in horizontal electron emittance by the implementation of multibend achromats (MBAs). Importantly, this innovation provides an opportunity to exploit knock-on effects down the technological chain that mean that in many cases, the performance of the beamlines can be expected to be enhanced by orders of magnitude, depending on the relevant figure of merit. [1]

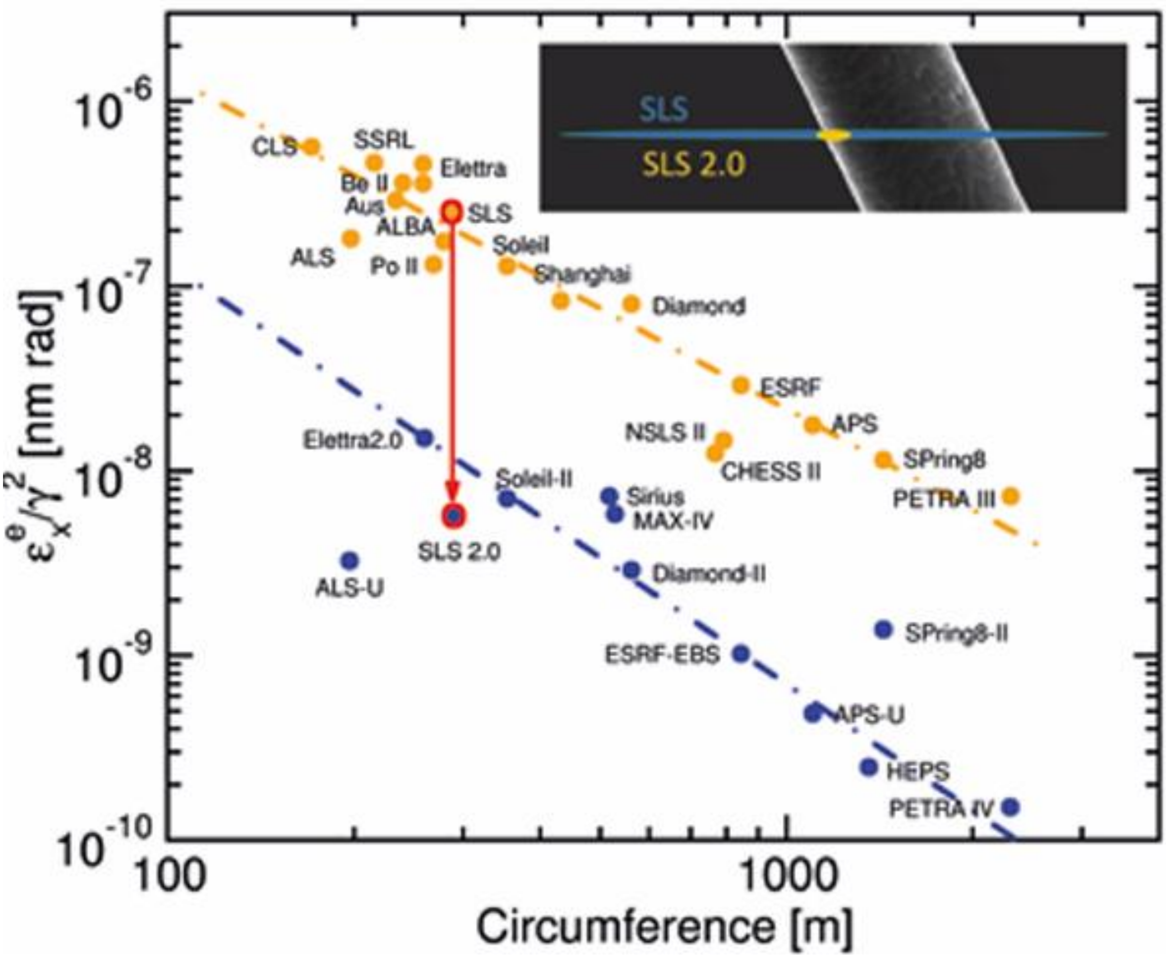

Figure 1. Horizontal electron emittance for various Lightsources and their upgrades. The inset shows the cross-section of the electron beam compared to a typical human hair [1]

This upgrade of the SLS and the achieved improved beam size also require a very precise alignment of all components. There are roughly 1000 Magnets on 60 support structures (Girders) over the 288-meter circumference ring. The electron beam is running inside a 20mm aperture vacuum chamber and in some areas like injection or straight section, this aperture even goes down to as low as 9mm. In Figure 2, the listed alignment requirements show the required precision.

Girder absolute	60 µm RMS
Girder- Girder	20 µm RMS
Individual component	30 µm RMS
Component roll error	300 µrad RMS

Table 1. Alignment Tolerances defined by beam dynamics

The layout of the SLS 2.0 consists of 12 almost identical Arcs, that are made up of five Girders. This means, that the Alignment of the individual components must be performed by 30 um RMS to each other on each Girder, using a set of mechanisms with five degrees of freedom. For vertical adjustment, each magnet can be aligned by wedges. In the horizontal plane, differential screws are used to move the magnets in small steps.

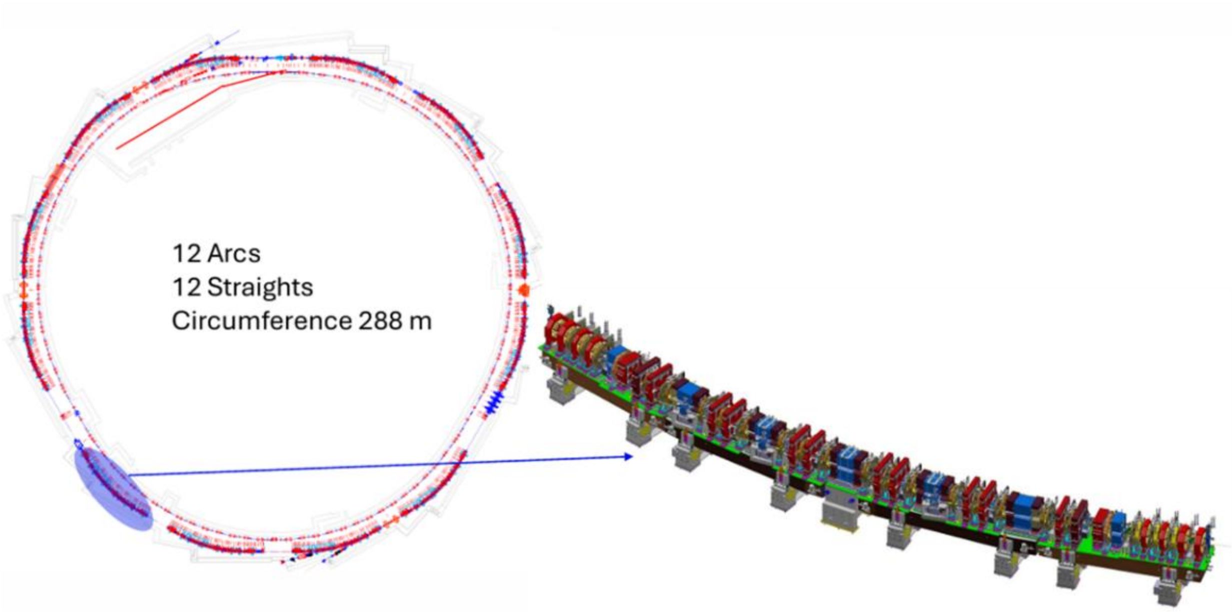

Figure 2. Layout of the SLS 2.0 Storage Ring [2]

Then the Girders must be aligned by a very tight tolerance of 20 µm RMS to each other. To achieve this, each girder is equipped with two mechanical wedges for vertical and horizontal adjustment as well as a motorized wedge for vertical alignment on each of the four feet.

The mechanical adjustment has more range of motion (+-2.5mm) to make up for eventual drifts in floor height or initial alignment errors, while the motorized adjustment is limited to +- 0.5mm to ensure a high stiffness of the system. The advantage of the motorized adjustment system is the possibility to control it remotely with running beam. [3]

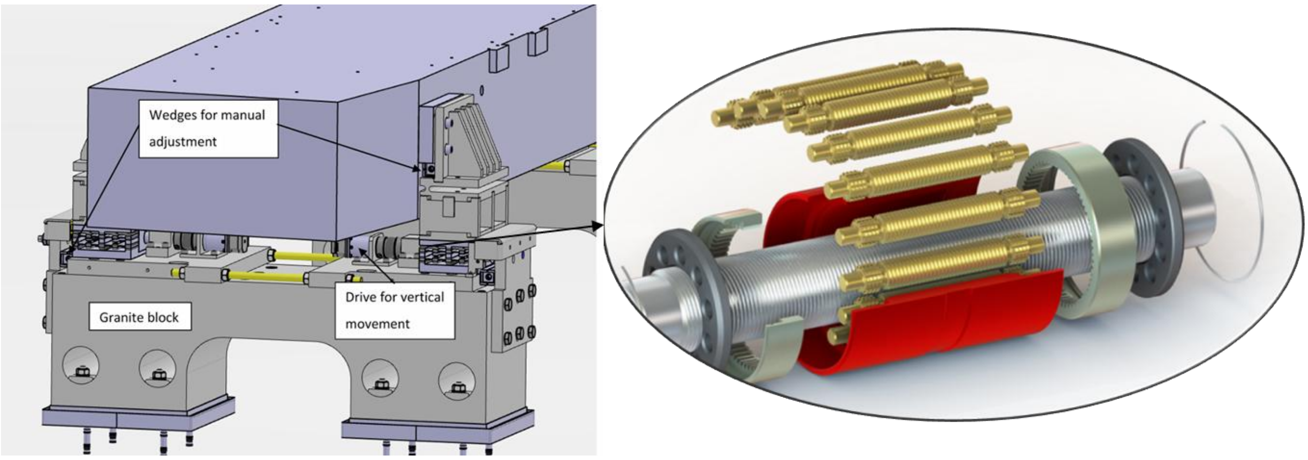

Figure 3. Adjustment Mechanisms of SLS 2.0 Girders with satellite roller screw and an effective pitch of 0.033mm leads to possible adjustment steps of 1 nm. [3]

4. ALIGNMENT STRATEGY AT SLS 2.0

The alignment of the SLS 2.0 spreads over various stages of the upgrade process. Beginning with a solid reference network that was already built with the original machine in 1999 but constantly maintained and updated to keep measurements around the ring as precise as possible. The network consists of 100 wall references and 53 floor references that are made from bronze CuSu 10 for a 1.5-inch reflector. In January 2025, the survey network for the final alignment was measured with 55 laser tracker positions and then calculated to get an up-to-date reference for the final alignment campaign. [4]

In parallel, all the 1000 magnets that keep the electron beam in its circular path were measured on magnetic measurement benches vibrating and moving wires. This way, every magnetic center could be defined with a precision of less than 30µm RMS to its fiducials. For some delicate permanent magnet assemblies, the local tolerances go down to as low as 10 µm.
The following passages describe the alignment procedure of the Girders inside the machine. [5]

4.1 Initial Alignment

The first step of the initial alignment is the positioning of individual elements to each other on a girder. Girders are around 4 m long and accompany 23 magnets. This alignment needs to be performed in a temperature-controlled environment. A climatized measurement hutch with a temperature stability of 25 +-0.5°C was provided. This was a crucial step since the natural temperature drift in the pre- assembly hall was up to five degrees Celsius daily, which could lead to misalignments of up to 50 µm.

The pre- aligned Girders were then installed in the Concrete tunnel on pre- leveled floor plates. They provide a +-0.5mm global floor level to limit the necessary stroke of vertical adjustment mechanisms.
Once in the ring tunnel, the Girders are aligned preliminary to the best precision possible. One major challenge is the unstable temperatures in the machine at that time. Up to minus four degrees Celsius from nominal operating temperature can lead to an offset of up to 70 µm at the beam height of 1.4m. This offset could be measured and predicted.
The bigger challenge is the missing load of the concrete roof shielding, that can be seen in Figure 4. During installation, all the 400 roof beams were removed, which leads to a missing load of roughly 2000 tons on the reference network. The network unfortunately doesn't behave uniformly elastic, so errors in the alignment due to uneven deformation of the reference are expected. This was not a big concern, since a final alignment campaign was planned anyways.

Figure 4. Initial Alignment of the SLS 2.0 Girders

4.2 Final Alignment

After installation of all Girders in their designated position, closing of the concrete radiation shielding and stabilizing the tunnel, a final alignment was performed under optimal conditions. In this final alignment campaign, the relative element to element alignment was not modified.

Two Magnets at the beginning and end of the girder defined the beam axis and the whole girder was moved so the actual beam axis fits the theoretical position.
Due to time constraints, this procedure could only be performed once and not improved iteratively. After the alignment, all components were measured again. The result of all arcs can be seen in Figure 5. It shows a bump in the orbit over the whole machine in the region of Arc 6, 7 and 8 of 200 µm. This orbit position alone would not be problematic, since it's a large-scale distortion that can easily be corrected. More concerning were the steps between arcs. Those steps between arcs of up to 300 µm can be very severe and lead to large misalignment of the beam going into a beamline. At the endstation of a beamline where science is conducted, 30 meters after the sourcepoint, this 300 µm step and the corresponding angle of 60 µrad can lead to an offset of 2 mm. Therefore, the decision was made to bring the orbit to zero for a better alignment base for the beamlines.

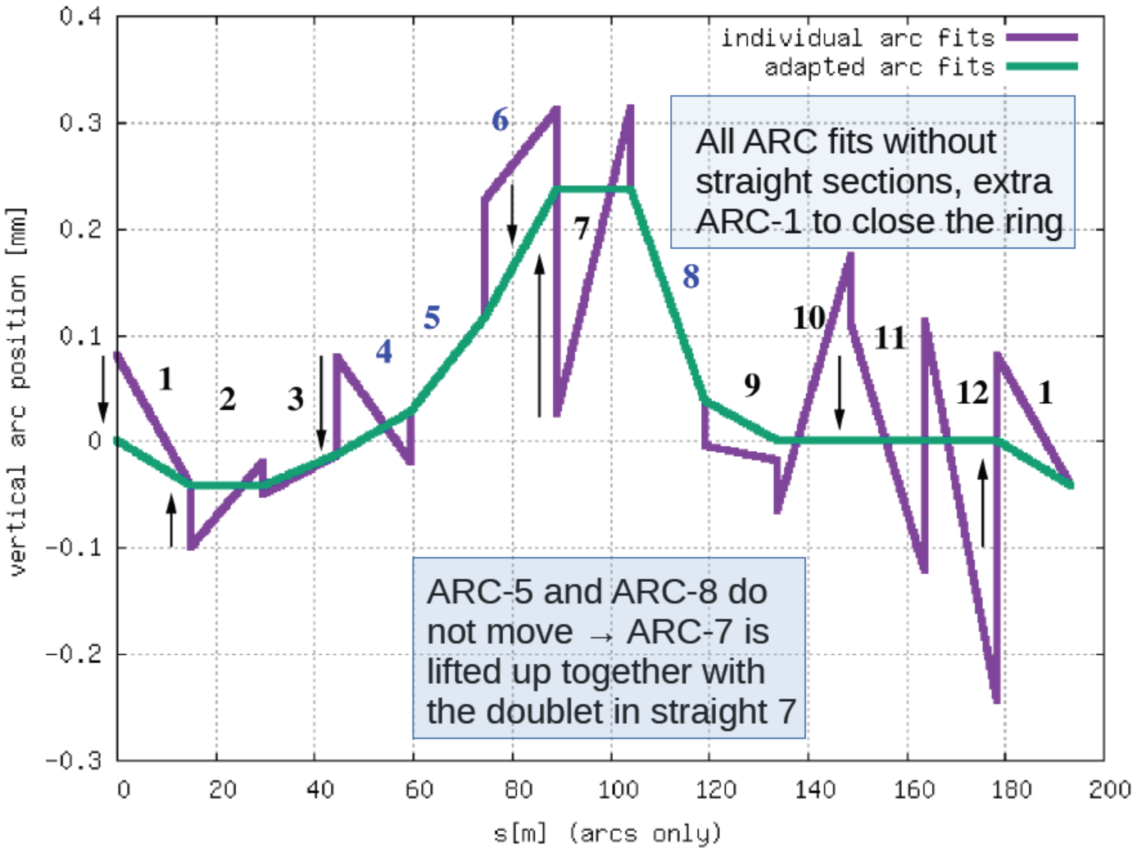

Figure 5. Arc Alignment after final alignment and possible adapted arc fit [6]

The steps between girders are even more critical, since they take up a lot of the electromagnetic corrector capacity. Those correctors are distributed around the ring to keep the orbit stable. If we can get rid of the misalignments, those corrector strengths can be reduced and lead to a higher quality beam. In Figure 6 one can see the initial misalignment of the Girders and the corresponding locally high correction necessary. These highest correction areas were targeted first and showed good correlation to the Girder misalignment.

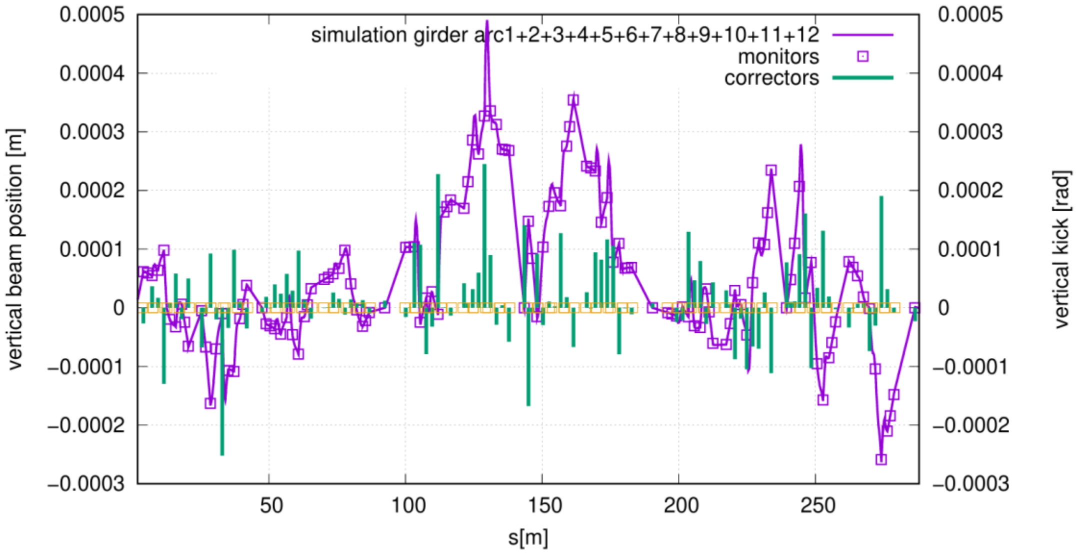

Figure 6. Girder alignment around the ring in purple. The green lines show the required corrector strengths necessary to correct those girder misalignments.

4.3 Beam Assisted Alignment

Figure 7 shows detailed alignment situation in Arc 06. A girder- girder alignment precision of 105 µm RMS well exceeds the rather strict design target of 20 µm. The reason for this strict design target is the well understood correlation between girder steps and corrector strength and the therefore designed possibility to realign the machine

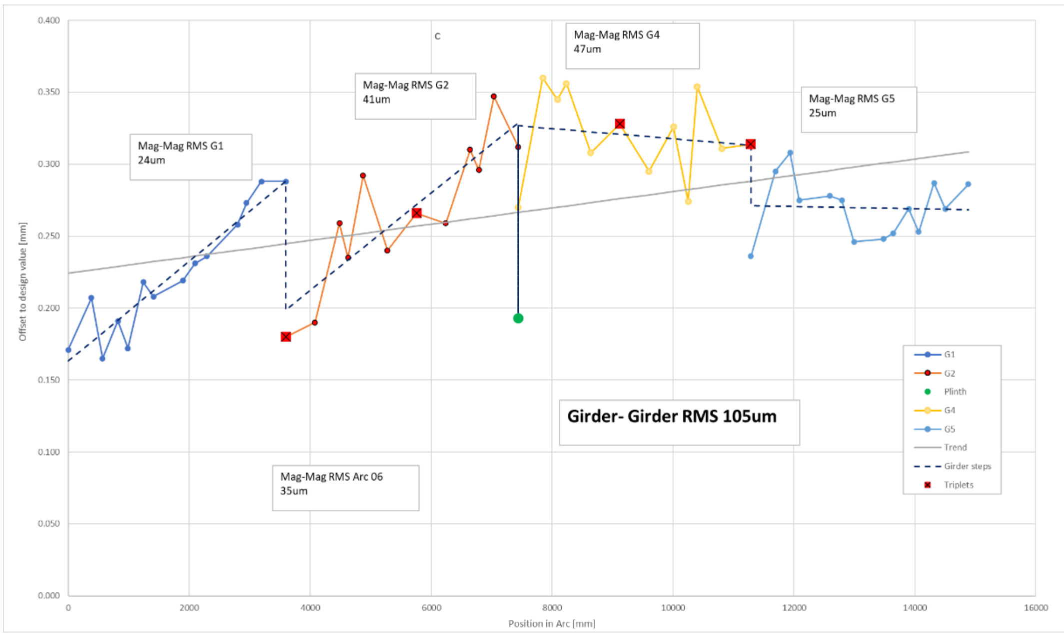

Figure 7. Detailed survey data for Arc 06. Clearly visible are the girder- girder steps. element- element alignment is not perfect, but close to the design target of 30 µm.

To remove the vertical girder steps seen in Figure 7, the remote girder adjustment systems seen in Figure 3 were used during beam operation, to get immediate feedback on the performed actions. As base, the survey data was used and target values for each girder support were calculated. By moving each motor independently and in 10 um steps, we could ensure that the orbit feedback system could react to the changes and correct them

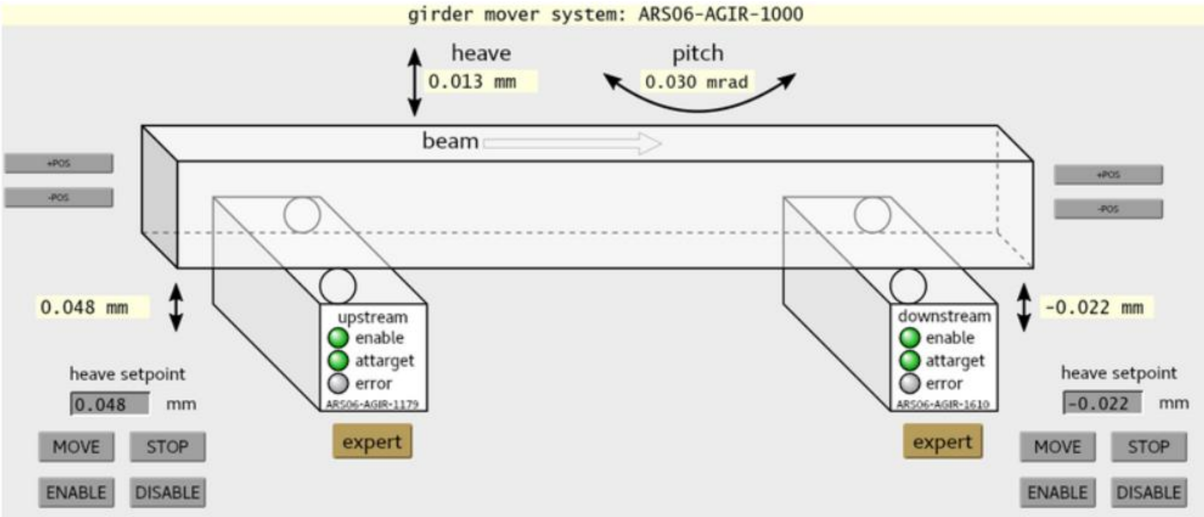

Figure 8. Controls Interface for Girder Alignment. Precision level of motors and encoders is one µm.

The Fast Orbit Feedback System uses rapid beam position measurements (BPMs) to detect the exact location of the beam and in case of an offset uses corrector magnets to actively stabilize the electron beam's orbit in real-time, achieving sub-micron stability. It has a correction rate of up to 100kHz and is a particularly valuable tool to keep the orbit of the machine stable. [7]
In Figure 9 one can see the real-time behaviour of the correctors during the realignment. The Corrector currents vary due to the orbit feedback system doing its job. Especially the corrector strength of corrector MCOY-2930 could be reduced by 50 percent due to physical realignment. This is a substantial contribution, and it immediately confirms the calculations of the effect of misalignments.

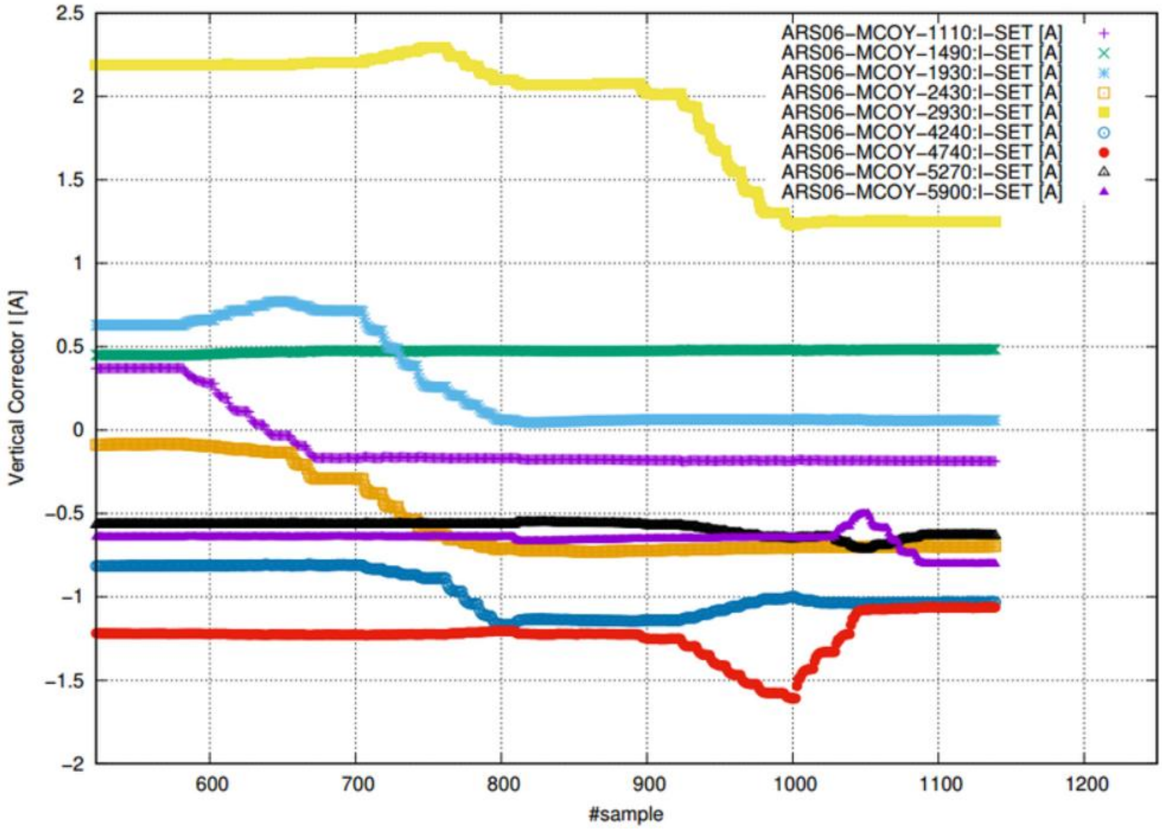

Figure 9. Vertical Corrector strength during girder realignment of Arc 06

Reducing the corrector strength allows to achieve the goal of maximum 2 A corrector current and leads to a brighter beam. The design target of 20 µm is also matched by basically bringing the Girder-Girder error to zero. However, we are still relying on survey data that has precision limits, and we don’t know if the now corrected position is the optimum yet.

5. FURTHER IMPROVEMENTS AND CHANCES

To make full use of the orbit detection and the possible correction to the micron or even sub-micron region, the next logical step would be to let the system run its own correction scheme. We could modify the correction matrix to not rely on input values from conventional survey data but set target values for the corrector magnets. Letting the system minimize corrector strength by possibly moving all 48 girders at the same time to find its optimal position is a challenging but fascinating task that needs to be very well prepared.

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BIOGRAPHICAL NOTES

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