Status Report on the Survey and Alignment Efforts and Results of the Advanced Photon Source*

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1. Introduction

The Advanced Photon Source (APS) is a third-generation synchrotron providing scientists with X-ray beams 10,000 times more brilliant than any currently available. The 7-GeV synchrotron light source produces X-rays in the soft to hard X-ray range of the electromagnetic spectrum and will be used for basic research in X-ray lithography, material science, chemistry, physics, micro-mechanics. and medicine to name some of the participating disciplines. The APS will be fully operational for beamline users in 1997.

The APS consists of a 70m-long linear accelerator, a positron accumulator ring (PAR), a booster injector synchrotron ring (SY) with a circumference of 368m, and the storage ring (SR) with a circumference of 1104m (Fig. 1). The 40m electron linac uses 200-MeV electrons for the production of positrons. In the 30m-long linear accelerator section following the electron linac the particles gain a mass of 450 MeV before entering the positron accumulator ring. From there the beam is injected into the booster synchrotron which accelerates the positrons from 450 MeV to 7 GeV before they enter the storage ring. The storage ring can accommodate up to 68 user X-ray beamlines. Currently the storage ring is being commissioned for the start of operations in 1997.

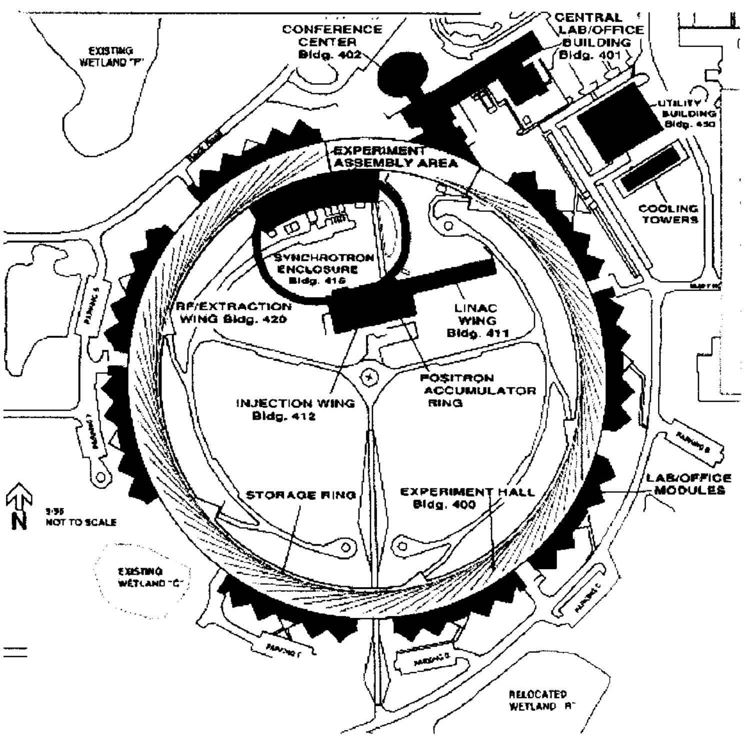

Fig 1. APS site

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2. Alignment Tolerances

2.1 Absolute positioning tolerances

The global placement tolerances require the positioning of each beam component in absolute space within a vertical and horizontal envelope of ±5mm of the ideal position. The circumference of the storage ring cannot deviate from its design value by more than ±20mm. The roll of each quadrupole, sextupole, and dipole has to be set within ±0.5mrad.

2.2 Relative positioning tolerances

The relative alignment between beam elements depends on the type of component and its location in the accelerator system. The most stringent requirements have to be achieved for the positioning of the storage ring multipoles. According to the design specifications for those magnets [1], a relative alignment tolerance of ±0.15mm is required in the vertical and horizontal direction. The tolerances for other beam components, depending on their location in the accelerator system, have been reported in more detail in the proceedings of the 1993 IWAA [2].

3. Special Alignment Tools

The forced centering system used for the alignment of the APS is based on the perfect lit of a sphere and conical socket. This concept was developed for the Advanced Light Source (ALS) project and guarantees very reliable and accurate repeatability in defining the center location of monuments. Figure 2 shows an APS floor monument with an illuminated Taylor Hobson sphere and the protective cover plate.

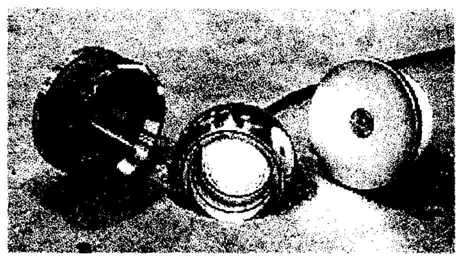


Fig. 2 APS floor monument

Based on this system, several custom adapters have been designed and built to make maximum use of the forced centering system and to increase the alignment productivity. For instance, a monopod was developed in a joint effort with the Stanford Linear Accelerator Center (SLAC) and the ALS. Figure 3 shows the final design of this device. It permits an easy setup on all secondary control points located in the storage ring tunnel and experiment hall floor. The plumb line is mechanically realized by the hollow upright aluminum tube. The four centering screws are adjusters to level a surface on top of the monopod precisely machined perpendicular to the monopod center axis. The monopod rests on top of a 3.5”-diameter Taylor Hobson sphere positioned in one of the floor monuments.

Fig. 3 Monopod

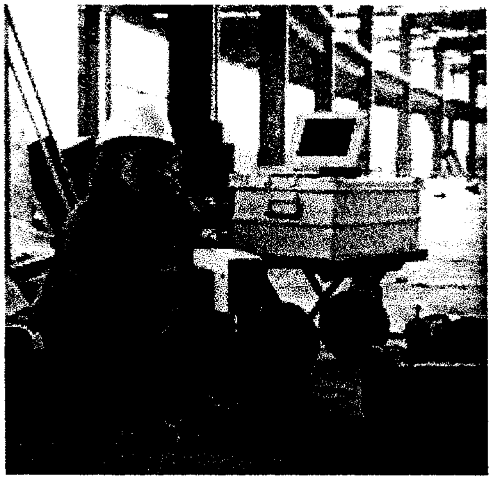


Fig. 4 ME5000 with adapter plate

In order to minimize the plumbing error of an instrument above a network control point, another special adapter was designed that reduces the instrument setup height to a few centimeters above the Taylor Hobson sphere. The adapter plate shown in Fig. 4 in use with the ME5000 consists of a 3.5” half-sphere mounted to the bottom of the plate, matching the radius of the Taylor Hobson sphere. Concentric to the center of the sphere, a Kern fixture is mounted on top of the plate. Two adjustment screws permit the leveling of the device before the instrument is mounted. All distance measurements of the secondary control network in the storage ring tunnel are accomplished using this system.

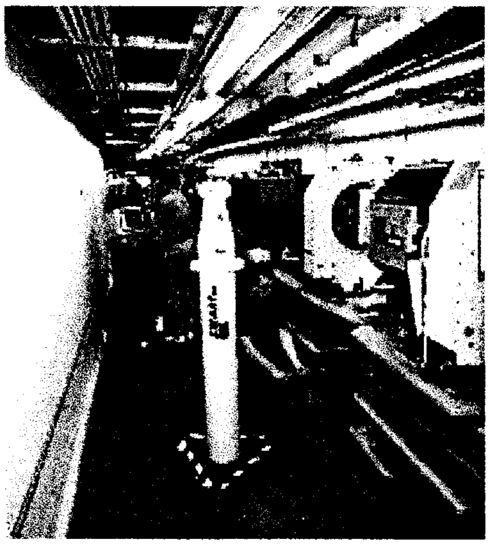


Fig. 5 Laser tracker system

For the determination of the primary and secondary control network, common survey instruments such as theodolites and the ME5000 are employed. However, during the positioning of the beam elements in the accelerator housing, new technology in the form of laser trackers is utilized. The laser tracker system proved to be invaluable in keeping the alignment efforts synchronous with the production rate of beam components to be installed. In less than one year all storage ring beam components were produced, installed and aligned to their final stage ready for the start of the commissioning phase. Figure 5 shows the SMART 310 from LEICA in operation during the positioning of a girder. A survey technician is using a wedge jack girder adjuster while the applied movement is being monitored by the laser tracker in real-time.

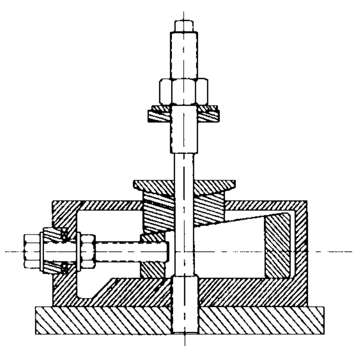


Fig. 6 Wedge jack adjuster

Wedge jack adjusters such as the one shown in Fig. 6 are used to support all storage ring girders at three points [3]. The system is used for elevation adjustments only and guarantees little or no cross coupling to the lateral and longitudinal adjustments performed by turn buckles attached between the girder and the girder support pedestals. The overall adjustment range is 8mm with a smooth elevation change of 0.35mm per turn of the adjustment screw. The last step in setting the proper elevation requires the stretching of the bolt supporting the girder attached to the support plate of the wedge jack adjuster. This ensures that the mechanism is locked in place.

4. Alignment Results

The APS primary control network consisting of 12 control points was measured in November 1992 using ME5000 distance measurements only. The lo absolute error ellipses obtained for all primary control network points were in the range of ±0.3mm [4].

About one year later the last measurements for the secondary control network were recorded. Again 1σ error ellipses of ±0.3mm were obtained for all 600 control points, resulting in a very accurate and homogeneous control network for the positioning of the beam components. Naturally, over time, the accuracy of this control system started to deteriorate with changes in the concrete floor. This became especially evident at a transition piece between sectors 33 and 34 of the storage ring. When the time came for the beam components to be positioned in this area, local measurements with the laser tracker system confirmed that one part of the floor plate had shifted lateral to the beam direction by 1-2mm. Due to the time constraints dictated by the installation schedule it was impossible to remeasure this section of the secondary network and the beam components in this area were positioned using beamline smoothing techniques.

After the completion of the storage ring girder alignment the position of all quadrupoles, sextupoles, and dipoles were measured once more using laser trackers [5]. In order to obtain the connection between individual tracker setups, additional temporary control points were installed and measured. The data was analyzed using a bundle adjustment routine developed at SLAC. The differences between the resulting magnet positions from the bundle adjustment and the ideal locations were then subjected to the smooth curve fitting operation [6].

The results of the smoothing process is shown in Figs. 7 and 9 for the transverse and vertical deviations from the ideal position. One can see that the smooth curve deviates from the ideal position by ±4mm, within the confines of the envelop for the absolute positioning of the beam components

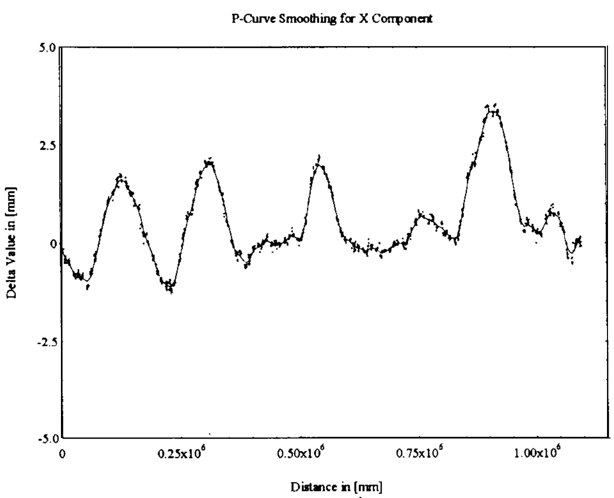


Fig. 7 Transverse displacements of all storage ring multipoles

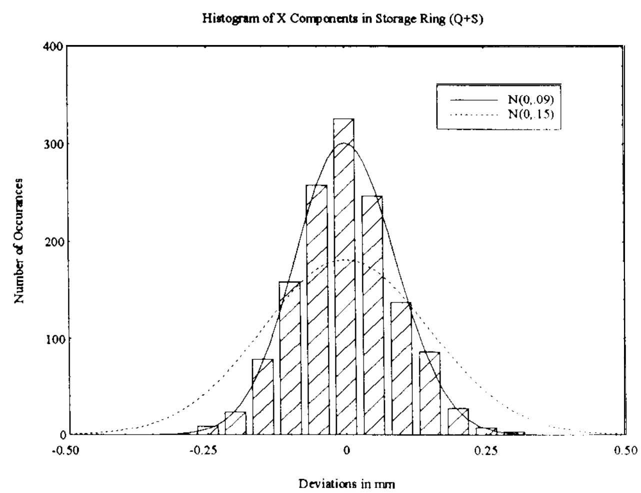
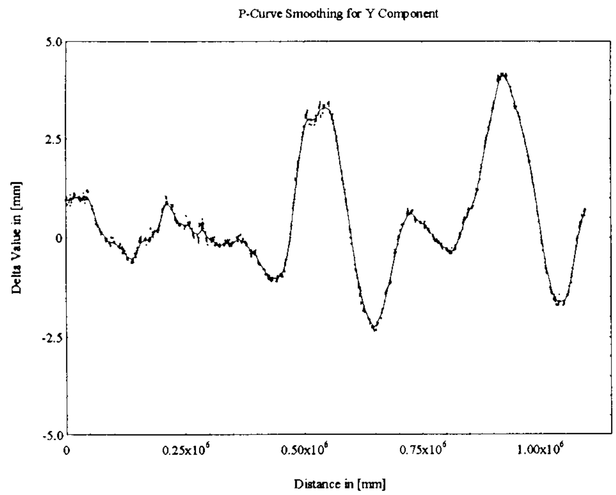


Fig. 8 Histogram of the transverse displacements of all storage ring multipoles



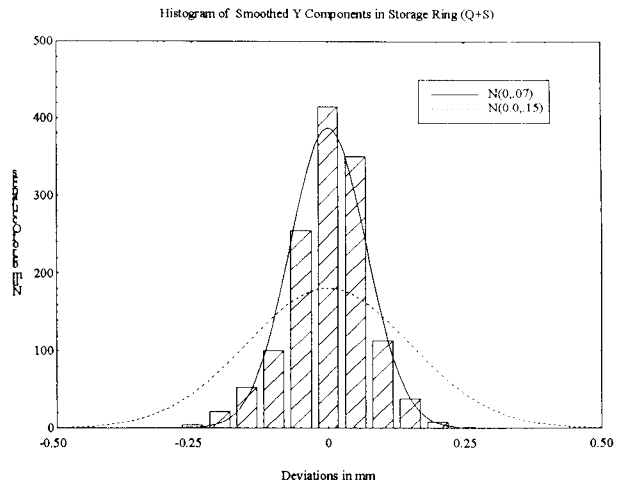


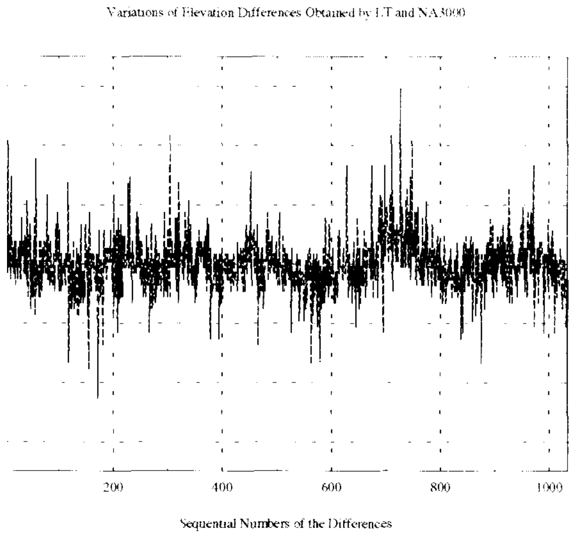
Fig. 9 Vertical displacements of all storage ring multipoles

Fig. 10 Histogram of the vertical displacements of all storage ring multipoles

Finally, Figs. 8 and 10 show the histograms for the deviations of the multipoles from the smooth beamline. All components have been placed within the 2σ range. Out of 680 multipoles, only 3% in the transverse direction and 2% in the vertical direction have been placed in the 1σ to 2σ range. The achieved relative position tolerances are ±0.09mm transverse and ±0.07mm vertical, well within the specified tolerance level [7].

The laser tracker system was used for the initial positioning of the beam components in the storage ring. In order to estimate the quality of the achieved vertical positioning, a separate conventional level run using the NA3000 was recently performed. The time lag between positioning the beam elements with the laser tracker system and the conventional level run was about seven months. During this time, some of the girders were retrofitted with vibration damping material - a process which disturbed the initial alignment and was monitored with laser tracker measurements.

The results of a comparison between the elevation differences obtained by the laser tracker, after analyzing the data using bundle adjustment, and the conventional level method is shown in Figs. 11 and 12 for about 50% of the storage ring. Figure 11 shows the variations between the elevation differences of adjacent fiducial marks obtained by the laser tracker and the NA3000 level. Figure 12 displays the result in the form of a histogram showing the normal distribution with a mean of zero and a standard deviation of ±0.05mm, justifying the use of the laser tracker for the vertical positioning of the beam elements.



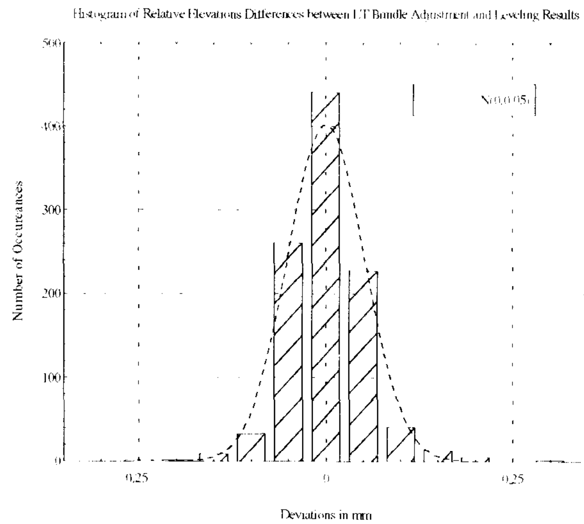


Fig. 11 Variations of elevation differences obtained by the LTS and NA3000 level

Fig. 12 Histogram of the variations in elevation differences

In June of 1993 a first settlement survey of the storage ring was performed. Approximately every six months thereafter the settlement survey of the storage ring control network has been repeated. A comparison of each survey epoch to the very first data set is shown in Fig. 13. One can see that for the most part the elevations are unchanged and repeat in a band of ±0.25mm with the exception of two areas which coincide with the vehicle tunnel underpass and an area in which backfill was used to stabilize the underground during the construction of the APS.

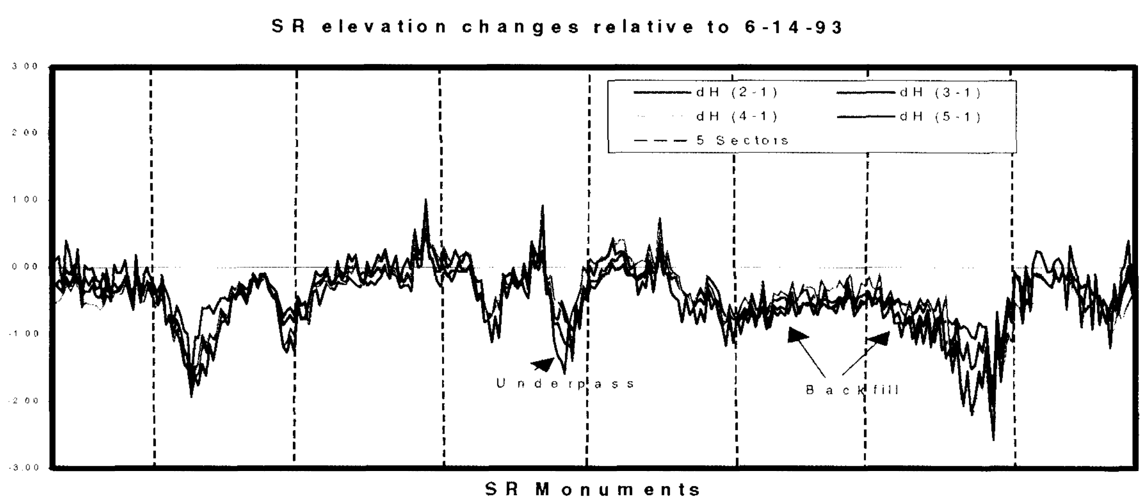


Fig. 13 Storage ring settlement surveys

Currently efforts are underway to install a settlement monitoring system using hydrostatic level sensors from Fogal Nanotech. In the fast phase each straight girder carrying the majority of the focusing multipoles will be outfitted with one sensor. This system provides continuous data about the long-term settlement of girders and the storage ring floor. The determination of elevation changes is based on the measurement of capacitive changes whereby the sensor and the water surface are forming the capacitor. The system has a resolution of ±0.05mm for the determination of the elevation difference between sensors and a measurement range of ±7mm.

A portable version of this system is now in use for monitoring the vehicle underpass area of the storage ring and experiment hall floor. This test has been set up to provide information about seasonal, temperature-dependent changes in that particular area. If necessary, the concrete plate spanning the top of the vehicle tunnel can be heated in order to compensate for large seasonal temperature fluctuations.

While settlement surveys monitor long-term elevation changes which could affect the operation of the APS, vibration studies have been conducted to measure the effects of vibration source on the beam stability [8]. Figure 14 shows the displacement spectrum of a typical storage ring quadrupole. One can see that the displacement reaches a maximum of 0.2μm at 10Hz, the girder resonance frequency.

This impacted the beam stability and lead to the development of vibration damping pads. The damping pads consist of two thin layers of viscoelastic material sandwiched between three metal plates [9]. Each layer is 0.15mm thick. This stack is inserted between the girder pedestal and the wedge jack assembly. By adding these vibration damping pads it was possible to reduce the quadrupole displacements to 0.07μm at a resonance frequency of 9.5 Hz as shown in Fig. 15. Currently about 50% of the storage ring has been underlined with damping pads; the remaining girders will be retrofitted in the near future. This process naturally impacts the alignment already achieved and requires the support of the alignment team during the installation process.

To date, no noticeable girder settlements have been recorded due to the insertion of the damping material. In order to prevent the girders from sliding on the viscoelastic material, all girders are locked in place once the final position has been reached.

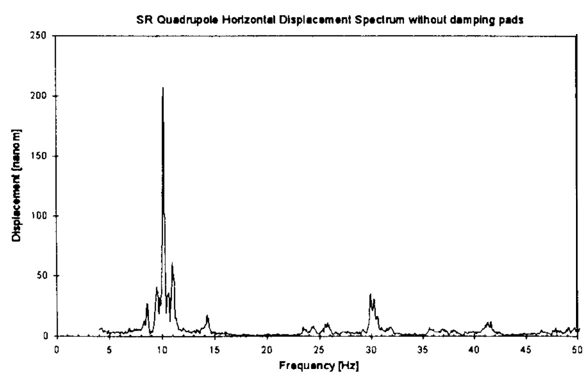


Fig. 14 Displacement spectrum without damping pads

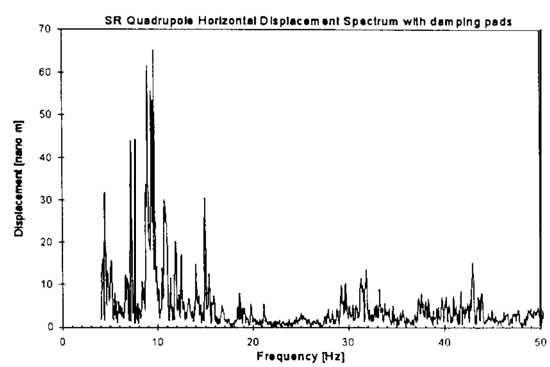


Fig. 15 Displacement spectrum with damping pads

5. Summary

Considering that a relative positioning accuracy of ±0.09mm in the lateral direction and ±0.07mm in the vertical direction has been achieved, and taking into account the standard deviation for the determination of the magnetic center versus the mechanical center of ±0.075mm, the position between magnet centers is estimated to be within ±0.125mm less than the required ±0.150mm.

The successful alignment of the APS storage ring is also documented by the rapid progress in the commissioning program. Shortly after the start of the storage ring commissioning phase, the beam was transported around the entire ring without the use of correctors. Multiple turns were recorded shortly thereafter and rf capture of the beam has been demonstrated. In March 1995, only two months after the start of the commissioning phase, the first X-ray light produced by a bending magnet was recorded, and during August the first undulator to produce X-ray light was installed, The present goal is to achieve higher beam current and a longer beam lifetime with an improved vacuum.

6. ACKNOWLEDGMENTS

I would like to acknowledge all APS survey personnel for their effort in the alignment of the APS. Especially I would like to thank M. Penicka and J. Error for their dedication to the alignment of the APS, and S. Zhao who was in charge of the data analysis and provided the graphs showing the results of the alignment effort.

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