A 3-D Coordinate System for the NSCL

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In 2005, the National Superconducting Cyclotron Laboratory embarked on a project to upgrade the alignment techniques used to position and measure the active beamline components. The project transitions the laboratory from a system based on optical metrology and tape measures to a true 3-dimensional measurement system using a laser tracker. This presentation gives an historical perspective and reports on the project's progress.

1. INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) is a heavy ion nuclear physics facility at Michigan State University. Ionized beams from Electron Cyclotron Resonance ion sources are accelerated, first in a K500 superconducting cyclotron, and then in a K1200 superconducting cyclotron coupled to the first. The primary beam list includes beams from 2.4 GeV ^{16}O to 16.7 GeV ^{209}Bi. The research program predominantly uses in-flight fragmentation to create short lived radioactive beams. Those beams are analyzed in the A1900 fragment separator before being transported to one of seven experimental vaults. The ion sources, cyclotrons, beamlines, and experimental end-stations at the NSCL were installed and aligned using simple optical instruments. Typically, the optic axis of a jig transit was placed on the theoretical beam path and the magnets were adjusted to minimize the transverse error. Such a system provides good accuracy in the most important directions, but is insensitive to errors along the beam path. It has been very difficult to check the position of active beamline components at a later date because of the disassembly needed to re-install the optics on the beam path. Several beam tuning issues over the years have suggested that there is a stability problem with the high energy beamlines. Leveling measurements implied that the positions of the magnets were changing, either through building movement or drift in the supports.

To measure the state of the beamlines, a true three-dimensional measurement of the active beamline components of the laboratory was implemented. This required the installation and calibration of a floor and wall monument grid throughout. Every beamline magnet needed to have fiducials installed and calibrated to the beam axis. A measurement of the fiducials in the monument grid system gave a snapshot of the beamlines as they exist that day. At this point, the positions can be analyzed and adjusted for the best transmission of beam.

This presentation describes the history of alignment at the laboratory, our implementation of a tracker-based 3-D system, and the current status of the project.

2. AN HISTORICAL PERSPECTIVE

The NSCL began as a university laboratory in the 1960s with the construction of the K50 cyclotron. The construction was funded by the National Science Foundation in 1961 and the cyclotron first operated in 1965. The first jig transit was purchased at this time and was the work horse of the alignment effort. Then, as now, the beamlines were straight lines of quadrupoles with branches at large vertical field dipole magnets. Since all the magnets were room temperature, metal reference targets were mounted on the pole tips before the beam chambers were installed.

Individual magnets were leveled using machinist levels. The beam height was transferred from room to room by gluing a small piece of fine grid graph paper to the building supports with the beam height labeled (Fig. 1).

In the early 1980s, a major upgrade to the laboratory was installed with the K500 superconducting cyclotron. This involved several extensions to the building and planning for the eventual K1200 cyclotron installation and the S800 spectrometer. At this time, the laboratory began using Computer Aided Design (CAD) extensively, including layouts of the beamlines and shielding walls. A coordinate system was chosen, with its origin near the southwest corner of the laboratory at floor level. This choice produced positive values for the coordinates of most of the beamlines, the exception being the components installed above the K1200 cyclotron pit. To facilitate the installation of the beamlines and stacked concrete block shielding walls, a grid of foil alignment targets (Fig. 2) were laid out across the floor, using a 1940s vintage theodolite and a long tape measure. Trilateration located the corners of the stacked concrete brick shielding walls and beamline crossing points relative to the grid with tape measures.

Figure 1. An early height reference.

Figure 2. An early floor grid monument.

The late 1980's brought the completion of the K1200 superconducting cyclotron and a complete reconfiguration of the high-energy beamlines to form the A1200 fragment separator. This required higher accuracy in the bend angles of the beamline dipoles, so a digital theodolite was rented to lay out the beamlines on the floor. The intersection points of the beamlines under the dipoles were labeled with foil targets and the distances to each quadrupole magnet were measured with a tape and marked on the floor. Because of the higher beam energies from the K1200 cyclotron, the beamline magnets were replaced with superconducting quadrupoles and dipoles.

For the quadrupole magnets, the support links for the helium container and internal steel/coil assemblies were adjusted to force the magnetic axis in alignment with a line formed by the centers of the two end vacuum flanges. A blank-off vacuum flange was modified to accept a glass alignment target. The repeatability using the copper gasket to locate the mapper and alignment target was found to be approximately 127 μm (0.005”). The superconducting dipoles have room temperature pole tips and operate without the magnet steel being saturated. Two dowel pin holes in the lower pole tip of each magnet located an alignment plate with an appropriate pattern of small dowel pins defining the beamline paths through the dipole.

The quadrupole magnets were installed first. The jig transit was force-centered above the foil floor targets at beam height, using the next target to set the azimuthal angle. The beam height was defined as the median plane of the K1200 cyclotron and it was transferred throughout the laboratory using optical alignment scales mounted to the shielding walls

(Fig. 3). With the jig transit's optical axis on the beam path, the quadrupoles were placed on their stands, the stands were anchored to the floor, and the magnets were aligned to the theoretical beam axis. A plumb bob and a tape measure were used to set the distance along the beam path. Once the quadrupoles were installed, two transits were moved to positions along the beam path between two quadrupoles, using the alignment targets on the magnets to calibrate the optic axes. A dipole was placed and aligned using the fixture clamped to the lower pole tip, viewed simultaneously from two directions.

In the mid 1990s, the S800 spectrometer was built in a large pit at the eastern end of the laboratory. The spectrometer consists of a large diameter quadrupole doublet and two 75 ton superconducting dipoles bending upward from the bottom of the pit, mounted on a rotating carriage. In order to get the dipoles close to their theoretical positions, a rented total station was used with conventional land surveying retroreflectors mounted to the return yoke steel. The fine adjustment of the position was set using a home-made 3-D tooling dock (Fig. 4). This was a very tedious process, with the operator standing on a scaffolding to take the vertical readings.

Figure 3. An optical tooling scale used as a vertical reference.

Figure 4. Installing the S800 spectrometer using a tooling dock.

Another alignment application is the positioning of experimental detectors for users. A large segmented gamma detector array (SEGA) required a precise 3-D measurement of the positions of the detector segments relative to the mounting frame. A twin-theodolite system was fabricated [1] using inexpensive digital theodolites and optical mounts to force-center the instruments in known locations. The measured angles were converted to X, Y, and Z coordinates using the laboratory CAD system. This system worked well for this specific case, where there was plenty of space around the detector mounting frame, but would be difficult to apply elsewhere in the laboratory.

In 2005, with the inherent complications associated with tuning radioactive secondary beams, it was decided to eliminate any question regarding motion over time of the beamline magnets. In order to recreate the original alignment procedure, the beamline would need to be taken apart, an unsatisfactory solution. An alignment system that would allow the fiducialization and position measurement without affecting the beamline was needed. The obvious choice was a laser tracker combined with a permanent monument and fiducialization system. Various models were considered with an emphasis on the included software and the FARO [2] Laser Tracker/X with CAM2X software was selected.

3. MONUMENTATION

The reference coordinate grid consists of both floor and wall monuments. Figure 5 shows a CAD drawing of the laboratory with the monuments indicated as large square dots. Except for a couple of very tight locations, every probable laser tracker location can view a minimum of three monuments. The original floor coordinate system was retained in order to simplify referencing old drawings.

Figure 5. Locations of the laser tracker floor and wall monument grid points.

A typical wall monument is shown in figure 6. It consists of a 5.08 cm x 5.08 cm x 1.905 cm #410 stainless steel ground bar with a precision hole drilled and reamed in the approximate center. A Hubbs [3] pin nest is used to hold the Spherically Mounted Retroreflector (SMR). Each monument is labeled with a serial number: WM###.

A typical floor monument is shown in figure 7. An 8.89 cm (3.5") hole is core-drilled in the floor after scanning for rebar. The monument is fabricated from a 2"-NPS electrical conduit coupling, a steel conduit plug welded to one end, a round rod of #410 stainless steel with a precision hole and a lip to protect the mating surface, and an aluminum conduit plug machined to be flush with the end of the coupling. The magnetic stainless steel rod is attracted to the internal magnet of the pin nest. The monument is embedded in the floor with non-shrink grout. With a pin nest inserted, the SMR's center is high enough to be viewed from any location above the floor. Each monument has a serial number of the form FM###.

Figure 6. Wall monument.

Figure 7. Floor monument.

The goal was to create a new, well defined coordinate system grid as close to the old coordinate system as possible. The references available were: a level plane measured by the tracker, the height of the median plane of the K1200 cyclotron, and the pre-existing foil targets on the floor. A large number of floor monuments were installed, extending from the cyclotron vault around the building. Several foil targets were chosen, located on the oldest part of the building floor. The cyclotron height, the new floor and wall monuments, and the level plane were measured in the default "World" coordinate system of the tracker. The cyclotron height was defined to be Z=1.2446 m (+49.000"). Using a Hubbs double vector target, the centers of the old foil targets were also located in this coordinate system. Since the vertical height of the foil targets was not known, their (X,Y) positions were projected onto a level plane at Z=0.000. The original coordinates of the foil targets were used as nominal positions for the alignment fit. This fit positioned the wall and floor monument grid to closely match the original layout. Since the original grid system was mainly used to lay out shielding walls, the beamline components are not expected to match it perfectly.

4. FIDUCIALIZATION

The mounts for the fiducials on the superconducting magnets are similar to the wall monuments. Each magnet has at least three bars welded to the cryostat. As mentioned earlier, the quadrupole magnets' links are adjusted to place the magnetic axis on the line formed by the centers of the two vacuum flanges. In the fiducialization operation, the relationship between this axis and the three fiducials is measured. In the case of the large A1900 quadrupole triplets, the bolt pattern defines the rotation of the magnet assembly about the beam axis. With the smaller quadrupole doublets, the rotation about the beam axis is defined by the lid of the cryostat. For the superconducting dipole magnets on the beamline, the view of the pole tip steel is completely blocked by the cryostat and vacuum connection to the next magnet. Since the return yoke steel is ground flat and sandwiches the pole tip assembly, its outer surface is used as a reference.

The fiducialization process consists of creating a new tracker graphics file for each magnet. In that file, the fiducials and all the reference surfaces and points on a magnet are measured. This file is exported to the laboratory CAD program, where additional graphics are added to make the image more recognizable. Each magnet CAD file was inserted into the lab master layout, once the positions of the fiducials in the laboratory coordinate system were known.

5. PROGRESS

The tracker was delivered in late September 2005 and two laboratory employees were trained on the CAM2X software in late November. Maintenance shutdowns of one month in September, one week in December, three weeks in January, one week in April, and one month in June were used to install the monuments and fiducials, to measure the fiducialization relationships, and to locate each magnet in the laboratory coordinate system. The result is an As-Built CAD model of the superconducting magnets on the beamlines (Fig. 8). The figure displays the monuments, the shielding walls, and the superconducting beamline magnets. Absent are the cyclotrons, ion sources, diagnostic chambers, and experimental end stations.

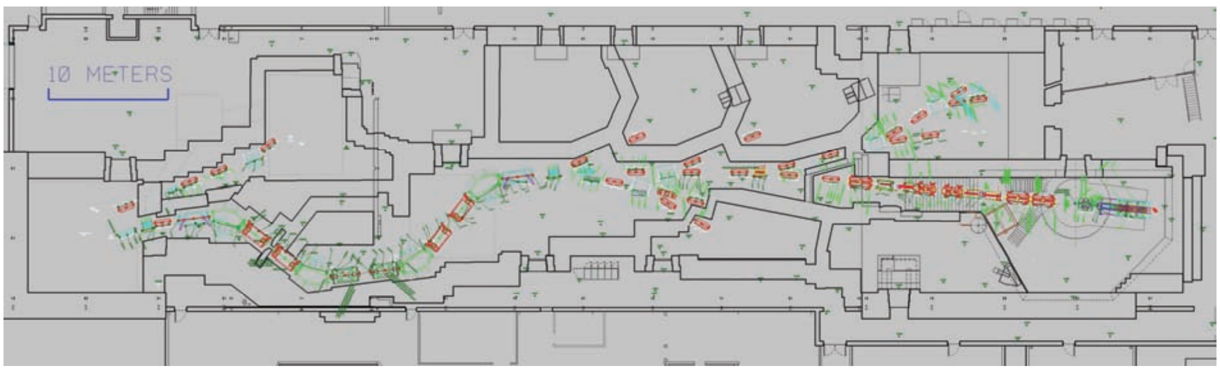

Figure 8. As-built laboratory layout from laser tracker measurements.

6. MISALIGNMENTS—EARLY RESULTS

When the position of an accelerator system component is measured for a second time, the answer is always different, reflecting errors in measurement, mounting, and even the movement of the building as a whole. One of the characteristics of the NSCL's laboratory and office building is that it is in reality nine buildings placed next to each other. This reflects the additions to the original building since the early 1960s. As each section was added, it was installed next to the previous one without tying the two floors together. Thus the beamline crosses several joints along its path. With the new system, the relative motions of different parts of the floor can be monitored.

A second issue is the stability of the magnet stands. The laboratory has used several different generations of magnet support stand as it grew. For the lighter weight magnets, the steel cryostat vacuum vessel slides across a surface for horizontal adjustments. Commercial leveling pads are used for vertical motion. This has limited the accuracy in such adjustments to the order of 127 μm (0.005") at best. For the much heavier magnets of the A1900 fragment separator and the S800 spectrometer, roller bearings support the horizontal motion with ACME threads for fine adjustment and worm drive jacks move the heaviest dipoles vertically.

6.1 S800 Beamline

The first test of this project was a re-measurement of the last two superconducting quadrupole triplet beamline magnets on the S800 beamline. The beam tuners were having some difficulty with steering in these magnets and this was a good place to get some experience with a simple problem. The tracker was installed between the last quadrupole and the target position of the spectrometer and calibrated to the central pivot bearing of the spectrometer, a vertical reference on the wall, and a foil target upstream of the triplets which had been placed during the original beamline layout in 1996. An SMR nest was fabricated which replaced the optical target in the original alignment flanges for these magnets.

The beam axes of the two magnets were measured and found to be a few millimeters off horizontally and about half a millimeter off vertically. Both triplets were adjusted to put them back on the beam axis as defined by the local references. During the next experiment in this vault, the tuning of the beam was greatly improved.

Presently, an analysis is being carried out on the horizontal straightness of the beamline upstream of the two triplets. Figure 9 shows the horizontal error relative to a line between two of the original layout targets. (The plot folds back on itself due to the shape of the spectrometer.) Preliminary results imply that realignment is in order. Since there is a gap in the experimental schedule for this beamline, the adjustment will take place this fall.

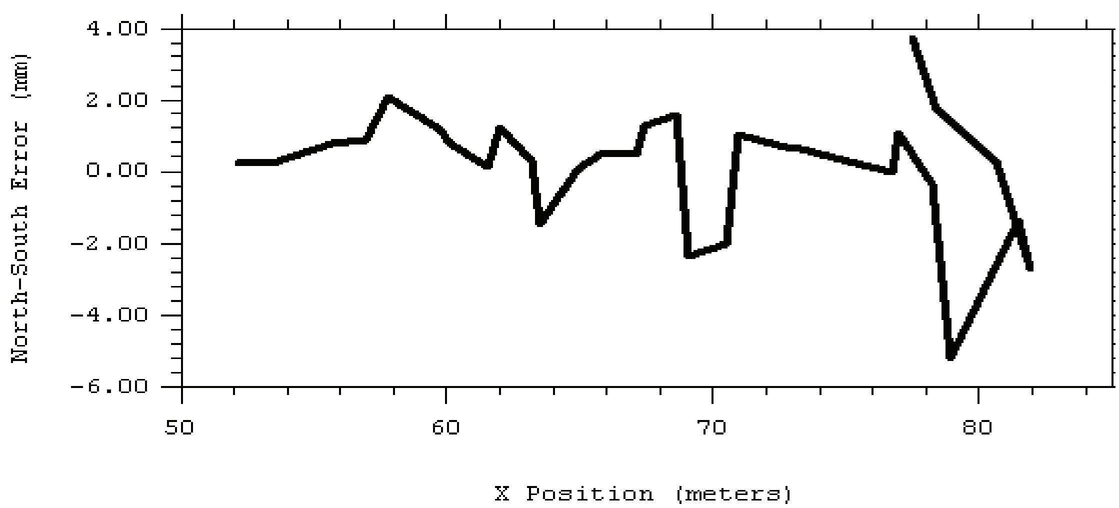

Figure 9. Horizontal misalignment in the S800 beamline.

6.2 Vertical Measurements

With the fiducialization files completed and the locations of all of the fiducials measured, the vertical heights of the beamaxis points on the individual quadrupole magnets can be compared. Figure 10 shows the vertical position of the superconducting quadrupole magnets along one of the beam paths from the K1200 cyclotron to an experimental station at the far end of the laboratory.

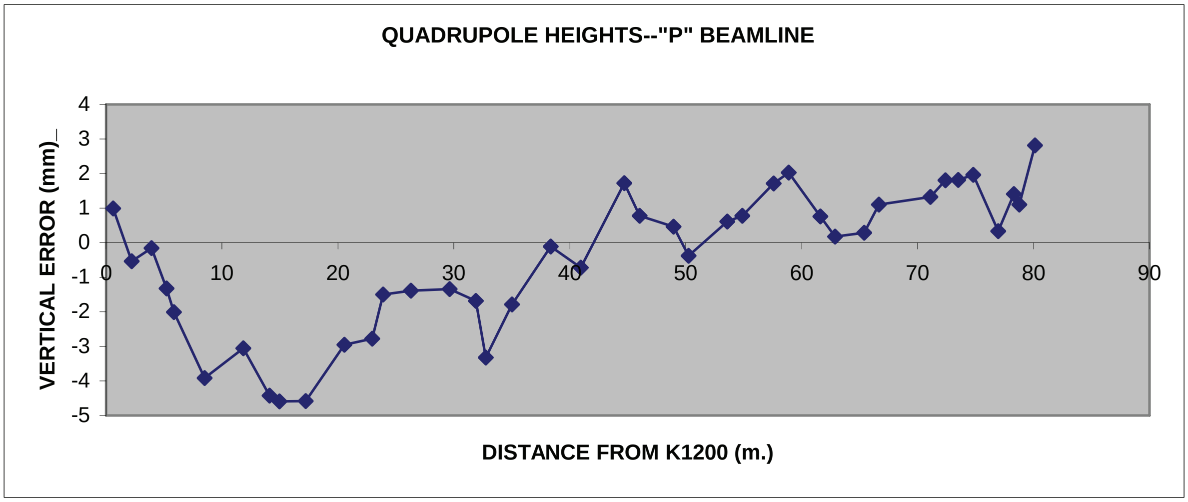

Figure 10. Vertical misalignment in the beamlines from the K1200 cyclotron to the Gas Stopping Station.

Each magnet is represented by two points, at the entrance and exit. There is a pronounced dip early in the beamline, at the location of the A1900 fragment separator. In 2001 and 2002, vertical corrections were made in this area due to a similar dip at that time. The root cause of these problems is not known, but this area has the highest concentration of both heavy magnet steel and shielding. In addition, many of the magnets show a difference in height between the two ends, which can cause steering problems for the beam tuners.

A six-month time period has passed from the initial installation of the floor monuments, so a re-measurement of the monuments on the north side of the facility was carried out. A set of four points in the oldest part of the laboratory was chosen as reference. As can be seen in Fig. 11, there appears to be a small shift at the higher values of X position. The one point separate from the others is a wall monument. A full survey of the entire system will be the next step.

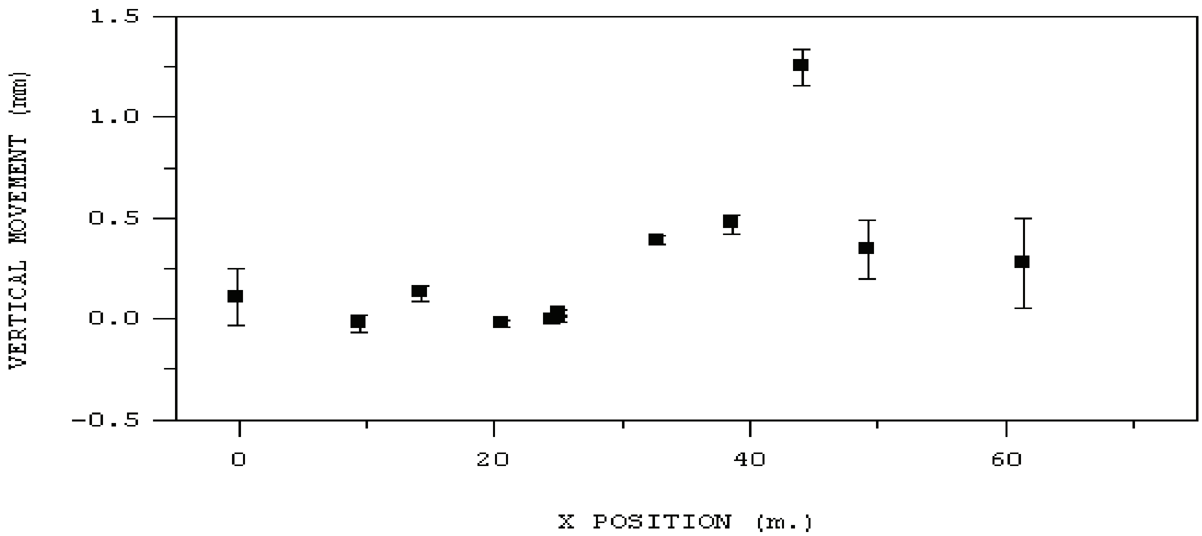

Figure 11. Motion of the north hallway monuments after six months.

7. SUMMARY

The NSCL has begun a project to bring true 3-D measurement of beamline components to the laboratory. In its early stage, several misalignments have been discovered. Improved beam delivery should result once corrections are implemented.

Acknowledgments

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References

[1] D. P. Sanderson and W. F. Mueller, "3-D Measurement of the NSCL Position-Sensitive Gamma Ray Detector Array", IWAA2002, Spring-8, November 2002.

[2] FARO Technologies, Inc., Lake Mary, FL.

[3] Hubbs Machine & Manufacturing, Inc., Cedar Hill, MO.