10 GLOBAL SUPPORT SYSTEMS

10.1 Survey and Alignment

10.1.1 Scope

This section outlines the survey and alignment requirements and the technology and tools for achieving the NSLS-II equipment positioning goals. The required alignment tolerances are defined primarily by the physics requirements of the accelerator. At this stage of conceptual design, these tolerances are not known with high precision; however, similar parameters are available for other light sources of equivalent dimension. Our conceptual design of the survey and alignment system is based on the assumption that the tolerance requirements for NSLS-II will be similar to those of APS, for example. An assessment will be performed, however, during the preliminary engineering design phase to identify any extraordinary position requirements of the accelerator systems, and the survey and alignment system will be modified as necessary to meet them. State-of-the art equipment and methods will be employed, but no new technology will need to be developed to meet the NSLS-II alignment requirements.

Survey and alignment provides the foundation for positioning the beam-guiding magnet structures in all 6 degrees of freedom within the required tolerances. Although the tools and instrumentation available for this task have changed over the years and faster and more accurate measurements are possible, only limited control of the environmental conditions is possible. This ultimately sets an upper limit for the achievable measurement and subsequent control network accuracy.

The scope of the survey and alignment work for NSLS-II includes the following:

- Provision of engineering staff to review the design of components having stringent alignment requirements. Engineering staff trained in state-of-the-art methods, software, and systems will be required to ensure that component designs are consistent with the survey and alignment systems that will be used to obtain the anticipated tight tolerances needed to achieve the desired emittance levels.
- Specification of alignment tolerances for each piece of equipment, and a determination of how to achieve them within the limitations of available equipment and hardware. Procedures, methods, and equipment will be specified.
- Procurement of alignment equipment, measurement equipment and instruments, targets, monuments, and hardware.
- Technical staff to achieve the precise alignment requirements during fabrication, assembly, and field installation. Technical staff trained in the use and calibration of state-of-the-art instruments and systems will be required.
- Provision of calibration equipment and facilities to maintain survey equipment within calibration tolerances.

10.1.2 Tolerances

The required positioning tolerances are an essential part of the survey and alignment design. Those tolerances dictate the instruments and methods necessary to obtain the positioning goals. Table 10.1.1 provides the required global tolerances, while Table 10.1.2 outlines the relative tolerances for the NSLS-II girder-to-girder positioning. These tolerances represent the most stringent requirements for the storage ring.

Table 10.1.1 NSLS-II Required Global Tolerances.

Global tolerances	± 3 mm
Horizontal positioning	± 3 mm
Vertical positioning	± 3 mm

Table 10.1.2 NSLS-II Girder-to-Girder Positioning Tolerances.

Relative tolerances	Girder to Girder
Horizontal positioning	± 0.15 mm
Vertical positioning	± 0.15 mm
Longitudinal	± 0.50 mm
Roll angle	± 0.5 mrad

10.1.3 Design Philosophy

10.1.3.1 Control Network Design

Depending on the size of the system to be constructed, a primary and secondary control network may be required to achieve these tolerances. NSLS-II covers an area of about one-eighth of a square kilometer with a radius of ~124 m and a circumference of ~780 m. The NSLS II construction methodology demands that separate tunnel segments be successively available and ready for installation purposes. This requires that each segment be fitted with an independent preliminary control network terminated by a primary monument at each end suitable for less demanding layout work such as the blue-line survey of the major beamline components, girder supports, and photon beamline layout in the front-end sections [10.1.1]. Only after all segments have been measured, processed by least squares, and analyzed will the final control network be ready for the positioning of the girders. Prior to construction, a calculation of the anticipated error propagation of the primary and secondary control network geometry will be needed.

10.1.3.1.1 Primary Control Network

The primary control network spans the entire accelerator facility and ties the accelerator enclosures into one reference system. It consists of a monument located at the center of the storage ring, a second similar one located at a convenient location in the infield close to the storage ring enclosure, and multiple monuments distributed throughout the storage ring—for instance, at the beginning and end of each separate tunnel segment. The two monuments located in the infield should be very stable. Therefore, they require a deep foundation and a secondary outer shell for temperature stability, as shown in Figure 10.1.1 [10.1.2]. These monuments can also be used by the construction companies for layout and construction surveys.

The central monument usually defines the origin of the local right-handed coordinate system, while the second infield monument provides the orientation of the control network. The storage ring monuments are accessible through penetrations in the roof wall shielding. One of these should be located near the linac so no additional penetrations for the linac are necessary. Depending on the instrumentation used, all of the primary control points should be inter-visible. The spacing between storage ring penetrations is normally guided by the law of error propagation and should not exceed approximately 250 m.

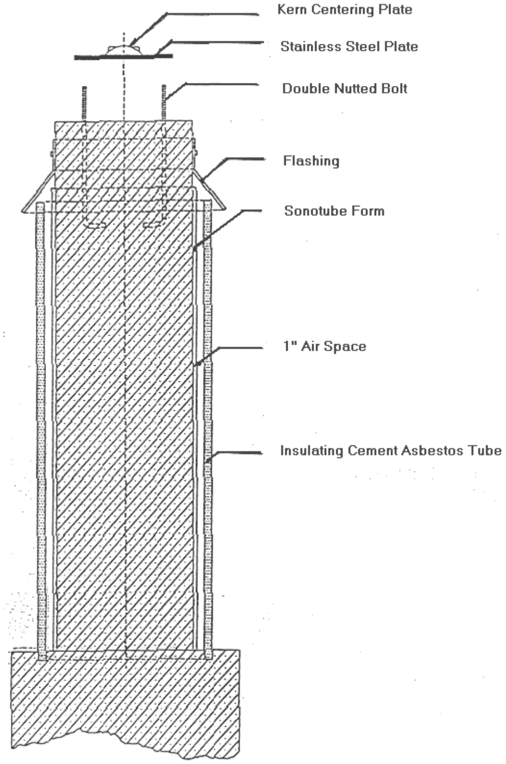


Figure 10.1.1 APS central monument.

The primary control network can be measured as a trilateration network only. Current instruments are able to resolve distances to ±(0.1 + 0.1*D*) [mm], where *D* is the length of the measured distance. This level of accuracy is not attainable with triangulation networks. By using a trilateration network, it should be possible to obtain a control network point accuracy of ±0.3 mm, similar to what has been achieved at APS [10.1.3] and as shown in Figure 10.1.2.

An alternative approach to determine the primary control network utilizes GPS observations for all primary control points. If public reference stations are not conveniently available, a local GPS reference station needs to be established at the storage ring center monument [10.1.4]. This base station supports differential GPS and would also be beneficial for the construction survey, as many survey companies have access to GPS and Real Time Kinematic (RTK) positioning technology. It is expected that utilizing DGPS, millimeter accuracies can be obtained. This approach needs to be further evaluated during the preliminary design phase to determine if it meets the requirements.

Both methods of measuring the primary network are highly dependent on the construction sequence and method, as lines of sight either between the monuments or the GPS satellites are required. This task has to be scheduled after the storage ring tunnel has been built but before the experimental hall enclosure is constructed.

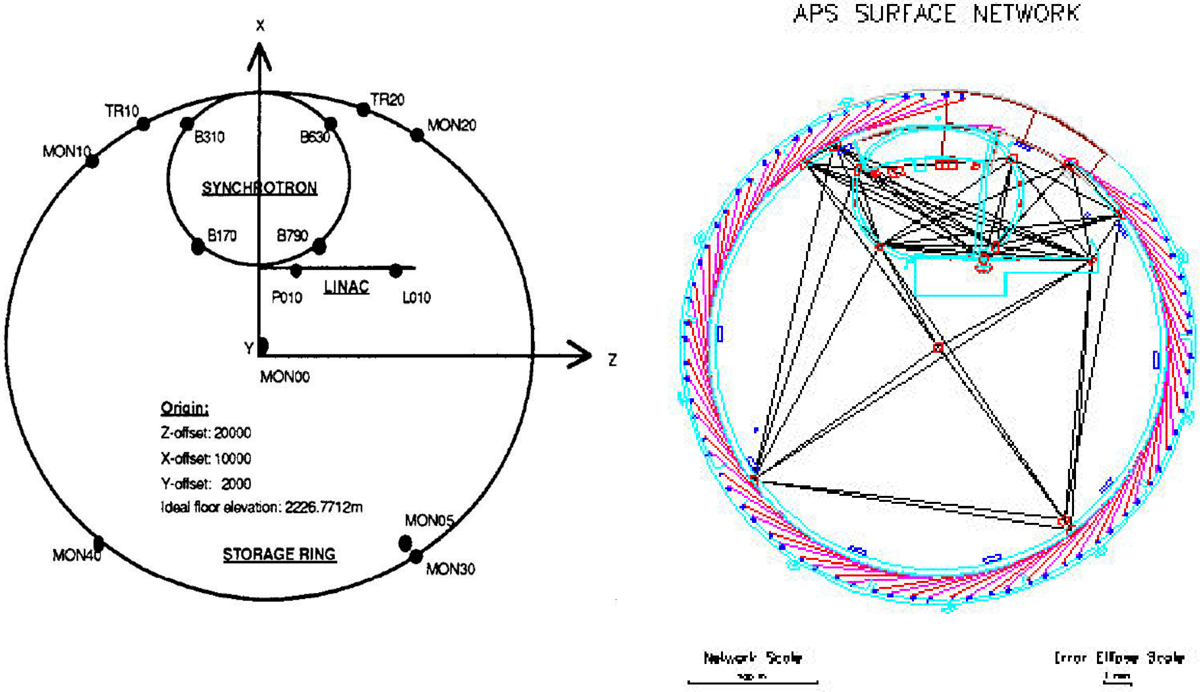


Figure 10.1.2 The APS coordinate system and primary control network.

10.1.3.1.2 Secondary Control Network

The design of the secondary control network is determined by the layout of the storage ring. If, as in the case of APS (see Figure 10.1.3), ratchet doors for each beamline are available, one can extend the secondary control network into the experiment hall, providing a more stable control network design and the means to perform alignment work on beamlines while the machine is operational. The present conceptual design of NSLS-II envisions the installation of similar ratchet doors. Therefore, the secondary control network will be extended to the storage ring enclosure.

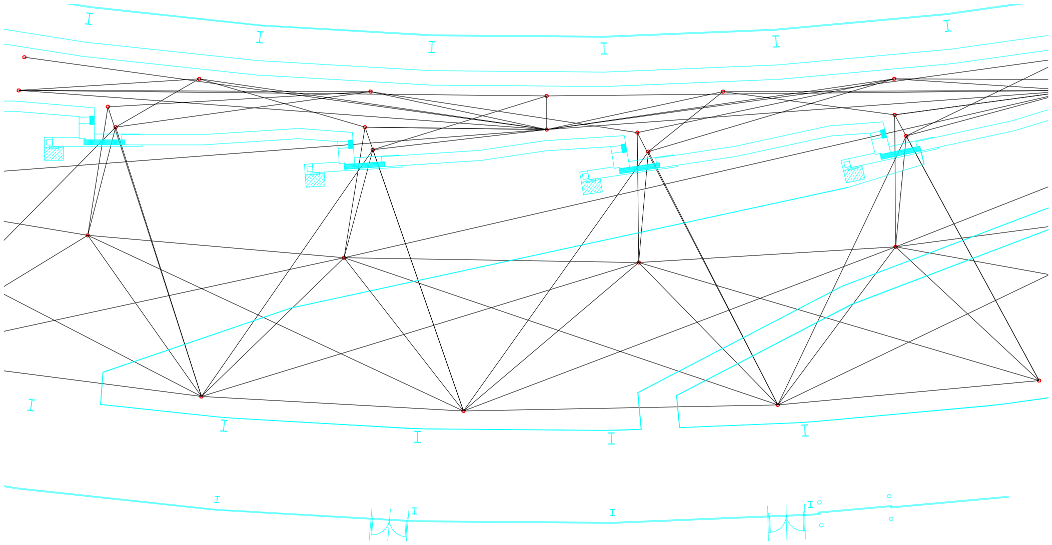


Figure 10.1.3 The APS secondary control network.

Extending the secondary network to the experiment hall floor will benefit the layout work for the individual beamlines while the accelerator is in the commissioning phase. Each BM and ID beamline should receive two control points strategically located at an offset from the ideal beamlines and visible from the storage ring through the ratchet wall openings. Prior to the installation of the ratchet wall collimators the tie between the beamline layout in the front end and the experiment hall has to be established using optical tooling instruments. The marking of the front ends needs to be done while no girders have been placed in the tunnel and is best performed while the quadrupole and girder support locations are being laid out. Otherwise, line-of-sight to these areas will be very restricted and the markings may no longer be possible. The layout of the front-end locations is very important, as it provides the only means to extend the alignment control through the beam ports to the experiment floor.

Laser tracker instruments will be used for measuring the secondary control network, followed by a least squares analysis of the data to produce the final control points prior to setting out the machine components.

Current laser tracker systems obtain point accuracy on the order of ±0.05 mm in a spherical volume with a radius of 10 m around the instrument measurement head. For measuring the secondary control network with laser trackers, the primary control points are included in the measurement process and are part of the data analysis. This constrains the error propagation of the secondary control network to the level achieved by the primary reference network. The primary and segments of the secondary networks must be established, measured, and analyzed before accelerator equipment can be installed. However, sufficient time has to elapse for the concrete to cure before the control network monuments can be considered stable. Installing the floor monuments of the storage ring will necessitate core drilling to recess the target fixtures. The wall-mounted targets will be attached to concrete anchors with threaded inserts.

The secondary storage ring tunnel network should consist of at least four survey monuments located in cross sections of the storage ring spaced 10 m apart, as shown in Figure 10.1.4. An *a priori* error analysis needs to be performed to estimate the optimum locations for these targets and the expected point accuracy. The envisioned tunnel network creates a compact box structure to obtain a stable network geometry. Control points on the infield side of the tunnel are usually always accessible. The control points opposite the aisle should be located such that they will be visible after the girders have been positioned. The floor monuments are measured using common geometric leveling procedures to an accuracy of ±0.1 mm or better. This information, in conjunction with the laser tracker measurements after proper analysis of the redundant data, provides the 3D control network that is used to place the accelerator components. An estimated accuracy of ±0.3 mm should be achievable for the secondary control network.

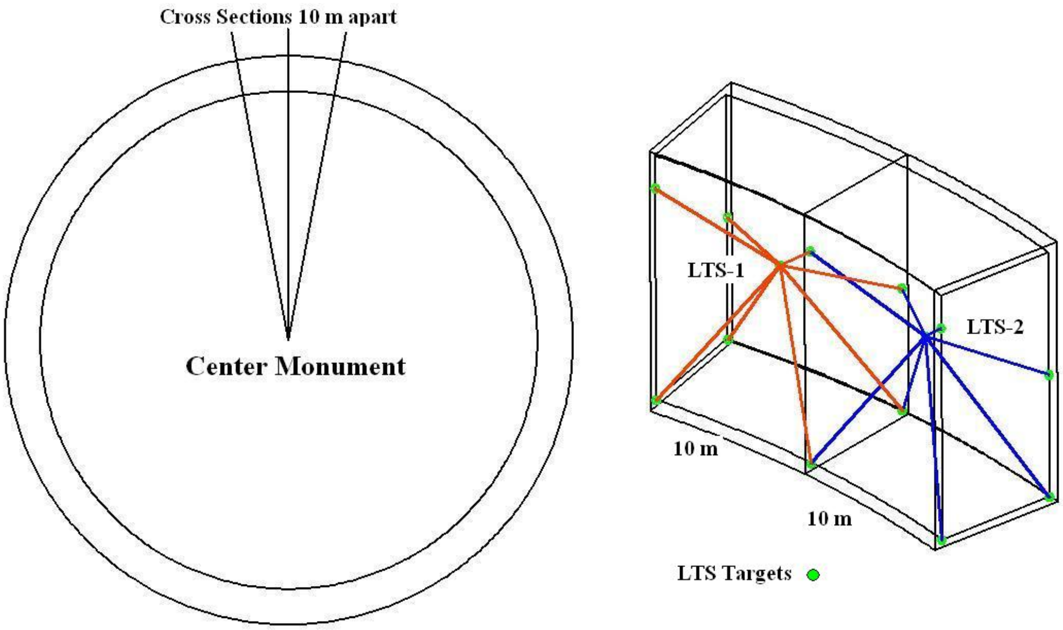


Figure 10.1.4 Sketch of a possible network design.

A variety of monuments for 1.5 inch Spherical Mounted Retro-reflectors are commercially available and can be mounted at the predetermined locations, as shown in Figure 10.1.5. This type of SMR and its accompanying receptors will be used for all survey and alignment work at NSLS-II, where possible.

Figure 10.1.5 Laser tracker 1.5 inch sphere mount.

For both the primary and secondary control network, error propagation calculations will be required before the realization of the reference network. This step provides information about the network density, optimal geometry, and minimum required measurement redundancy without diminishing the point accuracy of the control networks.

10.1.3.2 Elevation Control Network

Similar to the primary and secondary position control networks described in the previous section, we will establish primary and secondary elevation networks that are measured using common geometric level methods employing digital level instruments of proper accuracy.

Most survey instruments are referenced to local gravity. In particular, the leveling process measures elevation differences between two points with respect to the equipotential surface of the geoid. This leads to differences between a local planar system in which the accelerator is constructed and the curved geodetic reference system.

At APS, all accelerators are located in a plane tangential to a best-fitting osculating sphere at the latitude of the center monument. The difference between this sphere and the tangential plane is on the order of 2.3 mm at 175 m from the center monument, the location of the storage ring. GEONET, the software used by APS to reduce these measurements to the reference sphere, takes local deviations into account and adjusts accordingly. In the case of NSLS-II, this may not be an issue, as the booster and storage ring are located in the same enclosure. Both would have approximately the same radii and therefore the same correction factor.

In the NSLS-II storage ring tunnel, the storage ring, the booster ring, and the transport line components will be close to each other. Components will be placed and rough-aligned first, with the components that are farthest from the tunnel entrances placed first. Care must be taken to maintain line-of-sight. To accomplish this, 3D computer graphic modeling will be used. After the heavier components are placed and aligned roughly, fine alignment will proceed using laser tracker and optical level instruments. Some settling of equipment and facilities is anticipated, and it is expected that the alignment adjustment will require checking several times during set-up, commissioning, and initial operation. Therefore, alignment equipment and expertise will have to be maintained in a constant state of readiness.

In any case, for a project the size of NSLS-II with its required high positioning tolerances, measurements for determining elevations and positions will be two distinct and separate operations. Each step requires specialty equipment designed for that purpose. Even if the existing laser trackers provide 3D point information, it is necessary to supplement the vertical information with elevation measurements derived from optical level instruments for increased accuracy.

10.1.3.3 The Lattice

To obtain congruence between the survey network and the lattice layout provided by the machine physicists, the datum of both of these systems must be the same. The six parameters (x, y, z, yaw, pitch, and roll) provided by the lattice for each beam component must be transferred to the Survey group and will be stored in a database that is used for all calculations to set the girders and other accelerator components. The database also contains the fiducial information of each component that needs to be placed. GEONET, a software analysis program originally developed at SLAC for this purpose and developed further at ANL and SLAC, performs these calculations and will be used at NSLS-II.

10.1.3.4 Smoothing

The initial positioning using the reference coordinate system can only be as good as the achieved network accuracy. This accuracy represents an upper limit. However, due to inherent target and instrument errors as well as environmental effects, this limit is not achievable and the actual positioning tolerance in the global system will be less than the obtained control network accuracy. Therefore a smoothing step is required.

For this part of the process, the control network is abandoned and only the local relation between adjacent girders is measured and verified. Instruments with sufficient accuracy, such as laser trackers or special offset measurement devices, can be used for this step. In particular, a comparison between the as-built and the ideal location will provide information about the relative girder position. The girder and magnet fiducial markers will be used in this step. As shown in Table 10.1.2, the girder-to-girder tolerances are relaxed in comparison to the magnet-to-magnet requirements shown in Table 10.1.3. Nevertheless, during the fiducialization process great care has to be taken to obtain the best possible references.

Table 10.1.3 Magnet-to-Magnet Positioning Tolerances.

Relative Tolerances	Magnet-to-Magnet
Horizontal positioning	± 0.05 mm
Vertical positioning	± 0.05 mm
Roll angle	± 0.5 mrad

10.1.3.5 Fiducialization

During the fiducialization process, reference markers are determined with respect to the magnetic axis of the device. These markers are accessible after the magnet has been assembled on a girder and the vacuum chamber has been inserted. At that time, direct access to the magnetic axis is no longer possible and all positioning is performed with respect to these fiducials. Any positioning error during the fiducialization step can only be uncovered after the machine startup, with beam-based alignment methods. Unlike most of the other steps described here, this step does not provide measurement redundancy unless independent repeat measurements are performed.

For components requiring less accurate positioning, referencing to the mechanical axis may suffice. However, for NSLS-II, the magnet-to-magnet positioning tolerances, shown in Table 10.1.3, are exceedingly stringent; therefore, a combination of magnetic and dimensional measurements is required.

Usually, rotating coils or stretched wires are used to establish the beam axis. Once the optimum position of the device is found, the information is transferred from the beam axis to the outside reference markers. This is done for each of the magnets prior to the assembly on a girder. The fiducial information is used in the assembly process. The transfer of the position information from the magnetic axis to the reference point can be performed with a 25–50 µm accuracy, depending on the method used. However, in case of NSLS-II, the accumulation of errors in determining the reference targets, the mechanical assembly of the magnets on the girder, the alignment of the magnets on the girder, and so forth may exceed the required tolerance limits. It is therefore envisioned that all multipoles will be assembled and aligned on a girder using a stretched wire technique [10.1.5]. In this way, the intermediate steps to obtain fiducial information for each magnet separately are circumvented. After this step, the girder will be considered the smallest unit that needs to be placed in the storage ring tunnel.

The girders need to be fitted with permanently mounted SMR receptacles above each of the support feet on both the inboard and outboard side. This is required because the girder will have more than three support feet for reasons of stability and vibration damping. It is envisioned that laser trackers will be used to perform the coordinate transfer from the wire, via a touch-free probe, to the girder fiducials that are used to position the girder and to check for local deformations while aligning the girder in the storage ring tunnel. It is important that there be a defined stay-clear area around each of the girder fiducials. In particular, above each fiducial no obstructions are allowed; doing otherwise would prohibit the use of level rods on these markers.

R&D is planned to carefully evaluate this approach for the magnet alignment and fiducialization prior to construction of NSLS-II.

10.1.4 Implementation

Close coordination between the construction efforts and implementation of the control network must be maintained while NSLS-II is being built. It is also imperative that the survey and alignment team be involved early in the design of the girder and magnet supports and moving systems, because the positioning resolution and performance are directly linked to these devices.

10.1.5 Training

At minimum, operators of survey equipment should have several years of experience in properly handling and operating instruments of that type. Instrument operators will have to work closely with the technicians who will make the required adjustments. In particular, when using laser trackers to provide real-time, online alignment capabilities, Survey and Alignment technicians will apply the required adjustments; these two steps go hand-in-hand. Most laser tracker manufacturers provide onsite training for operating their systems. For the alignment of the front ends and beamlines, optical tooling is required because space is limited. Training in the use of optical tooling instruments is commercially available. All personnel involved with the survey and alignment tasks should have experience and aptitude in the precision alignment of 3D components and hardware.

10.1.6 Component Assembly, Testing, and Calibration

Many of the instruments that are employed for survey and alignment must be tested and calibrated on a regular basis. An alignment and calibration room will be provided for this purpose. This room will be environmentally stable and will have sufficient space for secure storage of all calibration equipment (including a Coordinate Measuring Machine and one or more large surface plates), as well as for the survey instruments themselves. The alignment and calibration room will also have enough additional space to align critical assemblies. Because survey instruments are very delicate, in-house calibration is generally preferred over shipping equipment out to a vendor. Calibration procedures and training are therefore required.

The alignment and calibration room will be large enough for calibration as well as for critical assembly work to be completed in a temperature-stable environment, thus allowing alignment processes to be tested accurately before they are used for the accelerator.

10.1.7 R&D

Two important R&D tasks have been identified. The first is an error analysis of the network configuration, to determine the network layout. It is also important in that step to incorporate the anticipated construction methodology. The second important R&D task determines the magnet measurement process and its effects on the survey and alignment process. If it can be shown that the stretched wire method can be used to position the magnets on girders, then the girder will become the smallest unit that the survey team has to contend with. However, close interaction will be required between the magnet measurement and survey groups. In particular, the girder fiducialization process needs to be established, because special equipment for the touchless wire pickup is required.

References

[10.1.1] H. Friedsam, “The Alignment of the Advanced Photon Source at Argonne National Laboratory,” International Workshop on Accelerator Alignment, CERN, Switzerland, 1993.
[10.1.2] R. Ruland, “Synchrotron Radiation Sources A Primer,” World Scientific Publishing ISBN 981-02-1856-7.
[10.1.3] H. Friedsam, M. Penicka, and S. Zhao, “Status Report on the Survey and Alignment Efforts and Results of the Advanced Photon Source,” International Workshop on Accelerator Alignment, KEK, Japan 1995.
[10.1.4] H. Friedsam, R. Ruland, private communication.
[10.1.5] Z. Wolf, “A Vibrating Wire System for Quadrupole Fiducialization,” SLAC, LCLS-TN-05-11.

10.2 Process Water Systems

10.2.1 Introduction

In order to achieve thermal and mechanical stability in the accelerator and experimental equipment, it is essential that the process water systems provide thermal-hydraulic stability. Therefore, not only must we maintain constant hydraulic conditions; simultaneously, we must remove all generated thermal loads while supplying a thermally stable, ±0.2ºF inlet temperature. To provide the desired parameters, the process systems will be divided into two generic types:

- Aluminum system(s) consisting of only aluminum and stainless steel components, supplying control for the aluminum vacuum chambers (i.e., "beampipes") throughout the rings
- Non-aluminum system(s), consisting of stainless steel components, providing control for all non-aluminum subsystems throughout the rings

10.2.2 Thermal Loads

The actual distribution of the thermal loads is both machine and component dependent. For example, both the storage ring and linac are independent machines with their respective thermal–hydraulic requirements. Also, within the storage ring there are distributed magnets and power supplies, each requiring its own respective parameters. Therefore, we will further divide the non-aluminum system into two separate types, allowing for maximum flexibility and control:

- An independent system for the linac
- Independent systems for the storage ring and its components and constitute subsystems

10.2.3 System Design and Parameters

The linac system will be an independent system supplying a constant pressure and flow with an inlet temperature of approximately 113ºF ±0.2ºF. This system will have a design very similar to the system described for the storage ring, as shown in Figure 10.2.1.

The storage ring design has thirty cells. As two cells constitute a super-period, for both the aluminum and non-aluminum systems the storage ring system has been divided into fifteen repeating sections, with each section having two process water systems, one for the aluminum and one for the non-aluminum needs within that given section.

Each aluminum system, supplying one-fifteenth of the vacuum system, will provide a constant pressure and flow with an inlet temperature of approximately 85ºF ±0.2ºF.

Each non-aluminum system, supplying approximately one-fifteenth of the storage and its subsystems, will provide a constant pressure and flow with an inlet temperature of approximately 85ºF ±0.2ºF. This sectional division will allow for differences in thermal distribution around the ring, and as such, each independent process system can be tailored to the specific thermal needs within its respective section. Also, by distributing the systems, an individual system will be smaller both in size and corresponding pipe runs.

A schematic of a non-aluminum system, using a total of 6 MW thermal loads evenly distributed over the fifteen sections, is shown in Figure 10.2.1. No heat exchanger is needed. "Cold" deionized water is supplied via a common header and pressurized via a 5 HP pump. This flow is controlled by the cold control valve and is then mixed with the hot water returning from the various components and subsystems. This hot water is itself pressurized via a 15 HP pump and is controlled by the hot control valve. Within a few minutes of operations, this hot water is within range and the thermal control is established. We have allowed for an 80 psid pressure drop across the components and magnets, and a 15ºF differential across these same components. The overall system pressure is maintained by a back pressure control valve, thereby setting up a controlled leak of inlet cold water versus outlet hot water. The cold water will be supplied via a common header and all necessary subsystems and water quality control will be carried out at that level.

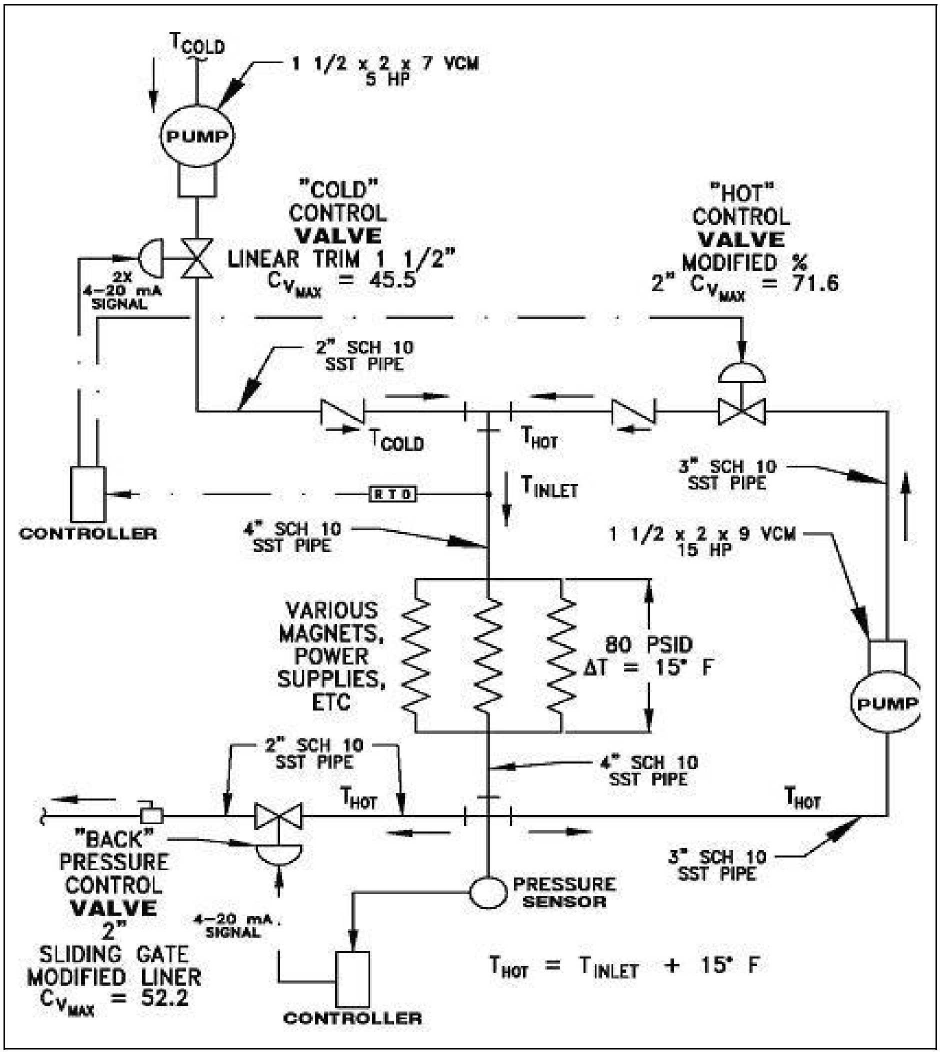
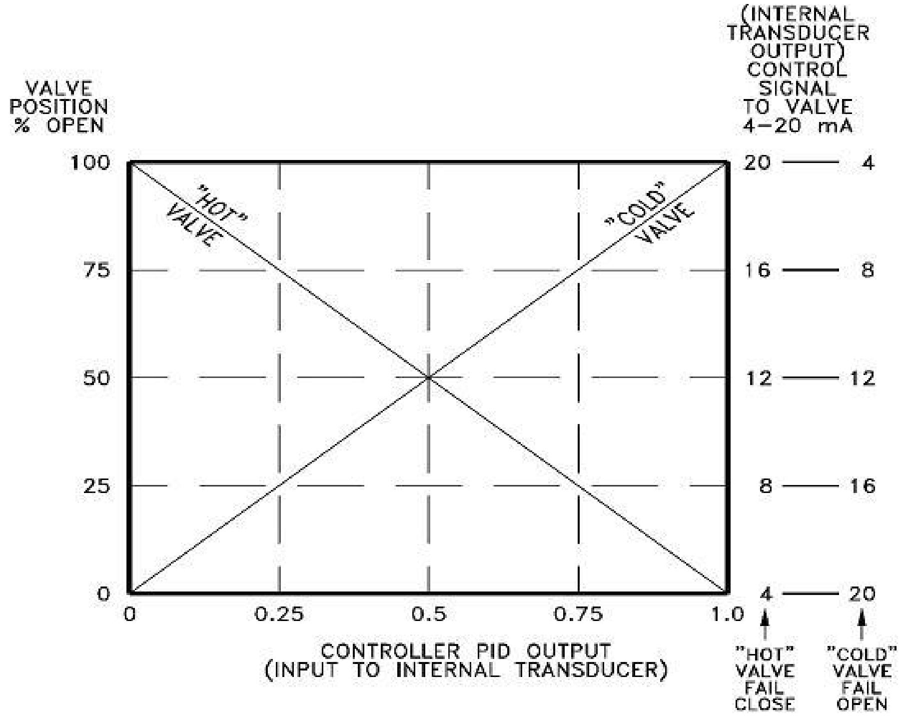


Figure 10.2.1 Non-aluminum process water system (deionized).

A split ranging scheme, which is shown in Figure 10.2.2, maintains the temperature control. The hot valve will be a 2" fail-closed valve with a maximum $C_v = 71.6$, while the cold valve will be a 1 ½" fail-open valve with a maximum $C_v = 45.5$.

The actual rate and any off-set in an individual valve's operation will be tailored during its tuning phase, where a standard PID single-loop controller using a split ranging scheme is used.

Figure 10.2.2 Control scheme: split ranging.



An aluminum system is shown schematically in Figure 10.2.3. Since the absorbers will absorb most of the thermal load, a total of 75 kW evenly distributed over the fifteen sections was used in sizing the system shown. A heat exchanger is needed, along with a control valve on the cold side of the heat exchanger. A 5 HP pump supplies the necessary pressurization and the system is sized for approximately 2.5 ft/sec through each of the vacuum chamber’s flow channels.

Each one-fifteenth section will consist of nine parallel flow paths feeding five straight section beampipes and four dipole section beampipes. Within each beampipe type there is a fixed number of flow channels (or passages).

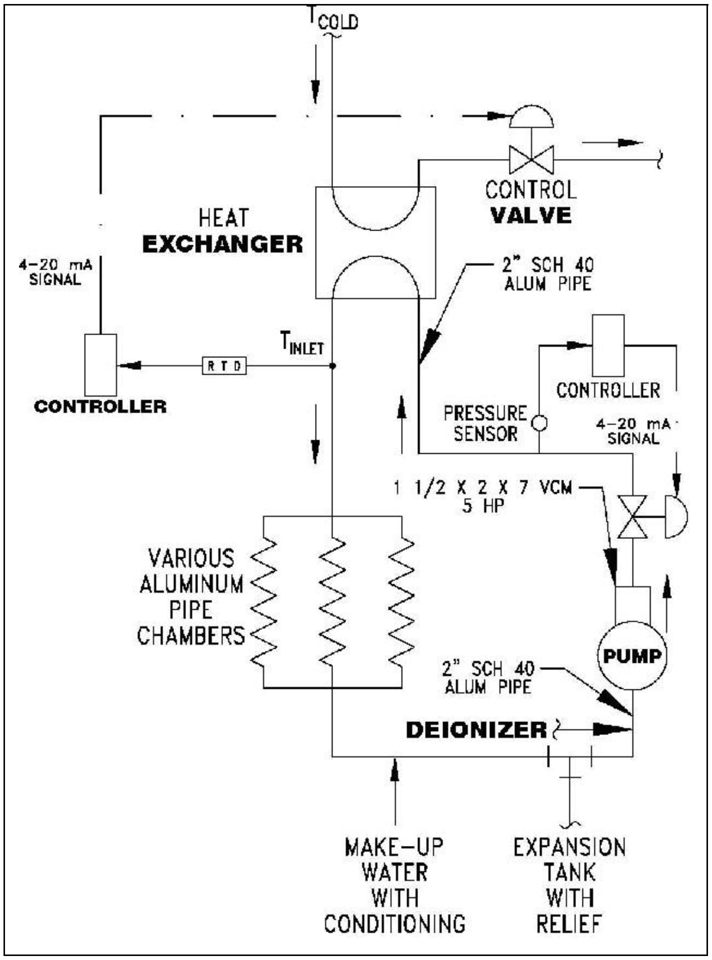


Figure 10.2.3 Aluminum Process System (Independent).

10.2.4 Water Quality Control

The water quality must be maintained in order to minimize any corrosive action that may occur. The following parameters will be maintained:

- Resistivity = 1.0 MΩ-cm ±5%
- pH = 7.5 ±0.2%
- Oxygen concentration = 10–20 ppb ±1 ppb

This water control will be maintained for the non-aluminum (non-linac) systems on a "global" level in the header-supplied cold water. For the linac and aluminum systems, this control will be maintained at the individual system level. For all cases, an industrial stand-alone system will supply the necessary water quality control.

10.2.5 Aluminum Bakeout System

A viable vacuum system must obtain a level of cleanliness that only can be achieved by removing all the entrapped gases within the piping enclosure. Thus, for the aluminum system to achieve its necessary vacuum for operations, a bakeout must be performed. This bakeout will be conducted at a constant 125ºC and will be maintained for the necessary time period as determined by the chamber's exposure to containments. In order to achieve this requirement, each aluminum system will allow for an independent, roll-up, bakeout system to be connected to it. The aluminum pumping station will be isolated from the chamber and this bakeout system will be connected via a valve.

This bakeout system will consist of a pump, electric heater, and appropriate valving and controls such that a constant flow of 125ºC water will be maintained to the beampipe under consideration. The aluminum pumping stations will have the following design parameters:

- P_{DESIGN} = 150 psig
- T_{DESIGN} = 275ºF

The aluminum system, including the isolation valves, in contact with the bakeout water flow and the beampipes, will be designed for:

- P_{DESIGN} = 200 psig
- T_{DESIGN} = 275ºF

The bakeout system pump/heater will supply water at 150 psig and a temperature of 260ºF (~125ºC). Since the saturation temperature associated with 150 psig is T_{SAT} = 366ºF (@ P = 165 psia), and the operational bakeout temperature is 260ºF, we can see that there is 106ºF subcooling available, thereby ensuring that no change of phase will occur. 260ºF corresponds to a saturation pressure of 35.427 psia, which thus allows for a differential pressure drop of 129 psi before flashing will occur. Once the desired bakeout time has been achieved, the heater will be turned off and the water will be circulated to slowly cool down the beampipe section, thereby effectively ending the bakeout.