ii. Tunnel Survey and Magnet Alignment

Survey will utilize state-of-the-art technology yielding accurate geodetic information in a fraction of the time required by conventional means. RHIC R&D has fostered an integrated plan which includes geodetic survey of primary monuments, establishment of a tunnel net, cryostat design engineering and magnet positioning as a mix of input variables leading to a series of steps to attain positional and smoothness accuracies required for RHIC magnet installation in the accelerator tunnel. The RHIC reference geometry and the collider layout in the tunnel are shown in Fig. 0-3.

Primary Monument Survey. Twelve primary survey monuments located on top of the berm around the RHIC ring were surveyed by the National Geodetic Survey (NGS) in 1981 and must be remeasured to correct for earth settlement that has occurred over the ensuing years. The original quoted error of primary monument survey was about 2×10^{-6} or an uncertainty of one to two millimeters over the RHIC ring radius of 620 m. Measurements were carefully done using conventional triangulation techniques to extend a geodetic grid already in existence at Brookhaven. Accuracies of a few millimeters uncertainty are necessary for a project of this scale but proved very labor intensive, consuming man-years of effort only to be stopped before completion at the termination of the CBA project.

Today, primary survey data of higher accuracy can be obtained in terms of days, not years, by utilizing new technologies. For RHIC's primary monument survey and the tie to the BNL grid, a Kern Mekometer (ME-5000) precision laser distance meter will be employed. This instrument has been thoroughly characterized and evaluated for accelerator survey work at the Stanford Linear Accelerator[8] and checked for accuracy at Kern's "Aare Test Facility" and DGFI, the German Geodetic Research Institute. Field accuracies for the ME-5000 show errors to be typically a few tenths of a millimeter over 432 and 864 meter distances, an improvement of an order of magnitude or so over CBA measurements. The ME-5000 measures the phase of a periodically modulated He-Ne laser beam reflected from a precisely fabricated corner cube retrodirector. By modulation of both polarization and frequency of the light beam, unambiguous distance measurements can be made to 0.01 mm resolution and 0.1 ppm accuracies over distances from 10 m to 10 km.

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[8] T. W. Copeland Davis, Report SLAC-375, Conf.-890 7/90, VC-419, October 1990

The Mekometer will be mounted on the primary monument stands and towers around the RHIC ring, together with a precision theodolite to permit simultaneous measurement of distance and angle to the target.

A second, optional, method to measure the position of the 12 primary monuments could employ satellite based Global Positioning System (GPS) technology. Typically one receiver is placed at a known NGS control point and others at primary control points to be measured. Each receiver accumulates data of satellite time synchronization, orbit information and simultaneous phase measurement of at least four satellite carrier frequencies for a minimum period of 45 minutes. Received information is stored on cassettes and post processed by computer to yield the longitude, latitude, height of unknown stations, distance between each station and azimuthal directions between all points. Six "orders" of GPS geometric relative positioning accuracy standards are defined by the Federal Geodetic Control Committee (1988) document,[9] the highest being classified as order AA. Its accuracy standard for three dimensional surveys using space system techniques is defined in terms of base error and line length dependent error. The maximum allowable error for a single dimensional measurement at 95% confidence level is:

$$S = 3\text{ mm} + 10^{-8} \times (\textit{Line Length})$$

For RHIC the longest line length is no more than a few kilometers, making line length errors inconsequential. One sigma error can be expected to be less than 2 mm in all three dimensions. An NGS calibrated base line of 14000.0138 m located in St. Petersburg, Florida was used by a commercial survey company to check the accuracy of GPS technology. Two antennas were set up at either end of the base line and satellite data was recorded for 1 hour. The data was reduced and the GPS derived length agreed to within 3 mm of the NGS calibration. GPS technology is clearly a time saver, without a sacrifice of accuracy, when compared to conventional means.

Standard 30 mm diameter CERN type self-aligning stainless steel bushings will be grouted into the floor of the RHIC tunnel beneath twelve 24-inch vertical pipes located in the ceiling. These transfer points will act as primary monuments and are located near the

[9] Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques, Federal Geodetic Control Committee, Version 5.0, May 1988.

ends of each arc sextant of the machine. The measuring instruments will be positioned on top of the berm over the primary monuments and collimated. Once positioned, data taking begins and continues to accumulate data measuring relative position of the primaries with respect to the ring center monument and the existing geodetic grid. When enough data has been accumulated to gain the desired accuracy, the antennas are moved to new positions and set up for another satellite receiving session. Survey jobs of a size larger than RHIC have been completed in one to two months of work which includes setup, session and data reduction time.

Secondary Tunnel Net. Once the coordinates of the tunnel primary monuments are known, secondary control points will be located in *x, y* and *z* around the remainder of the ring. These monuments will be physically the same as the primaries and installed in their rough positions before magnets are placed in the tunnel. Accuracy of placement of the secondaries is unimportant, so long as the monuments are placed about two feet away from the inner and outer tunnel walls, positioned opposite each future arc dipole location and slightly offset from its magnet stand center support leg. A similar scheme will be used to extend monuments through the insertion regions of the sextants with minor adjustment because of the non-periodicity of its magnetic elements.

The exact three dimensional positions of the secondaries will be carried from the primaries at each end of the sextant through twelve secondary monument pairs and close at the midpoint of the sextant. The geodetic figure (Fig. 0-4) of the RHIC arc full cell shows a braced quadrilateral framework of a width to length ratio of approximately 1 to 4. From experience gained at CERN's ISR and SPS projects, length measurements will be used employing laser distance meters to keep errors down to the 0.025 mm range. Additional

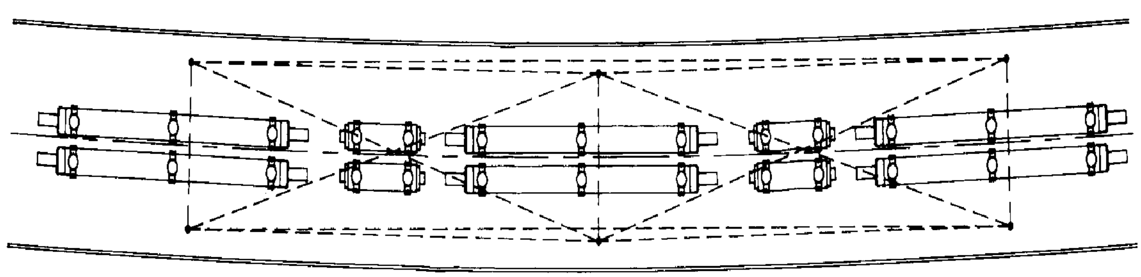

Fig. 0-4. RHIC secondary monument distance measurement.

stiffening of the tolerances can be obtained by measuring offsets of two consecutive quadrilaterals to assure the precise position measurement of secondaries of the geodetic framework of each sextant. Vertical positional measurement will be done by conventional angularity measurements. Errors in closure at the center of the sextant will be less than 0.5 mm plus the relative position error differential of the primary monuments.

Magnet Installation and Positioning. Final positioning of magnet elements to meet machine accuracies (Table 0-2) is simplified by integrating these requirements at every stage of planning starting with cryostat design. Figure 0-5 shows a cross-section of the cryostat, including removable survey targets mounted on its cold mass and base.

Magnet stands will be placed in the RHIC tunnel to a few millimeter accuracy and secured in place. Two stands are required to support each blue and yellow ring magnet and will be cast to shape to reduce costs as opposed to cutting and welding plate stock.

Absolute position of the cold mass in the cryostat, through the cradle assembly, post support and base, is controlled by machining tolerances; thus the position of the cold mass with respect to cryostat base fiducials should be reproducible to within the stack-up of specified machining errors. Before shipment to BNL, the supplier will measure and record the offset dimensions of the end fiducials of the cold mass with respect to cryostat base fiducials as specified in the RHIC Dipole Request for Proposal (Section 4.1.4 Position and Orientation Measurements). Upon receipt at BNL, the cryostat will be resurveyed to assure that the assembly has not been damaged in shipment by comparing suppliers fiducial data to as-received at BNL and to check that the cold mass has been correctly assembled in its cryostat, based upon deviations from normally expected variances of fiducial values. After the magnet assemblies pass cold tests, they will be trucked to the RHIC site. There, a specially designed cart will be used to carry the cryostats into and along the tunnel and place the dipoles and quads upon their stands. The stands are designed to accommodate a sliding plate and vertical screws so that each cryostat can be independently positioned in x, y and s space and corrected for rotation errors of the magnetic field.

Table 0-2. Magnet Position Tolerances at 4 K

Beam Position Monitor - Reference Orbit†	$\Delta x = \Delta y = 0.25$ mm rms
Sextupole - Beam Position Monitor This tolerance refers to the magnetic center of the sextupole relative to the center of the BPM, all along the axis of the sextupole.	$\Delta x = \Delta y = 0.13$ mm rms
Quadrupole - Beam Position Monitor This tolerance refers to the magnetic center of the quadrupole relative to the center of the BPM, all along the axis of the quadrupole.	$\Delta x = \Delta y = 0.25$ mm rms
Dipole - Reference Orbit Tolerance refers to the magnetic center as given by fiducial marks of the dipole relative to the reference orbit all along the axis of the dipole. The dipole magnetic center is defined as the magnetic center of its magnetization sextupole.	$\Delta x = \Delta y = 0.50$ mm rms
Dipole Rotation The average horizontal component of the dipole magnetic field is to be less than 1×10^{-3} rms of the vertical component of the field.	$\Delta\Theta = 1$ mrad rms
Quadrupole Rotation	$\Delta\Theta = 1$ mrad rms
Longitudinal Error Refers to the longitudinal position of all magnets with respect to their ideal position along the reference orbit.	$\Delta s = 1.0$ mm rms
Long Term Position Stability The design shall make every effort to keep the long-term position stability, including creep effects, consistent with above position tolerances.	

†Reference orbit positions are based upon tunnel net and primary monument measurements.

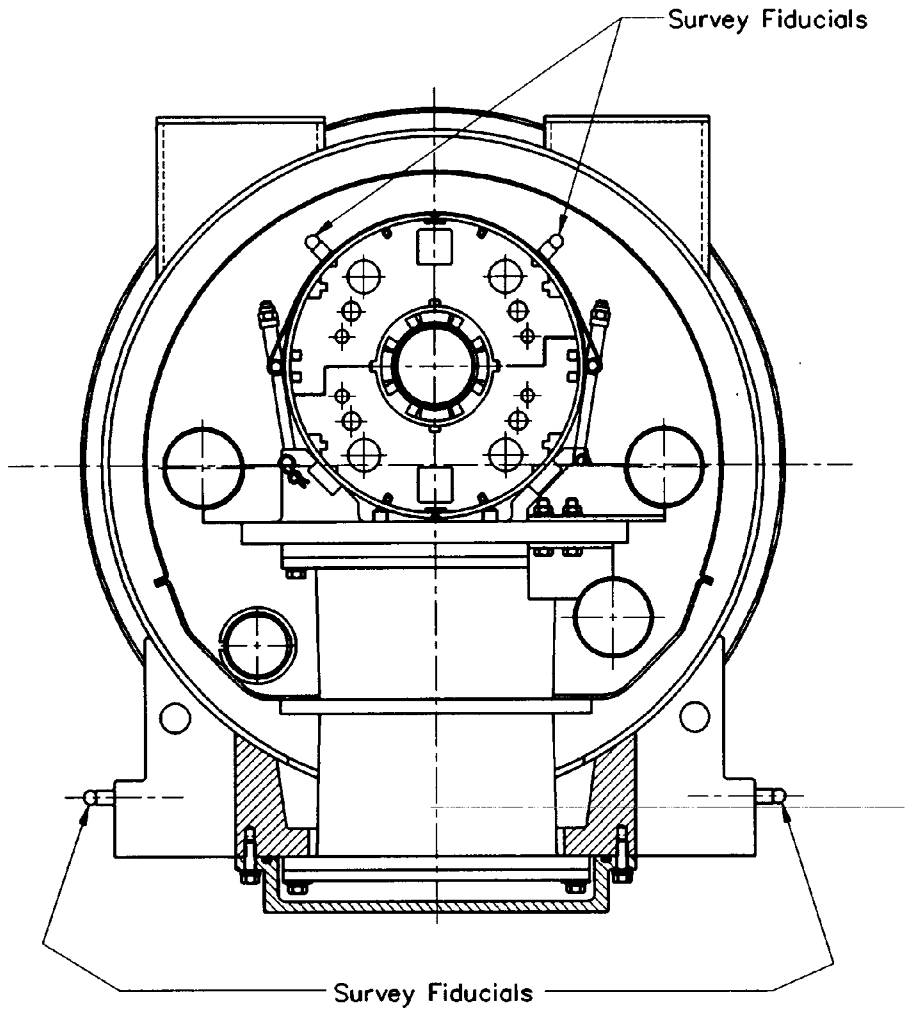

Fig. 0-5. Cryostat showing survey targets.

Final positioning and smoothing of the magnetic elements to the machine's reference orbit will be done in one operation utilizing digitally encoded electronic theodolite systems. Electronically encoded T 3000 theodolite heads will be plugged into the secondary tunnel net monuments as shown in Fig. 0-6. Positional tolerances for dipoles are less stringent so

the secondary monuments were pre-positioned opposite the center support legs of these elements to afford larger sighting angles for the quadrupoles where greater accuracy is demanded. Up to eight theodolite heads can be connected to an on-line personal computer, each having angularity setting capability of less than 0.5 arc seconds which translates to errors of less than 0.025 mm in a 10 m sighting distance. The electronic theodolite system has many features that enhance useability and speed setup time, including an automatic electronic leveling feature with compliance to ±10 minutes and a setting accuracy of ±0.1 seconds. As long as the 30 mm CERN bushings are grouted to a verticality of no more than 10 minutes maximum error, there will be no need for manual adjustment procedures.

Real time saving is afforded by the use of the computer interface. Since the position of the tunnel net secondaries and primaries are known from previous measurements, a computer program will be written to smooth the measured positions of the tunnel net monuments. Placement of the quadrupole and dipole magnetic elements in their proper positions with respect to the machine reference beam orbit therefore becomes a less laborious task. Since the position of the center of the quadrupole and dipole magnetic fields

are known with respect to the cold mass fiducials, the cryostats are moved to position the cold mass fiducials to precalculated locations in space so that the magnetic elements are longitudinally centered and radially located as per RHIC lattice design. Cryostat base

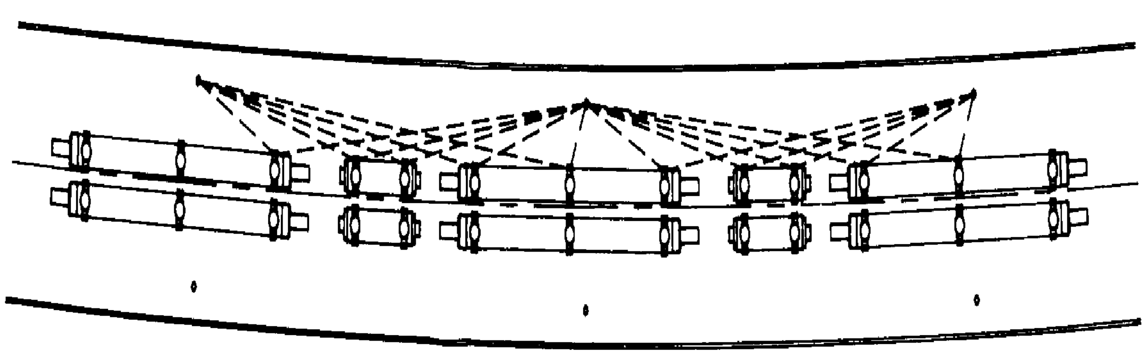

Fig. 0-6. Electronic theodolite positions for magnet installation.

fiducial positions will be checked against offset measurements obtained during incoming test and will, along with cold mass position data, become a permanent record data base for future reference.

The electronic survey system can be operated in two modes to assist placement of the magnets in their final positions. The inspection mode can be used where the operators set the theodolite cross hairs on the cryostat targets, coordinate values are computed and deviations from the desired positions stored in memory are displayed on the screen of the CRT. Cryostat position would then be adjusted until the computed deviations are driven to zero. The second method employs laser heads mounted on the optical telescopes of the theodolites. Each of the theodolite heads are positioned to pre-calculated angles and the cryostats are moved to a point where the laser beams intersect at the cryostat targets. In both cases there is no need for manual data taking or hand calculations, for magnet position is based only on smoothing calculations from the original measured positions of the primary and secondary monument locations and offsets to the beam reference orbit position.

Four or more theodolite heads would be optimum for cryostat positioning in the tunnel. Two would be plugged into the tunnel net sockets along the wall and two or more heads positioned in tripods at appropriate positions to minimize angle measurement error. The exact position of each of the auxiliary heads is calculated by system software after a tunnel net theodolite and auxiliary sight a reference bar of known length. Once all measuring element positions are known in three dimensional space coordinates, methods described above can be used to place the cryostats in their smoothed locations, and in one case, without having to change the position of the theodolite heads. The ability to utilize numerous measuring elements is clearly an advantage. All measurements for magnet installation can be done from one or the other side of the tunnel and in the second mode, at least, setting errors are minimized because the theodolite heads remain in static position, untouched after initial setup.

The concept and use of electronically encoded theodolites, an on-line computer to pre-smooth magnet positions and essentially "point" to their final positions will not only increase accuracies but save time as well. As magnets are initially installed in the tunnel by electronically aided methods, results will be checked by conventional means and a best method of magnet installation and smoothing will be adopted.