SEP 23 1964

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BNL 8316

ACCELERATOR DEPARTMENT

(AGS)

Internal Report

MASTER

ALIGNMENT STABILITY OF THE 33-BEV SYNCHROTRON
AT BROOKHAVEN NATIONAL LABORATORY, 1959-1963

O.S. Reading

July 15, 1964

Abstract

The AGS is stable well within its present operating tolerances. However, when major shielding load or construction changes are made in its immediate vicinity, some realignment may become desirable. Only one general and one partial realignment have been considered desirable in the four years since its construction. These realignments were accomplished without handicaps to the operation of the machine when it was shut down for other reasons.

This report summarizes the variations in alignment observed, also some test measurements of settlements under various load conditions. The detailed records of the measurements and computations are on file in the survey group office or in the BNL Records Center.

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Details of the main factors considered in designing the foundations for the machine are discussed in a report "On Foundation Design, AGS - January, 1958" by the Stone and Webster Engineering Corporation, F.W. Swiger, Engineer. A second report by the same author, "Feasibility of Conjunction Section," February 8, 1961, gives a formula for predicting settlements under various load conditions. Measurements made during maximum excavation and after completion of the construction of the conjunction section to the North Experimental Area agreed quite closely with these predictions. The analyses of these reports and the precise survey measurements summarized in this report furnish much information on the behavior of the sandy moraine soil of this locality under various foundation loads.

Alignment Specifications

The 33 billion electron volt alternating gradient synchrotron at Brookhaven National Laboratory consists primarily of 240 main magnets of approximately 17 tons each, also accelerating equipment and some 60 additional multipole correcting magnets mounted on a circle 842.90 feet in diameter. The foundation design studies contemplated holding the alignment of these magnets within $\pm$ five mils in relative position with no abrupt discontinuities exceeding 10 mils. Provision was made for readjusting the magnets to compensate for changed shielding and experimental equipment loads. These were predicted as likely to cause changes in the alignment of many times the specified tolerance.

The surveying techniques used to set the elements of the machine to these tolerances are described in detail in BNL Report "Precision Surveying for the 33-Bev Synchrotron at Brookhaven National Laboratory, August, 1963."

Survey Operations

The vertical alignment of the machine is measured in reference to the median plane of the machine orbit. Precise spirit leveling is run over some 200 stainless steel bench marks as indicated in Fig. 1. Levels to three plates ground to a standard elevation and fastened on the top of each magnet are used to set or to readjust the magnets in correct relation to the adjacent bench marks.

The horizontal positions of the machine elements are set in relation to the standard reference circle of 421.45 feet radius as measured to sockets in the tops of the magnets from 24 horizontal control stations equally spaced around the ring. The results of the vertical and the horizontal measurements will be discussed separately. Fig. 1 is a diagram of the survey marks to which measurements are made.

Vertical Measurements

Most of these data concern variations in elevation of round-headed stainless steel nails or rivets driven or cemented into the ring pile caps supporting the magnet girders. (The variation of the reference pads on the tops of the magnets follow very closely changes in the pile cap foundations.) Additional marks are set in the control station monuments, the tunnel walls and target building floors.

Fig. 2 shows cross sections of the ring tunnel and target building to indicate the vertical position of the bench marks in relation to the foundation elements. Precise levels were run over most of the ring bench marks as follows: 1957 October, 1958 January, April, July; 1959 January, April, August, October; 1960 January, July; 1961 January, October; 1962 January, June, September; 1963 March, May, August.

FIG. 1

FIG. 2

The machine was carefully adjusted to alignment during January and February, 1960. Some readjustment of magnets in the Target Building were made to compensate for major changes in shielding during 1960 and 1961. A complete realignment of the main ring was made during August and September 1962 after the extensive construction for the North Experimental Area was completed. The changes of elevation of the magnet pile caps at various times during the two-and-one-half year interval are diagramed on Fig. 3. Elevations of the marks at the time of maximum excavation of the areas near the ring (when the machine was not operating) are also shown.

Precision of Vertical Measurements

The precision of the vertical measurements is exceptionally high, due to optical tooling scale rods, suitable bench marks and air conditioning. The mean differences in elevation of the forward and backward runs around the 120 bench marks of the half mile ring nearly always have closed within 0.030 inches and occasionally less than 0.010 inch. All of this leveling is accomplished under specifications requiring re-measurement whenever the forward and backward runs give differences exceeding 0.002 inch between the elevations of successive bench marks.

Datum

This precision was so high as to justify the computation of a special datum to more clearly portray the changes in relative elevation of the many components of the machine. At first it was intended to refer the levels to a datum held by two deep bench marks established in connection with test borings for the foundations of the AGS. These bench marks are made of iron pipe four inches in diameter driven to a depth of 100 feet with the mark mounted on an inside tube two-and-one-half inches in diameter sliding in the outer tube, then driven to a depth of 125 feet.

FIG. 3

One of these bench marks, Deep T, passes through the foundation mat supporting the shielding in the target building, being isolated from the mat with a third tube. This bench mark was expected to extend below the soil compressed by the mat and its shielding load and to be sufficiently decoupled to serve as a datum for the settlement of the mat and the machine as the shielding load was applied. It soon became evident however that the Deep T bench mark was settling as the shielding was loaded on the mat in comparison with bench marks 200 feet or more away from it along the tunnel. It appears that the soil was consolidated to a greater depth than anticipated or that the compression seized the upper part of the outer tube and transferred part of the load to its lower end where compression of the sand there carried the inner tube down by the amount of settlement of Deep T. Incidentally, the use of air space around the pile caps or even sheet piling to a depth of 10 feet did not decouple the mat load as much as expected. See Fig. 5.

The other similar deep bench mark, "Deep F", is in the open more than 200 feet from the heavily loaded mat, far enough away to be free of mat load effects. However, assuming that the inner tube of this bench mark takes the temperature of the surrounding soil, the seasonal variations in soil temperature at different depths as measured during the test boring program cause the bench mark to vary in height through a range of 0.038 inches from August to March. Even this range may be exceeded because of convection exchange in the air between the inner and outer tubes and conduction of top tube temperatures. Unfortunately, no arrangements were made to measure the temperature of the inner tube to furnish definite corrections for this varying temperature. Any future deep bench marks intended for such precise leveling will of course be provided with devices for measuring their temperature at suitable intervals.

Date	Deep F _r Datum Elevation	A ₁ Bench Mark Elevation	Charge in A ₁	Average Fing Eley. F ₁ to F ₁ *	Ring Elev. Differences Base, A ₁	Ring Elev. Differences Base, D F _r	Changes from Base Year Deep F _r	Gen. Room Bench NW
1958 June	837.098	841.1976	0	841.1976	0	4.100	0	877.250
1958 Dec.	Same	841.2006	+ 0.003	841.188	- 0.012	4.090	- .010	877.242
1959 August	Same	841.222	+ 0.024	841.183	- 0.039	4.085	- .015	
1960 July	Same	841.205	+ 0.007	841.172	- 0.033	4.074	- .026	
1961 Dec.	Same	841.183	- 0.015	841.157	- 0.026	4.059	- .041	877.197
1963 Dec.	Same	841.134	- 0.064	841.126	- 0.008	4.028	- .072	877.242

* Beginning in 1960 data used in determining average ring elevation were pile caps from A₁ through F₁ only.

In view of the uncertainties in the elevation changes of the deep bench marks and the distance to previously established government bench marks, the leveling data was reduced to a special datum computed as the average elevation of the pile caps of that portion of the ring which had small if any changes in loading.

Thus, the graphs of settlement given in this report were corrected by applying the algebraic difference between the average elevation of all pile caps H_1 downstream to F_1 as leveled during January, 1958 minus the average elevation of the same bench marks of the leveling circuit being corrected (until July, 1960).

Since July 1960, the average elevation of the pile caps A_1 to F only have been used to compute the datum corrections because of the changing loads in the vicinity of the target building and construction near the north side of the ring. This reduction procedure emphasized the relative settlement of the elements of the machine where loads had changed unconfused by variations in single marks.

The differences in elevation found during each leveling circuit were abstracted by adding them algebraically to a standard elevation of a single bench mark ($A_1 = 841.2006$ inches). Thus the difference in the datum corrections of each circuit give the average settlement of the ring without material changes in load during the time interval between circuits assuming that bench mark A_1 remained unchanged.

The following Table shows the differences in elevation between Deep F_R held as a datum bench mark, the bench mark A_1 in a relatively undisturbed area, and the average elevation of all bench marks of the ring where no material changes in load had occurred (H_1 to F_1 until January, 1961, then A_1 to F_1): These data indicate a general settlement of the ring ~ 0.07

inches, with little relative settlement of the generator foundations. The differences found vary by the unknown changes in the elevation of Deep F with changes in ground temperature.

Settlement in the Vicinity of the Mat with Shielding Loads

The tunnel which provides shielding from radiation generated by the machine, is interrupted for 250 feet by the target building. In the target building, shielding is provided by blocks of dense concrete which load the floor up to 5800 lbs. per square foot. The load of this shielding is carried by a heavily reinforced concrete mat four feet deep and 48 feet across extending 285 feet along the ring. This mat is decoupled from the piles and pile caps supporting the magnet girders by an air space of four inches and a ten-foot square enclosure of sheet piling driven to a depth of ten feet surrounding each pile cap. The three survey monuments in the mat area are also decoupled by a three-inch air space between pipe set in the mat and the tubular piles driven 20 feet below grade to support the monument, Fig. 2A. Levels were run each week as the shielding load was gradually placed on the mat. The settlements are shown in Fig. 5. Note that the decoupling provided was not very effective in reducing the settlement of various pile caps and monuments. These settled approximately eight tenths as much as the adjacent mat. Apparently the compression of the sand was sufficient to transfer a large part of the stress to the piles and force them to settle also. The unloaded floor (bench marks T-A series) adjacent to the mat but also decoupled from it, did not settle nearly so much. These marks are immediately above reinforced concrete trenches which may have functioned with the floor as girders to keep the marks from settling with the soil immediately beneath them and close to the mat.

TARGET BUILDING MAT - SETTLEMENT WITH SHIELDING LOAD (IN THOUSANDTHS OF AN INCH)

FIG. 5

The data of Fig. 3 and Fig. 5 now cover a span of four years and give some information about the relative secondary settlement with time as well as the relative initial settlement shortly after the loads were applied.

Elevation Changes for Steel Shielding Load of the First Neutrino Experiment - Fig. 4

During November, 1961, an additional shielding load of steel armour plate was placed on the mat in the vicinity of pile caps G4 and G5. A load of approximately 2600 tons for the sides of the neutrino spark chamber shielding was first placed on the mat causing a maximum settlement of 0.123 inch in pile cap G5 when measured the day following completion of the load. During a subsequent ten-day interval a further settlement of 0.005 inch was measured. Then an estimated load of 500 tons was added to form the roof of the chamber. This caused a further settlement of 0.024 inch. The total maximum settlement immediately after placing the roof for the total extra load of 3100 tons is 0.162 inch. Fig. 4, shows the elevations before and after the placing of the additional 2600 ton load and the 500 ton roof load.

It is noteworthy that the machine continued to operate for a week after the 0.138 inch settlement occurred without remark from the experimenters or Control Room although no measurements of beam orbit oscillations were made. The machine was then shut down to place additional lead shielding close to the magnets and advantage was taken of this shutdown period to releve the magnets from G_2 to GH_2 to standard orbit heights.

A tilt of the lowest magnet of 0.4 mil radians outward was observed before the magnets were releveled. This tilt gradually decreased proportionally to the decreases in settlements of the adjacent magnets. (All the additional shielding load for the neutrino experiment was placed outside, eastward, of the ring). A check of the radial positions of the magnets was made after they were releveled and they were found to be within ± 0.020 tolerance.

Settlement of Pile Caps in Relation to Hammer Blows for Last One-Half Foot Penetration

A record was kept of the number of hammer blows required to drive the piles of the magnet girder foundations the final half-foot of penetration. The average number of blows for the four 50-foot piles locked together by each pile cap was compared with the settlement measured from August, 1958 to August, 1963. No significant correlation settlement with variation in average number of blows per last half-foot between adjacent pile caps was observed. For example, variations from 41 to 63 blows required for the last half-foot of penetration showed less than 0.003 difference in settlement over the five-year period. The differences that might exist are completely masked by the effects of load changes.

Pile Cap Settlement with Magnet Load During Erection of Machine

Two 17-ton "A" magnets were loaded on the central girder between control monuments about 45 feet distant. The differences in elevation of the loaded pile caps and control bench marks 45 feet distant but having no additional load was measured at 24 hours, one week and one month intervals after the magnets were placed. Relative settlements of .003 to .006 inches occurred the first day increasing to .006 to .008 inches at the end of one month.

Pile Cap Settlement With Magnet Load

Pile Cap No.	Av. Blows of Pile Driver for Last 6"	Excavation for Tunnel	<u>Total Settlement After:</u>		
			1 Day	1 Week	1 Month
LA3	37	Low trench	.004	.004	.004
LA4	52	Low trench	.004	.004	.004
CD3	28	Deep trench	.006	.007	.008
CD4	37	Deep trench	.004	.003	.006
E3	36	Med. trench	.006	.007	.008
E4	36	Med. trench	.006	.007	.007

Probable error of measurements - 0.001 inch

Elevation Differences Between Pads on Top of Magnet and Adjacent Pile Caps

The ring magnets were leveled to standard orbit as they were assembled in 1959 to plus or minus .002 inch for each of the three pads on each magnet. A careful realignment of the machine was made in January, 1960. The amount of change in elevation of each pad to bring it to standard height was recorded together with the change in elevation of the supporting pile caps. Pad 2, (nearest the single jack and over the orbit) had settled an average of 0.004 inches more than Pad 1, (centered over the back leg of the magnet) and 0.003 inches more than Pad 3 (near the double jack end of the magnet and over the orbit). The average difference of Pads 1 and 3 was 0.001 mil or 0.04 mil radian of tilt. All of the pads followed the settlement of the pile caps plus or minus 0.010 excepting those magnets known to have been changed by mechanical work.

Magnet Tilts

In connection with the realignment of the machine after construction of the I10 Conjunction Section in September, 1962 the tilt of the magnets accumulated during the 30-month interval from the original alignment in 1960 was measured (except for the magnets from Station G to I whose levels were partially changed to avoid strain on the vacuum chamber before their position prior to realignment could be measured). The tilts observed are plotted in mil radians, in Fig. 6. Two of the magnets had tilts of 0.58 mil radians and these were near the construction area. Seven other magnets had tilts above 0.2 mil radians; the others 0.20 mil radians or less.

Settlement of Survey Monuments and Tunnel Walls

Most of the leveling to check the alignment of the ring was run on pile cap bench marks only to save time. The bench marks on the monuments and in the tunnel wall were included in the ring circuits about once a year

FIG. 6

by side shots. Changes in elevation of the nearest pile cap were accompanied by the same changes in monument and wall bench marks within ± 0.020 inches with the exception of settlements of 0.024 at G and 0.089 at GH monuments due to heavy steel shielding loads on the east side of the target building mat; a settlement of 0.057 in the wall at J and a rebound of 0.133 in the monument at IJ also occurred, evidently due to construction of the Conjunction Section. It is thus evident that the design of tunnel wall footings, pile caps and monuments are sufficiently balanced not to set up stresses in the machine complex except where very unequally distributed loads were imposed.

Rebound of Foundations with Excavations

A further phenomenon of interest for foundation studies of similar terrain is the rebound of the ring foundations when adjacent areas were excavated. The rise of the ring from stations HI to KL during the interval from July, 1960 to the present is believed to be due to excavations for the target building extensions, the engineering services buildings and the 80-inch bubble chamber building. Smaller rebounds occurred as excavations were made for power substations above the ring near each end of the target building. The dates of all these rebounds correlate well with the times of excavation. The large excursions of the 1962 curve of Fig. 3 showing rebound after excavation in the region from Station H to Station K agree closely with the predictions of the report "Feasibility of Conjunction Section." The formulas of this report by F.W. Swiger thus furnish a tested guide for estimating settlements to be expected during future construction.

Levels Remote from Ring

Concrete shielding blocks were placed on the six-inch thick bituminous concrete pavement of the parking lot east of the first target building in

July, 1959. The blocks were piled so as to impose loads of one ton, two tons and three tons per square foot of loaded area. Settlements were measured as follows:

Load	One ton	Two tons	Three tons
One month	0.034	0.040	0.060
One year	0.087	0.127	0.167

These measurements were discontinued after one year because the blocks were removed to clear the area for the target building extension.

80-Inch Bubble Chamber

The floor and tracks for the 80-inch bubble chamber were leveled prior to the erection of the chamber on June 9, 1962 and again on December 28, 1962 after the main parts of the chamber had been assembled in place. The weight added is approximately 450 tons with the center of gravity of the load near the center of the building. Fig. 9 shows the settlements which occurred during this interval in thousandths of an inch.

Fig. 9

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Fig. 9

Southwest Area Neutrino Steel Shield

Some settlement irregularities were observed as a load of armor plate steel shielding 24 feet thick was placed on uncompacted ground to shield neutrino experimental apparatus in the Southwest area. A hole approximately five-and one-half deep was dug with a crane, then trimmed with hand shoveling to an approximate level of undisturbed soil. No compaction was used on this base soil but about six feet of armor plate was piled on it just before a heavy rain. This rain washed some soil in and around the steel. Some irregularities in settlement were noted but no elevations were measured at the time. The surface of the pile was leveled approximately using small pieces of steel as shims as its thickness approached seven feet.

Elevations of four corners of the pile were measured as the thickness was about nine feet (42 inches above the black-top pavement) and at intervals later until the pile was finished at 24-feet thickness (222 inches above the black-top). The rather irregular settlements of the four corners of the pile are shown in the following Table:

<u>Date</u>	<u>Height Above Black-top</u>	<u>Settlement at Corners</u>			
		<u>NW</u>	<u>NE</u>	<u>SE</u>	<u>SW</u>
6/24/63	42 inches	—	—	—	—
7/3/63	66 inches	0.22	3.45	0.65	+0.16
7/9/63	96 inches	0.46	0.67	0.41	-0.20
7/12/63	132 inches	0.38	0.35	—	0.29
8/28/63	222 inches	0.42	0.18	0.74	0.72
Totals		1.48	4.65	1.80	1.37

The measurements were discontinued when corners were obstructed by adjacent concrete shielding.

Variations in Horizontal Positions

The position of the machine elements in a horizontal plane are measured and set from 24 control stations equally spaced around the ring and near the outer tunnel wall so as to be intervisible. The angles between these control stations are measured with T3 theodolites to ± 0.2 sexagesimal seconds. The distances between the primary control stations are measured to ± 0.001 inch with steel tapes using electric resistance measurements for temperature compensation corrections. These techniques establish the relative horizontal positions of adjacent control stations within ± 0.005 inch.

Nine such precise traverses around the ring have been measured at intervals since June, 1958. The radial and tangential offsets needed to place the control station bushings equally spaced around a circle of 5165.400 inch radius were computed for each set of measurements by a formula developed by Dr. Hartland Snyder. The changes in horizontal positions thus obtained for three of the traverses are shown in Fig. 7. For clarity the data for only three of the nine traverses are shown on this graph. The major changes from superperiods G to L are in the vicinity either of extensive shielding load changes or where there was excavation and fill for the North Experimental Area construction. The 0.145 change in Station IJ is an area where the adjacent tunnel wall was removed to construct the Conjunction Section. The sources of the smaller changes in the position of Stations A to F are not known. Some of the amounts of change in position are doubtless due to the smoothing effect of Dr. Snyder's formula, which computes the smallest offsets needed to re-establish a perfect circle with the assumptions that all measurements have the same weight or precision. Thus, a big change in one locality would give smaller and smaller offsets all around the ring. The positions of Stations FG to H and Station IJ

POSITION CHANGES RING CONTROL MONUMENTS FOR AGS SURVEY

OSR-5

-21-

have been reset with new offset discs since the setting of January, 1960. The instrument supporting stands are offset from the control stations by the amounts computed from the latest traverse when checking the horizontal positions of the ring magnets.

The ring magnets were aligned during January and February, 1960 and changed only to compensate for excessive shielding loads between Stations G and H until advantage was taken of the shutdown for construction of the North Experimental Area to realign the entire ring during August and September of 1962. The changes in positions needed to bring the magnets back to their specified positions from the settings made two-and-one-half years before are shown in Fig. 8. In general the readjustments required follow the displacements of the control stations as obtained from the latest precise traverse. This indicates a real displacement due to shielding and construction changes. The discrepancies from the control station positions in the vicinity of Stations BC, C and CD are believed to be due to a reversal of the offset corrections by inexperienced personnel when the magnets were originally aligned in 1960.

The large changes next to G, I, J, LA and AB are believed to be due to mechanical changes in vacuum pumps and target boxes which were not observed and corrected at the time the mechanical changes were made.

These data are considered to justify the following conclusions:

1. The repeatability of the survey measurements indicate that any differences in excess of 0.010 in either horizontal or vertical positions are real.
2. A check of alignment (with readjustment if required) must be made of the magnets adjacent to any changes in target boxes, vacuum manifolds or other mechanical elements of the machine.

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3. Generally a larger readjustment has been required for the quadrupole and sextupole magnets (indicated by heavier lines on the graph) than for the heavier dipole magnets of the ring. This is probably due to different mechanical supports, also to stress when servicing adjacent vacuum manifold and pumps. The differences have no relation to foundation stability but do indicate the desirability of frequent multipole alignment checks.

4. The foundations and mechanical superstructures held the magnets in specified positions within ± 0.030 mils over several years and another ± 0.080 mils even when major construction changes were made, such as removal of sections of tunnel walls. (Vertical changes as much as 0.320 occurred during this construction.)

5. If extensive alterations to the machine and greatly increased shielding loads become necessary with multiturn injection and increased intensity, a careful realignment after the construction is completed should suffice indefinitely to keep the machine in operation. However, should it become necessary to make mechanical changes by remote control, additional check surveys (with realignment if needed) are advisable. Any provisions for remotely controlled mechanical replacements should also include provisions for remote check surveys.

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