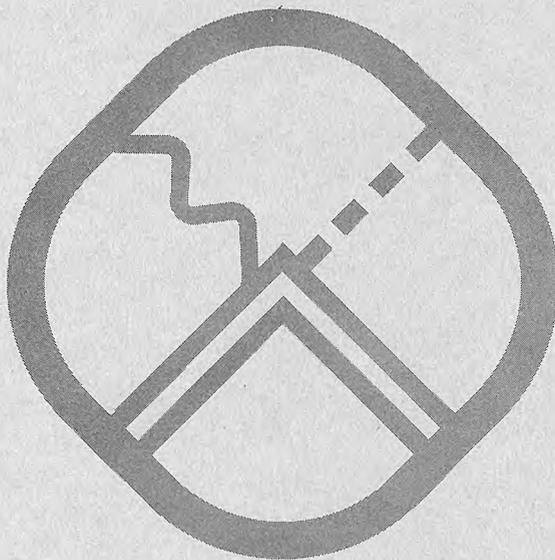


**MAGNET POSITIONING PROBLEMS FOR A
300 GEV PROTON SYNCHROTRON**

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I Introduction

1

An earlier report, "A Proton Synchrotron for 300 Gev," has shown that a 300 Gev Alternating Gradient Synchrotron could be operated if the magnets could be positioned, and held in position, well enough so that the short range random derivations of the magnets from a circle would be less than 0.1 mm. A misplaced magnet tends to deflect the orbit of the beam of protons and a series of errors in the placement of the magnets can very well deflect the beam out of the vacuum tube aperture. Two A.G. synchrotrons with 1/8th mile diameters have been constructed to similar tolerances and the drift of the magnets of one of them, the CERN P.S., in the first month of operation, was sufficiently small that it did not affect the beam. The question is whether it is indeed possible to achieve and maintain the same tolerances for a machine that is 1.6 miles in diameter. From the preliminary study on which this report is based, it appears that the same techniques of surveying and foundation design that were used for the A.G.S. and the P.S. will provide the desired precision and stability.

II Relationships between magnet placement errors and displacements of the beam.

The basis of this part of the analysis is in Section 4 of Courant and Snyder's paper.² For this discussion we will consider

¹ M.L. Sands, Synchrotron Laboratory Report No. 10. California Institute of Technology, September, 1960.

² E. Courant and H. Snyder. Theory of the Alternating Gradient Synchrotron. Annals of Physics, Vol. 3, page 1, 1958.

the desired path of the beam to be a circle of radius ρ . The presence of the straight sectors that bring the orbit to a shape of mean radius R will be neglected. Let the curve on which the magnet centers lie be described by $r = \rho + \xi(\theta) = \rho + \sum \xi_k \cos k\theta$ where $\xi(\theta) = \sum \xi_k \cos k\theta$ describes the magnet positioning errors. What is of primary interest is the deviations of the equilibrium orbit from the curve of magnet centers. The maximum value of these deviations due to any one Fourier component, $\xi_k \cos k\theta$ is given by

$$X_k = F \left[1 + (F-1)^2 \right] \frac{1-k^2}{2-k^2} \xi_k, \quad (1)$$

F is the form factor for betatron oscillations, and ν is the number of betatron oscillations per revolution.

The curve of Fig. 1 shows the ratio of the maximum displacement X_k to the periodic positioning error ξ_k as a function of k . It can be regarded in a sense as an amplification factor. Two important features appear. One is that the effect of long-wave deformations of the magnet path from a circle is quite small. For example, a disturbance with 5-fold symmetry produces an X_k only 1/40th of the amplitude of the position error. The other is that disturbances with symmetry orders near the number of betatron oscillations per revolution are devastating in their effect and must be scrupulously avoided.

In extrapolating from existing machine design to the proposed design, it is interesting to note that the amplitude of these "resonant" displacements of the beam, due to periodic errors of wavelength near the betatron oscillation wavelength, is proportional to $\nu = 2\pi R/\lambda$.

The proposed machine is, therefore, $43.25/8.75$ times as sensitive to periodic magnet position errors as is the Brookhaven A.G.S. It is, therefore, particularly necessary to avoid any nearly ν -fold symmetry in any aspect of the magnet or tunnel design.

In addition to possible periodic errors in the placement of the magnets there will be small random errors in their location. These can be represented by a function $\mathcal{E}(\theta) = \sum_k \mathcal{E}_k \cos k\theta$ in which the \mathcal{E}_k are fairly uniform in value. The graph of Fig. 1 shows that the random errors of critical importance will be relative errors of placement of magnets separated by one-half the wavelength of the betatron oscillations or less. A consideration of the effect of random errors has been undertaken by Courant and Snyder. It is safe to assume that, with 98 percent probability, the displacement of the closed orbit will be less than

$$X = \frac{2\pi}{|\sin \pi \nu|} \frac{R}{\rho} \frac{|n|}{\nu} \left(\frac{F}{M}\right)^{1/2} \mathcal{E}_{\text{r.m.s.}} \quad (2)$$

where n is the field gradient index and M is the number of magnets. The substance of this equation shows that $X/\mathcal{E}_{\text{r.m.s.}}$ varies as $\nu^{1/2}$. So the proposed accelerator is

$$\sqrt{\frac{43.25}{8.75}} = 2.2 \text{ times}$$

as sensitive to random errors as the Brookhaven A.G.S. For the proposed design

$$X = 99 \mathcal{E}_{\text{r.m.s.}}$$

so for $X < 1.0$ cm, $\mathcal{E}_{\text{r.m.s.}} < 0.1$ mm ≈ 0.004 ". The magnets of the Brookhaven A.G.S.³ and also of the CERN P.S.⁴ were positioned to about $.005$ ". This would produce in the 300 Gev accelerator an X of 1.25 cm.

³ BNL Annual Report July 1959, BNL 560 (AS-13) page 23.

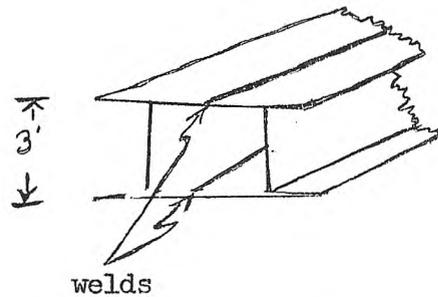
⁴ Geodetic Survey of the CERN 28 Gev Synchrotron, Andre Decae, Sept. 1960, CERN 60-19. page 42.

The question then reduces to the following: can this dimensional stability and positioning accuracy be obtained in the contemplated 300 Gev design.

III Design of the foundations.

Two approaches to foundation design are feasible. One is to anchor the circular foundation firmly to the earth in the expectation that the earth will distort slowly or infrequently enough that occasional surveys will be sufficient for keeping the beam in operation. The Brookhaven A.G.S. is built on 50 foot pilings driven into the sand. Changes of level and radii occurred during the settling that followed placing of the heavy shielding, but these settled down to rates well below that tolerable. A preliminary study of the geology of California indicates that sites exist that are sufficiently stable for a machine to be built with a foundation anchored firmly in bedrock close to the surface. Since this is the case, foundation cost estimates have been made on the basis of the Brookhaven foundation design. This procedure seems reasonable, since the piers need not be as long as the Brookhaven pilings and the loading per meter of ring for the contemplated machine is only 1/7th that of the Brookhaven A.G.S. (0.9 tons/meter cf. to 3.8 tons/meter).

Another approach to foundation design is to build a rigid ring which is essentially floated on a base. A set of suitable supports would consist of continuous flow oil pads held up by a set of hydraulic jacks all connected to an equal pressure constant volume source. The coefficient of friction of oil pads has been made as low as 10^{-6} in the design of bearings for large radio telescopes. The main difficulty of this approach is making the rigid ring sufficiently rigid. If the ring were made of two 3 foot I-beams welded together as sketched below, random radial forces separated by distances of 90 m or less would have to have an r.m.s. value of less than 10 pounds.



If factors of convenience to utilities, transportation, etc. were to dictate the choice of a site where foundation stability was questionable, more thought could be given to a floating ring design. The CERN P.S. has such a design, but it is not easy to scale up the costs to the larger diameter.

IV Stability of the earth over distances of 1 - 3 miles.

The requirements on the stability for the foundations of the contemplated machine, if it were fastened to the earth, are that distortions of the magnet centers from a circle over arc lengths of several hundred meters must not exceed a few centimeters, periodic distortions (ripples) with wavelengths near 180 m should be much less than 0.1 mm. and random distortions over intervals of 90 m or less should not exceed 0.1 mm. The most extensive data on distortions on the earth's surface have been taken in California because of the known tectonic activity in this area.⁵ In this area data exist for displacements over intervals of 24 m, 1500 m, and 20-100 km. The measurements over 24 m are by Benioff. In a tunnel through solid rock

⁵ There is much literature on this work. We are indebted to Profs. Allen, Benioff, Hellsley, and Wilver of CalTech for helpful discussion. See for example, C.A. Whitten, Journal of Geophysical Research, 59, 9, 1960; Parkin, E.F., American Geophysical Union Transactions, 29,17, 1948; Benioff, H., Bulletin of the Geological Society of America, 70, 1019, 1959; Reid, Bulletin of the National Research Council, No. 90, Physics of the Earth, VI, Seismology, p. 88, 1933. Edited by Macelwaine, Wood, Reid, Anderson, Byerly.

at Isabella, California, he compared the distance between two points of the solid rock in the tunnel with the ends of a 24 m fused quartz rod, anchored at one end in the rock. He finds strains of 1.4×10^{-6} per year. This type of displacement alone would only make the orbit elliptical by 1.5 mm where the tolerance is 3.3 m. He has no data on flexing or twisting that would produce ripples in the orbit.

In 1931-33 Michelson and co-workers⁶ measured the velocity of light in a one-mile pipe east of Los Angeles. Surveys showed the distance between the piers at the ends of the pipe to increase by 13.1 mm out of 1,594,259 from Feb. 1931 to Feb. 1933. In March 1933 there was an earthquake, after which a survey in July 1933 showed the length to have returned 8.5 mm towards its original length. As a long-wave coherent displacement this again is completely negligible. Notice that this represents earth displacement on a particularly bad location. The piers were set on the surface of an alluvial fill near Irvine, California. The fill is of recent geological origin, and is believed by the geologists to represent as unstable a base as could be found short of straddling an active fault. The fill has not compacted, is water permeable and poorly drained, and an active fault (Norwalk) disappears under it a few miles northwest of Michelson's site.

The CERN proton synchrotron is on a water-impermeable molasse under drained marshland, and is believed to represent a fair location geologically. It showed cyclic expansion of 3.0 mm per 3 km in one direction and no measurable displacement perpendicular to that.⁷ The strains were cyclic with a period of half a lunar month. This elliptical distortion again represents a negligible disturbance.

⁶ Michelson, Pease, and Pearson, *Astrophysical Journal*, 82, 26, July 1935).

⁷ Decae, *op cit* p. 19.

At Brookhaven the A.G.S. is on a 1500 foot sand deposit over 3×10^6 years old.⁸ It shows appreciable slippage when major loads, such as shielding, are shifted. Monuments 25 meters apart showed relative shifts of .75 mm, a strain of 3×12^{-5} . After initial settling had occurred, the monuments were found to be stable to 0.1 mm. The nature of the settlement can be judged by the fact that the shielding pad settled 1.25 cm on being loaded, but by July 1959 was only settling at 0.1 mm per month. If the shielding load is properly spread on the sand this should produce only a long-wave-length distortion of the beam orbit of completely negligible amplitude.

Four careful surveys thus show that dimensional stability of the quality required of the foundations for the contemplated accelerator has been realized. If an accelerator were to be built in California on a rigid foundation, certain precautions would have to be exercised in choosing a site. The general northward drift of the coast of 5 cm/year produces long-range strains of 0.1 second of angle per year, well below the tolerable level.⁹ Actual slippages occur along the fault lines, sometimes as great as 5 m in a single break. Most of the obvious slippages occur in connection with earthquakes, but Whitten has also found steady creep along the fault in some areas.

Another source of concern is the subsidence of large areas due to lowering of the water on oil tables. This can produce drastic irregularities. The occurrence of these effects -- shear action, seismic activity, and subsidence -- calls for the choice of a base that will not be disturbed by them in a way that will affect the operation of the accelerator. Alluvial fill, especially if permeated by water, is quite likely to shift

⁸

BNL annual report, 1959 10c cit.

⁹Whitten, op cit.

and settle under the influence of these motions. For example, the moraine on top of the molasse at CERN showed large displacements. As examples of trouble-free locations, two areas have been found in Southern California that appear quite stable. One is southeast of Riverside near Perris. A large crystalline granite slab several miles in each direction is just below the surface (~10 feet) and it is several miles from the nearest known fault. The rock should show only long-range deformations and should not exhibit any subsidence. There is some seismic activity in the area, but this should not cause any displacements of foundations secured to the rock. Another promising site is the Linda Vista Mesa north of San Diego. The U.S. Naval Air Station at Miramar is on this mesa as well as a number of industrial developments. The base is a relatively consolidated Marine Eocene rock.¹⁰ No faults are nearby and seismic activity is quite low in the area. It is well drained and shows no signs or prospects of subsidence. A detailed survey to find other satisfactory sites has not been made. Unless a floating ring were to be used as a base for the magnets, one would have to be careful, since so many of the level areas near metropolitan centers are water-soaked, fault-controlled alluvial fill. The site would also have to be fairly level over a 2 x 3 mile area to avoid excessive excavation costs.

V Surveying

In order to position the magnets in the first installation and to check on their position at subsequent times, an adequate surveying technique is needed. It is assumed here that the aperture centers can

¹⁰ Hertlein and Grant, Vol. II of the memoirs of the San Diego Society of Natural History, Part I.

be located to better than 0.1 mm and that suitable reference points can be marked on the magnet frames whose positions relative to the aperture center are known to be better than 0.1 mm.

Since long period departures from circular symmetry are tolerable, the expense of radial tunnels is not felt to be justified. M. Decae¹¹ gives the following realizable deviations from a circle using excellent, but known, surveying methods in a survey that starts above one point in a 1 km radius circular tunnel and works around the tunnel.

<u>Angular interval</u>	<u>Deviations in mm</u>
$\frac{\pi}{1000}$	0.01
$\frac{\pi}{100}$	0.1
$\frac{\pi}{30}$	0.1
$\frac{\pi}{10}$	2
$\frac{\pi}{4}$	5
$\pi/2$	10
π	30

The interval $\frac{\pi}{100}$ would cover an arc of 45 m which is $\frac{\lambda}{4}$ for the proposed machine. So his figure of 0.1 mm for positioning accuracy is in the range of the desired $\epsilon_{r.m.s.}$. Since the principal source of surveying error is refraction due to thermal gradients in the air, any appreciable improvement in positioning accuracy would involve isothermal sighting tubes or sighting through vacuum tubes. The axial positions can be made somewhat more precise, as they need be, because of the knowledge of the vertical through use of a precision level at each point.

¹¹ op cit. p. 50

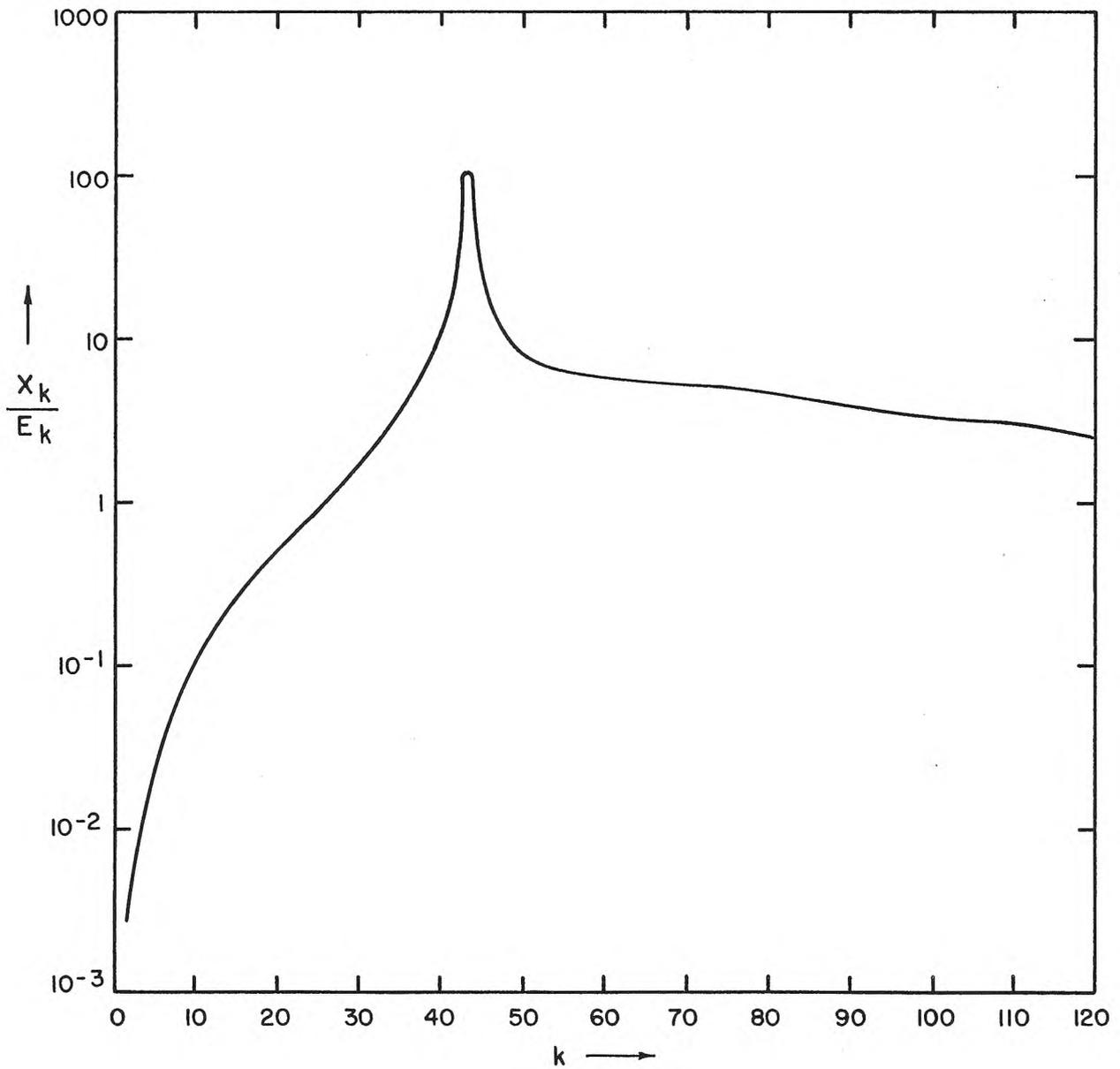


Fig. 1. Ratio of maximum displacement, X_k , to a periodic magnetic positioning error E_k . The magnet positions are along $r = \rho + E_k \cos k\theta$.

