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ARGONNE NATIONAL LABORATORY
P. O. Box 299
Lemont, Illinois

THE SOVIET 10-BEV PROTON SYNCHROTRON

by
John Marshall

The University of Chicago

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Introduction

The information contained in this report was collected mostly from papers presented by various Soviet scientists and engineers during the Moscow conference on the physics of high energy particles of May, 1956. Some of it was obtained by personal observation and a small amount from information divulged during the CERN symposium of June, 1956. Some of it is certainly inaccurate and it is far from complete. I hope that other people who have supplemental or contradictory information will communicate such information to interested people.

The papers from which this report was compiled were as follows:

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2. A. A. Kuzmin, A. L. Minz, S. M. Rubchinsky, M. M. Veisbein, F. A. Vodopyanov, and V. A. Uvarov, Accelerating-Field Frequency to Magnetic Field Intensity Linkage-Systems in Proton Synchrotrons.
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4. E. G. Komar, I. F. Malyshev, I. M. Royfe, N. S. Streltsov, and G. A. Zeitlyonok, Ion Beam Injection System of the 10 Bev Proton Synchrotron.
5. L. I. Boltin, S. K. Esin, V. S. Kladnizky, I. F. Malyshev, A. M. Nekrashevich, V. A. Petukhov, I. M. Royfe, L. S. Shutskever, K. D. Sinelnikov, L. P. Zinovyev, P. M. Zeidliz, and G. A. Zeitlyonok, Injection System of the 10 Bev Accelerator.
6. F. A. Vodopyanov, Master Oscillator of f-H Linkage System of the Proton Synchrotron.

7. Y. M. Levedev-Krasin, Accelerating Elements of the Proton Synchrotron and the Principal Problems of Their ? Supply.
8. G. M. Drabkin, I. Kh. Nevyazhsky, A. C. Temkin, and V. F. Trubezkoy, Application of Ferrite-Core Inductance Coils in the Synchrophasotron Power Amplifier.
9. G. M. Drabkin, L. M. Garevich, B. M. Gutner, and N. K. Kaminsky, Automatic Tuning of the Resonance Circuit of Power Amplifier of r.f. Supply of the 10 Bev Proton Synchrotron.
10. G. M. Fedotov, E. G. Komar, N. A. Monoszon, and N. S. Streltsov, Some Design Particularities of the 10 Bev Proton Synchrotron Electromagnet.
11. E. G. Komar, N. A. Monoszon, I. A. Mozalevsky, A. M. Stolov, and A. A. Zhuravlev, Magnetic Characteristics of the 10 Bev Proton Synchrotron.
12. S. V. Fedukov, I. A. Mozalevsky, E. A. Myae, A. M. Stolov, M. D. Veselov and A. A. Zhuravlev, Investigation of 10 Bev Synchrophasotron Magnetic Field.
13. M. A. Gashev, E. G. Komar, N. A. Monoszon, A. M. Stolov, and F. M. Spevakova, 10 Bev Synchrophasotron Electromagnet Power Supply.
14. E. G. Komar, I. F. Malyshev, J. L. Michelis and A. V. Popkovich, 10 Bev Proton Synchrotron Vacuum Chamber.
15. S. A. Vekshinsky, Vacuum Pump Assemblies for Accelerators.
16. I. S. Danilkin and M. S. Rabinovich, Some Problems of the Theory of Cyclic Resonance Accelerators Arising in Connection with Experimental Investigations on the 180 Mev Proton Synchrotron.
17. V. A. Petukhov and L. P. Zinovyev, Experimental Investigations on the Model of the 10 Bev Accelerator.

TABLE OF GENERAL CHARACTERISTICS

Proton energy	10 Bev
Repetition rate	5 per minute
Magnetic field	13,000 Gauss
Orbit radius	28 meters
Width of magnet yoke	7.5 meters
Height of magnet yoke	5.3 meters
Width of yoke members	1.5 meters
Width of magnet pole	2.0 meters
Number of magnet blocks	48
Weight of magnet block	750 tons
Total weight of magnet	36,000 tons
Lamination thickness of pole	1 cm
Lamination thickness of yoke	4 cm
Insulation between laminations	1.2 mm plastic impregnated material
Magnet material	< 4% Silicon steel (?)
Length of straight section (derived from figures above)	(6.7 meters)
Foundations	reinforced concrete bearing on sand
Foundation dimensions	9.2 meters wide x 3.5 meters deep
Magnet windings	12.5 cm x 2.4 cm copper bar with cooling tank 1.8 cm I.D. soldered to it
Weight of coils	57 tons per magnet block (2700 tons altogether)
Insulation of coils	asphalt impregnated dried in (vacuum or pressure?) oven

Injector

Protons are first accelerated with a Cockroft-Walton accelerator to something less than one Mev. Then they are accelerated with a linac provided by the Kharkov group to nine Mev before being injected into the ring magnet.

The linac is oriented at right angles to the straight section into which the beam is injected. The initial deviation of the proton beam is effected with a wedge magnet which bends the protons of the order of 80° . Approximately the last 10° of bending is done electrostatically with five separate high voltage electrodes separated by 3 cm or so from a grounded electrode and which altogether extend over a distance of several meters. An adjustable voltage of about 100 kv is applied to each of the electrodes. Each electrode is mechanically adjustable from outside of the vacuum.

It is expected that injection will be possible for about 50 turns with the magnetic field rising so as to shrink the orbit radius by about 1 cm per turn.

Radio Frequency

The acceleration of the protons is effected, by drift tubes I believe, at two straight sections opposite one another, with injection and deflection of the proton beam occupying the other two straight sections. The frequency of the oscillator is controlled by a magnetic search coil in the field of a model section of the magnet which is connected electrically in series with the main magnet. The voltage from this search coil is electronically integrated to give a voltage proportional to the magnetic field in the magnet; this voltage is transformed by an electronic analogue computer to a frequency put out by a master oscillator. The master oscillator drives a series of amplifiers to excite the accelerator drift tubes.

The frequency at injection is 192 kc and at full beam energy is 1.45 Mc. The oscillator frequency is controlled to an accuracy of 0.1%.

Magnet Power Supply

The power supply provides an emf of 11,000 volts for a period of 3.3 seconds, during which time the magnet current rises from zero to 12,700 amperes (Fig. 2). The voltage is then reversed for another 3.3 seconds while the current returns to zero. A demagnetizing cycle occupies the next 5.4 seconds, after which the main cycle starts over again. Thus a magnet pulse is provided every 12 seconds.

Fig. 2

The power supply (Fig. 3) consists of:

- I. Four independent fly-wheel M.G. units - 2 rotating clockwise and 2 rotating counter-clockwise. Each unit includes:
 1. One 2500-kw wound rotor type motor with liquid resistor control.
 2. One 50-ton fly-wheel for energy storage. The fly-wheel speed decreases by 15% during a pulse.
 3. One 37,000 kva generator wound with two independent, 3-phase windings, 30 degrees apart.
 4. One 270-kw control power generator.
- II. Ten ignitron rectifier-inverter units (Fig. 4), each one including 12 ignitrons in 3-phase, full wave connection. Two ignitrons are paralleled in each circuit position with an auto-transformer arrangement for sharing the load. The entire installation thus includes 120 ignitrons, each one having the following specifications:

Figure 3

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I max.	800 amperes	} Ignitron specifications
I average	100 amperes	
V max. inverse	15 kv sealed off	

Each ignitron is provided with three igniters. The average life of each igniter is 3000 hours, so that the life expectancy of the ignitron itself is 9000 hours.

Each pair of ignitrons is provided with a quick-acting breaker to open the circuit in case of a flash-back.

One of 10 Ignitron Rectifier-Inverter Blocks

Fig. 4

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The four alternators are connected in parallel in each of their two 3-phase output circuits. They are brought up to speed with their field circuits de-energized and their fields are switched on with the help of damper windings to minimize oscillations around exact synchronism. During a pulse energy is extracted from the fly-wheels so that their speed decreases by about 15%. The motors are provided with liquid resistors which are adjusted (or switched in) during a pulse in such a way as to make the motor load more or less uniform in time.

Demagnetization is achieved by two auxiliary power supplies which presumably provide the same output voltage as the main supply, but which need not be nearly so ripple-free and which need put out only a small fraction of the current. The two auxiliary power supplies are switched in by their respective ignitrons alternately, depending on whether the particular demagnetizing phase is one of forward or backward current. The details of this system are not accurately known.

Each fly-wheel M.G. unit is approximately 60 feet long. The four units are arranged side by side in a room covered by a crane with a span of approximately 90 feet.

Magnet

The magnet is constructed with a cyclotron-like "H" shape in a very straightforward manner, providing for a large vacuum chamber with easy access to the sides of the chamber for vacuum maintenance and placing of targets. Obviously cost is not a primary consideration. In general, dimensions are quite generous.

The magnet yoke is constructed of 4-cm thick plates of silicon steel, with silicon concentration up to 4%. The horizontal portions of the yoke consist of bundles of vertical steel plates 1.5 meters high and stacked to a thickness of approximately 85 cm (scaled from a photograph). The laminations are insulated from one another by 1.2-mm thick, plastic-impregnated insulation (material unknown). They are welded together at a large number of places around the outside so as to make mechanically stable bars. The outside corners are chamfered except for the two pairs of end plates on each bar, and these protruding corners are drilled and bolted together to fasten one bar to the next. Appropriate spacers are inserted so that the bars just touch at the inside but are correctly spaced at the outside. Toward the ends of each quadrant, specially tapered bars have been inserted in what looks like an afterthought arrangement to adjust the taper so as to squeeze in more iron.

The vertical yoke members consist also of 4-cm thick laminations welded into packages 2.3 meters high by presumably 1.5 meters thick and a little less than 2 meters long. The plates are oriented so that their

flat surfaces are tangential to the approximate circle of the machine. Each magnet block has four of these side yoke packages, two inside and two outside. Where the two inside or the two outside packages adjoin, there is a vertically elongated hole large enough for a man to crawl through or for a diffusion pump connection to pass through.

The pole structure, certainly the pole shoes (pole tips) and presumably the main pole structures themselves, are made of 1-cm thick laminations for reduced eddy currents in this most sensitive part of the magnet. The poles are held to the yoke members by bolts which pass through the tapered gaps between adjacent top and bottom yoke bars.

The entire ring consists of 48 magnet blocks (Fig. 5), each one having four top yoke bars, four bottom yoke bars, four side yoke members and the pole structure. The weight of each magnet block is about 750 tons.

The upper yoke members are supported on shims made of insulating material which are placed on top of the side members. The individual shims are adjusted in thickness so as to apply a reasonable force to the vacuum chamber. The thickness of the shims was adjusted by observing the mechanical deflection of the chamber walls with the load applied.

Magnet Coils

The magnet windings (Figs. 6 and 7) are fabricated from copper bar 2.4 cm x 12.5 cm in cross section. Along one edge a circular groove is formed and a copper tube of 18-mm inside diameter is soldered into it. The tube carries cooling water. This construction reflects the difficulty which apparently exists in the Soviet Union in obtaining unusual drawn copper tubing shapes. Most electronuclear machines built there up to now have employed air-cooled coils. The weight of coils associated with each of the 48 magnet blocks was stated to be 57 tons. This would correspond to about 150 turns of copper of the stated dimensions. This is probably arranged either in three layers of about 25 turns in each coil or in four layers of about 19 turns. The coil insulation was impregnated with asphalt in vacuum (or pressure?) ovens.

The power supply was stated to give a peak current of 12,700 amperes. This implies an excitation of 1.9×10^6 ampere turns for the magnet. If all of this appeared across the 40-cm gap it would produce a magnetic field of 60,000 gauss. Actually the magnetic field is stated to be 13,000 gauss. The statement was also made that "one-fourth of the magnetic energy appeared in the gap" (as translated). This fits roughly with the above computation which shows that the efficiency of the magnet is $13000/60000 \cong 22\%$.

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1 of 48 magnet blocks of 10 Bev proton-synchrotron, each one weighing ~ 750 tons.

Figure 5

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Stated figures reasonably consistent with conductor arrangement as above in each upper or lower coil. (75 turns per coil)

Cross-section of water-cooled copper conductor in coil

Figure 6

Connections of windings to minimize first harmonic error in magnet excitation.

Error is due to leakage current in cooling water connections.

Figure 7

Vacuum System

The vacuum chamber of the 10-Bev proton synchrotron is of the double wall variety (Fig. 8) with a rough vacuum between the two walls so that the fragile, thin-walled inner chamber does not have to withstand any appreciable mechanical forces. The outer chamber surrounds the pole shoes of the magnet which give it mechanical support. The top and bottom of the outer chamber are made of textolite sheets, while the side walls are of sheet rubber supported by stainless steel plates (Figs. 9 and 10). The stainless steel plates support the pole shoes against atmospheric pressure and maintain accuracy of gap width. Windows are cut in the stainless steel plates to reduce eddy currents and these windows are for the most part filled with textolite inserts to prevent sucking in the rubber sheets of the side walls.

The laminations of the pole shoes (1 cm thick) are bolted together to make good mechanical units, of which there are 48, both top and bottom, in each magnet quadrant. This would make each pole shoe unit about 91 cm long by 2 meters wide and perhaps 20 cm thick. The thickness is not known but it cannot be far from this value, judging from slides projected during the talks. Insulation between laminations is provided by pressed lacquered paper. The pole shoe units are gasketed to one another with round rubber gaskets. This would imply that the inner wall of the vacuum chamber is integral with the pole shoe. Perhaps it is cemented in place.

One diffusion pump is connected to the vacuum chamber through each magnet block. Alternate pumps are connected from the inside and the outside so that access may be had through every other crawl hole in the yoke to the crawl space adjacent to the vacuum chamber and between the magnet coils. Thus there is complete access available to the vacuum chamber walls.

The outer rough vacuum wall of the chamber is made vacuum-tight with rubber gaskets placed between the textolite sheet and the turned over edge of the rubber side wall sheet. These gaskets are vulcanized (I believe) to gaskets which run across the top and bottom of the chamber to seal the joints between adjacent textolite sheets. The gaskets are compressed with wedges which push against the magnet poles.

Helium is introduced in the inter-gasket spaces (just which I am not sure) for vacuum testing.

Vacuum Chamber

Figure 8

Figure 9

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Method of Sealing wall of Rough Vacuum Chamber
at joint between two adjacent Textolite Sheets.

Laminated Pole Shoe

Rubber gasket is compressed by "wedges" (not shown)
Details are not understood.

Figure 10

The diffusion pumps (Fig. 11) used are of 38-cm diameter, each with two high speed jets and one ejector. They are provided with a linear, double venetian blind-type of baffle which is continuously cooled with liquid nitrogen. Each filling of the nitrogen reservoirs is good for 10 or 15 hours of operating time. Unbaffled, their speed is 5000 liters per second. They were developed by the "Scientific Research Institute of Vacuum."

Fig. 11

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A water-cooled cap is placed above and around, to some extent, the top pump jet. The statement was made that this cuts down by a factor of more than one hundred the amount of oil that diffuses back toward the vacuum vessel. The oil in the bottom of the pump has to travel through a maze so that the lower boiling fractions tend to pass through the later jet stages leaving the low vapor pressure stuff for the first stage.

Without nitrogen on the baffles the pumps can reduce the chamber pressure to 2×10^{-5} mm of mercury. With nitrogen the pressure is 4 to 5×10^{-6} mm, but they expect 3.6×10^{-6} mm in the future.

I have no details about the fore pumps.

The sections of vacuum chamber in the straight sections are presumably made of steel and are supported against atmospheric pressure by external welded ribs.

Experimental Facilities

A proton beam is expected to be extracted at one of the straight sections (the one opposite the one used for injection?). A concrete wall 8 meters thick is placed here with a slot at beam height for the beam to pass through. Presumably beams of other particles as well as of protons are expected to be extracted also through the same wall. An experimental building is placed on the other side of the wall. I did not see this part of the installation and therefore can give no more information than this.

No shielding is provided around the machine itself. The control and power building is protected by being situated a large distance away.

Buildings

The proton synchrotron is installed in a large circular building of concrete or masonry construction (Fig. 12). It is provided with a crane over the machine running on circular tracks around the building. At roughly half the outside radius of the building there is a circle of steel column supporting the inner crane rail and the roof. A second circular crane runs between this circle of columns and a group of columns at the center of the building.

Adjacent to this building, but missed by the writer, is an experimental area shielded by an 8-meter thick concrete wall from the machine.

One hundred meters away from the circular building is a large square building which houses the power supply for the ring magnet and the control room (not seen by the writer).

Fig. 12

Foundation

The 36,000-ton ring magnet is supported on a reinforced concrete foundation 9.2 meters wide and 3.5 meters deep (Fig. 13). The concrete is laid on the undisturbed sand of the local soil. A trench-like groove in the upper surface of the foundation ring provides a crawl space for access to the bottom bolts of the assembly. (Bolts to hold down the lower poles and magnet windings.)

The design of the machine with magnet quadrants and straight sections results in a non-uniform distribution of the load on the foundation. Accordingly, the foundations have deflected non-uniformly, the centers of the magnet quadrants having sunk from 10 to 15 millimeters more than the centers of the straight sections. Apparently no effort has been made to correct the magnet alignment. Instead, pole face windings have been installed to correct the median plane height and tilt and the first harmonic of the radial equilibrium orbit position.

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No provision appears to have been made for foundations of additional shielding which might be installed later.

Fig. 13