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Whether magnetism takes its name from a region in Asia Minor (Magnesia), as claimed by Lucretius, or from the shepherd Magnes, who was amazed to find the iron crook of his staff clinging to an overhanging rock, as related by Nisander and repeated by Pliny, we shall probably never know. That it always had, and still has, great fascination for anyone who sees it for the first or thousandth time is sure.

The first magnets were natural magnets, or lodestones. As might be expected of something so marvelous and apparently contrary to "common sense," these lodestones were objects of awe and superstition. What the people of the Dark Ages lacked in experimental knowledge they supplied by an abundance of imagination. We are told that, among other things, magnetism could cure disease; affect the brain, causing melancholia; and act as a love philtre. A magnet would lose its power when rubbed with garlic or in the presence of diamonds.

As science began to emerge from magic, it was discovered that a magnet could be made by holding an iron bar near a lodestone. It was noted that the attractive power was concentrated in places which we now call poles. Some time around the eleventh century it was discovered that when a magnet is freely suspended about a vertical axis one of the poles will set itself in a northerly direction. This knowledge enabled seamen to navigate their ships when out of sight of shore and gave them confidence to venture to unknown lands.

It is interesting to note that the Chinese knew of these phenomena as early as A. D. 121, but because of the total absence of communication, Europeans had to discover them independently.

The first person that we know of who gave magnetism serious experimental study was Peter Peregrinus, who published his "De Magnete" in 1269. Peregrinus made a large lodestone in the shape of a sphere, and by means of small magnets showed that this sphere had two poles somewhat similar to the

*Work done under the auspices of the U. S. Atomic Energy Commission.

earth. He also showed that "like" poles of a magnet repel each other, whereas "unlike" poles attract. He further demonstrated that when a magnet is broken in two, the parts are still magnets.

These achievements of Peregrinus seem all the more remarkable when we reflect that he was nearly alone in his age as being a scientist. The vast majority of so-called "scholars" of his day (and even as late as the seventeenth century) were content to quote Aristotle rather than investigate for themselves. A story goes that two learned men were involved in a rather heated argument about the number of teeth that a horse has. Each cited Aristotle at length, yet they were unable to settle the debate. All the time a horse was tied near by but neither disputant bothered to get his information "straight from the horse's mouth."

Later, William Gilbert, physician to Queen Elizabeth, extended Peregrinus's studies in a book which also bore the title "De Magnete." He showed that when a compass is held vertically the needle dips toward the earth. (This dip becomes greater at higher latitudes, and at the pole the needle will point directly into the earth.) Gilbert also found that a magnet loses its strength upon being heated, and that a steel bar becomes magnetized if it is jarred while in the field of another magnet. He attributed the earth's magnetism to deposits of iron ore. (Although the phenomenon of the earth's magnetism is not clearly understood to this day, it appears that this explanation probably is incorrect.*) And finally, Gilbert demonstrated that magnetization does not increase the weight of a magnet.

By the early nineteenth century science was progressing as never before. In 1819 Hans Christian Oersted, a Danish physicist, at the end of a lecture, accidentally placed a current-bearing wire over a compass needle and parallel to it. He was astonished to see the needle swing until nearly perpendicular to the wire. When he reversed the current in the wire, the needle swung in the other direction. Thus it was that electromagnetism was first observed.

Later experimenters found that an electromagnetic field can be greatly strengthened by winding the conductor to form a coil. Further strengthening can be obtained by putting an iron core in the coil. If this core is made of soft iron it loses most of its magnetism when the current in the coil is turned

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*For an interesting new theory of the earth's magnetism, see Walter M. Elsasser's, "The Earth as a Dynamo," Scientific American, May 1958, p. 44.

off. A steel core, on the other hand, will retain much of its field and become a "permanent" magnet. This ability to hold its field can be improved still further by various heat and pounding treatments. Small amounts of impurities also change the magnetic properties significantly. For instance, the permeability (magnetic quality) of pure iron is about 200; for supermalloy, an alloy of nickel and iron, it is more than 100,000. An alloy containing about 8% aluminum, 14% nickel, 24% cobalt, 3% copper, and the rest iron, will give permanent magnets retaining a field of more than 12,500 gauss. The "gauss" is a unit indicating the intensity of a magnetic field, and is equal to one line of magnetic force per square centimeter. We will be making reference to this term later to show the strengths of some of the world's largest magnets, but first we will consider different methods for measuring field strengths.

A very rough determination of a magnet's strength can be made by the weight of iron filings it will pick up. This method, however, is cumbersome, especially when dealing with very strong magnets. Furthermore, in many modern applications much more sensitive measurements are needed.

The earliest device for making reasonably accurate measurements of magnetic field strength was a torsion balance called a magnetometer. This was built by Charles A. Coulomb, a French physicist, and was used by him in 1785 to measure electrical as well as magnetic forces. His magnetometer consisted of a bar magnet suspended by a fine fiber so that it could rotate about a vertical axis through its center. The rest position of the magnet is aligned with the earth's field. If the magnet is twisted from this position a torque (force which produces a twisting motion) is set up, tending to urge the magnet's return to its rest position. By measuring this twist and by having previously derived the mechanical laws of his magnetometer, Coulomb was able to calculate the magnetic field strength. This early measurement provided the basis for all our quantitative knowledge of magnetic phenomena, and consequently may be considered a milestone in the experimental study of magnetism.

Other methods for measuring field strengths have been developed since the time of Coulomb, and some are more accurate. Most of these devices make use of the fact that magnetism can produce electricity. Before describing these devices, we must first consider the principle upon which they operate.

In 1830 Joseph Henry, an American, found that a current is produced in a conductor when it is moved in such a way that it "cuts" magnetic lines of force. Michael Faraday in England independently discovered the same thing soon after. Because Faraday published his work first, he is usually given credit for the discovery. What they learned can be better understood by reference to Fig. 1. It is convenient to think of magnetic lines of force going from a north magnetic pole (N) to a south magnetic pole(S), as shown in the diagram. If the wire (W) is moved to the right or left no current will be produced. However, if it is quickly moved up, the galvanometer will record a sudden pulse of current. If the wire is moved down, the galvanometer will "kick" in the opposite direction. If the conductor is moved faster, or if the magnet is made stronger, the current will be greater.

Now we may examine several different methods for the more precise measurement of magnetic field strength. One system consists of a "flip coil" and a ballistic galvanometer, an apparatus for measuring the quantity of charge displaced by a current of short duration. The flip coil, which is mounted in the magnetic field to be measured, is mechanically flipped one-half turn. It cuts the lines of force and in so doing generates a current, which is in turn detected by the ballistic galvanometer. This process might be likened to opening a screen door against a spring--the harder the push, the wider the door opens. The current generated is compared to that produced with a magnet of known strength, and in this way the relative strengths are determined.

A ballistic galvanometer is not readily portable and requires a long time to get ready for the next "shot," so it is usually replaced by a cathode-ray oscilloscope (the granddaddy of the TV picture tube). This development of course did not occur until the twentieth century, after the invention of the electronic vacuum tube. Another improvement was to use a synchronous motor (like that in an electric clock) to keep the coil rotating at a constant rate, thus enormously increasing the output over a single flip of the coil, and vastly improving the sensitivity.

Another method of measuring magnetic fields, and especially those of great strength, takes advantage of what is known as the Hall effect. When delicate measurements became possible, it was found that the electrical resistance of certain metals changes slightly in the presence of a magnetic field. In particular, the effect with bismuth is hundreds of times as great as with most naturally occurring metals. The procedure is as follows: (See Fig. 2). A very thin pancake spiral of bismuth wire is placed perpendicular to the field to be measured and a current is then set through this coil. Its change in resistance is then measured by connecting the coil as one arm of a Wheatstone bridge, a device for making an accurate determination of resistance. This change in resistance is compared to that produced when the bismuth coil is placed in a field of known strength. This method is particularly useful in measuring nonuniform fields and is quite accurate. A field of 16,000 gauss, for instance, can be measured with an accuracy of a few gauss.

We have told about magnetism and its measurement, but still haven't spoken of what it really is. To begin, we know that matter is made up of subatomic particles, chief among which are the proton, electron, and neutron. The electron, which bears a charge, spins on its own axis and revolves about another axis in a manner similar to the two motions of the earth. It is believed at present that all magnetic phenomena are due to this motion of the electron.

An electron can spin either clockwise or counterclockwise. If two electrons spin in opposite directions they nullify each other, and the molecule as a whole has no magnetism. Most nonmagnetic substances have their spins balanced, but the magnetic materials do not. The latter have an excess of one kind of spin in the following relative amounts: iron 2.2, cobalt 1.7, and nickel 0.61.

A thoughtful reader may ask, "If this explanation is correct, why aren't metals that can be magnetized always magnetic and always of a fixed strength?" The answer is as follows: If you tie a number of bar magnets together in a bundle with their like poles aligned, they will make one strong magnet. However, should you then cut the string and shake the magnets in a box, they will tend to neutralize one another so that the box as a whole will not be a strong magnet. Thus we see that a magnetic material becomes a magnet only when its particles are appropriately aligned.

We will conclude this article with a brief account of some interesting electromagnets.

A magnet with an unusual history is the one used in the 37-inch cyclotron now at the University of California at Los Angeles. This 80-ton magnet was originally designed for spark quenching in a Poulsen-type arc radio transmitter, which was to be used in China. International complications and the invention of the De Forest grid vacuum tube (triode) made this plan infeasible. After lying in a scrap heap for years, this magnet was rescued in 1931 by Dr. E. O. Lawrence and incorporated into a cyclotron at Berkeley. (It was used for research there after World War II, when this cyclotron was dismantled and shipped to Los Angeles). Initially, this magnet had pole pieces $27\frac{1}{2}$ inches in diameter and gave a field strength of 18,000 gauss. In 1936 it was rewound with 37-inch pole pieces. At that time it was referred to as the "giant magnet."

The construction of a much larger cyclotron, with a pole-piece diameter of 184 inches, was completed at the University of California Radiation Laboratory in Berkeley in 1942. When first built it had a magnet containing 3700 tons of steel, with 300 tons of copper in the coil windings. During the war this cyclotron was used to produce the first significant amounts of fairly pure uranium-235. In 1955 this cyclotron was rebuilt; 4000 tons of steel went into the yoke of the magnet, which has a field strength of 23,400 gauss.

The electromagnetic method used to separate the isotopes of uranium requires a uniform field. At Oak Ridge, Tennessee, 96 vacuum tanks and an equal number of magnets were grouped together in the shape of a race track. The dimensions of each tank were about $4 \times 8 \times 2$ feet. A uniform field of approximately 3000 gauss had to be maintained throughout the entire volume of 6400 cubic feet--a world's record at that time (1943). When this isotope separator was built there was a great shortage of copper, so the coils for several magnets were wound with silver from the U. S. Government supply at West Point. Nearly 20,000 tons of silver were used, having a value close to $400,000,000. The coils have since been rewound with copper.

The Bevatron magnet at Berkeley weighs 9,700 tons (about the same as a medium cruiser) and uses 347 tons of copper in its coils. Its magnetic field measures 16,000 gauss. It may be interesting to note that a magnet of this size consumes 3,500 kilowatts of electricity each hour it is in operation, which is enough to supply an average community of 30,000.

A proton synchrotron even larger than the Bevatron is the Soviet Union's new Phasotron, whose magnet is 200 feet in diameter and weighs 36,000 tons, about the same as a World War II aircraft carrier.

At Brookhaven National Laboratory, Upton, Long Island, a new accelerator is being constructed which will have a ring-shaped magnet 840 feet in diameter. Not to be outdone, the Russians are reportedly working on an even larger version of the Brookhaven machine with a ring-shaped magnet 1,500 feet in diameter.

The world's most powerful continuously operating magnet is located in the low-temperature laboratory of Nobel prize winner W. R. Giauque on the campus of the University of California at Berkeley. This magnet has no iron core because its field is so great (97,500 gauss) that the iron would saturate and thus be of no value. The coil that produces this enormous field uses 9,500 amperes of current and must be cooled with kerosene, which is in turn cooled by water. At present this magnet is being rebuilt to give an even larger field.

Other magnets have been built to give pulsed fields of a much higher strength. In 1924 Peter Kapitza, working in the Cavendish Laboratory at Cambridge, England, produced a transient field of 100,000 gauss by discharging the current from a large number of storage batteries through a coil. In 1927 this was increased to 320,000 gauss by using the energy stored in the flywheel of a moving generator. This system made switching easier, since in an alternating current there is periodically no current, and the circuit can then be opened without serious arcing.

This limit was pushed to 450,000 gauss by T. F. Wohl, using a capacitor bank as his source of power. His magnets, like flashbulbs, could be used only once because the terrific fields generated blew the coils apart. By November, 1957, Furth, Levine, and Waniek obtained a transient field up to 1.6 million gauss before their beryllium-copper coil melted. This is the record to date, but new magnets of ever increasing magnitude are being designed.

Lucretius believed in "atoms and the void" at a time in antiquity when these concepts were merely speculations of the mind and unconfirmed by experiment. He gave advice on how to live and how to die which many people today regard as unsurpassed in wisdom and foresight. But surely Lucretius never dreamed of the offspring of his "Samothracian rings which leaped up, and the iron filings which seethed so furiously in the brazen bowl when underneath was the magnet stone."

LEGENDS

Fig. 1. A simple device for generating electric current. The wire is moved upward so that it cuts lines of magnetic force. A current flows through the wire and is registered by the galvanometer.

Fig. 2. Circuit for measuring magnetic field strength by the Hall effect. The bismuth coil R_x is connected as one arm of a Wheatstone bridge. R_1, R_2, and R_3 are variable resistors which have been previously calibrated. The operation of a Wheatstone bridge is described in any standard college physics text.

Fig. 3. Magnet yoke and main coils of the 184-inch synchrocyclotron at the Lawrence Radiation Laboratory, University of California, Berkeley. This photograph shows the magnet during construction; the coils are now enclosed in tanks and cooled by circulating oil.

Fig. 4. Aerial view of a giant proton synchrotron now under construction at Brookhaven National Laboratory, Upton, Long Island. The ring-shaped magnet is 840 feet in diameter. Astride the tunnel, on the right, is the target building which will house the indoor laboratory area. This machine will accelerate protons to 25 billion electron volts (Bev).

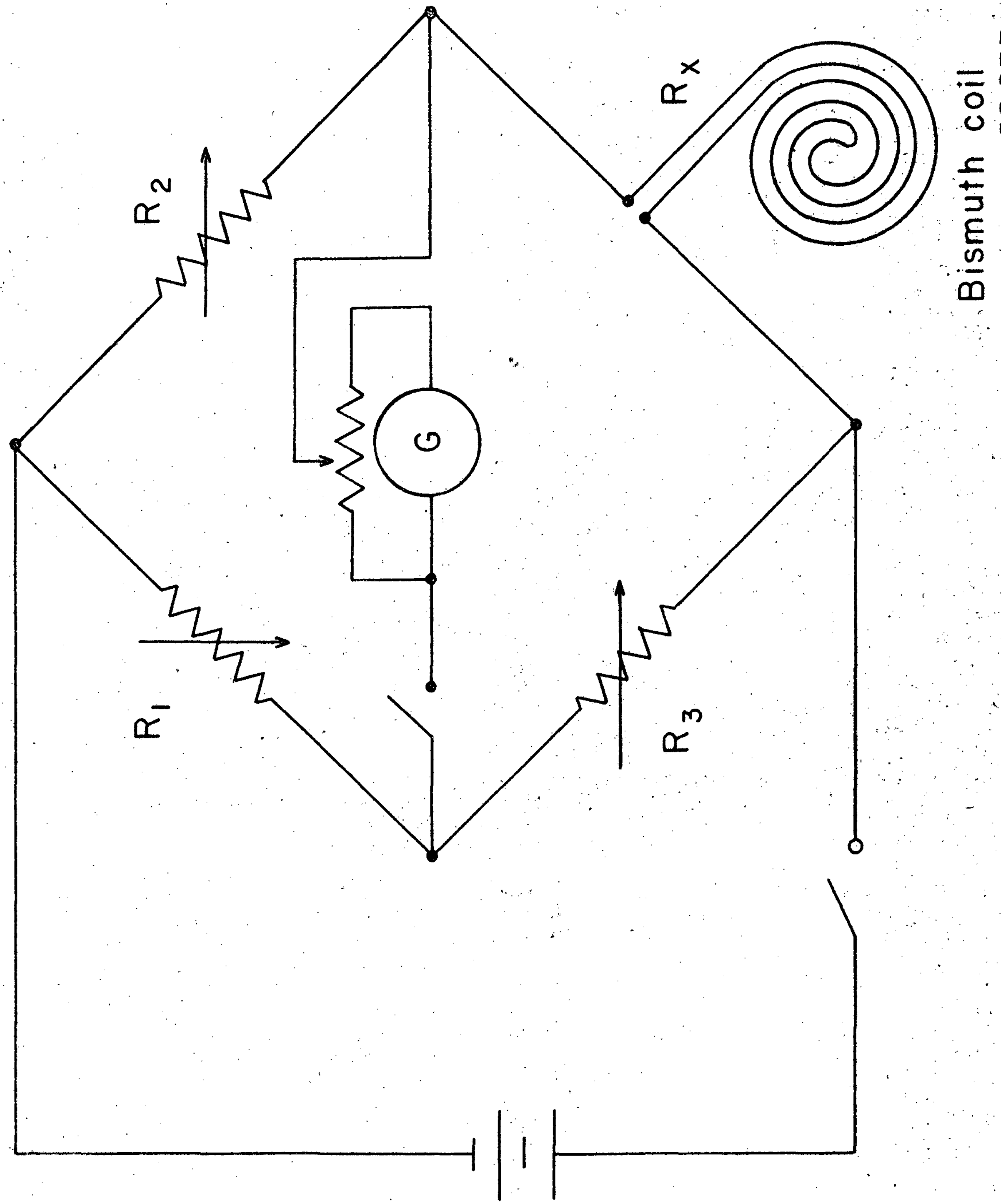

Fig. 2.

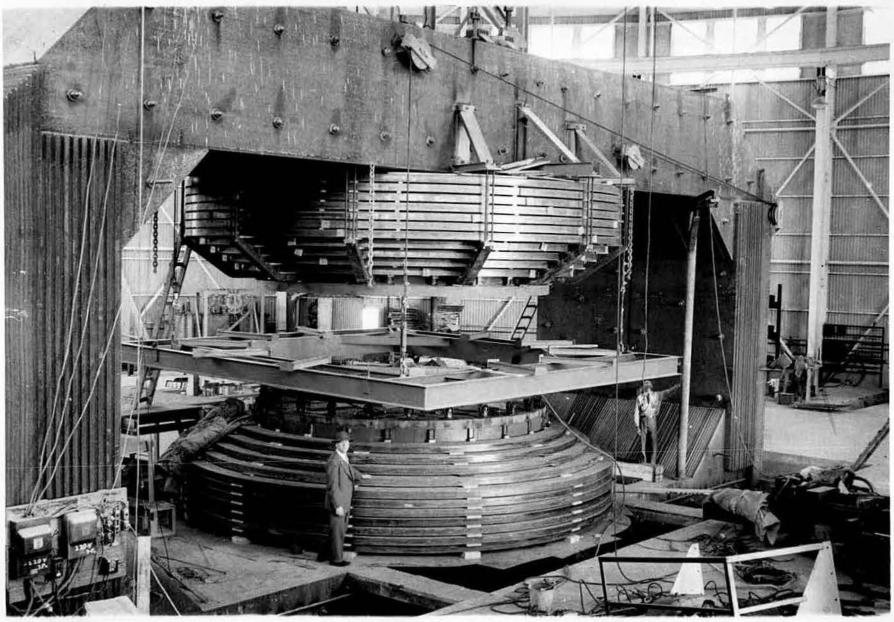

Fig. 3

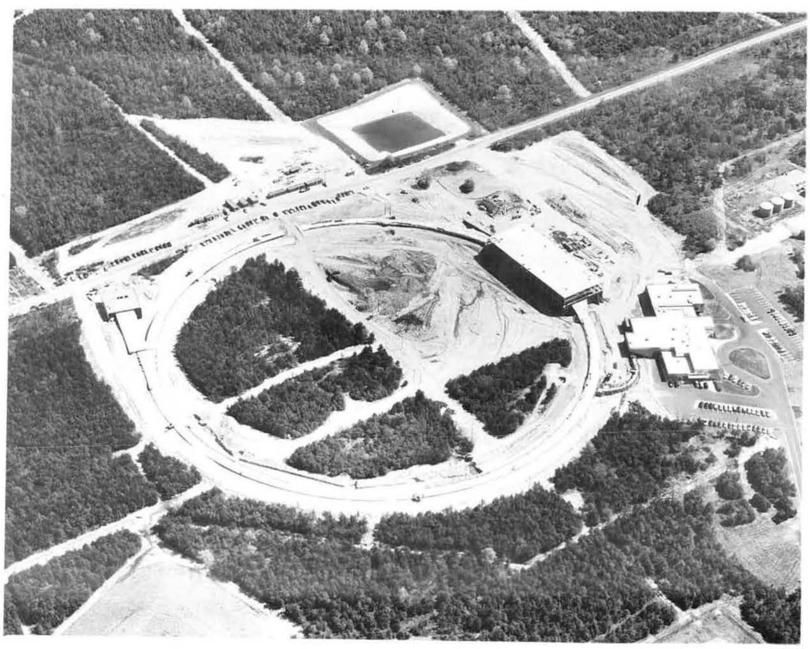

Fig. 4.