sandrovich Fridman's calculation (made in the 1920's) of a simple spherical universe filled with uniformly distributed matter. According to these results, the universe will reach its greatest extent about 35 billion years from now and begin to collapse, at first slowly, then more and more rapidly, and finally reach a condition of infinite curvature and infinite density.

Finally Wheeler considered whether a terrestrial-size piece of matter, say 1600 tons of iron, could be induced to undergo gravitational collapse and produce a kind of gravity bomb. In principle, he concluded, a gravity bomb would be possible. But it would be technically infeasible to set up such a thing (the iron would have to be spread into a thin spherical shell many feet in diameter) and, even if set up, it would require much more energy to compress the thing to the critical density than would come out of the explosion.

National Magnet Laboratory studies magnetism, probes matter

We recently visited the National Magnet Laboratory, a facility that specializes in producing intense magnetic fields and studying the behavior of matter in these fields. NML, which is supported by the Air Force Office of Scientific Research, is on the campus of the Massachusetts Institute of Technology and holds the world's record for continuous magnetic fields—226 kG in air. Its enthusiastic staff and visitors are doing research in many branches of physics but are particularly renowned for solid-state work.

The facility occupies a converted bakery building. (Our cab driver insisted there was no laboratory on Albany Street, only a cupcake factory.) It has the largest power capacity of any magnet laboratory in the world: a 10-MW dc supply. For short intervals even greater power is available: 16 MW for 1 min and 32 MW for 2 sec (from the energy stored in two 80-ton flywheels). The power supply consists of four independent generators, each with its own regulating system so that as many as four magnets can be operated simultaneously. Ripple voltage and current fluctuations are less than 0.02%.

To cool the magnets, water is pumped from the nearby Charles River—also popular for cooling sailors—at rates up to 4000 gallons per minute.

Bigger and better magnets. When talking about high magnetic fields one must answer several questions simultaneously: how strong? how long? how big a region? At other laboratories megagauss fields are generated for microseconds in volumes of about 10 cm³ by an implosion technique. (PHYSICS TODAY, Feb. 1966, page 37). Half-million gauss fields have been produced for milliseconds in a somewhat larger volume by discharging a capacitor bank. But the strongest field generated continuously has been about a quarter of a million gauss in a 32-mm bore. To be more specific, the strongest continuous field was produced last fall: 226 kG in air at NML. The same magnet is expected to reach its design intensity of 250 kG in the near future.

To generate an intense, continuous magnetic field in a small region one must build a magnet not only strong enough to withstand magnetic forces but also able to get rid of the heat generated by the high currents. A typical magnet running at 250 kG may have a local heat dissipation as great as 40 kW/cm³ and a magnetic stress greater than 3×10^9 dynes/cm² (50 000 psi).

If the magnet designer wants greater field intensity, he must use a large conductor volume to reduce magnetic stress to a tolerable level. But large conductor volumes mean inefficient current distribution: the power requirement increases even faster than the (expected) square of the field. Byond about 300 kG the power cost goes up rapidly.

The laboratory now has a selection of about 20 solenoid magnets capable of generating at least 100 kG. For optical experiments there are magnets with transverse as well as the usual longitudinal access to the field volume. Some are designed to give high homogeneity. These solenoids have to be made relatively long to reduce edge

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effects, but as a consequence they are relatively wasteful of power (greater length means more I^2R losses). One NML magnet has been made homogeneous to within a part in a million over a fairly large volume. Such uniform fields are useful for high resolution in nuclear-magnetic-resonance experiments.

NML's record-breaking 226 kG magnet was preceded by a similar design that reached 205 kG in air (in a 5.5-cm bore) and 255 kG with two iron pole pieces inserted (which reduced the field region to a 2.5-mm diameter). Both magnets are actually three nested concentric magnets in one. The outer magnet is a solenoid wound with cable of square cross section (with a hole in the middle for cooling). The inner ones each have smaller lengths as well as diameters and are of the variety invented by Francis Bitter. Basically the Bitter magnets are a pile of zirconium-copper sheets arranged to conduct current in a helical path and circulate cooling water at the same time.

For the weaker magnet the copper sheets have cooling channels arranged radially like the spokes of a wheel. The sheets for the strongest magnet resemble a physicist's attempt at "op art"—the pattern is a series of perforations arranged in ever-widening concentric circles. The cooling water circulates axially, and although it comes in direct contact with the copper, electrolytic conduction is negligible compared with the total power consumption.

Pulsed and superconducting magnets. Not all of NML's magnetic research and development concentrates on high-power solenoid magnets. There is also a significant effort in producing pulsed magnetic fields and superconducting magnets.

Pulsed fields are produced by discharging a bank of capacitors into a coil. By rapidly transferring the energy from the capacitors into the field and then back into the capacitors, excessive heating is avoided and water cooling is not needed. The shortness of the pulse also allows higher intensities than continuous-field magnets. The coils are usually made up of beryllium-copper, an alloy that is stronger than copper but has greater resistivity.

The technique of capacitor discharge has produced one million gauss, but at this intensity the coils do not stand up well. NML has a 100-kJ, 3000-V capacitor bank that is used with a variety of coils developed by Simon Foner. One coil, for example, produces 500 kG in a 1.9-cm bore for 0.5 millisec. If the researcher is willing to settle for less field intensity, he can produce a field either over a larger volume or for a longer time (for as long as 10 millisec).

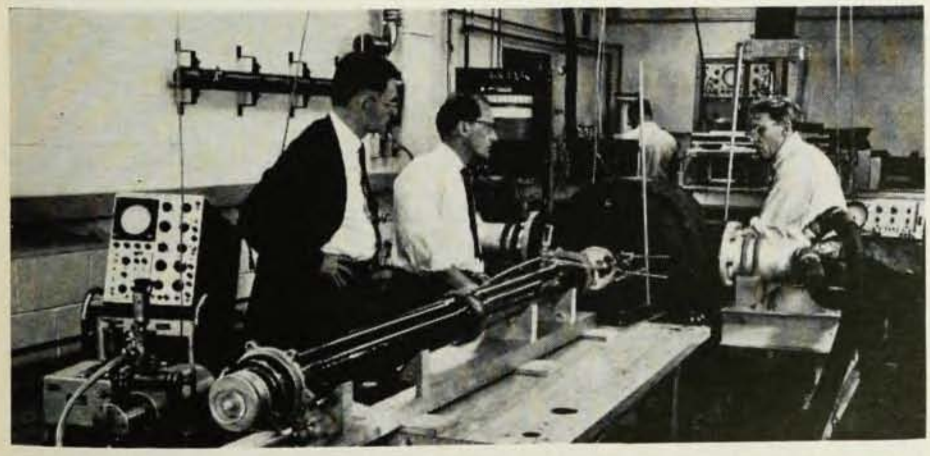
Superconducting magnets are becoming more and more popular for the production of moderately intense magnetic fields at a reasonable cost. At present superconducting magnets can produce as much as 130 kG over a one-centimeter bore. Fields as high as 150 to 175 kG seem possible in the near future. Beyond this intensity few materials remain superconducting.

At NML, D. Bruce Montgomery has evaluated many different superconductors and obtained plots of j, the current density, versus H, the applied field (using NML's high-field continuous magnets). The upper critical field, the field at which the last trace of superconductivity disappears, was expected to be about 700 kG for vanadium-gallium (V_3Ga). Montgomery and H. Wisgall (Giessen, Germany) found that the critical field actually appears at about 180 to 195 kG, depending on the method of sample preparation.

Montgomery feels that the best currently available material for highfield superconducting magnets is niobium-tin (Nb_3Sn). He finds that there are still traces of superconductivity as high as 221 kG. Unless an unexpected kink develops in the j vs H curve at higher fields, Montgomery thinks the critical field will occur at about 240 kG.

Even if traces of superconductivity remain, however, the current density must stay great enough to build a working magnet. If the current density is too low, too many turns are needed to produce a practical field. For niobium-tin the practical limit to field intensity seems to be about 180 kG.

What kinds of experiments? The range of experiments done at NML is just about as wide as the variety of phenomena one can study in intense magnetic fields. Research and develop-



CYANIDE LASER (337 microns) used as source for cyclotron resonance measurements in 150-kG magnet. Left to right: Benjamin Lax, Kenneth J. Button, H. A. Gebbie (inventor of the cyanide laser, visiting from Teddington).

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ment is being done in solid-state physics, atomic physics, plasma physics, millimeter and submillimeter wave generation, magnetism, medicine and biology. Some of the experiments we learned about are discussed below.

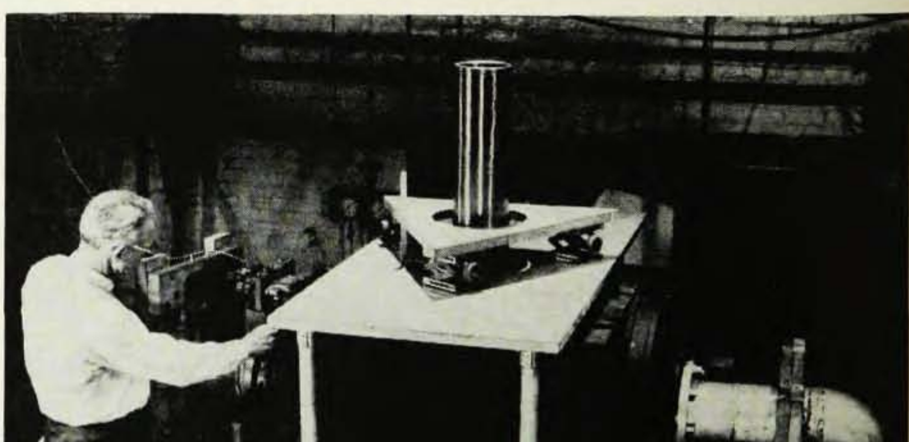
Kenneth J. Button, A. H. Gebbie, and Benjamin Lax are using a combination of an ethyl-cyanide laser (337 micron wavelength) and magnetic field (170 to 180 kG) to provide a new kind of resonance spectrometer. The combination of far infrared radiation and high intensity magnetic fields can be used for cyclotron resonance measurements on a large variety of semiconductors with many impurities or imperfections. In the past it has been difficult to observe cyclotron resonance in these materials because the charge carriers would meet an impurity before completing a cyclotron orbit about the direction of the magnetic field. NML people get around the problem by using a high magnetic field. This reduces the radius and increases the cyclotron frequency. Hence the driving frequency must be in the far infrared range instead of the customary microwave or millimeter range used in studies of simple and perfect semiconductors. NML expects to use the spectrometer for magnetic-resonance measurements as well.

If one sends ultrasonic waves into a solid and applies an intense magnetic field, the interaction of the field with the electrons in the solid will diminish the sound intensity and alter the sound velocity. This magneto-acoustic effect is being used by L. J. Neuringer, Yaacov Shapira and others to study properties of superconductors, semiconductors and ordinary conductors.

Q. H. F. Vrehen and Lax have studied the effect of crossed electric and magnetic fields on the interband absorption in semiconductors. Their experiments led to a new mathematical model for energy bands, which contains a relativistic-like effective mass analogous to the one in Dirac's theory.

A hunt for the Dirac magnetic monopole is being conducted by Henry Kolm. Using high magnetic fields, he is trying to extract the elusive particle from both extraterrestrial and terrestrial material. (A recent theory of Julian Schwinger's predicts that the monopole has a magnetic charge twice that predicted by Dirac.)

Medical and biological researchers are having a field day at NML. It turns out that some biological phenomena appear to be affected by high magnetic fields. Visitors are studying such varied things as the behavior of squirrel monkeys in a high magnetic field and the effect of high fields on blood agglutination. Many physicists can testify that high fields affect human behavior. Just try putting your head in a high field for any length of time and notice how dizzy you feel.



226-kG MAGNET. Field was produced in air. Magnet has a bore about 3 cm in diameter. Its three concentric coils take 10.5-MW power.

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How NML is organized. Lax, who was formerly associate director of MIT's Lincoln Laboratory, serves as director of NML. While he headed Lincoln's solid-state division he helped establish a coöperative program with Francis Bitter's magnet laboratory on the MIT campus. Out of this association grew the idea for a national laboratory. The Air Force Office of Scientific Research officially established the laboratory in July 1960 and has provided funds ever since. Scientists moved into the old bakery building in October 1962 and the following year they began to produce intense magnetic fields.

For a national laboratory, the size of the staff and the building it occupies are surprisingly small. But, as the directors put it, the distinctive quality of the laboratory comes from the spirit, creativity and ingenuity of its people. Because of its small size the laboratory can hire only one or two young physicists a year. Lax regretfully notes that he has had to turn down many fine candidates.

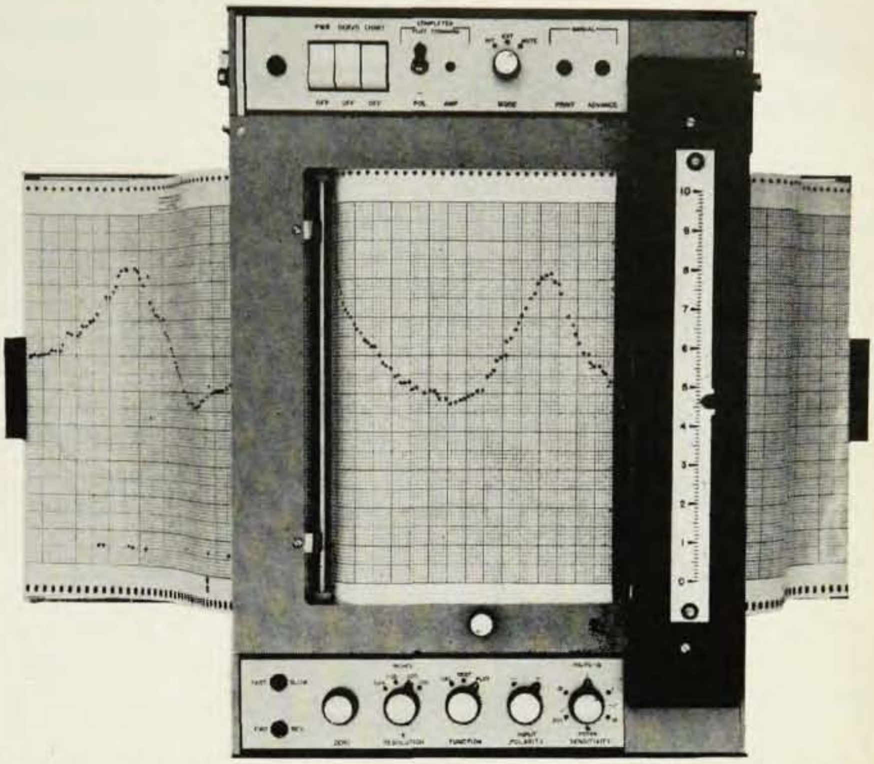
The laboratory has attracted visitors from all parts of the world. Last year 56 different experiments were done by visitors, who used about half the available magnet time. Visitors are frequently surprised to learn that there are no charges, except for the amount of liquid helium they use. Technicians and equipment are lent to the visitors if they need them. Arrangements to use the laboratory can be made by writing to Donald T. Stevenson (assistant director).

Big-team operations are not necessary at NML. An individual physicist can have the satisfaction (and headaches) of designing and running his own experiment.

The laboratory operates 16 hours a day, five days a week. NML would prefer to run 24 hours to meet the demand by visitors, but there is not adequate support to do this.

Although NML is the world's biggest magnet laboratory, other nations are planning to build comparable facilities. The Soviet Union is building a 12-MW facility at the Lebedev Institute; Great Britain is planning a 16-MW lab; and France is planning a 14-MW facility (there is already a 3.4-MW laboratory at Grenoble).

ANALYZER PLOTTER



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