CERN COURIER

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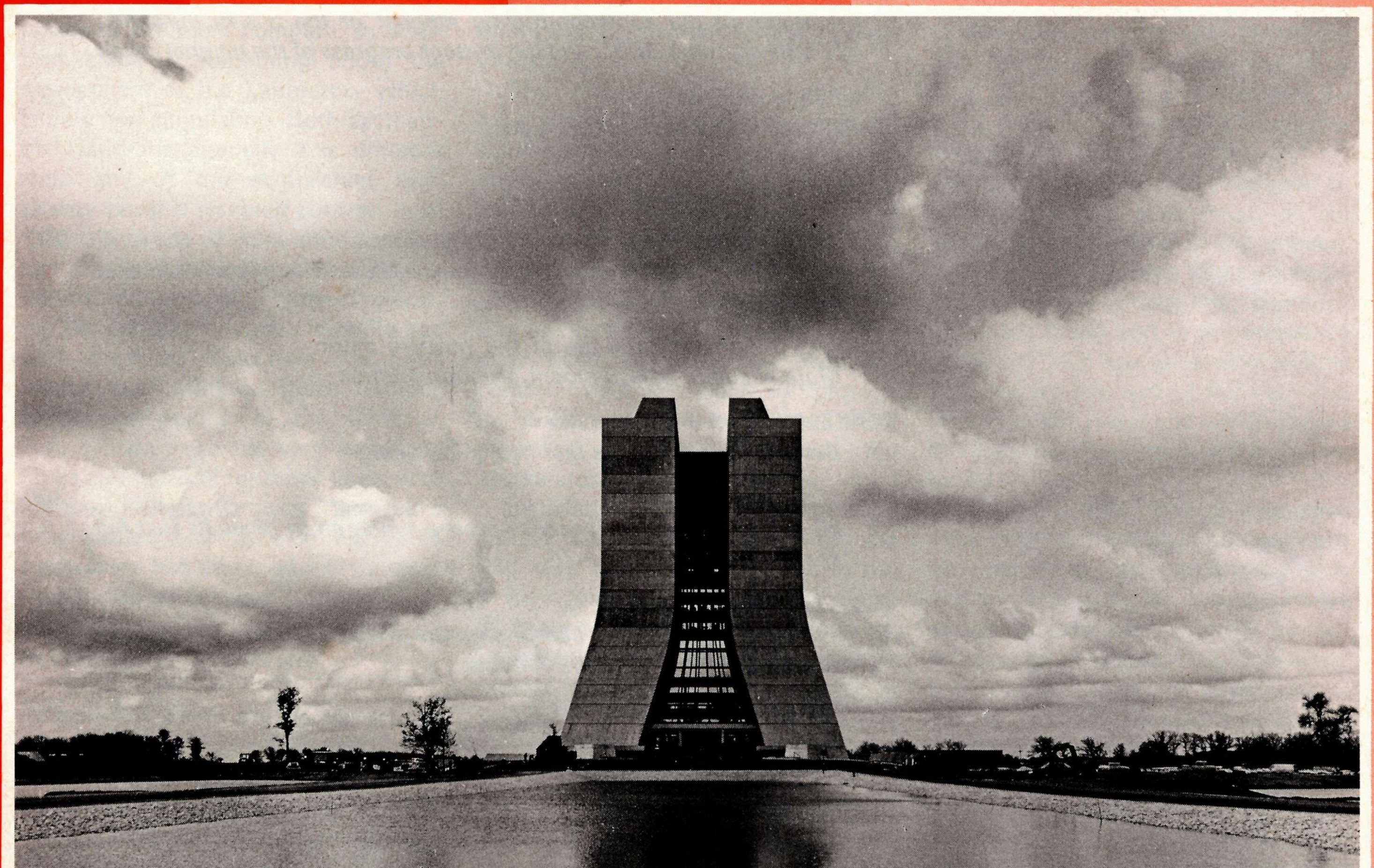

CERN, the European Organization for Nuclear Research, was established in 1954 to '... provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto'. It acts as a European centre and co-ordinator of research, theoretical and experimental, in the field of sub-nuclear physics. This branch of science is concerned with the fundamental questions of the basic laws governing the structure of matter. The Organization has its seat at Meyrin near Geneva in Switzerland. There are two adjoining Laboratories known as CERN Laboratory I and CERN Laboratory II.

CERN Laboratory I has existed since 1954. Its experimental programme is based on the use of two proton accelerators — a 600 MeV synchro-cyclotron (SC) and a 28 GeV synchrotron (PS). Large intersecting storage rings (ISR), are fed with protons from the PS for experiments with colliding beams. Scientists from many European Universities as well as from CERN itself take part in the experiments and it is estimated that some 1500 physicists draw research material from CERN.

The CERN Laboratory I site covers about 80 hectares almost equally divided on either side of the frontier between France and Switzerland. The staff totals about 3100 people and, in addition, there are about 1000 Fellows and Scientific Associates. Twelve European countries contribute, in proportion to their net national income, to the CERN Laboratory I budget, which totals 391.1 million Swiss francs in 1974.

CERN Laboratory II came into being in 1971. It is supported by eleven countries. A 'super proton synchrotron' (SPS), capable of a peak energy of 400 GeV, is being constructed. CERN Laboratory II also spans the Franco-Swiss frontier with 412 hectares in France and 68 hectares in Switzerland. Its budget for 1974 is 227.1 million Swiss francs and the staff totals about 350 plus 10 Scientific Associates.

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Around the Laboratories

Cover photograph: The Hi-Rise — main building of the Fermi National Accelerator Laboratory. This splendid building houses most of the staff and visiting scientists and is the central point of architectural attraction on the site. The FermiLab, the newcomer among high energy physics research centres, is featured in our opening article. (Photo FermiLab)

Fermi National Accelerator Laboratory

It will have been obvious from our recent issues that the Fermi National Accelerator Laboratory has rapidly established itself among the finest research centres in the field of high energy physics. It is operating the world's highest energy, highest intensity proton accelerator and, until it is joined by the CERN SPS, has a monopoly on some almost completely unexplored regions of physics.

This is reflected in the vocabulary of the high energy physicists at the FermiLab where the word 'excitement' is one of the most common. In addition, there is something about the atmosphere of the Laboratory which is new and stimulating. Both aesthetically and managerially it is different from any of the established high energy physics research centres. Aesthetically, a site of great attractiveness has emerged from the corn fields of Illinois. Managerially, a way of operating the Laboratory which is not in line with practices elsewhere has been implemented. Behind these features is the personality of the Director, R.R. Wilson, who set very ambitious goals and reached for those goals with his own distinctive style. There have been problems en route but the Fermi Laboratory has emerged with stature from its formative years.

Performance of accelerator

Research is based on the use of the synchrotron which is able to accelerate protons to energies between 200 and 400 GeV. Acceleration to 500 GeV will be attempted again when repair of a commercial transformer is completed. The design intensity is set at the high level of 5 × 10^{13} protons per pulse.

Since the report given at the Stanford Accelerator Conference (see June issue page 199) reliable machine operation at 300 GeV energy (over 75 % average operational efficiency during high energy physics runs) continued through May and June. A 400 GeV run during intense heat rocked the boat a little and the machine has taken time to settle down again (efficiencies down to 50 %) even though operating back at 300 GeV. In August a two week run with a 200/300 GeV beam pulse using a front porch was successfully accomplished with two experiments doing physics with slow spill at both energies during the same beam pulse. The next 400 GeV run will wait several months until the transformer is back in service.

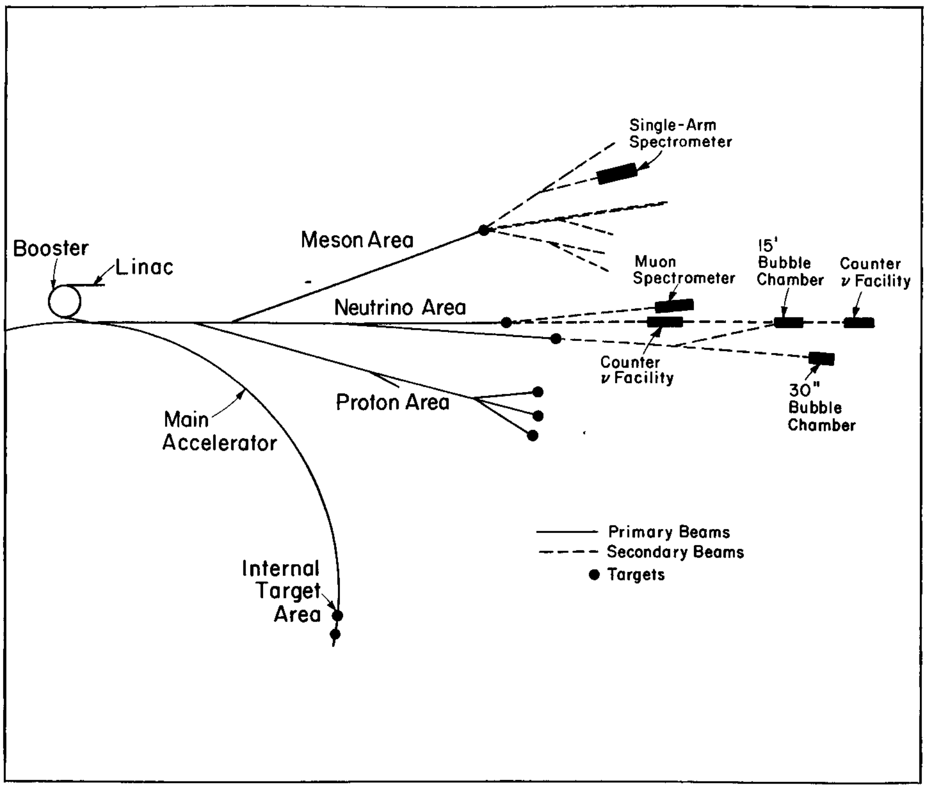
The recent reliability difficulties have been caused by a series of seemingly disconnected faults and, in addition, the growing beam intensity is bringing problems in its wake — both in terms of beam instabilities and of the effect of the intense beams (particularly on the extraction septa). Since the Stanford Conference, the peak beam intensity has been increased by 40 % to 1.4 × 10^{13} protons per pulse and there have been some extended runs at 10^{13} with the accelerator operating reliably.

Installation of a debuncher, to reduce the energy spread in the 205 MeV beam from the linac to the 8 GeV booster, has enabled about 20 % more protons to be fed through the booster. It has also improved the quality of the beam so that with single-turn injection into the booster virtually all the beam from the booster can be accelerated in the main ring and with two-turn injection about 90 % can be accelerated. Efficient four-turn booster injection is the ultimate aim. Another intensity gain came from injecting a thirteenth pulse from the booster to fill the main ring circumference; until recently only twelve had been manageable.

The higher intensities are provoking beam instabilities in both the booster and the main ring and there are signs of collective phenomena. Work on control of resonances has been successful in holding down the instabilities so far. Further help should come from horizontal and vertical super-dampers (which feed back voltage signals fast enough to deal with fluctuations in individual bunches) due to be installed in the main ring in October. R.f. system beam loading problems and related longitudinal space charge problems are also being attacked.

These improvements are expected to take the peak intensity to around 2 × 10^{13} by the end of the year. After that, the climb higher is likely to be much harder. There is a problem of low acceptance in the booster and its ejection system will be redesigned to take the septum further out of the vertical aperture. Also in the booster, the r.f. cavity supplies need attention to increase the voltage they can supply at the lower end of the frequency spectrum. Two special cavities will be installed by the end of the year just to help at this lower end which should increase the acceptance of the booster by 40 %.

In the meantime, the high intensities have improved the ability to wipe out electrostatic ejection septa in the main ring by depositing too many protons on the septum wires and the protection system to prevent this happening, now in the process of upgrading, is having a hard job keeping pace with the growing numbers of protons. In a bad spell, a couple of septa were seriously damaged within a week. They are similar in design to those developed for the CERN SPS with spring wires to pull any broken septum wire out of the path of the beam. A technique of machine winding the plane of septum wires has been tried; it gave a plane accurate to one part in a thousand and took only one day to wind. If this septum works well in the accelerator, machine



Schematic representation of the beam layout in the experimental areas at the FermiLab. The Meson Area takes a variety of secondary beams from a single target bombarded by protons up to 300 GeV energy. The Neutrino Area has detection systems for neutrinos generated by protons up to 500 GeV energy and muons up to 150 GeV. The Proton Area can take protons up to 500 GeV energy.

winding will become the standard method.

It looks as if the accelerator requires a progressive shakedown as each new energy and intensity peak is scaled. Nevertheless, the accelerator team are obviously capable of taking the problems in their stride and each advance brings a fresh gleam to the eyes of the high energy physicists who are well aware that they are sitting on a physics gold mine.

Layout of experimental areas

On the main ring itself is an internal target area where studies on proton interactions over the whole range of energies from 8 GeV to 400 GeV are possible. A hydrogen jet target built by a group of Soviet scientists from Dubna has been the major installation and there are also thin fibre targets.

The ejected beam serves three experimental areas known as Proton, Meson and Neutrino. During normal operation all three are fed with protons every pulse; usually there is slow ejection over a one second flat-top at the peak machine energy and then a short burst to the Neutrino Area for the bubble chambers. There can also be a 'front porch' at lower energy (say 200 GeV during a 300 GeV run) should some experiments require it. At peak intensities it is possible to have 10^{13} protons sent to the Neutrino Area and still leave several times 10^{12} for each of the other Areas.

The ejected beam is split first (taking off a vertical slice with an electrostatic septum and several Lambertson type septum magnets) to bend protons off to the Proton Area. This Area is designed for experiments using primary protons of energy up to 500 GeV and intensities up to 10^{13} protons per pulse. Thus the shielding problems are severe and experiments are installed in channels below ground level to take advantage of earth shielding. Three of these subterranean channels exist (Proton-East, Proton-Centre, Proton-West) and are fed by a splitting station which either splits the proton beam to any channel, sends it to Centre and East or sends it to Centre and West. Eventually splitting to feed all channels will be installed. Proton-East is used to generate a neutral beam for photoproduction experiments (using a 30 m deuterium filter, a beam with only one neutron per 500 gammas is obtained) and further downstream an electron-photon facility is about halfway to completion (experiments are expected next year). Proton-Centre is used for a lepton production experiment. Proton-West is still being brought into action. Eventually the Proton Area is likely to be a source of the highest energy secondary beams beyond the range which can be comfortably handled in the Meson Area.

After the ejected beam has had a fraction peeled off towards the Proton Area, a second vertical split is performed to send protons off towards the Meson Area. This area is operated for experiments with secondary beams coming from a single target bombarded by a primary beam of energy up to 300 GeV and intensity up to about 10^{13} protons. About ten experiments can be set up simultaneously using six fixed beam-lines (M1-280 GeV/c medium resolution which has a second branch; M2-300 GeV/c diffracted protons; M3 - neutrons; M4 - neutral kaons; M5 - test beam; M6 - 200 GeV/c high resolution which also has a second branch). In general the charged beams have branches to accommodate more experiments and the neutral beams have experiments lined up in series. The meson detector hall houses the bulk of the equipment for the experiments with some pre-fabricated tunnels extending out on its downstream end. Extending the ability of the beam-line to the target (probably using superconducting magnets) will eventually enable the area to draw secondary beams from 400 GeV protons.

Primary proton beam remaining after the two splits to the Proton and Meson areas continues on to the Neutrino Area. This area is designed to use up to 500 GeV protons at the design intensity of 5 × 10^{13} protons per pulse. The neutrinos are generated from pions and kaons allowed to decay over 400 m from the target bombarded by the proton beam. Focusing systems point the pions and kaons towards neutrino detectors including the 15 foot bubble chamber which can take hydrogen, deuterium or neon fillings. After the decay region, 1000 m of earth shielding filters out the particles other than neutrinos so as to avoid flooding the neutrino detection systems with other particles, particularly muons.

By varying the target and focusing system (run in on train loads on a narrow gauge rail system), the parameters of the neutrino beam can be changed. The beam can be either a 'broad-band' spectrum of neutrino energies with a 100 μs spill via two pulsed focusing horns (this is not compatible with running muon experiments), an alternative broad-band spectrum using focusing quadrupoles which are not pulsed (which allows muon experiments) or a dichromatic beam selecting pions and kaons of energy less than 200 GeV.

The muons are collected as a byproduct to the neutrino beam and used in a separate experimental facility off-set from the neutrino line. A large spectrometer incorporating the magnet of the former Chicago cyclotron magnet is used in the muon experiments. Alongside the muon spectrometer is the first of two electronic detector set-ups (an iron calorimeter) for neutrino experiments; the second (a liquid scintillator calorimeter) is downstream of the 15 foot chamber.

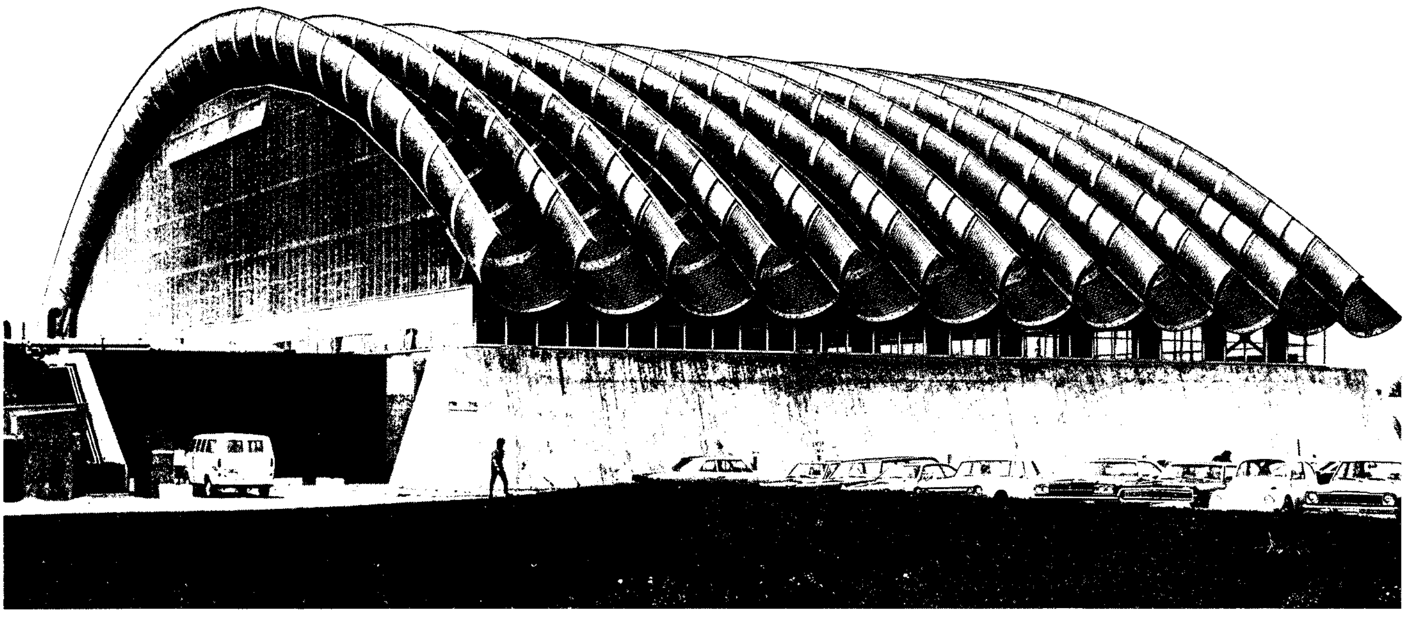
Also in the Neutrino Area is the 30 inch bubble chamber formerly at Argonne. In association with a tagging system, this is in use with a hadron beam-line N3 of high resolution capable of handling particles up to 500 GeV. A branch N5 takes hadrons around the neutrino shield to the 15 foot chamber.

Experimental programme

The FermiLab has a user community of about 1150 high energy physicists. Of these up to 250 will be at the Laboratory taking part in experiments at any one time. As all the beam-lines are brought into full action, this number may rise to 350 or higher though the money available to finance operation at this level may intervene to set the top limit rather than the interest in the experimental programme. The physicists are predominantly from the USA but there is a strong participation from other countries, particularly the Soviet Union, and the flags of twenty nations were flying at the dedication ceremony of the Laboratory last May.

Sixty experiments have been completed, about 30 others are set up in the experimental areas either in a state to take data or testing and another 30 are in the pipe-line for installation during the next year. In a normal week of operation about 25 experiments will receive some beam, a third of them taking data at any one time. This latter figure is another which will rise as the experimental areas 'shake down' and as still higher beam intensities are reached.

The first series of experiments included many of the 'search and survey' type, looking in the newly available energy range for such things



The Meson hall which houses the bulk of the detection systems for experiments on secondary beams with energies up to 300 GeV. The beams, emerging from a single target, enter from the left and 'fingers' to accommodate additional detectors protrude behind the building on the right.

as the magnetic monopole and the isolated quark. There are still searches of this type going on but the emphasis is swinging to more detailed studies of the behaviour of the different types of interaction at high energies. Elastic and inelastic scattering experiments are growing in number as are experiments with multiparticle detection systems and, further off, hyperon and neutral kaon experiments.

As examples of what is under way: In the Meson Area the total cross-section experiment of the Brookhaven / FermiLab / Rockefeller team continues. They have already seen that the region over which the strong interaction acts, grows as the energy increases for all hadrons (except for the antiproton where the energies investigated are probably not yet high enough). They are now running at lower energies to link up the new data with results from the CERN PS and Brookhaven and then hope to extend to the highest possible energies of the FermiLab particularly to confirm that the antiproton behaves like all the other hadrons. Another experiment is studying charge exchange at high energies in the interaction between the negative pion and the proton (giving a neutral pion and a neutron or an eta meson and a neutron) using a sophisticated neutral pion detector developed by a Berkeley/Cal. Tech. team. The conversion between protons and neutrons is an obvious candidate for helping to understand the strong interaction.

In the Neutrino Area, a muon experiment of the missing mass type, gathering information only on the incoming and outgoing muons, has been completed and the muon spectrometer is now able to study the emerging hadrons and electrons as well. Data has already been collected by a FermiLab/Oxford/Rutherford team using hydrogen and deuterium targets and the difficult analysis task has begun. The two neutrino experiments using electronic detection systems of Cal. Tech./FermiLab and Harvard/FermiLab/Pennsylvania/Wisconsin are continuing in this completely unexplored field and are being joined by the 15 foot bubble chamber whose present status is described below. The 30 inch chamber which did such fruitful work in the first years of accelerator operation will fade in importance as the 15 foot comes on.

In the Proton Area, the lepton experiment of the Columbia/FermiLab team, which was one of those to spot the unexpected very high rate of production of leptons from hadron collisions, is continuing with a detection system adapted to catch both emerging leptons. A photoproduction experiment of Columbia/FermiLab/Hawaii/Illinois is now setting up and will also have an unexplored field to investigate.

The detection systems (with the exception of the 15 foot chamber) are tailored to the requirements of specific experiments rather than being large multipurpose systems such as are being devised for a large part of the CERN SPS experimental programme. This may prove to be a logical sequence in that the more quickly built special systems at the FermiLab will be taking a first look at phenomena in this new energy range while comprehensive, general systems will be in action for broader, more detailed studies when the SPS comes on in a few years' time.

15 foot bubble chamber

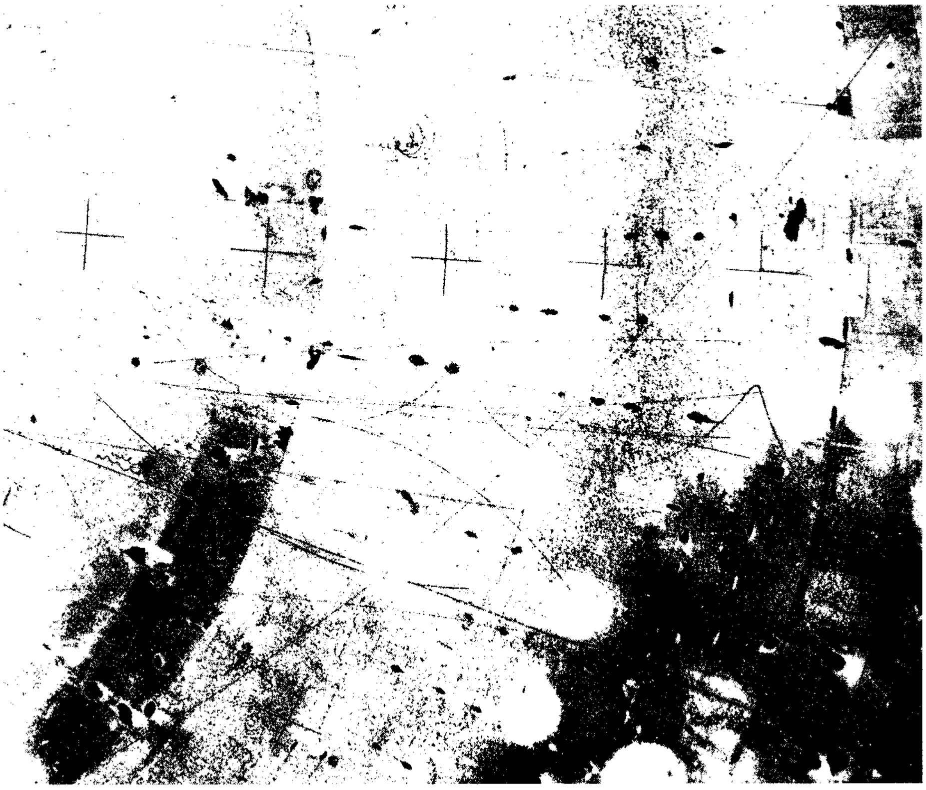
At the end of July the 15 foot bubble chamber took its first pictures for physics. Two experiments collected a few thousand photographs, one studying neutrino interactions and the other studying hadron interactions.

The chamber operated for the first time in September 1973 (see vol. 13, page 336). Its major design parameters are — volume of 30 000 litres about 4.5 m along the beam direction, capable of operating with hydrogen, deuterium or neon in a 3 T magnetic field produced by a surrounding superconducting magnet, piston plunging from below at rates up to four times per accelerator cycle, two sets of three cameras positioned on top.

As is usual with these large complicated systems, the first engineering run uncovered a number of problems. The fish-eye windows through which the cameras see the chamber volume were chipped. They have been newly designed but only four are installed to confirm that the trouble has been cleared before the last two are made. (The two sets are intended to operate independently of one another so that neutrino and hadron pictures can be interleaved.) The piston and its seal were a source of dirt which spoiled the pictures. A new surface (fibreglass filled teflon) on the piston and a chrome plated seal seems to have cleared this. The cameras were not operating properly because the stray field of the superconducting magnet was affecting the motors which pull the film. This has been corrected (initially over-corrected, tending to pull the film too hard — the motors had to be turned down).

The chamber was cooled again in June when the modifications were complete. The superconducting magnet was then brought on successfully though the field has been limited to 1.8 T until extra refrigeration can be applied. The magnet is being handled rather gingerly after the experience of the 3.7 m European bubble chamber, BEBC (see page 294). The contact between the teams bringing in the 15 foot and BEBC has, incidentally, been very helpful to both sides.

Fairly reliable chamber operation was achieved over several runs giving



A probable neutrino interaction (the three tracks emerging from the vertex on the left of the picture where the invisible neutrinos have entered) photographed during the July/August run of the 15 foot bubble chamber.

reasonable quality pictures. The track resolution is at the level of 300 μm (the film grain resolution limit being 100 μm) under the following operating conditions — temperature 25.5 K, chamber pressure minimum of 22 psi, flash operated as fast as 3 ms after passage of the beam giving an unusually short time for bubble growth and, hence, very good resolution. There is still some fogging due to dirt in the chamber and on the fish-eyes but it is expected that this will get progressively better. Baffles may be needed to hide bubbling at Scotchlite joints. The coated metal piston remains in place and eddy currents in the metal are a significant load on the chamber refrigeration system. This limits the picture taking rate at present to one per machine cycle and to approach the design rate it will be necessary to install a plastic piston. Such a piston, consisting of a plastic mushroom around a light stainless steel frame, is on site being tested.

The chamber has been warmed up again for a wash and brush up while the 30 inch chamber is back in action, and work on the helium refrigeration system will attempt to improve the magnet performance. Installation of the plastic piston and additional optics will probably await the next warm up so that multi-pulsing on one accelerator cycle will not take place before next year. The chamber is due back on the air about the end of October with the two horn focusing system installed to help on the neutrino pictures. It is then hoped to have extended physics runs.

The first experiments include a 50 000 picture study of hadron interactions by a FermiLab team using a 250 GeV negative pion beam. This will be used as a test experiment to check the performance of the chamber. The neutrino experiment is a collaboration of FermiLab and Michigan with physicists from ITEP Moscow and Serpukhov participating as part of the FermiLab team. They will gather 300 000 pictures (hoping soon to be seeing an event about once every twenty pictures) for a comprehensive investigation of neutrino interactions at high energies. Results are likely to come from this data over several years but some important information might emerge in a few months. For example, the possibility of a new class of particle with associated 'charm' quantum number could result in single strange particles being produced in the neutrino events. The 'signature' for this in terms of track configuration is rather clear in the neutrino pictures and it may be possible to say something about charm rather quickly. The chamber could also catch intermediate bosons up to a mass of about 7 GeV and will add to the knowledge on neutral currents. The speed of analysis depends greatly on being able to determine the neutron background.

Additional detectors around the chamber include an external muon identifier — a blanket of multiwire proportional chambers built by a Berkeley/Hawaii collaboration which are being tested and will be brought into action later in connection with the neutrino studies to spot muons emerging from the chamber volume. A novel way of learning the energy distribution of the neutrino beam going into the chamber has been proposed by the Soviet scientists involved in the neutrino experiment. It is a Cherenkov counter which can pick out muons from a high background of other particles by using fine straws to convey the Cherenkov light to photomultipliers. Only particles travelling along the neutrino beam direction, or at a very small angle to it, will produce light which will make its way to the photomultipliers. By setting the pressure in the counter it can also be made to select muons as well as giving their momentum (and thus the momentum of the neutrino produced in the same decay). The technique is being tested and looks promising.

The Energy Doubler/Energy Saver/Beam Stretcher

Future developments at the FermiLab seem almost certain to be closely bound to the progress in mastering the phenomenon of superconductivity. Physical sizes, construction and operation costs of 'conventional' magnet/power systems make it unreasonable at present to go any other than the superconducting way to build and power the next generation of proton accelerators and storage rings. Thus there is growing interest in building up expertise in the field of superconductivity and in tackling practical projects as soon as is feasible. The next few topics indicate how this is being done.

With the conventional magnets

installed in the main ring, the highest possible field is 2.25 T, which means that the ring can hold protons up to a peak energy of 500 GeV. Pulsed superconducting magnets, based on the use of niobium-titanium superconductor, are usually designed for about 4.5 T maximum field. Thus, a complete set of such superconducting magnets installed in the FermiLab tunnel would hold protons up to a peak energy of 1000 GeV. This project is known as the Energy Doubler.

The Doubler could serve other purposes also. Power consumption is a serious problem in operating the existing machine at high energies. For example, even at the 300 GeV, 6 s repetition rate, the average power required is 40 MW. To run at 400 GeV with a short cycle time and a reasonably long flat-top could easily take the average power above 80 MW. The Doubler could be used to do the last 100 GeV's worth of acceleration with the conventional machine taking the protons to 300 GeV in 2 s and passing them to the Doubler for further acceleration over 5 s plus a 2 s flat-top for a total pulse of 12 s but a slightly improved duty factor. This would absorb 20 MW average power. The Doubler could also be used as a 'beam-stretcher' between 200 and 500 GeV simply to hold the beam so that it could be drawn off to experiments over many seconds thus greatly increasing the duty cycle of the machine and increasing its potential for experiments.

There are several parameters of the Doubler which lead to considerably different design approaches to those used elsewhere when considering superconducting synchrotrons. The first is that slow rates of rise of the magnetic field to the 1000 GeV level are envisaged giving a cycle time close to 100 s. The conventional machine, having fed the Doubler, could continue lower energy operation in the meantime. The slow pulse rate eases the burden on the refrigeration system (a.c. losses are expected to be about 2 W per metre) and imposes less stringent requirements on the superconductor itself. The second important Doubler parameter is the project cost. Since almost 2000 km of superconductor would be needed to build the thousand magnets of the complete ring, this cost restriction involves buying superconductor for less than $ 3 a metre and requires a high current density design for the magnets. It also involves establishing simple production techniques to keep magnet fabrication costs down.

The Doubler will be installed in the main ring tunnel suspended from the roof 1 m inside and 1 m above the existing ring. It will repeat the magnet lattice which has 780 bending magnets (dipoles 6 m long) and 150 quadrupoles. The bending magnets are seen as cold bore, warm iron with an elliptical cross-section about 20 × 30 cm^2. The aperture for the beam is set by the needs of resonant ejection and is an ellipse about 5 × 3 cm^2.

Twelve refrigerators, each of 1500 W at 4.2 K equivalent cooling capacity, will sit on top of the ring tunnel next to the existing Service Buildings. The helium to cool the magnet coils to superconducting temperature has to be conveyed around almost 6000 m of the tunnel circumference. A novel system has been invented where the helium flows through the coil region from magnet to magnet over a distance of 120 m. It then passes through a valve, boils and returns to the refrigerator in an annular space surrounding the magnet vessel acting as a heat exchanger. No separate helium transfer lines are then needed in the tunnel.

Both the magnet design and the refrigeration scheme are being tested. A series of dipoles have been built to investigate production techniques. They have an inner stainless steel vacuum tube surrounded by molded fibreglass epoxy which positions the first layer of the superconducting coil and has cooling channels cut into it.

Two further layers are added, with intervening cooling passages and steel bands are then clamped around to give mechanical rigidity.

The superconductor has been of two types so far: solid wire 0.375 × 0.2 cm^2 containing 2300 filaments of niobium-titanium superconductor 35 µm diameter and 7 strand Rutherford-type cable soldered into rectangular cross-section, as above, containing 1120 filaments 20 µm diameter for each strand. About ten different types of wire of improved construction are to be tried in the near future as pilot production runs in preparation for the first 300 km production run next Spring.

Recently about ten different 0.75 m dipoles have been tested. All but two using the solid wire conductor. The magnets using solid wire have all shown severe training but those made from the cable conductor do not. The peak field has been 4.1 T but no measurement of field quality in this recent series has been done yet since the primary purpose is to establish design concepts for the dipoles and to formulate training criteria. Three 6 m dipoles have been built using the solid wire conductor and have fallen well short of design field but are put to use in the refrigeration tests. (Two 0.75 m dipoles constructed the same way as the 6 m dipoles exhibited the same low field performance.) The combined achievements of the present 0.75 m dipole series, namely, an improved structural system capable of supporting fields of 4.1 T and magnets from cables which exhibit little training, have encouraged the group to move on to a 3 m dipole using cable. This magnet will be built in a manner that will allow the field quality measurements to be made as was the case earlier in the original short dipole series of a year ago.

Many of these tests are being carried out in the model section of main ring tunnel, known as the Protomain. Component layout can also be checked there since conventional main ring magnets and their supplies are also in position. The intention is to install eight 6 m dipoles and two 2 m quadrupoles and to cool them using the 600 W refrigerator which has been installed and tested. So far a 120 m length of co-axial pipe has been fed with helium from this refrigerator with a 6 m dipole replacing the inner pipe at one end. The cooling system tests, particularly with the powered 6 m magnet in place, have been encouraging.

When these development stages bear fruit, the next step will be to build enough magnets to install a loop of the Doubler in a sixth of the main ring. This will be cooled, powered and fed with protons ejected from the ring.

Energy transfer system

Some of the early decisions in the design and construction of the accelerator at the Fermi Laboratory were based on the parameter of 200 GeV as the machine energy. Thus, the cables which link the substation, where power arrives on the site, to the magnets of the main ring were built to be comfortable when transferring energy equivalent to 200 GeV operation. They are 13.8 kV cables which are thermally rated for 60 MVA. For higher than 200 GeV operation the machine pulses are lengthened, keeping the power flowing through the cables down to acceptable levels. Some 400 GeV runs have been tried with the cables carrying current equivalent to an 80 MVA thermal rating and a couple of failures indicated that not much more could be squeezed out of them.

The ducts where the cables run cannot accommodate sufficient additional cable, so some new exercise is needed to make the system comfortable for 500 GeV operation at 100 MVA equivalent. Although installing conventional cables in a new cable duct would be the cheaper approach in terms of immediate investment, so much of the possible future programme at the Laboratory is dependent on the use of superconductivity that it was decided to build a superconducting energy transfer line between the substation and the main ring — a distance of 500 m. If this line is mastered successfully at the 100 MVA level, it would also make a contribution to the development of large-scale systems to carry power in national electricity networks. The line could also pay for itself in about five years in terms of operating costs for power compared with additional conventional cables.

To run the superconducting cable d.c. would be very costly because of the necessary terminations — the electrical plant needed to shape the power from the line into the pulse for the accelerator magnets and vice-versa. The line will therefore be a.c. with six co-axial conductors (two three-phase links) each capable of carrying 6250 A.

The design of the cable absorbs some ideas from previous work on superconducting power transmission, particularly that done at Brookhaven National Laboratory and at the Linde Division of Union Carbide. The inner conductor will be pure niobium covering a convoluted copper tube of a type already commercially available. There is then tape-wound insulation and an outer niobium layer on larger tube. This gives a reasonable degree of flexibility so that the cable could be wound on a drum. Rather than attempt to link sections of cable with the attendant problems of superconducting joints, it has been decided to run long lengths of cable and to pull sections of cryostat around it, making the junctions between these cryostat sections. Cooling will be by liquid helium and it is estimated that the refrigeration plant will have to cope with about 200 W. An adequate refrigerator is already available at the Laboratory.

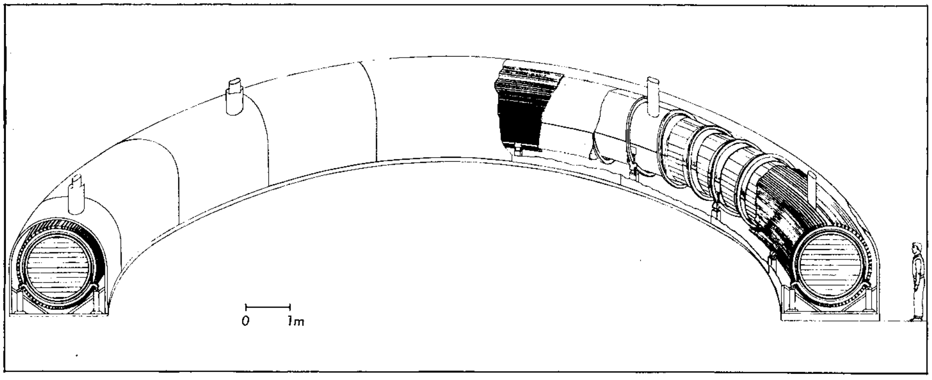
The project is not really in line with the interests of the power companies. They will want to use superconducting lines at some hundreds of kV rather than the 13.8 kV of the FermiLab line. Nevertheless, the currents are comparable and any practical experience accumulated in this field, will be useful. It will also serve to continue to stimulate industry for the production and application of superconducting materials.

The project was given the go ahead at the end of July for a sum of $ 0.5 million. It is hoped to have the superconducting energy transmission line in operation early next year.

Superconducting energy storage

Superconductivity could also ease another problem at the Fermi Laboratory and at the same time convey some important information to the electrical power industry which could have great influence on its evolution in the years to come.

The Laboratory problem is to ease the pain of pulsing the accelerator to 500 GeV. This involves surges of power to and from the main ring magnets over a time interval of about 10 s. The power is drawn direct from the Commonwealth Edison grid in the Chicago region and a special 'static compensator' system (see vol. 8, page 108) is inserted between the accelerator and the grid to prevent the reactive power surges from swinging the voltages on the grid to an extent that troubles other users. By 500 GeV



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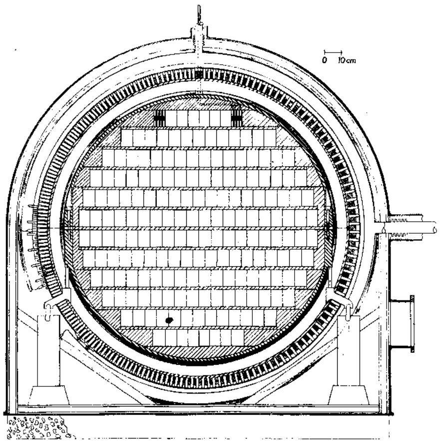
1. A cut away drawing of the superconducting energy storage coil which has been proposed by a Wisconsin/FermiLab collaboration to store 10 MWh. It would provide power for the proton synchrotron.



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2. Cross-section of the energy storage coil. The 188 turns of superconductor (10 × 1.2 cm^2) are in the central region and around the outside is the aluminium conductor which will take the brunt of the power surges.

the real power surges are in the 0.1 MWh region and the effect on the grid is becoming uncomfortably high. It would be nice to have a power store on site and to draw on it for the accelerator pulses while the store is fed in a steady way from the grid.

The power industry's problem is on a much more dramatic scale. They have to install sufficient generator capacity to cope with peak demand for electricity during the day and yet the demand drops by about a half during the night. There is thus a vast investment in equipment which functions well below full capacity for much of its life. In addition, some plants (such as present nuclear reactors, the proposed breeder reactor and coal stations) cannot easily have their output turned up and down. Gas and oil stations are therefore usually used for 'peaking' to meet high demand. Unfortunately, these are the expensive sources of power. If methods could be found to store huge amounts of power, generating plant could be built adequate only to meet the demand averaged over 24 hours.

Several techniques of energy storage are under study (involving, for example, banks of batteries or compressed gases) and one technique is in use at hydroelectric plants (water is pumped up in off-peak hours so that it can fall to drive turbines again during peak demand). The idea of storing energy in superconducting coils is the one that interests us here. It will probably not be the cheapest technique in terms of capital investment, but looks potentially the most efficient of all. The University of Wisconsin and Los Alamos have been interested in this idea for several years and other studies include those of M. Ferrier of the Electricité de France.

In August 1973, the Wisconsin people (particularly R.W. Boom, H.A. Peterson and W.C. Young) got together in a study group (chaired by F. Mills) with the Fermi Laboratory to design a storage system appropriate for the 500 GeV accelerator. The aim is to construct a 1 MWh store which could be tapped for 0.1 MWh over a 10 s cycle. A scheme has emerged involving a coil about 9 m in radius and of circular cross-section, 0.7 m radius, with 188 turns of superconductor (each turn having 4 parallel conductors) carrying 80 kA. The geometry ensures that no severe stresses are experienced in the coil. The superconductor is niobium-titanium in copper, giving a conductor 10 × 1.2 cm^2 of similar type to that used on the 15 foot bubble chamber.

A key feature is that the superconducting coil is surrounded by a shield coil which is connected in parallel to it. The electrical parameters of the two coils ensure that it is the shield coil which gives almost all the 0.1 MWh to the accelerator pulse from the 10 MWh stored. Thus, it is the shield which experiences the temperature rise due to a.c. losses. It is wound of 188 turns of hollow aluminium conductor cooled by helium gas to 40 K. Its heat rise will require 0.8 MW of room temperature refrigeration to be installed. The power grid can make up the power taken from the coils in comparatively leisurely fashion and it has been calculated that the effect of the grid of pulsing the accelerator at 500 GeV will be less than that now experienced at 200 GeV.

The power industry would eventually require huge systems to store up to 10 000 MWh but their cycle times would not have the complications experienced in use at an accelerator. The Wisconsin/FermiLab device would be an excellent test bed for large power storage systems and industry has already expressed interest in a pilot project of this scale.

Preliminary cost estimates are in the region of $ 20 million and it is unlikely that all this money could be found from within the high energy physics budget in these belt-tightened days. It is hoped, therefore, that the power industry and energy agencies will provide some financial support for the work. Support for research and development is needed during the next year with the intention of beginning construction of the superconducting power store in 1975.

One of the FermiLab's most popular features — the herd of buffalo. It is touches like this and the 'prairie project' which show concern for environment and for the tradition of this region of America. It is also fun.

POPAE

For the much longer term, ideas are being shuffled around concerning very high energy storage ring systems. The operation is under the code name 'POPAE' standing for Protons on Protons and Electrons.

The tentative aim is to have colliding beams of protons in the 1000 GeV range in two intersecting rings and another ring of electrons in the 20 GeV range. With some modifications for producing electrons, the existing (or energy doubled) accelerator could be the source of all the particles. Luminosities in the 10^{34} per cm^2 per s region are dreamed of.

Just how POPAE will evolve is heavily dependent on the progress of work on superconducting magnets and on the Energy Doubler. Many of the basic parameters — magnet field strengths, ring sizes, injection energies — would change if the Doubler can be brought into operation. Nevertheless, T. Collins and D. Edwards are already working to string consistent sets of figures together so as to get the thinking on the project on the move. A study was held in September, involving storage ring specialists from other Laboratories also.

The scheme is obviously a major exercise which is unlikely to take the form of a firm proposal for several years. It will then be judged alongside developments at other Laboratories and against the alternative of building a much larger synchrotron to raise peak proton energy, for example, to 5000 GeV. And finally, the USA government would need to be persuaded to provide the spinach to get POPAE really going.

Medical facility

A possible non high energy physics off-shoot in a completely different area concerns the use of particle beams in medical therapy and diagnostics. The linac is able to supply intense beams of protons up to an energy of 200 MeV at a rate of 15 pulses per second. The booster needs them for only about one second in every six, in line with the total accelerator cycle, and there are thus potential protons (which would be expensive to provide elsewhere) for other purposes if this should prove useful.

Medical applications of particle beams have been touched on in our pages before. For cancer therapy there is interest in using pions (the LAMPF machine at Los Alamos will soon provide particles for treatment of its first patient), heavy ions (such as are becoming available at Berkeley) and neutrons (such as are used at the Hammersmith Hospital in the UK and at three centres supported by the National Cancer Institute in the USA). Protons are also of interest particularly for diagnostic work (see the report from Argonne, page 303).

The linac at the FermiLab could obviously provide 200 MeV protons for tumour diagnosis and neutrons for therapy. Neutrons produced by a 66 MeV proton beam (which emerges from tank 3 of the linac) would be capable of irradiations of 1 rad per second at a distance of 1 m from the target. L. Cohen from a Chicago hospital has been prominent among the medical community concerned with developing these possibilities and D. Young and M. Awschalom have led the studies in the Laboratory.

Thoughts first turned to the building of a clinical facility at the output end of the linac so as to have 200 MeV protons and neutrons produced from 66 MeV protons which have drifted (still being focused) through the last tanks. Cost estimates for the full clinical facility looked high and it would have taken several years to

A night view from the top of Hi-Rise which again illustrates the architectural attractiveness of the site. It shows the 8 GeV booster with its central cooling pond and services building. In front of it is the cross-gallery, housing the control room, and on each side are the symmetric arms of the linac (on the right) and the link to the main ring (on the left).

(Photos FermiLab)

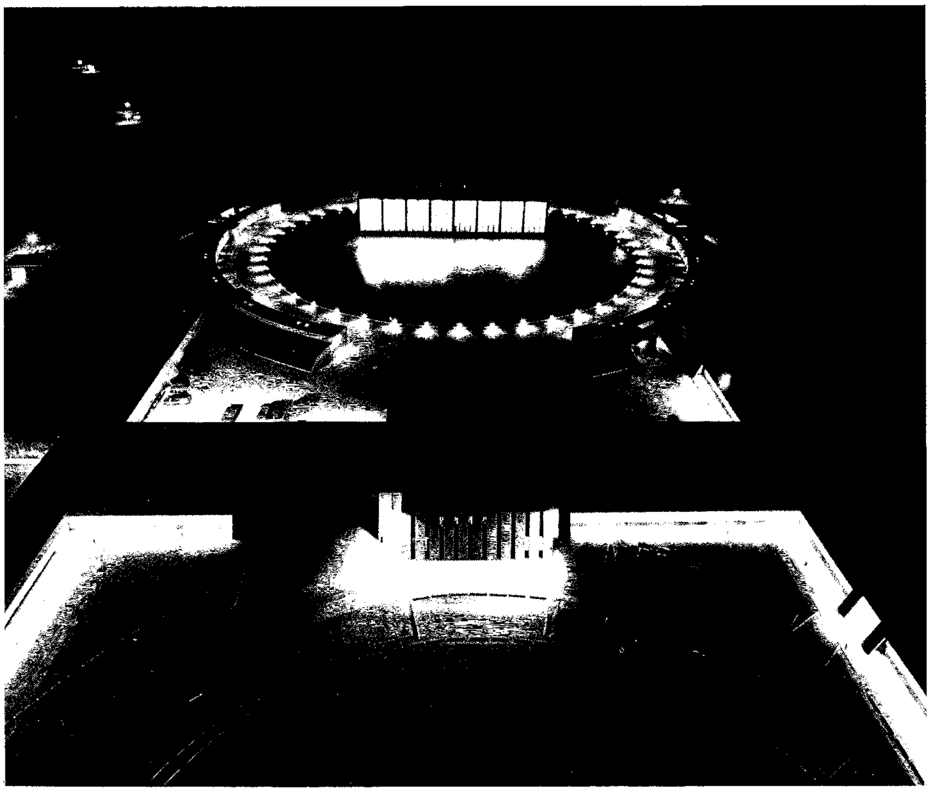
bring into action; present authorization has therefore been limited to tapping 66 MeV protons to do a series of studies on neutron beams. These will involve measurements of target efficiencies, design of neutron collimators and the calibration of neutron doses in relation to the doses available at other treatment centres. Whether this 66 MeV test facility will be set up close to the downstream end of tank 3 or at the output end of the linac, is still under discussion.

Any subsequent development to a full clinical facility to receive patients will obviously await the results of the tests. A national advisory committee has been set up to ensure that the FermiLab work is co-ordinated with other efforts in the USA on the medical applications of particle beams.

This review of present activities at the FermiLab will carry with it some of the flavour of the Laboratory. The high energy of the accelerator is reflected in the high energy of the staff. Drive and enthusiasm characterize almost all that goes on.

Of course, the Laboratory is new and it has for several years a monopoly on a wide range of physics. It would be difficult for the atmosphere to be stale in these circumstances. Nevertheless, there is a conscious effort to sustain enthusiasm and to avoid as far as possible becoming institutionalized. Staff numbers (about 1300 at present) are being kept low, staff mobility is being kept high. New, challenging projects are stimulated as much as possible.

However, for the first time, fiscal year 1975 which began in July brought no new construction money into the FermiLab. More is needed in order to build up the accelerator and the experimental areas to cope with the full 500 GeV, 5×10^{13} potential. Operating money (covering salaries, general materials and the high power bill) is at $ 35.6 million for FY 1975 (whereas about $ 60 million is calculated as necessary for full operation). To this is added $ 11.3 million for equipment such as detectors and beam-line components. $ 96.1 million has been projected for the total Laboratory needs of FY 1976.



Leaving aside these major concerns which will greatly influence the Laboratory's future, we can give a little space to mentioning other features of the FermiLab which deserve articles in themselves.

A special effort has been made to establish a framework of equal employment opportunity. The Laboratory Policy Statement says categorically 'in any conflict between technical expediency and human rights, we shall stand firmly on the side of human rights'. Thus positive steps are taken to encourage the recruitment and training of staff from minority groups.

A spectacular site has been created. The architectural attractiveness of the central Hi-Rise building, the auditorium, the layout of the accelerator, the experimental halls, etc. all lead to the suspicion that the FermiLab is sponsored by Kodak Ltd as well as the US Atomic Energy Commission.

Use is also being made of the site to preserve features of the region or to re-establish an ecological environment that has been lost. A herd of buffalo enjoys one field, a herd of Angus cattle (surely the most attractive creatures of their genre) enjoys another. The centre of the ring is being given over to a long-term (ten year) project to restore an area of prairie to its pre-urbanization state. It will be the biggest nature reserve of its type in the world.

Quite apart from the central task of high energy physics research, the FermiLab is contributing to the enrichment of the scene in many other ways.

CERN News

New record in mental arithmetic

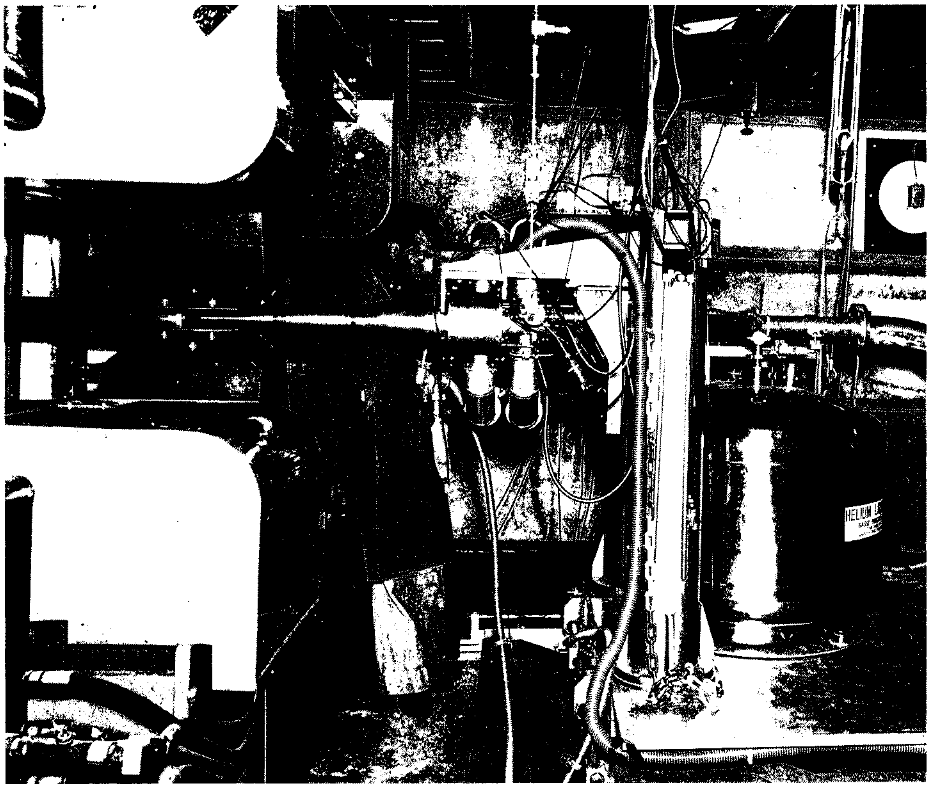
Although in modern scientific circles, the trend is more and more, to reach for the computer when there are any sums to do, there is still one man at CERN who can use his own brain and compete with the electronic usurpers. As a traditional item in the series of lectures given to summer students, Willem Klein demonstrated his powers of mental arithmetic, showing his prowess in memory exercises, rapid calculations, constructing magic squares, and lacing it all with his own special brand of humour. But he kept his pièce de résistance for the end.

In the September, 1973, issue (page 258) we reported his extraction of the 19th root of a 133-digit number. This year he wanted to go one better.

Six papers were passed around among the audience, on which members wrote down one figure. The six-digit number thus composed was fed into a computer which, somewhat laboriously, multiplied the number by itself thirty-seven times to give a 220-digit number. A team of people was needed to write this down on the row of blackboards, lined up side by side. Willem Klein then turned around to look at the number and, three minutes and twenty-six seconds later, he staggered the audience by writing out the six figures of the 37th root — figures confirmed by the computer and by the members of the audience who had selected them.

Frozen spins

The construction of a frozen spin target at CERN was proposed in November 1971 based on preliminary investigations described in CERN COURIER vol. 11, p. 353. One of the difficulties of traditional polarized targets — that is targets in which as many protons as possible are lined up in a particular direction — is that the target has to be contained between the poles of a very strong magnet and the space around in which detectors can be set up is rather limited.



The frozen spin target, in its cryostat, inserted between the poles of the high field magnet. This magnet is situated in one corner of a large volume magnet where the target is moved for experiments.

CERN 50.9.74

In the frozen spin system, the target is first polarized dynamically at near zero temperatures in an intense uniform field of 2.5 T by irradiating it with microwaves. The microwaves are then switched off, following which the target cools still further and it can now be moved gently into a less intense and less uniform field of about 1.0 T. This field is created by a magnet with a large volume between the pole pieces, which can be filled with detectors covering a solid angle of almost 4 π. The temperature of the target during the irradiation is about 0.5 K settling to 0.05 K when the microwave power is cut off and the target has been moved into the beam. At such a temperature the target remains almost permanently polarized.

The large volume magnet employed is the old ETH magnet, which has had a long and honourable career at CERN. Within it, over to one corner, the polarizing magnet has been built. The target, 15 cm long and 1.6 cm diameter consists of small propanediol spheres which are loaded into the cryostat at liquid nitrogen temperatures. During tests in July, less than 1 % decay in polarization was observed in a target which had been polarized to some 90 %, moved into the main magnet volume, kept there for eight hours and then returned.

Crucial to the operation of the system is the design of the dilution refrigerator which was developed by T. Niinikoski in the Low Temperature Laboratory of Helsinki University of Technology, while the other cryogenic components, the pumping system, the transport mechanism and the

NMR electronics were made at CERN.

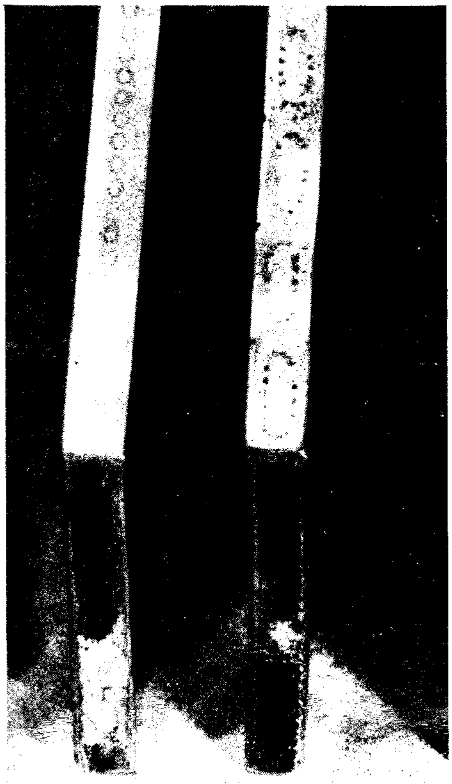
Targets of up to 50 cm^3 volume can be accommodated in the cryostat. Through it ^{3}He is circulated at a rate of 25 mmol/s which allows 100 mW of microwave power to be fed in without the temperature exceeding 500 mK. Polarization rates of 15 %/minute have been observed. The rate of cooling is such that after polarizing, 100 mK is achieved in three minutes and 50 mK in eight minutes. The lowest temperature so far attained is below 15 mK but the precise value can not be measured with the present thermometer system. The cryostat works smoothly with no tendency towards instabilities or oscillations under normal operation and it is insensitive to the rapid magnetic field variations to which it is subjected when being moved.

The first experiment to be done with the Frozen Spin Target is the measurement of all the spin parameters, P, A and R in the reaction $\pi^- p \rightarrow K^\circ \Lambda$ when the Λ emerges in the backward direction and the incident pion beam has a momentum of 5 GeV/c. The incoming beam, which comes to the target along the axis of the cryostat, is monitored by two silicon diodes mounted inside the cryostat where they operate at a temperature of 1 K. An array of optical spark chambers viewed by seven TV cameras, and scintillation counters record the emerging particles. The experiment is a collaboration between CERN, ETH Zurich, Helsinki University of Technology, Imperial College London and Southampton University.

Persistent currents in the BEBC magnet

As previously reported (see March p. 78 and June, p. 170), the magnet of BEBC, the 3.70 m bubble chamber, has since last March been systematically taken to pieces because of intermittent short-circuits between the non-superconducting auxiliary wires and the coils and earth. This did not prevent the magnet from reaching its design field.

After the coils had been examined, various theories were put forward to explain the causes of the short circuits, and we shall now summarize the situation.



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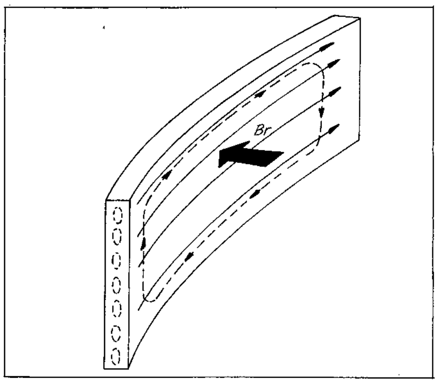
The two types of conductor used for the BEBC coils. Two companies, Siemens and Thomson-Houston, had shared the manufacturing of the conductor, applying different techniques. The photo shows the different geometrical arrangement of the superconducting filaments in the copper strip; the electrical properties of both types are almost identical.



This drawing illustrates a simplified model of the persistent currents. The transport current flows through the superconducting filaments (full lines). The radial component of the magnetic field (B_r) penetrates the conductor strip through the side and induces eddy currents which are superimposed on the transport current. The simplest model assumes that the induced currents are concentrated along the edges of the conductor, flowing in one direction along the upper edge and in the opposite direction along the lower one (dashed lines).

General layout of the conductor

The BEBC conductor was a major development in superconducting technology at the time of its design and manufacture in the years 1966-1969. It was Europe's first large scale industrial production, and involved 65 km of strip with more than 200 Nb Ti wires (200 μm diameter) in unit lengths of 1.5 km (see photo). This type of flat, untwisted conductor has a high aspect ratio (61 mm high by 3 mm thick) for side cooling and reflected the state of the art of manufacturing high d.c. current fully stabilized conductors at that time. Since then, the advanced requirements for pulsed applications have stimulated the development of new types of conductors with twisted filaments. In the meantime, evidence has been accumulating on the existence of the so called 'persistent eddy currents' in d.c. systems.

Origin of persistent currents

In service the conductor usually sees not only the axial (useful) field of the magnet but also a radial field, the strength of which at any point depends on the position of that bit of the conductor relative to the whole coil. The radial field is perpendicular to the flat faces of the conductor. Variations in the field, for example during charging or discharging of the magnet, change the magnetic flux, and induce eddy currents as illustrated in the drawing. If one takes a very simple model, these currents follow the superconducting filaments, the circuit being closed by short bridges in the copper substrate. The induced currents may be very large for a given flux variation, and may be as high as the critical current of the individual filaments. The decay time of the currents is very long, due to the low resistance of copper at a temperature of 4 K. Typical time constants range from weeks to many months according to field plots over the coil cross-section, and this justifies their description as 'persistent currents'.

Eddies created during charging or discharging are of course phenomena common to all magnets. In conventional ones they have very short time constants and can be neglected. In superconducting magnets with twisted conductors they quickly cancel each other. Only magnets built with flat, non twisted conductors show persistent currents with long time constants.

Magnetic field of the persistent currents

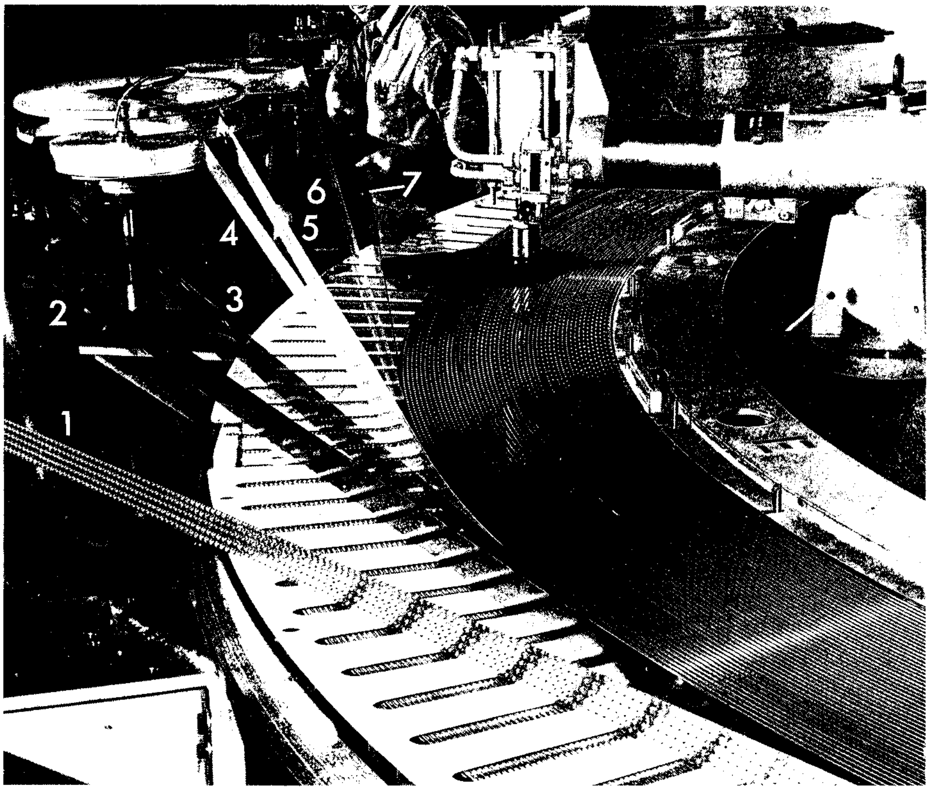
In the BEBC magnet, the zero-field measured after discharge of the coils amounts to 0.6 % of the rated field in the centre of the chamber and 1.2 % in the upper limit of the visible region near the walls. At full current, this rather inhomogeneous additional field should be much less because of the reduced current carrying capacity of the conductor. The superimposed field will decay very slowly and the drift in value is estimated to be of the order of 0.1-0.3 % over 100 hours. As the field has not been mapped over long periods of time, the above figures are only estimates and it will be necessary either to plot continuously the field drift at some well known points or to destroy the persistent currents before picture taking with the chamber starts. Both eventualities had been foreseen in the BEBC magnet.

a) Fieldmapping at any time is accomplished with an array of 180 calibrated Hall probes, arranged around the wall of the chamber vacuum tank. Readings taken at the boundary, permit calculation of the field within the chamber volume. The field precision obtained during the BEBC runs in 1973 was 5×10^{-4}. Data on the long term behaviour of the persistent field could not be taken due to frequent charging and discharging of the magnet.

The main drawback of this procedure lies in the quality and stability of the Hall probes. Repeated recalibrations over three years have not shown any deterioration and the method is therefore believed to be reliable.

b) The possibility of being able to make reliable measurements was much less certain in 1969 when the problem of persistent currents had to be solved. An alternative method was therefore tested on a model coil. When the coil was wound an insulated aluminium strip was inserted between the turns of the normal conductor. Passing a short current pulse through this heater strip in one pancake drives the pancake normal for a fraction of a second which is enough to destroy the persistent currents in it. The total field changes very little when only one pancake is quenched at a time; new persistent currents are therefore not induced. Such a procedure could be applied to all the pancakes in turn.

After successful tests in the model, it was decided to wind a heater strip into the BEBC coils (see photo) and to connect it to current leads on top of the cryostats. Provision was made for connections to the outside of the vacuum tank, but the actual connecting up was postponed until later as it could be done without dismantling the cryostats. Although the model tests had proven the feasibility of the method, its application to a magnet where 720 MJ of energy is stored is not a treatment to undertake light-heartedly. The main drawbacks are obvious: a rather high voltage is required to discharge 250 kJ to quench a double pancake within 0.1 s and rather thick wires ($3\ mm^2$)



Winding of a pancake on a turn-table at CERN. The various strips which are wound together are (from left to right), (1) the cooling strip which leaves free space for the flow of liquid helium, (2) a stainless steel strip to take up the majority of the mechanical forces, (3, 4) insulating strips, (5) the heat strip, made of aluminium and already covered by an insulating foil, (6) insulating strip, (7) composite conductor.

CERN 214.10.70

are needed to connect not only the heater strips but also the pancakes to the top of the cryostats. The magnet turns themselves must be used as return path for the heater current in order to get a bifilar arrangement. This makes the problem of reliable insulation difficult.

Movement of the conductors

During the last run of BEBC, transient short circuits, both of the coil to earth, and also between pancakes in the coil had been observed. Careful measurements indicated that they originated most likely from the connecting wires to the heater strips and the coil itself was not affected. In spite of the shorts, the magnet had been brought several times to the full current of 5700 A, corresponding to 3.5 T in the chamber and 5 T on the inner turns of the magnet. It was nevertheless felt, as reported earlier, that an immediate repair was necessary. Major damage to the coils themselves could not be excluded in the event of a series of simultaneous breakdowns (for example: general power failure at CERN and a helium compressor breakdown.)

Dismantling started, and during the second half of April the coils were opened and indeed showed the expected defects. One set of connecting wires showed traces of arcing either between these wires or from one wire to a tie rod. The coils themselves were not affected, except for a minor trace of arcing. The repair of the defect was straightforward and all connecting wires of the heaters are being removed following the successful trial of the Hall probe reconstruction.

However, it should be mentioned that the heater winding proved to be useful as a fault detector because of its high magnetic coupling with the magnet coils.

The inspection of the coils revealed another interesting effect caused again by persistent currents. The inner turns of some pancakes were found to be partly tilted and displaced inwards (i.e. towards the centre of the coil). This behaviour is unexpected if we assume that only the transport current passes through the conductor. Then the forces on the inner turn are always directed outwards, away from the centre. Buckling due to mechanical imperfections of the conductor is excluded by the close tolerances imposed in its manufacture; thermal effects would require excessive temperature gradients between the first and second turn which are ruled out by the helium flow pattern and the extremely slow cooling rate about 1 °K/h. Persistent currents is the only known phenomenon which would create a torque on the conductor and produce a force directed towards the centre of the coil.

Calculations have been made, assuming again the simple model mentioned above, where the persistent currents flow along the edges of the conductor. One sees that the upper edge of the conductor is subjected to a stronger force (away from the centre of the coil) than the lower one. This corresponds to a torque which is superimposed on what is still a net outward force if the persistent current is not too big. If however, the persistent current is larger than the transport current, the resulting current on the lower edge is reversed; thus creating an inward force. This is exactly what happens during charging of the magnet when the transport current (for example 1000 A) is much smaller than the critical current (around 25 kA at this field strength). The maximum forces on the edges of the conductor are exerted when the strength field is about half of the maximum. They can be as high as 100 N/cm of conductor length — enough to displace the conductor if the friction force between it and its axial support is insufficient.

The superimposed magnetic forces decrease when the main field is further increased above its mid-value; because the difference between the critical current and the transport current and therefore the persistent current becomes smaller.

The hypothesis that very large persistent currents exist at low field is well supported by calculations (based on the simple model) which reconstruct the remanent field after complete discharging of the magnet. Indeed currents of 10 to 20 kA must be assumed in order to obtain the measured field.

Improvements

The damage to the insulation of some of the wires connecting the heater strips to the top of the cryostat, was probably due to the movement of the conductor bringing it into contact with earth. An overvoltage is produced when the shorted loops are opened. The transient nature of these shorts is certainly best explained by the movement of the conductor.

In order to restrict the movement, the inner turn is now held in place by additional strips of fiberglass-epoxy, and care has been taken to prevent contact with other metallic parts should movement occur in the future.

Other chambers

The magnets of two American bubble chambers are wound with flat conductors of similar design, the Argonne 12 ft chamber and Brookhaven 7 ft chamber. The former has a maximum field of 1.8 T and an iron yoke thanks to which the radial field and consequently the persistent currents are negligibly small.

The magnet of the 7 ft chamber with its field of 3 T, in the absence of an iron yoke shows persistent currents, with a superimposed magnetic field and displacement of the inner conductor. Short circuits have not been observed in this magnet, due to the absence of thick wires or other metallic parts close to the inner turns of the coil. Additional insulating pieces have been incorporated in order to prevent any further displacements.

At the beginning of September, magnet re-assembly was at the following stage: the coils were back in the cryostat and the two cryostats and the vacuum enclosure were being re-installed in the magnetic shielding. A start had been made with a whole series of operations such as piping and electrical connections, various sorts of tests, etc.

General tests on the magnet should begin in November-December.

Conference Proceedings

Some copies of the following Conference Proceedings are still available from the CERN Scientific Information Service at reduced prices:

– CERN Symposium 1956 (Vol. 1. - Accelerators)	SFr. 10.—
– International Conference on High Energy Accelerators & Instrumentation, CERN 1959	SFr. 10.—
– 14th International Conference on High Energy Physics, Vienna 1968	SFr. 30.—
– Lund International Conference on Elementary Particles, 1969	SFr. 30.—
– 8th International Conference on High Energy Accelerators, CERN 1971	SFr. 30.—

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Mrs Janice Lefley
Scientific Information Service
CERN — CH-1211 GENEVA 23 / Switzerland

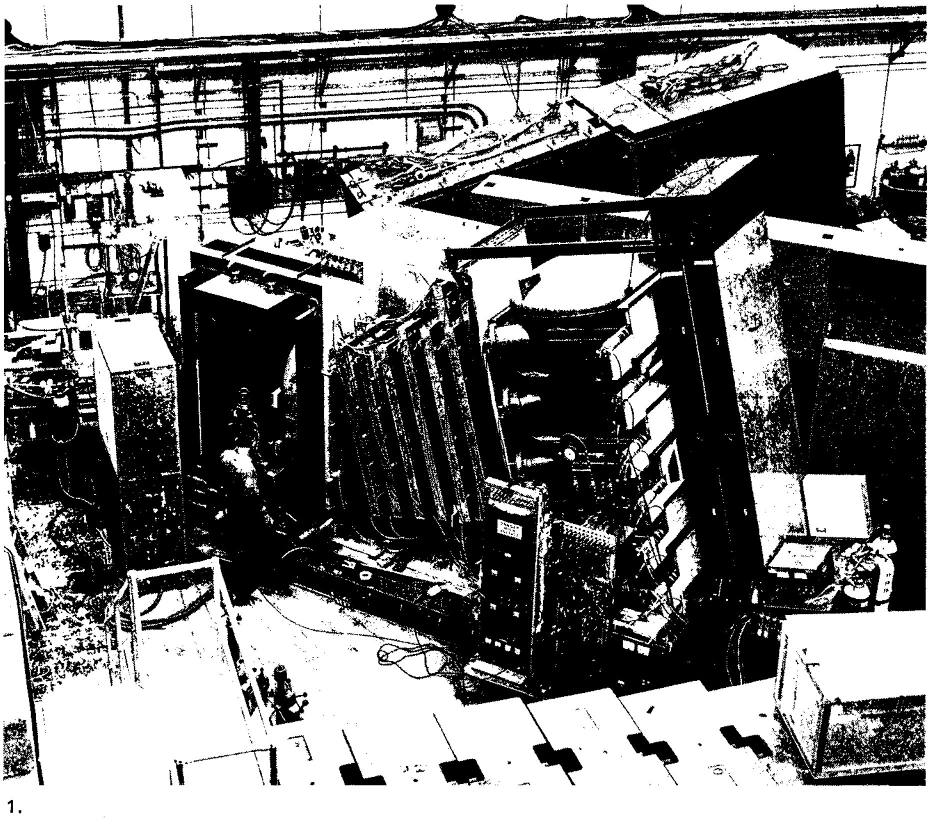
Around the Laboratories

CORNELL
Programme at electron synchrotron

The Wilson Synchrotron Laboratory at Cornell University houses the highest energy electron synchrotron in the world. The accelerator is at present capable of peak energies of 12 GeV and the experimental programme is geared to using the advantages in energy and duty cycle which are not available elsewhere. The linear accelerator at SLAC provides higher electron energies but much lower duty cycle. The 7.5 GeV synchrotron at DESY is the nearest competitor in energy with long duty cycle.

There are two ejected electron beams fed using a half integer resonance and two septa opposite each other at the same position in the ring. They can each slide into the beam region independently, so that the distribution of electrons between the beams, each maintaining the full duty cycle, can be varied. Up to now, one beam has taken the bulk of the electrons while the other has been used only for setting up. Because of the types of experiment using the ejected beams, this situation of one beam-line taking the large majority of the electrons is likely to be sustained.

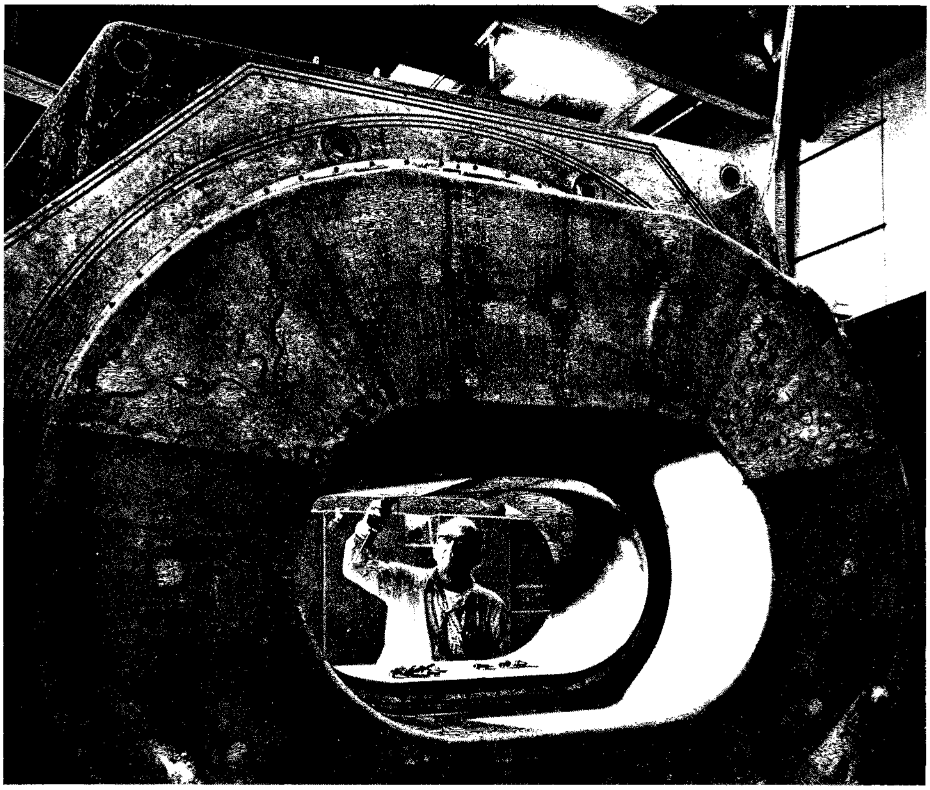
The use of photon beams has been out of fashion for a while, but an experiment using a unique photon beam, which is both 'tagged' (so that the photon energies are known with good precision) and polarized (so that the part played by particle spins in the interactions is well defined), is being developed for use by a Rochester/Cornell team to study omega vector meson production and other things. In addition, there is a synchrotron radiation facility which cashes in on the fact that, though the



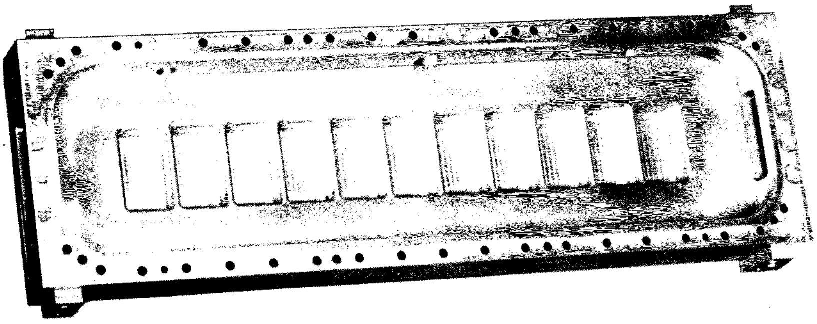
1.

1. The two large aperture spectrometers used in studies of inelastic electron scattering by Harvard and Cornell groups. The Harvard magnet is nearer the camera with the Cornell spectrometer visible behind it.

(Photo Cornell)



2\. *The magnet of the streamer chamber coming together in the experimental hall of the Cornell electron synchrotron. It will be used by a DESY/Cornell/Ithaca College collaboration to extend work already carried out at the DESY machine to higher energies.*



3\. *View of half of the eleven cell superconducting r.f. cavity, which was operated on the Cornell synchrotron to give the first ever acceleration of particles to GeV energies using superconductivity.*

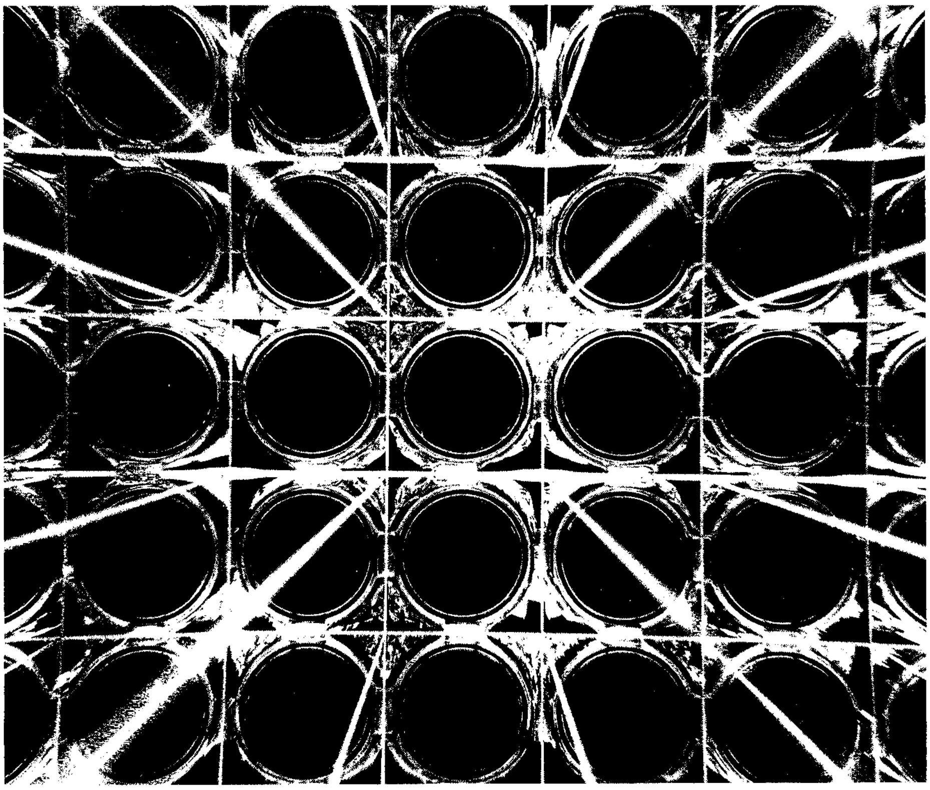
(Photo Cornell)

Cornell machine cannot compete with the intensity properties of the radiation emerging from the Stanford SPEAR storage ring at lower energies, in the X-ray region (energies above 6 keV) it can provide photon beams not available anywhere else. A Cornell/MIT team will use a double crystal monochromator in a series of experiments.

During recent months most of the experimental time has gone to studies of inelastic electron scattering carried out by Cornell and Harvard groups. One experiment concentrates on sorting out the contribution of the longitudinal and of the transverse polarization of the virtual photon to the cross-section in electron-nucleon interactions where different models of the nuclear structure have different predictions. With two spectrometers of large aperture they are able to catch the products of the interactions more efficiently than previous experiments and, with large amounts of data, do a more thorough analysis.

Another experiment will study inelastic electron scattering from complex nuclei. One of the topics is to measure the total cross-section of the virtual photons produced in the interactions to see the effect of 'shadowing' due to the presence of the nucleons. With incoming photon beams, the expected shadowing behaviour has been seen but, up to now, there is no evidence of shadowing using electron beams. It is possible that the previous experiments, which had only single arm spectrometers, missed the wide angle bremsstrahlung. The new experiment will have a spectrometer and another 'arm' with a lead sheet to convert the photons and two blocks of scintillator (with slots to let through the electron beam) each viewed by 32 photomultipliers. Tests indicate that this array will locate particles to within ± 0.5 cm.

A low intensity ejected electron beam will be used to feed two experiments which will both look at deep inelastic electron scattering. One is a DESY/Cornell/Ithaca College collaboration involving the use of a streamer chamber as detector. The experienced team at DESY, where another streamer chamber is in action for electron energies up to 7.5 GeV, wish to extend their work to higher energies and are providing the chamber and ancillary equipment. The magnet for the streamer chamber reached Cornell in July (though the trucking company seemed to have had some difficulty in deciding precisely where to deposit it). Because of cooling limitations it will be run at 2 MW input power rather than its potential 3 MW, but the loss of momentum resolution due to running at lower magnetic field will be compensated (to achieve a resolution



4.

4. Pattern produced by pointing a camera into a single block of lead glass with a photomultiplier against its far surface. The block is 48 cm long and of square cross-section, 4.5×4.5 cm^2. The photograph was taken at Cornell.

(Photo by Dale Carson)

of about 300 MeV) by having other detectors in action in a hybrid set-up. Two multiwire proportional chambers will be installed close to the streamer chamber volume and shower counters will add an energy loss measurement. About 100 000 pictures showing scattering with high transfer of energy are hoped for and they will be measured on two HPDs at DESY.

The second experiment by a Cornell group will use a large aperture magnet filled with multiwire proportional chambers (about 20 000 wires in all). About half the chambers are now complete and tested. To avoid flooding the chambers with unwanted data, a very clean incoming electron beam is needed (and has been achieved up to the magnet input) as well as special manoeuvres (such as horseshoe shaped shields around the beam path through the chambers to prevent low energy electrons produced by the beam swamping the chambers). An event rate of a few per second is anticipated and, when the system is eventually operating, it will obviously out-pace the capabilities of the streamer chamber.

At present the experimental programme involves about 80 physicists. Within the present scope of the programme and support facilities, about one more group could be accommodated. This is a small enough number to enable the Laboratory to maintain its university atmosphere which is unique among high energy physics research centres. The current budget provided by the National Science Foundation is about $ 3.5 million per year.

Future developments at the Laboratory depend heavily on the progress of the superconducting r.f. accelerating cavities. As reported in the June issue (page 165), encouraging results have been obtained with the eleven cell test section which was installed in the synchrotron earlier this year. It achieved the first ever acceleration of beams to GeV energies using a superconducting accelerating structure. The test section has now been removed to attempt to improve its Q value by tidying up the niobium spacer located between the two halves of the structure proper.

If these cavities can be mastered, they will make it possible to pour more energy into the accelerating beam to compensate for the high energy losses due to synchrotron radiation which rise rapidly with increasing energy. At present, for 12 GeV operation, about 1.8 MW are pumped into the five cavities distributed around the ring and a high proportion of this is lost due to the resistance of the copper walls of the cavities. A superconducting cavity would lose only about 20 W due to residual resistance in the cavity (though 40 kW of refrigerator power would be needed to prevent temperature rise).

If the superconducting cavities succeed, a 25 GeV electron synchrotron could be feasible with rebuilt magnets in the existing machine tunnel. A bigger jump in energy, however, would be much more desirable and some thought has been given to a new 50 to 70 GeV ring on a different site. Sums of money in the 30 to 50 million dollar region would be needed for such a project.

DUBNA
Determining the life of the positive muon

A further big increase in the accuracy of measurement of the life of the positively charged muon has been achieved at the Joint Institute for Nuclear Research by a team leaded by

V. Zinov. The positive muon decays into a positron, a neutrino and antineutrino with a lifetime now determined to be 2.19711 ± 0.00008 μs.

The first relatively accurate measurements (1 part in 10^{-3}) were made by several groups during 1962/1963. After an interruption of ten years, J. Duclos et al., using a new technique, succeeded in increasing the accuracy by several times (2.1973 ± 0.0003 μs, as reported in Phys. Lett. 47 B, 491, 1973). However, these and the preceding measurements suffered from a basic limitation on accuracy which stemmed from the small solid angle over which the equipment could record positrons.

The special feature of the new technique is that the positrons resulting from muon decay can be recorded by a Cherenkov counter capable of operating in 4π-geometry. Consequently it has been possible not only to increase the speed at which statistics could be collected, but also to reduce the background and eliminate the effect of the asymmetric way in which the positrons emerge. In addition, in view of the high positron energy of decay it has been possible to record them with the discriminator set at a fairly high level and eliminate the background of low energy particles.

The measurements were carried out on the synchro-cyclotron, generating a pure muon beam with a momentum of 130 MeV/c and an intensity of 7 × 10^3 particles. The Cherenkov counter was filled with water which acted also as a target, in the centre of which the muons were stopped. Only those events which corresponded to the appearance of just one muon and one positron within a gate 20 μs long were recorded by a computer working on-line. Measurements were made during four runs totalling 100 hours of accelerator operation during which 10^9 useful events were observed.

A further substantial increase in accuracy could be achieved with such a set-up by improving the high speed positron detectors and exploiting to the full their 4 π capability.

BERKELEY
Turn of the heavies

Storming down the hill from the SuperHILAC in the early hours of 1 August a beam of C^6 ions entered the Bevatron and 2.5 μA were accelerated up to an energy of 0.56 GeV/nucleon corresponding to 0.5 T in the magnets. This combination of the modified heavy ion linear accelerator and the rejuvenated Bevatron at the Lawrence Berkeley Laboratory, christened the Bevalac (June issue, p. 213) is now the most powerful heavy ion accelerator in operation. Not content with this first effort, the team headed by H. Grunder and A. Ghiorso set about tuning the transport line and by the following afternoon had injected 7.7 μA — later 10 μA — and had raised a beam of 1.6 × 10^9 particles to the maximum energy of 2.1 GeV/nucleon.

The transport line is a tricky part of the hook-up as the control system is, for the present, rather rudimentary, but before the end of the day some 60 % efficiency in transmission had been achieved and 15 μA injected. Moreover a beam of 4.5 × 10^8 ions had been successfully extracted. Work over the next few days pushed the intensity of the injected beam of C^6 ions up to 60 μA and on 11 August, the beam was used in an experiment on the superdense nuclear states.

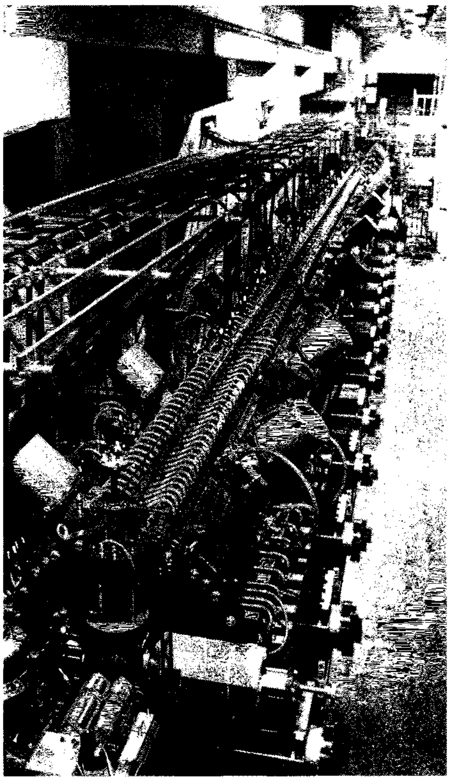
That completed, a new run was started with Ne^{10} ions and relatively quickly a beam of 16 μA was being injected into the Bevatron and an extracted beam of up to 1.5 × 10^8 ions at full energy was being recorded in the external beam channel, and was being used for experiments by physicists from LBL and SLAC.

Tests in the near future will be made with A^{18} ions and it is hoped to work up in due course to Kr^{36}. For much heavier ions to be accelerated the vacuum system of the Bevatron would have to be improved. For the immediate future the most important job is to get a new computer system into operation which can take over the control of the entire beam transport and acceleration process.

H. Grunder and A. Ghiorso exchange congratulations during the lab's celebration of the Bevalac's success.

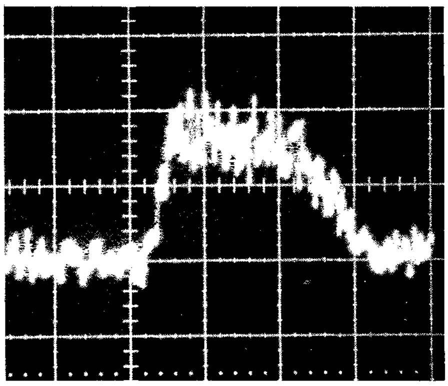
KEK
Linac operates

First beams were accelerated in the KEK linac of the National Laboratory for High Energy Physics at Tsukuba in Japan at the beginning of August. A beam intensity of 3 mA at 20.3 MeV and a pulse length of 20 μs was



The 20 MeV linac which has a single tank. It is scheduled to feed beam to the booster at the end of the year.

(Photo KEK)



The signal from the first proton beam at 20.3 MeV emerging from the linac at the Japanese National Laboratory for High Energy Physics. The pulse records about 4 mA of protons for about 20 μs.

recorded. The 750 kV Cockcroft-Walton preinjector was supplying 20 mA into the linac and the beam capture efficiency was very much as expected, since the phase stable angle is 60° and no pre-buncher was in operation. As the ion source was delivering 100 mA the losses during transfer from preinjector to linac seem excessive and a study is being made of the cause.

Acceleration takes place in a single tank with a cavity 15.5 m long containing 90 cells. A peak current of around 100 mA is wanted with a repetition rate of 20 Hz.

Tuning of the system is now going on so that tests on the 500 MeV booster can begin in December. At present, power is something of a limitation; the Laboratory is served by a 1700 kVA line and a generator of 1600 kVA but the 66 kV supply is due to come on stream on 10 November. Already, however, this month (September) the newly formed programme committee is studying the first experimental proposals for research with the 10 GeV synchrotron.

VILLIGEN
Progress at SIN

Since the March news in CERN COURIER covering the successful operation of both cyclotron accelerators and commissioning of the first pion beam, work at the Swiss Institute for Nuclear Research has concentrated on five main fields:

- Reaching for the design goals of the Philips injector cyclotron in the injector mode to the main ring cyclotron so that it could be handed over formally to SIN to assume responsibility for running in this mode;
- Improving the performance of both accelerators to increase the total proton transmission;
- Delivering low intensity (a few μA) proton beam onto the thin pion production target for a series of experimental runs in two pion beams (πM1 and πM3). These runs were scheduled to use rotating wheel targets designed for 100 μA operation in contrast to the first pion production run in February when a temporary target was used;
- Training personnel for operation and maintenance of the accelerator on a 20 shift/week basis;
- Completing the extracted proton channel, including both target stations and the main beam dump, and commissioning further secondary beams.

The first three goals have been achieved and the others are well on the way.

Up to the middle of March the injector cyclotron was used mainly to provide 72 MeV protons to the ring accelerator for its initial development. Serious efforts then started to reach the beam specifications – extraction of 100 μA of 72 MeV protons at 50.67 MHz.

The exacting requirements were successfully met at the end of March when the intensity was increased to 108 μA with excellent beam quality. The stability of the extracted beam was amply demonstrated in April when over 100 μA was produced for 30 minutes, followed by an 8 hour run at 20 μA. After these results were obtained, the final shorting bars were built into the r.f. system, allowing a rapid change from the 50.67 MHz injector mode to the 4 to 17 MHz variable energy mode. A typical change from 72 MeV protons to 33 MeV deuterons (8.5 MHz) is carried out in only 45 minutes.

In June the first operation of the whole accelerator system under SIN responsibility began. This has increasingly involved more SIN staff and considerable effort has been required to provide sufficiently reliable and stable beam conditions for an efficient experimental programme. Further important work needed to achieve this is to improve the major source of breakdown — the 50 MHz r.f. system of the injector, which is not yet equipped with the final version of important components such as the signal pick-up for the feed-back loops.

The accelerators themselves behave well, once both machines have settled into their operating equilibrium. To keep beam on target over several hours has been no problem. At present, the total beam transmission efficiency from the output of the injector cyclotron to the pion target can be tuned to typically 40 to 50 % while, in the best cases, 70 to 75 % has been achieved with intensities of 1 to 2 μA of extracted beam. Losses at high energy resulting in activation are within foreseen limits. There is a strong correlation of injector settings, 72 MeV beam quality and the adjustments of the injection parameters into the ring where most of the beam loss is occurring. The properties of the 72 MeV injected beam also strongly affect the extraction efficiency from the ring and the extracted beam quality. Even minor fluctuations in the injector cyclotron internal source produce noticeable effects in the 590 MeV beam. A further series of beam investigations is planned.

During the trial operation which ended on 26 August, the accelerator provided 150 μA hours of 590 MeV protons beam to the thin pion production target. Currents of 0.1 to 4 μA have been provided under steady conditions over periods of hours and during one run, 8 μA of extracted proton beam were provided without undue difficulties. During these runs the transmission efficiency from ring extraction to target was 95 % or better.

Two experiments have been setting up and taking data on the πM3 beam. The first group has successfully observed, with zero background, signature events from muonic helium (the 8 keV X-ray from the 2P — 1S transition). The second group has obtained preliminary polarization measurements at four angles with 350 MeV/c incoming positive pions on a polarized proton butanol target. In addition a parasite experiment has observed precession of polarized stopped muons in copper.

The πM1 beam has been used for data taking in an experiment on stopped pions in holmium. The splitting in the 5g — 4f pionic transition has been seen and this is expected to yield a 2 to 3 % measurement of the quadrupole moment. X-rays due to de-excitation of rotational states of dysprosium 156 following holmium pion capture have also been observed.

A two month shutdown began on 26 August. It will be devoted to commissioning the injector cyclotron in the variable energy mode and installation of better and more reliable components therein. The extracted proton channel will be completed up to the main beam dump together with the secondary beams from the second or thick target station. These will be the superconducting muon channel μE1 and μE3, the medical pion beam πE3, the low energy beam πE2, the high intensity beam πE1 and the unpolarized neutron beam nE1. Early in November, the experimental programme will begin again and it is hoped to provide beam to sixteen experiments by the end of the year.

DARESBURY
Catching gammas

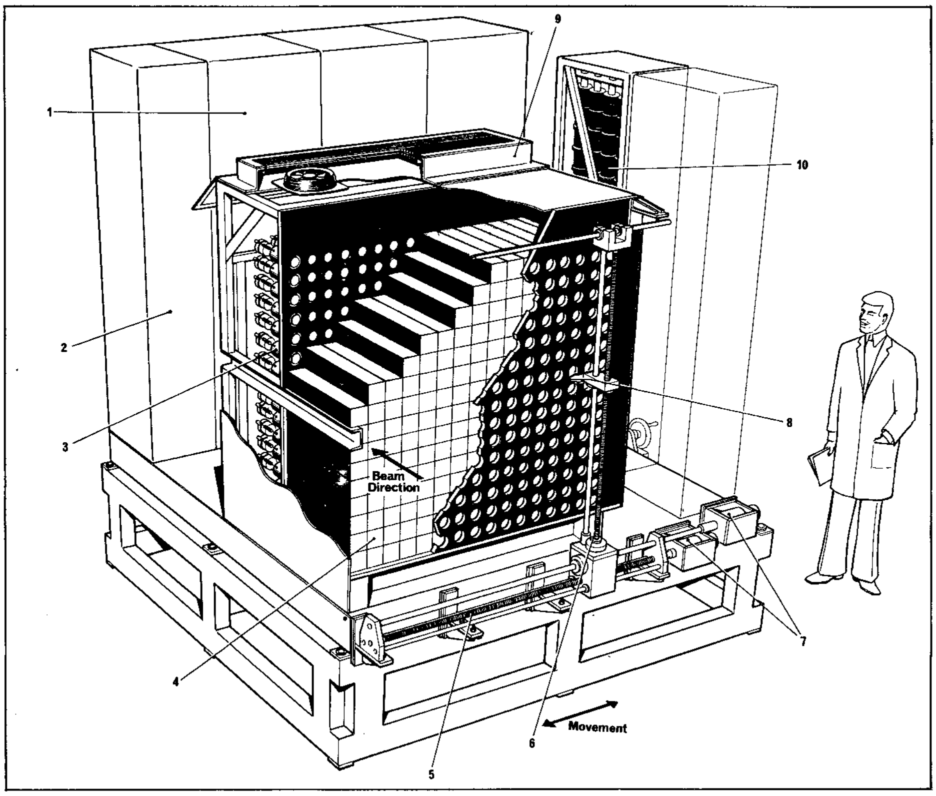
An experiment which uses many of the possible tricks for studying charged particles and photons is coming into action on the 5 GeV electron synchrotron at the Daresbury Laboratory. It employs a large aperture spectrometer (known as LAMP 2) and is fed with a tagged photon beam, with an energy range of 1.5 to 5 GeV, to look at the photoproduction of multi-meson states from hydrogen or deuterium targets. The experiment is being carried out by a collaboration of Daresbury/Lancaster/Sheffield.

The spectrometer consists of a large magnet (1.5 × 0.75 m^2 aperture) with eight multiwire proportional chamber modules, followed by a hodoscope and a large gamma detector. It is a flexible system which can be applied to the investigation of many interactions. The most technically novel component is the gamma detector and we will concentrate here on describing its abilities.

The gamma detection system is designed to measure the energies and the positions of the photons produced in the meson decays. It consists of 480 blocks of lead glass, each observed by a photomultiplier, in two separate independently movable modules of 240 blocks closely packed in a 15 × 16 matrix. The blocks were manufactured from type F2-620362 glass by O'Hara Ltd, Japan, and are each (80×80×400) mm^3 in volume. Each block in the matrix is wrapped in aluminium foil and layers of polyethelene 0.05 mm thick are layed between horizontal layers. Situated in front of each module is a two plane, or x-y, scanning system using a light emissive diode (LED) which can be moved under programmed control to the centre of any block. This enables the gain and calibration of each glass block and its phototube to be checked when the spectrometer is not receiving beam.

To help calibrate the photomultiplier and monitor gain levels, it was decided to develop a new blue light emissive diode made from ion implanted silicon carbide since it has a very suitable frequency spectrum (similar to Cherenkov light in the lead glass). Tests indicate that accuracies of better than 10 % should be possible. This will ultimately depend upon the spectral matching of the diode output, the photocathodes of the photomultipliers and on the variation in light transmission of the glass blocks.

Measuring and recording 480 pulse height distributions is done using a CAMAC analogue-to-digital conver-



One of the two modules of lead glass blocks used in a total absorption gamma ray spectrometer at Daresbury. The components are (1) electronic racks, (2) x-y scan and interlock controls, (3) phototubes, (4) lead glass blocks, (5) x-scan shift, (6) y-scan shift, (7) stepper motors, (8) light source, (9) fan housing, (10) delay cables.

ter. Channel stabilities of about 0.5 % have been achieved. A Honeywell 316 computer, interfaced to a six crate CAMAC system, controls read-out and test processes (such as operating the x-y scan system and photomultiplier high voltage multiplexer). The 316 takes care of testing and calibration but during data taking it passes data to the main IBM 370 computer via a 516 computer.

The lead glass spectrometer will measure gamma rays with a resolution dE/E equal to about $20/E^{1/2}$. It is hoped to measure the position of a gamma ray entering a block to within 20 mm.

ARGONNE
Proton radiography

A particularly lively topic at Argonne (as indicated in the June issue, page 205) is the development of practical methods of using proton beams to take medical radiographs. During the past year a small group has been working on this in collaboration with members of the medical faculty of the University of Chicago.

The great attractiveness of the technique comes from the fact that the number of transmitted protons varies very rapidly near the end of their range so that slight density variations in the material traversed can cause dramatic changes in the number of emerging protons. This is in contrast to the behaviour of X-rays which are exponentially attenuated while traversing matter. Since tumours and other abnormalities in human tissue are characterized by changes in density of a few percent or less from that of healthy tissue, proton radiography could make the detection of tumours more reliable at an earlier stage of development than is possible at present and with a significantly smaller radiation dose.

Tests of this technique began in February of this year with a 200 MeV proton beam from the ZGS booster and photographic film as a detector. A small depression 0.125 mm deep on one end of a 22.5 cm block of lucite could be clearly picked out, thus detecting a density variation of less than one part in a thousand.

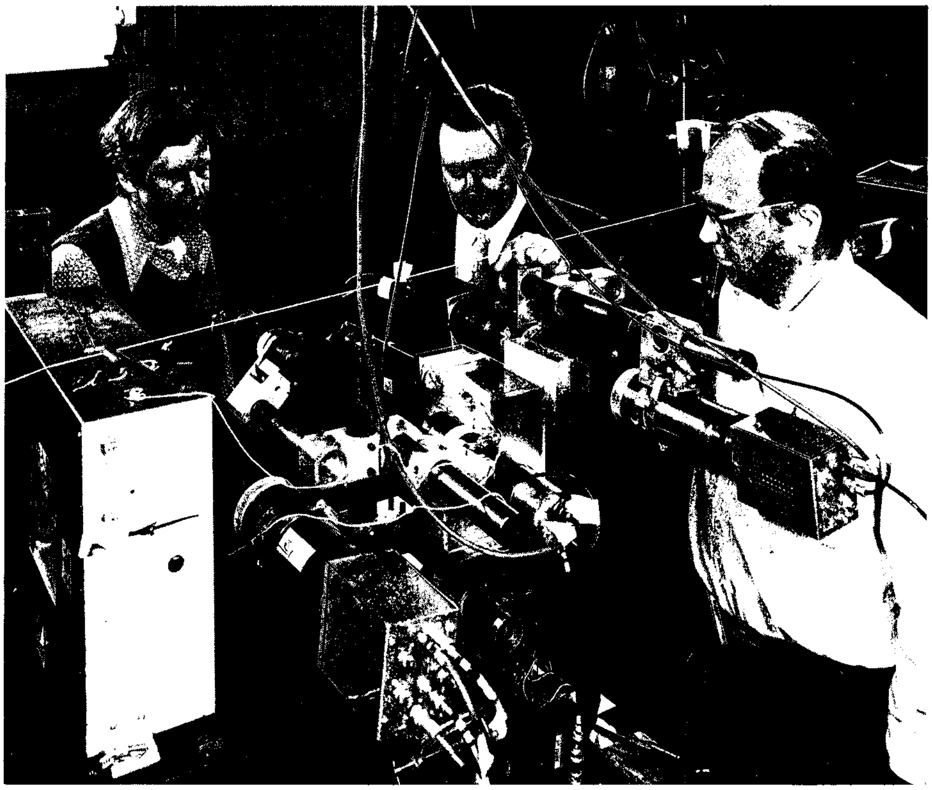
In April, a low momentum secondary proton beam from the ZGS was used on samples of human tissue. Scintillation counters were used to define a narrow proton beam 7 mm in diameter and to record the number of particles emerging on the opposite side of the sample. The measurements were made with the samples immersed in water to help eliminate the effect of surface irregularities. The beam was scanned across the sample and the resulting contour map of transmitted intensity formed the radiograph. The radiograph in the figure is a view of a human brain specimen with a blood clot clearly visible. The total radiation dose required to make this radiograph was approximately five millirems.

The ability of the technique to produce a well defined image would not be greatly altered by the presence of the skull, unlike the situation for X-rays. Based on experimental results and on calculation, it is believed that breast tumours as small as 2 mm diameter and brain tumours as small as 4 mm can be detected using very low dose rates (less than 100 millirems).

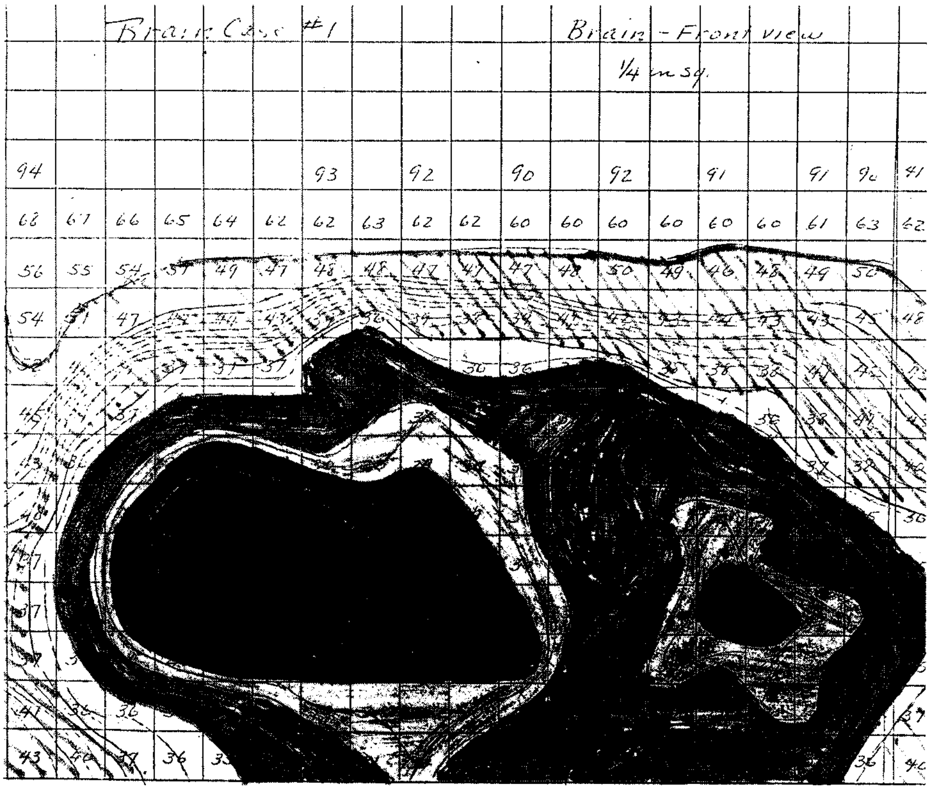
By early next year the group plans to have a facility for making proton radiographs of patients from the University of Chicago hospital. This will use a proton beam of 200 MeV or less from the ZGS booster collimated into a fine pencil beam (about 1 mm wide) and scanned across the portion of the patient's body to be examined. Integrating scintillation counters will be used initially to measure the transmitted intensity and a more sophisti-

Tests on proton radiography using a beam from the 200 MeV booster at Argonne. A brain specimen is contained in a water filled box visible at the centre of the photograph. It is scanned by moving it around in front of a low intensity proton beam coming in from the right. Counters detect the variation in intensity of the beam as it traverses different regions of the brain.

(Photo Argonne)



Map of the brain as produced by the proton beam. The darker region on the left is the location of a brain tumour.



cated system using proportional wire chambers is under consideration.

When the proton radiography project was first discussed at Argonne about a year ago, it was realized that, for proton radiography to become a common diagnostic tool, it would be necessary to have appropriate proton beams available at hospital locations. A small accelerator to produce the modest beam energy and intensity required for radiography could be simple, reliable and inexpensive. R.L. Martin produced a conceptual design for a 200 MeV proton diagnostic accelerator (PDA) which most hospitals could afford and operate. It is a small synchrotron accelerating negative hydrogen ions with slow extraction using a stripper foil to remove the two electrons from the ions after acceleration to full energy. It is planned to build two of these machines, one for development studies at the ZGS and one for clinical studies at the University of Chicago. Detailed design and concept tests are under way on the magnet and vacuum system.

The Argonne/University of Chicago group has recently received a two year contract from the National Cancer Institute for a feasibility study of proton radiography and they are very enthusiastic about the eventual value of proton radiography in medical applications, as an example of the unexpected benefits which can result from the high energy physics research.

Ron Martin expressed it in his usual pungent style by saying that 'anyone who wants to shut down accelerators such as the ZGS should have their heads examined and in another year Argonne will have just the tool to do it with.'

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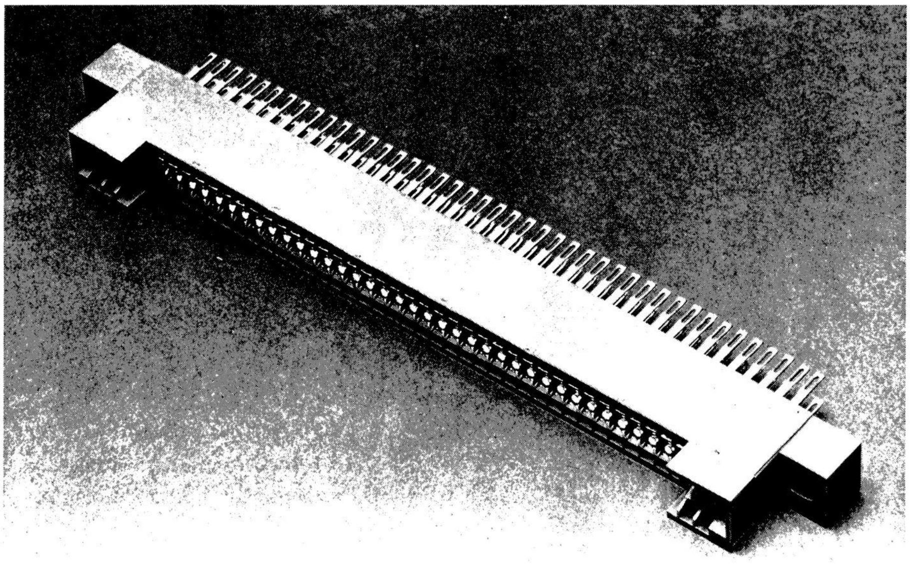

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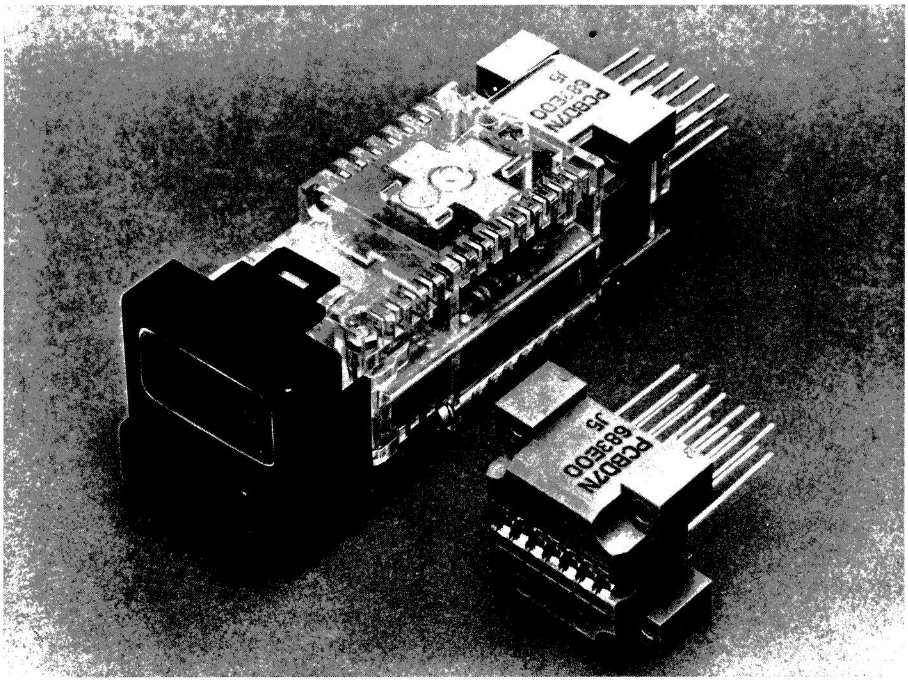

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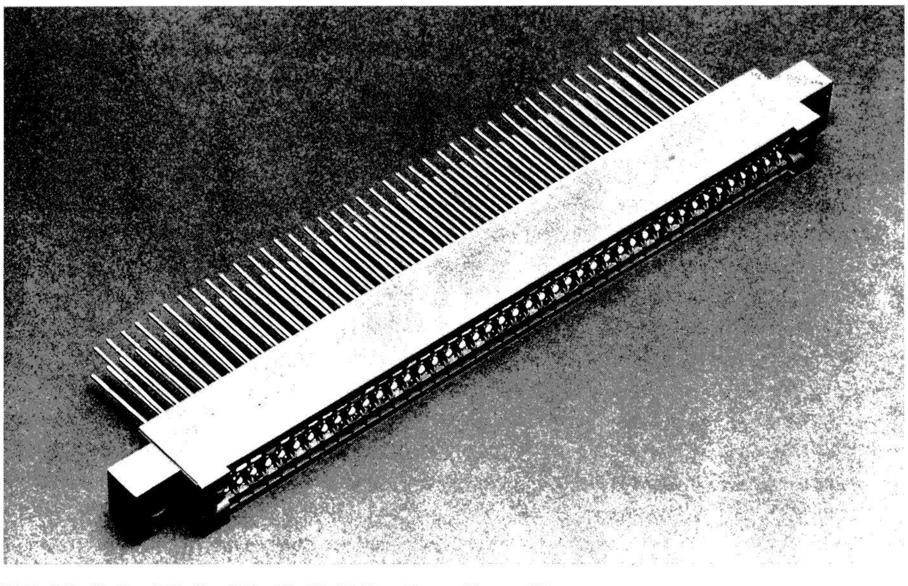

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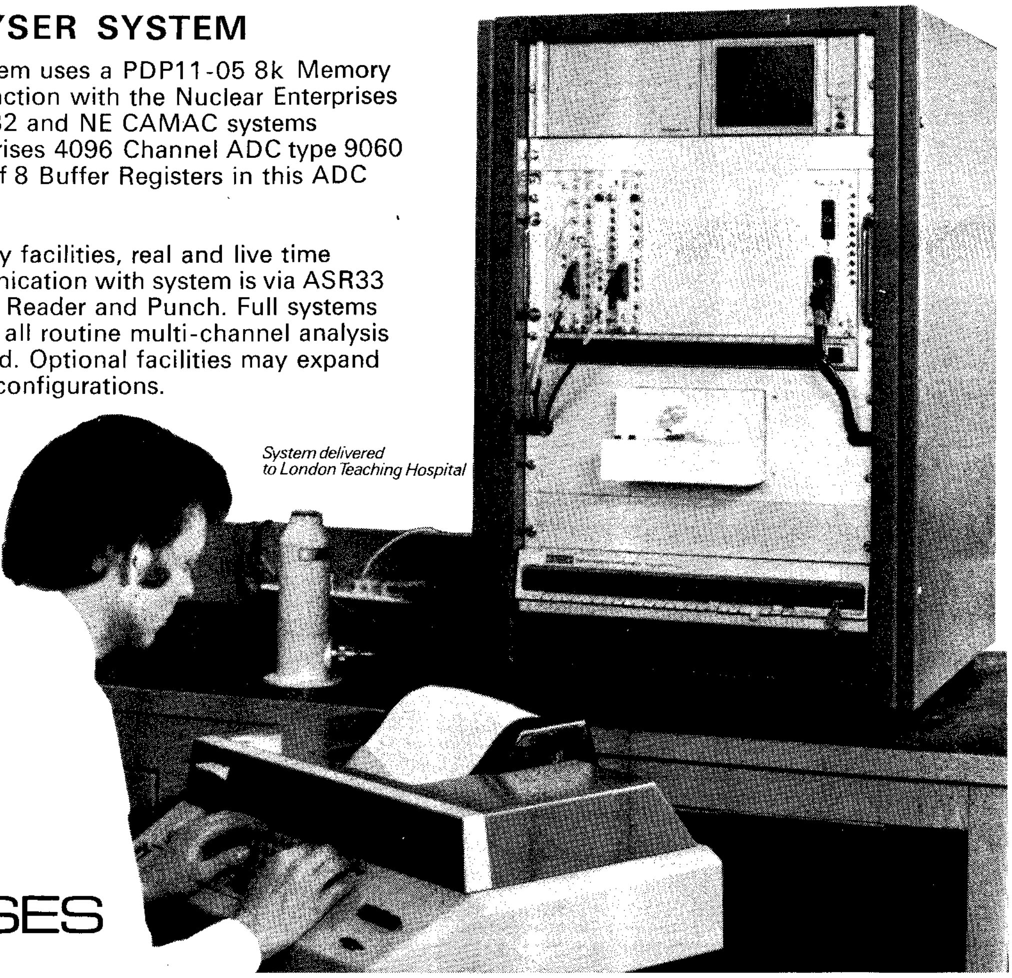

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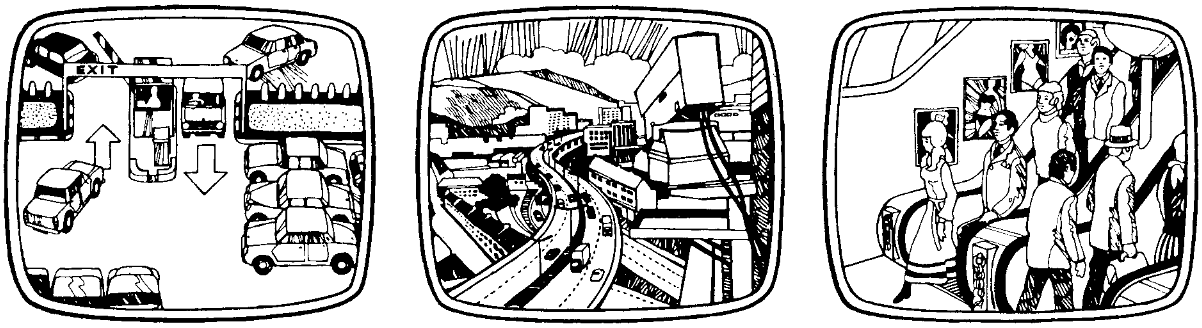
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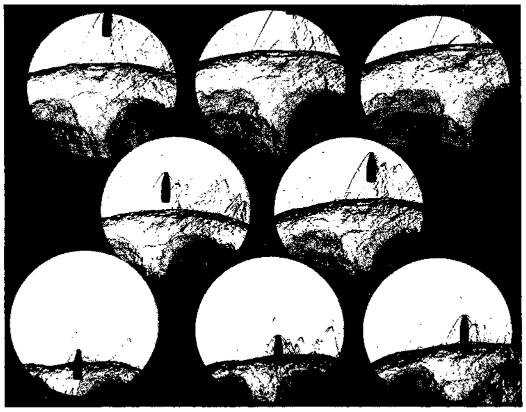

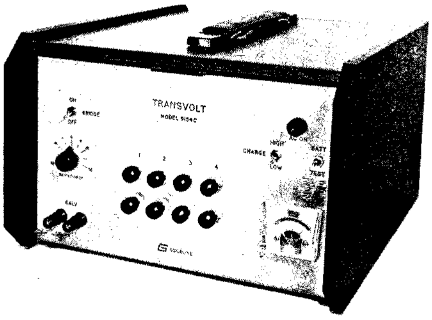
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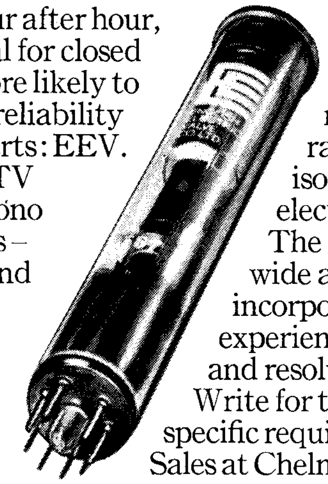

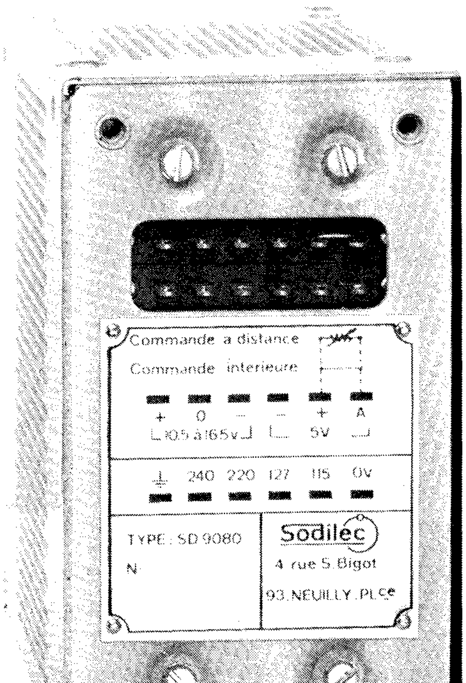

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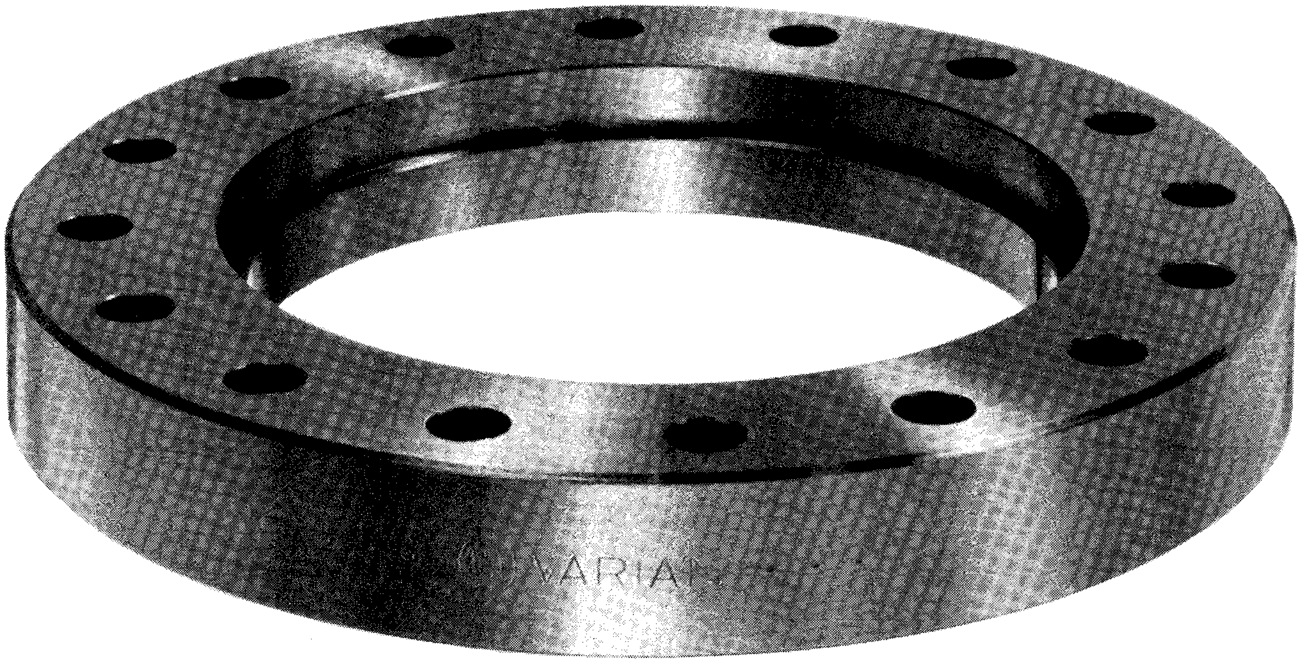
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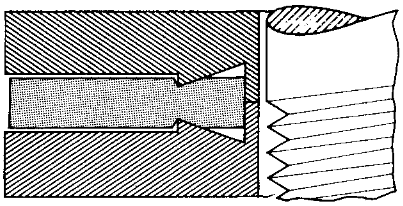

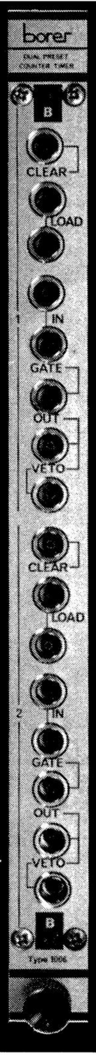
borer
DUAL PRESET COUNTER TIMER
B
CLEAR
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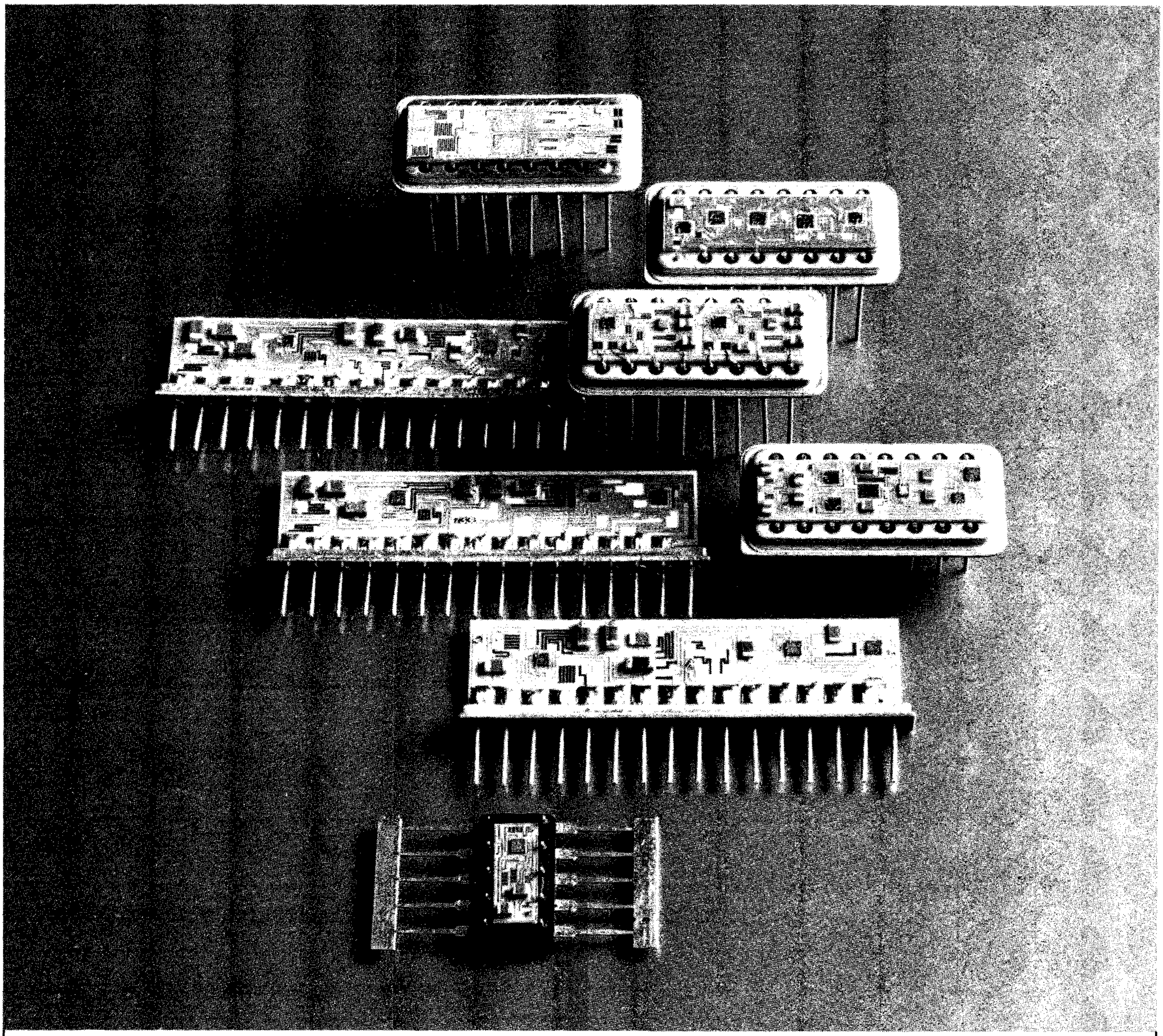

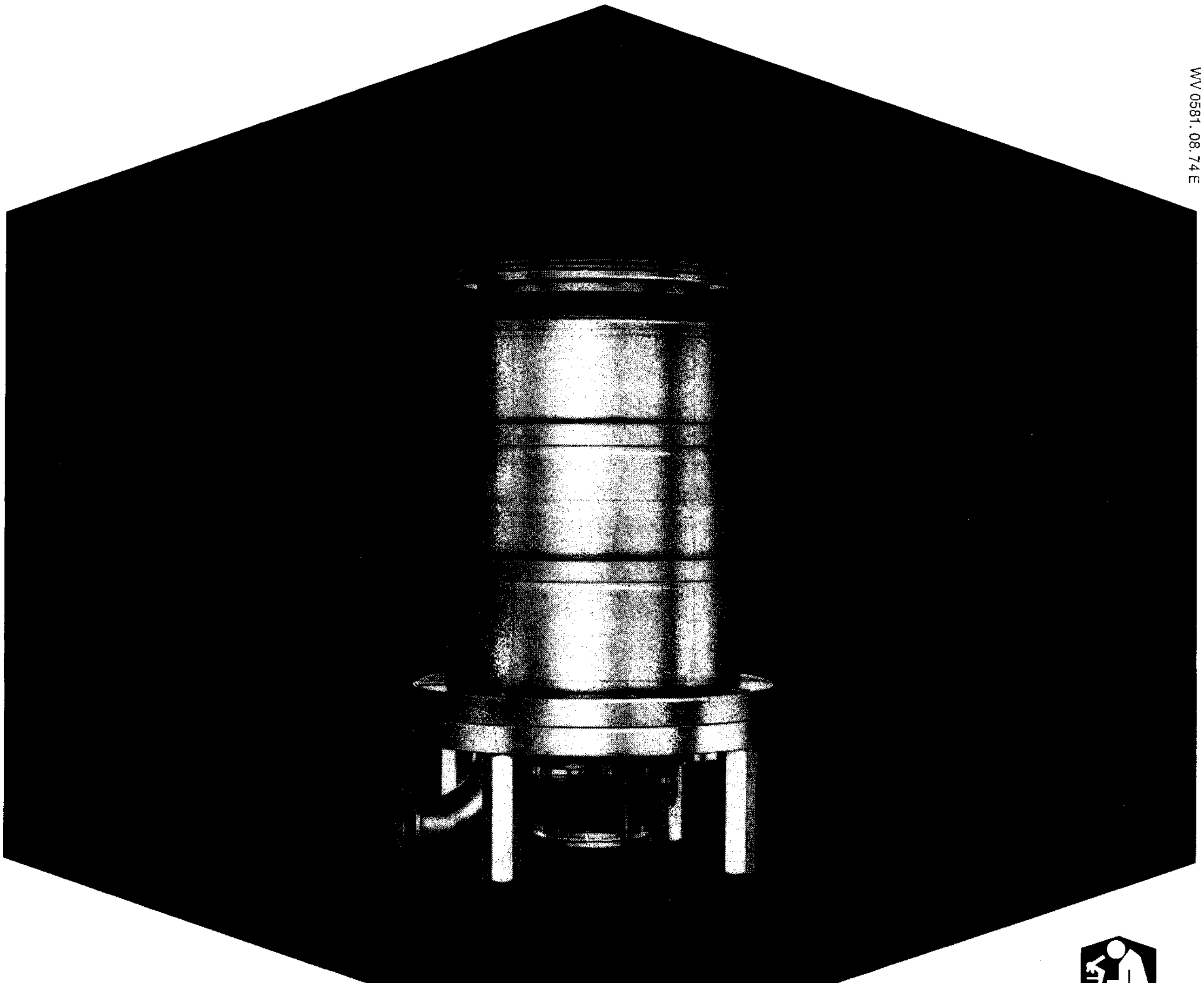

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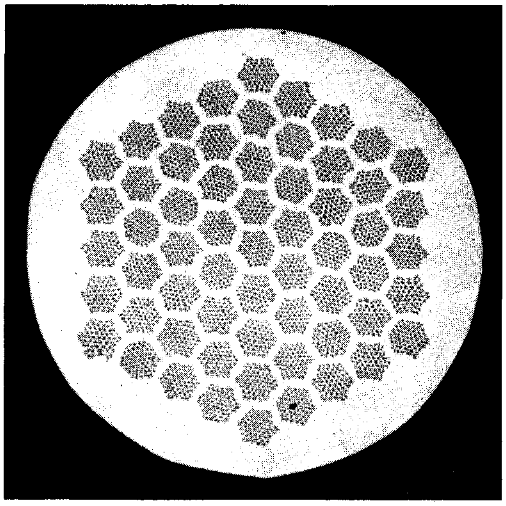

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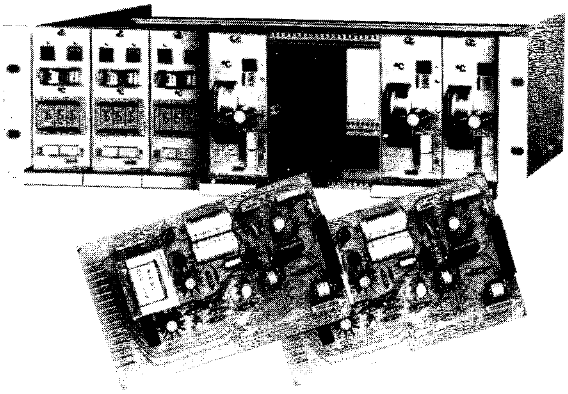

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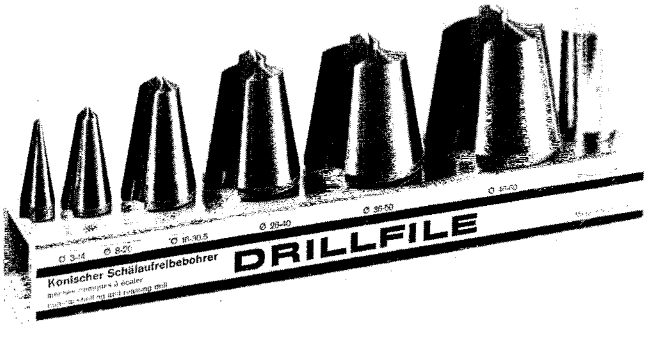

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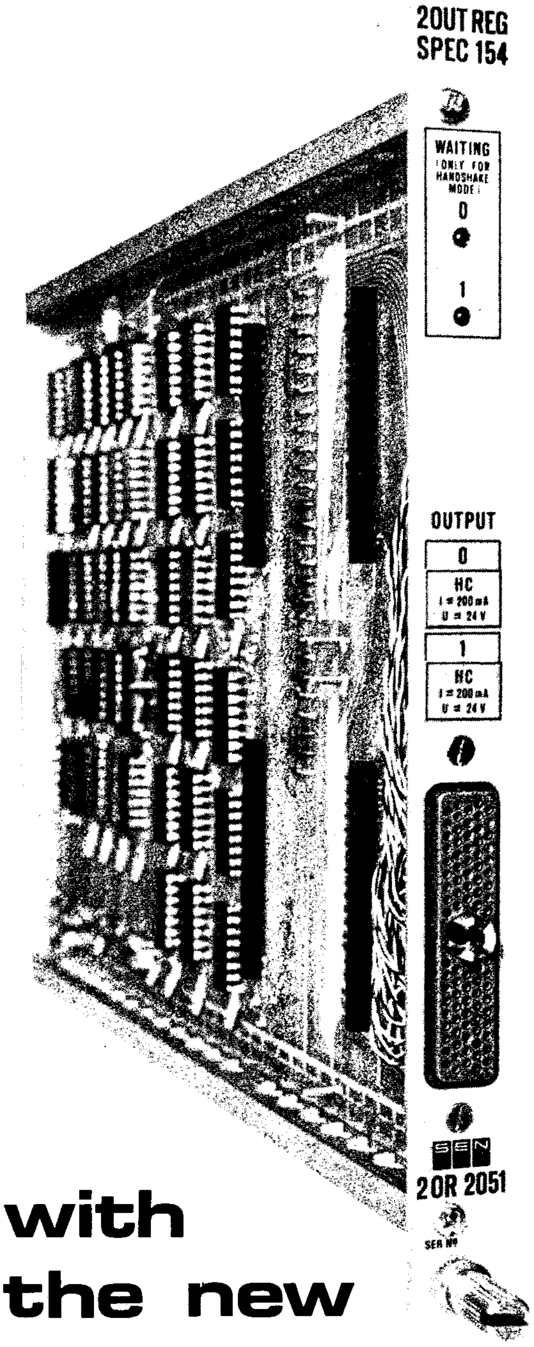
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I = 200 mA
U = 24 V
1
HC
I = 200 mA
U = 24 V
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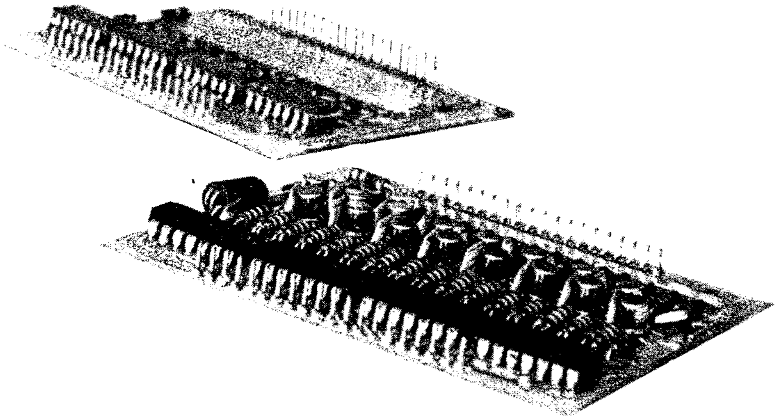

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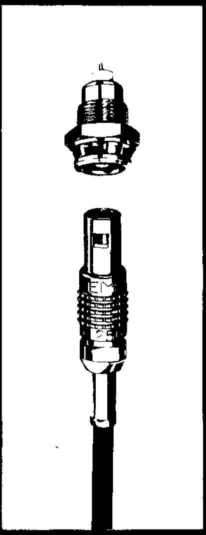

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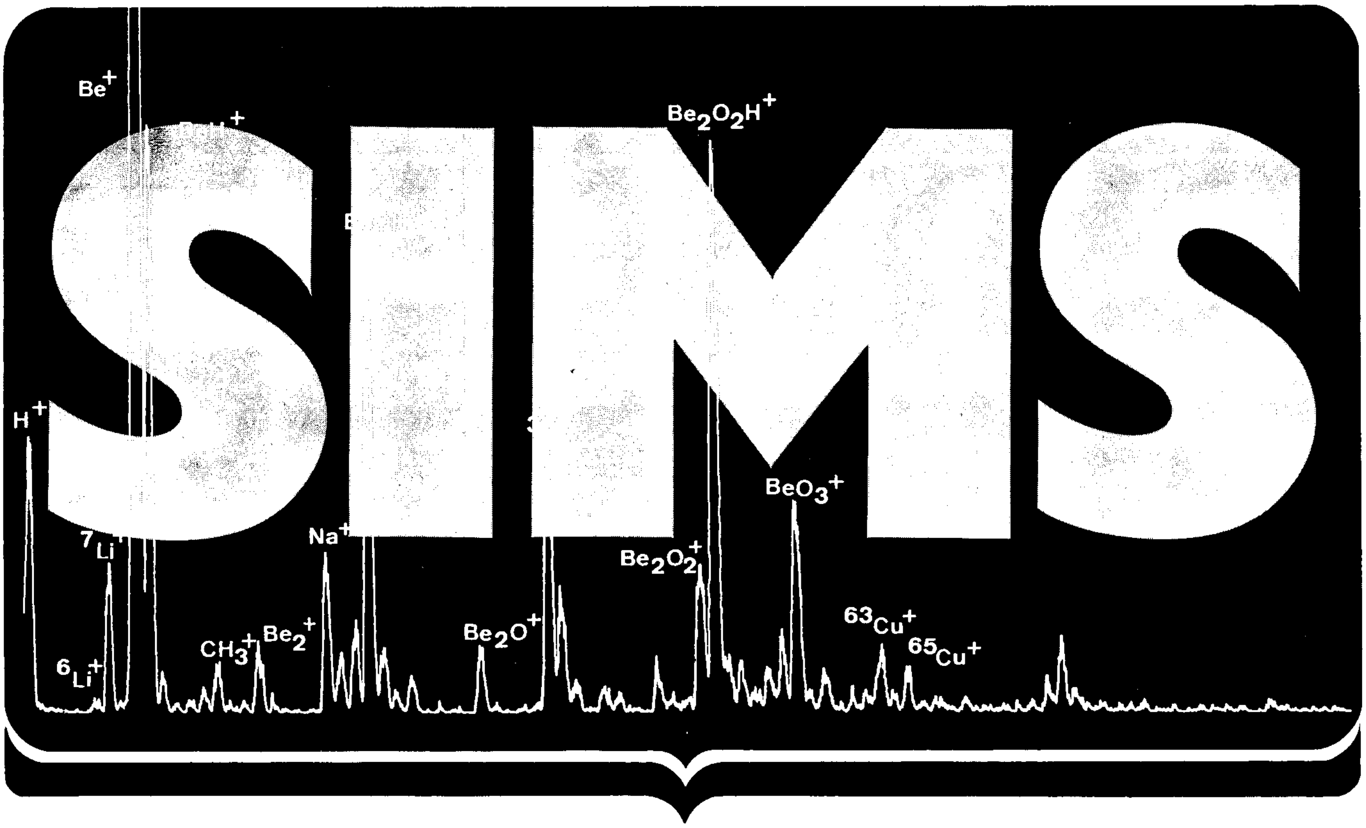
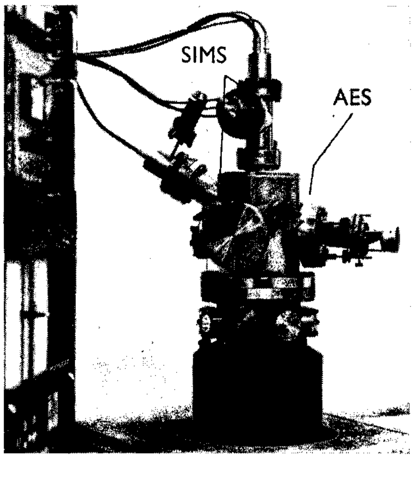
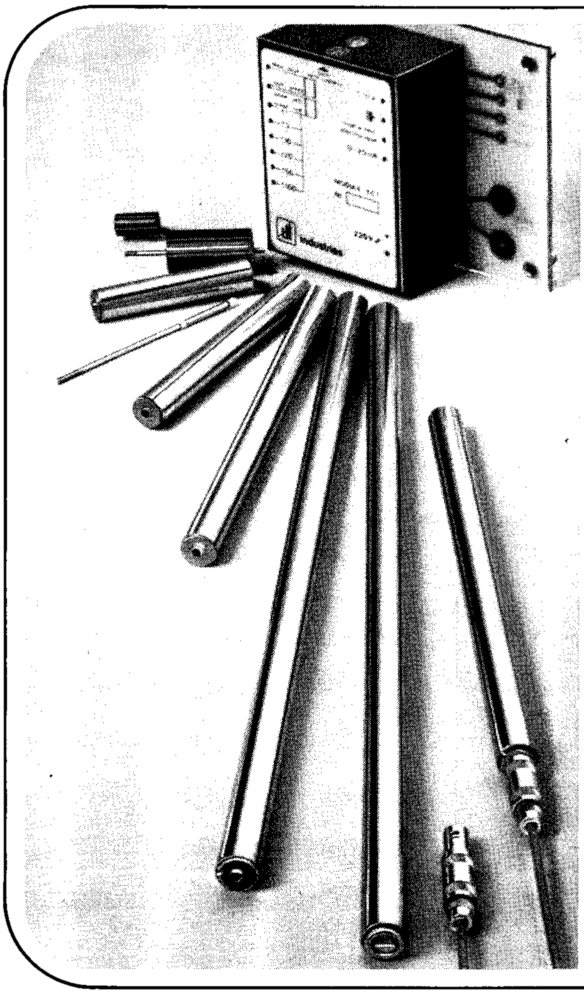

SIMS
Be$^+$
Be$_2$O$_2$H$^+$
H$^+$
^{7}Li
Na$^+$
BeO$_3^+$
Be$_2$O$_2^+$
^{63}Cu$^+$
^{65}Cu$^+$
CH$_3^+$
Be$_2^+$
Be$_2$O$^+$
^{6}Li$^+$


SIMS
AES



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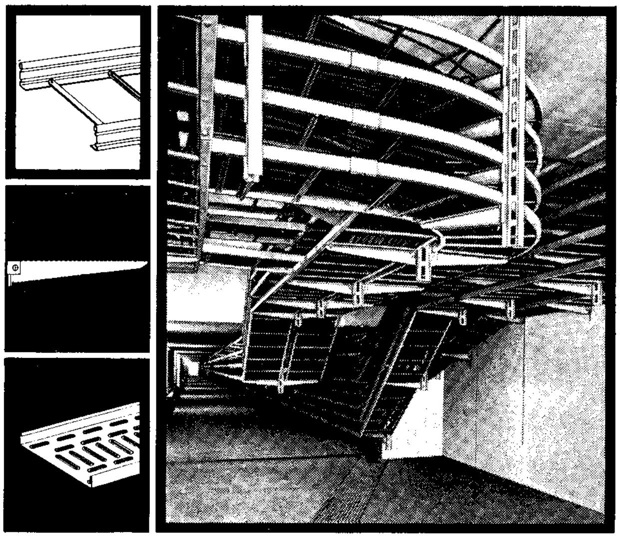

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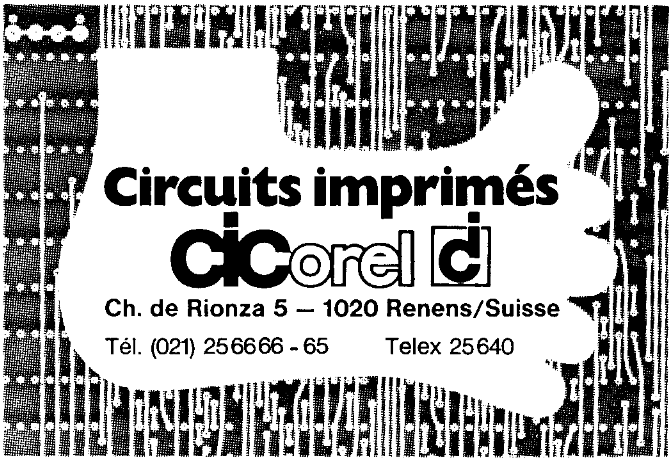

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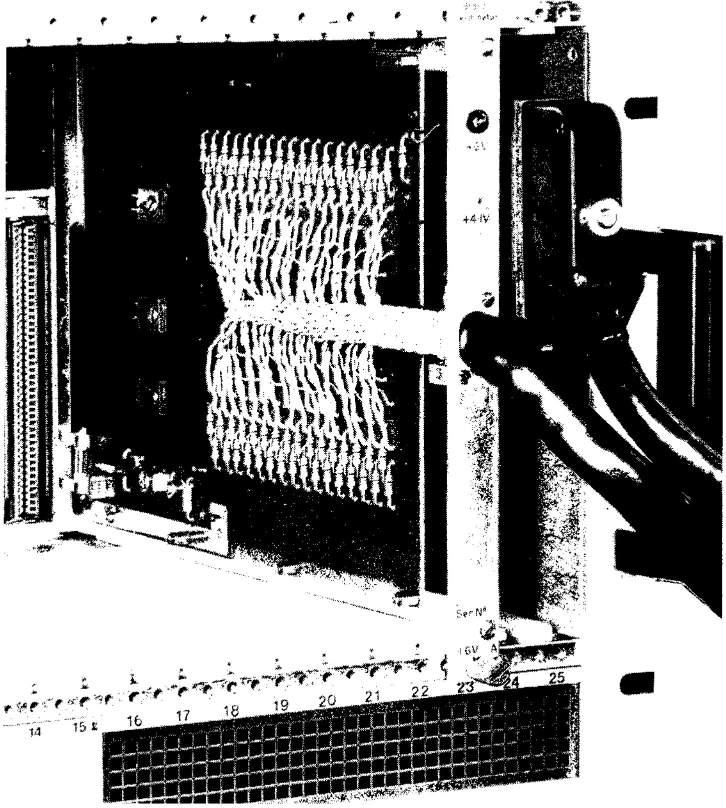
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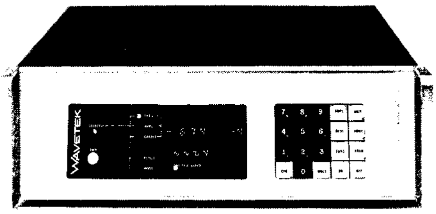

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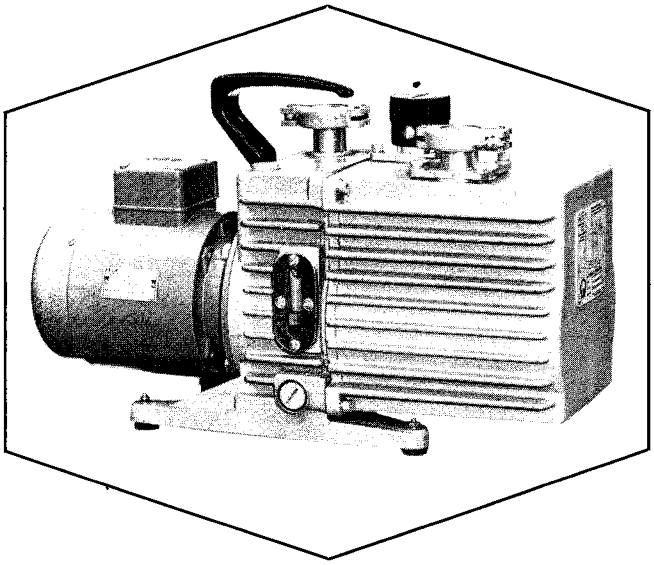

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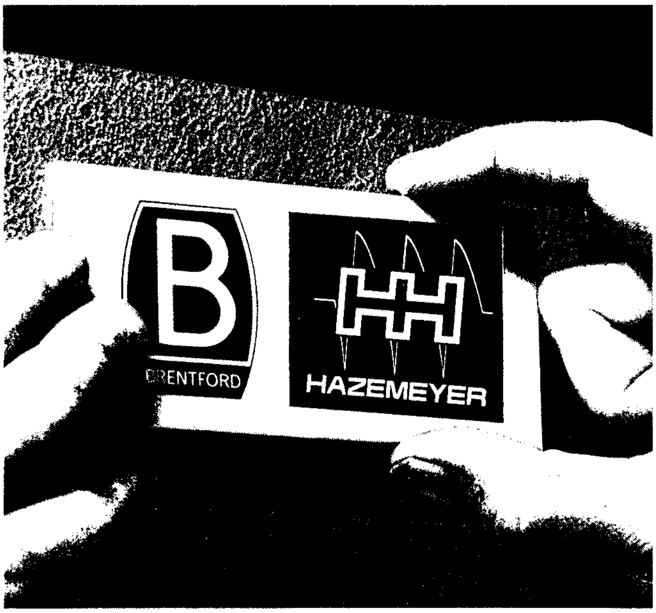

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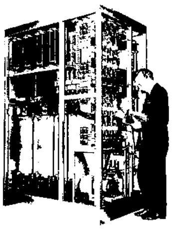

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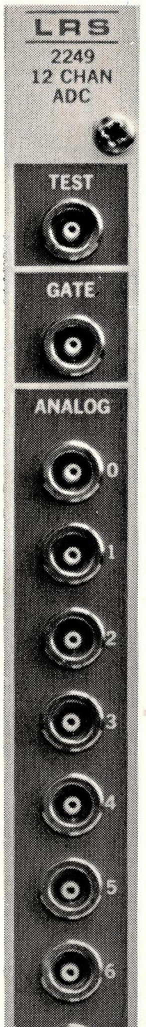

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