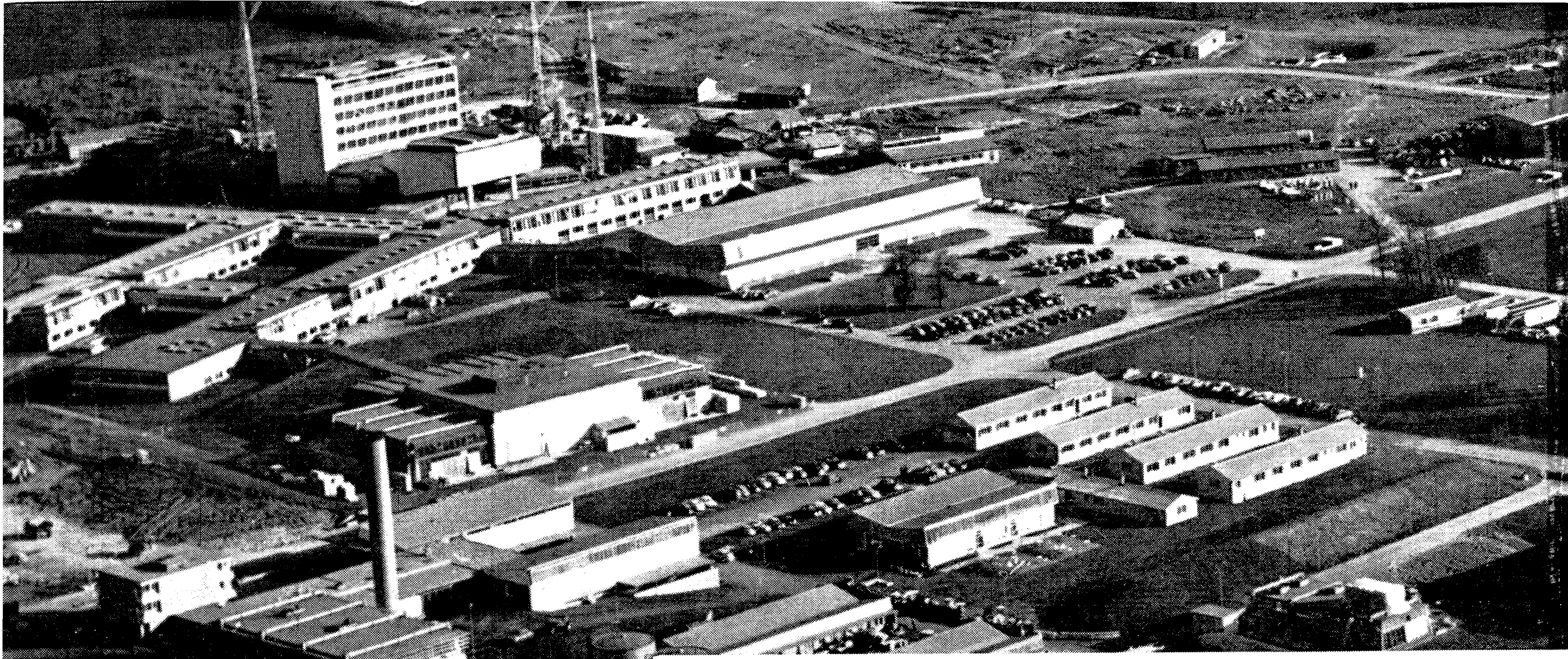
CERN COURIER

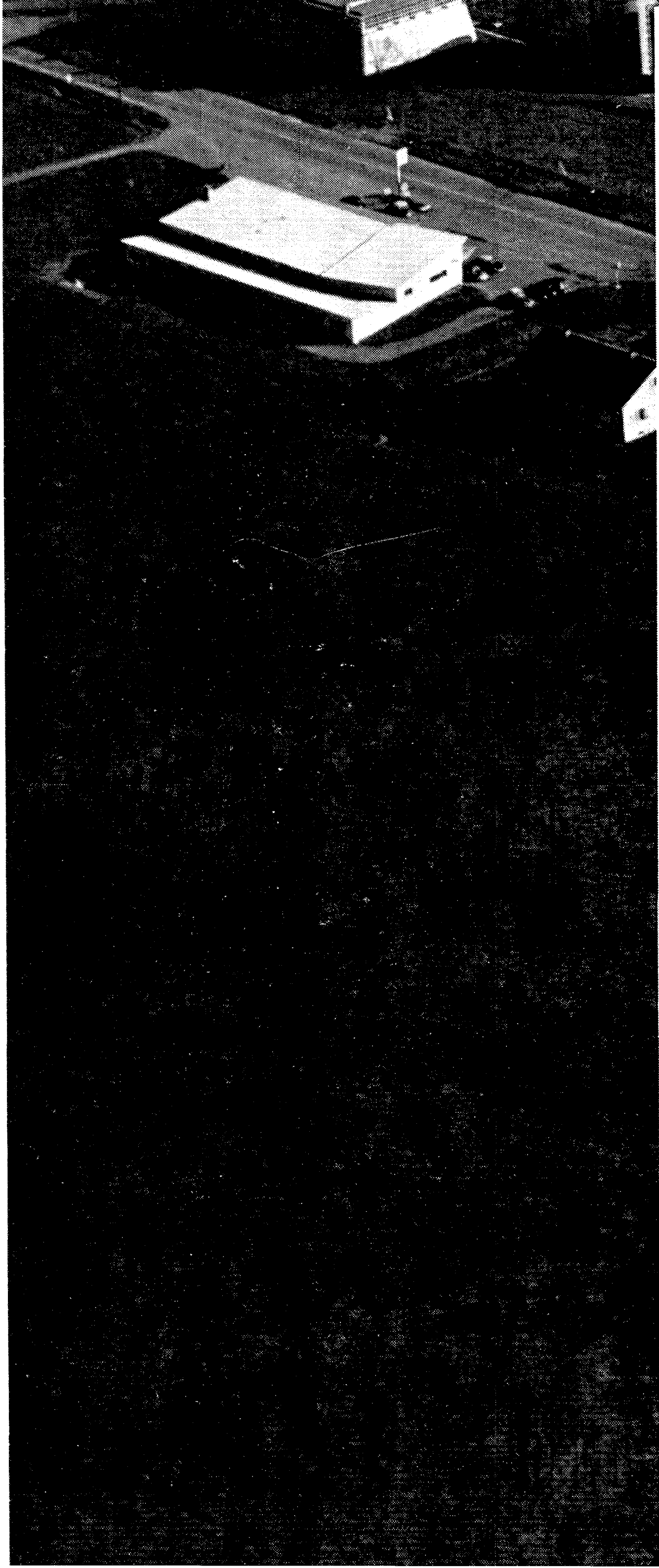
No 6-7

January - February 1960

PS Inauguration issue

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH





Contents

Information given in this publication can be freely used.
Photographs are available on request at
Public Information Office

CERN
Geneva 23 (Switzerland)
Telephone : (022) 34 20 50, ext. 788

Credits

The following have assisted the CERN Public Information Office in the lay-out of this publication :
M. Bron (drawing on pages 12-13), A. Duty (drawings on pages 15, 16, 18, 19), P. Gay (drawing on page 17), Westinghouse Electric Company (page 23). The photographs were taken by the CERN photographers, with the exception of those on the front cover (ATP), page 1 (G. Klemm), pages 2-3 (Swissair and X), bottom of page 5 (B. Sagnell and P. Grünert), page 6 (X), top of page 10 (Dagens Nyheter), page 10, third from the top (UKAEA), page 12, references 1 and 9 (G. Klemm).

This special issue of the "CERN COURIER" is published on the occasion of the inauguration of our large proton synchrotron.

It is our hope that this publication, as well as the brochure reprinted from its contents, will help all who take an interest in fundamental nuclear physics and in CERN.

To those not intimately acquainted with physics it may give some insight into the aims and methods of fundamental nuclear research and more especially of CERN, the first international organization to have channelled the creative and peaceful efforts of a large number of European countries. Thirteen Member States now make up CERN, united by their desire to know more about the fundamental structure of matter, their desire, also, to keep our continent abreast with the kind of research which—though not susceptible of economic applications—has nevertheless been the very basis of the tremendous advances in the understanding of the forces of nature and the ability to control them.

Since 1957, the CERN 600 MeV synchro-cyclotron is in operation and CERN physicists have already supplied valuable data to the world of science. At the end of last year the CERN 25 GeV proton synchrotron reached its full energy and is now gradually becoming available for fundamental research in the field of high energy physics. This is giving rise to great expectations.

Those concerned with the design of particle accelerators will also find in the following pages a review of many of the problems raised by the construction of our 25 GeV proton synchrotron, the world's largest particle accelerator for the time being.

We are pleased to offer this publication to all, as a souvenir of February 5 1960, the day when the largest of our scientific facilities was inaugurated.

C. J. Bakker

Director-General

CERN

THE STORY

OF THE

EUROPEAN ORGANIZA

On the evening of 8 December 1959, the big proton synchrotron of the European Organization for Nuclear Research accelerated a proton beam up to a kinetic energy of 28.3 GeV. It therefore greatly exceeded the energy of 25 GeV expected of the biggest accelerator in the world.

This success—which came unexpectedly soon—meant that six years after being set up, the Organization now had the two big accelerators provided for in the Convention for its establishment. The first, a 600 million electronvolt (600 MeV) synchro-cyclotron, had already been working for over two years, during which it had given the scientific world several original discoveries. The other accelerator, the biggest and most powerful ever constructed, was going to open up a new region of nuclear physics for CERN : the high energy region where the very sparse information hitherto available had been mostly provided by cosmic rays.

The European Idea

The post-war exodus of an alarming number of European physicists to countries with more advanced research equipment, provided the basic agreement for the setting up of a big European centre for fundamental nuclear research. European physicists considered that the equipment of the centre should, above all, include a high energy accelerator which would allow further research work on mesons, the new particles that were being observed in cosmic rays.

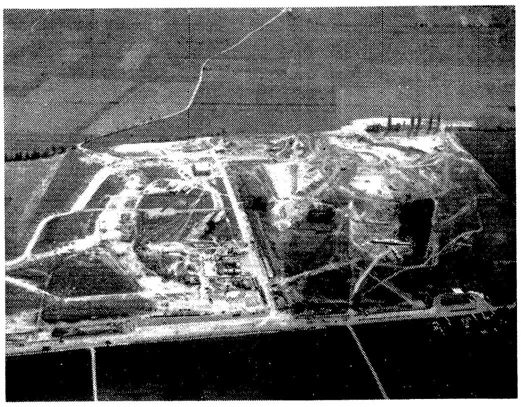
However, the idea of setting up a laboratory for pure research was not born until later. This was because those in favour of international co-operation were aware that public opinion might be willing to accept heavy expenditure on nuclear projects which would sooner or later provide some return, but that it might prove reluctant to countenance the spending of comparable sums on pure scientific research.

As time went by however, public opinion came to realize the need for disinterested research, the basic driving force of progress. Accordingly, Louis de Broglie's proposal at the European Cultural Conference in Lausanne, at the **end of 1949,** received the attention it deserved. He favoured the creation in Europe of regional research institutes for the types of nuclear research calling for powerful machines. Once the resolution to that effect had been adopted, it was up to an international body to lay the material foundations of European co-operation in fundamental nuclear research.

On **7 June 1950** UNESCO, the United Nations Educational, Scientific and Cultural Organization, held its General Conference at Florence. There Professor I. I. Rabi (USA) suggested that the time had come to set up regional co-operative laboratories.

At the instigation of Professor P. Auger of UNESCO, another conference was held at the **end of 1950** at the European Centre of Culture in Geneva. The necessity of European co-operation prompted Italy, France and Belgium to contribute a total of 10 000 dollars. With the UNESCO contribution it became possible to set up a planning office to choose a group of consultants from eight European countries.

These consultants met for the first time in **May 1951.** They suggested as a long-term project the construction of the biggest accelerator technically possible and, in the meantime, the construction of a machine with which the



TION FOR NUCLEAR RESEARCH

European scientists could become familiar with high-energy physics. From the administrative angle it was decided to set up an **interim organization** responsible for the preparation of construction plans and draft budgets.

In fact, this interim organization had the advantage of bringing together the views of the various governments before they became committed.

The Interim CERN

It was expected that with a budget of about 250 000 dollars the interim organization could complete the design of its accelerators in twelve to eighteen months.

The government delegates met twice more under the auspices of UNESCO, which invited all its European members, including the countries of Eastern Europe. Twelve Western countries were represented at the two big conferences held in Paris at the **end of 1951** and in Geneva at the **beginning of 1952.**

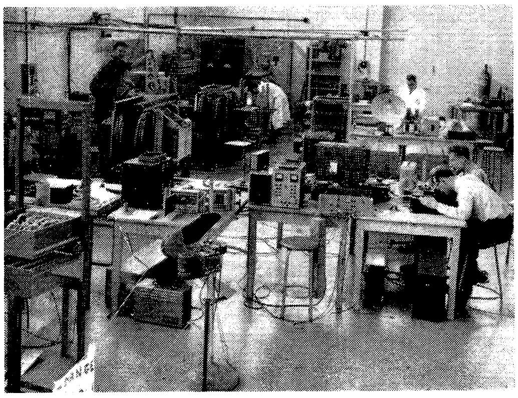
In Geneva, the representatives of 12 European governments signed the Convention setting up the interim Organization which came into being on **15 February 1952** with the title of "European Council for Nuclear Research", called "CERN" for short, after the initials of the French title. Belgium, Denmark, France, the German Federal Republic, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland and Yugoslavia, were then provisionally united to carry out nuclear research. During the whole lifetime of the interim CERN, the United Kingdom remained simply an observer although the interest shown in the project by that country soon took the shape of new ideas, the provision of consultants and gifts. The first Council Session was held in Paris in **May 1952.** The Senior Staff was appointed: E. Amaldi of Rome was appointed Secretary General and the direction of the four design groups for the proton synchrotron, the synchro-cyclotron, the Laboratory and the Theoretical Studies, was entrusted respectively to O. Dahl of Bergen, C.J. Bakker of Amsterdam, L. Kowarski of Paris and Niels Bohr of Copenhagen.

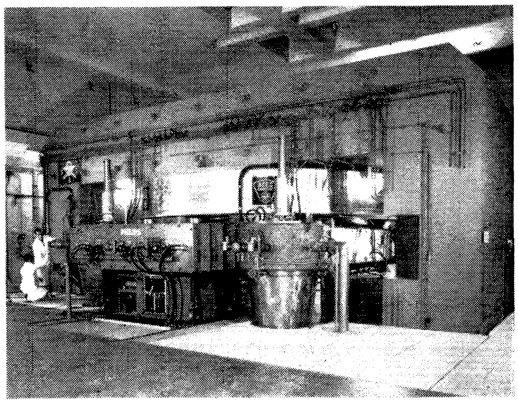
The Proton Synchrotron Group embarked on its ambitious project, the construction of the biggest accelerator in the world, based on a new and untried principle.

The Synchro-cyclotron Group assumed the task of providing CERN within a short time with a conventional machine of up-to-date design and sufficiently high energy to enable the European Organization to work in a new field of nuclear physics. It complied with the requirements of speed of construction, high energy and facilities for exploring new fields. By **1957,** CERN had at its disposal a 600 MeV synchro-cyclotron which was soon being used 24 hours a day and which rapidly provided scientific data of outstanding interest.

In **October 1952,** at its 3rd Session, the Council decided that the future European laboratories should be set up in Geneva. The places originally considered had been Paris, Copenhagen, Arnhem and Geneva. The latter was chosen because of its international nature, its geographical position and of Switzerland's offer to make available at Meyrin the 40 hectares of land necessary.

A description of CERN's two machines and of its future installations, and an estimate of capital and operational costs were submitted to the Council in **April 1953.** These reports were the prelude to the setting up of a permanent organization.





The Permanent Organization

The Convention establishing the permanent organization was signed in Paris on **1 July 1953.** The United Kingdom, which had been an observer until then, was the first to ratify the Convention on **30 December 1953.** Once Italy had ratified the Convention, on **24 December 1955,** the 12 European nations became jointly committed on specific major issues.

In the meantime, the interim CERN was kept in existence from quarter to quarter until **29 September 1954,** the date when the participation of a minimum of 7 States was secured. The European Council for Nuclear Research, a provisional body, ceased to exist. It became the " European Organization for Nuclear Research" but kept the initials "CERN" which had been adopted in 1952 for the interim period. Some activity was possible even on the very small budget available. On **17 May 1954** work was started on the Meyrin site.

On 1 October 1954, just after the establishment of a permanent organization, CERN's staff comprised 114 members. In the course of the same month, the Council appointed the Director-General of CERN, Professor Felix Bloch (USA), a Nobel Prize-winner for physics, on temporary leave of absence from Stanford University. Sir Ben Lockspeiser (United Kingdom) succeeded Mr. Robert Valeur (France) as President of the Council. It was at this time that the Council was organized in its present form, namely with two Vice-Presidents and with the Committee of Council, the Scientific Policy Committtee and the Finance Committee.

In **December 1954,** shortly after the Synchro-cyclotron Group had been transferred from Amsterdam to Geneva, the parameters for the proton synchrotron were adopted and it was decided to implement a programme of theoretical study of mesons and hyperons and of experimental study of nuclear magnetism and cosmic rays.

The laying of the foundation stone of the permanent Organization took place on **10 June 1955**, in the presence of the leading Swiss and CERN authorities.

Shortly after this, in July, CERN played its part as an international centre for fundamental nuclear research for the first time : it was the venue for a meeting of the Executive board of the International Union of Pure and Applied Physics. On **1 September 1955** Professor Bloch handed over his responsibilities to Professor Cornelis J. Bakker, Director of the Zeeman Laboratory of Amsterdam University and of the Nuclear Research Institute of Amsterdam, who until then had been in charge of the designing of the synchro-cyclotron.

At the **end of 1955,** the staff of the Organization consisted of 286 members. In December 1956 this figure had grown to 426, at the end of 1957 to 610 and at the end of 1958, to 755. To-day the CERN staff consists of 969 members including visiting scientists and temporary staff.

At the same time as its staff was growing, CERN's scientific and construction work was progressing. An initial programme for the study of cosmic rays began in **August 1955** at the Jungfraujoch. At Copenhagen, from the **end of 1954** until October 1957, a group of physicists organized a Theoretical Study Division which was subsequently to carry on the work in Geneva.

In **June 1956** negotiations with the Ford Foundation, starded by Mr. J. Willems, Chair-

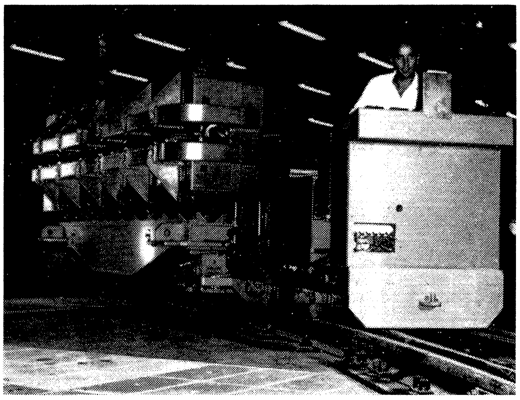
The four aerial photographs at the bottom of pages 2 and 3 illustrate the growth of the CERN Laboratory from May 1954 to July 1959. The photograph inset by the title was also taken in the Summer of 1959. The seal of the Organization is on top of page 3.

In the early days of CERN, a small nucleus of physicists set up their laboratory at the Institut de Physique, in Geneva (above). Later the Organization had its own accomodation at Meyrin and CERN constructed its first accelerator, the 600 MeV synchro-cyclotron (above).

The foundation stone was laid on 10 June 1955, in the presence of Swiss and CERN authorities (on the right). Since then, many official personalities have shown interest in the Organization, such as the French deputies (top of page 5) who paid a visit to the proton synchrotron in 1957.

The picture on the top right of page 5 shows the hundredth magnet unit of the proton synchrotron entering the ring building where the big accelerator is set up. The picture opposite, on page 5, was taken during the testing of the accelerating equipment which culminated in the operation of the biggest accelerator in the world at its full energy on 24 November.

The picture on the extreme right shows the Administration Building, one of the last to be completed, as it will look at the end of 1960.



man of the Finance Committee, resulted in a gift of 400 000 dollars which enabled CERN to welcome scientists from countries other than its own Member States. A further grant of 500 000 dollars was made by the Ford Foundation in December 1959.

The study of new ideas relating to particle acceleration was started in **January 1957.** This form of scientific co-operation and creative effort is continuing. At the same time the construction at CERN of a 10 cm bubble chamber was also started ; this was the first of this type of ancillary apparatus for use with the accelerators.

The "Health Physics" Section was set up in **February 1957** in order to ensure that CERN staff should be protected from the ionizing radiation produced by the accelerators in operation.

The international conference on accelerators and pion physics held in **June 1956,** like those held in **June 1958** and **September 1959,** gave CERN an opportunity of confirming that it is a forum of fundamental nuclear science.

First Results

On **1 August 1957** the synchro-cyclotron produced its first beam. This machine would give the scientific staff a chance of becoming familiar with a big particle accelerator before exploiting the giant proton synchrotron and concentrating all their efforts on using the research equipment.

A year later the 600 MeV synchro-cyclotron made front-page news. A particularly difficult experiment revealed for the first time a nuclear phenomenon foreseen by the theoreticians ten years earlier : the direct decay of one of the least known nuclear particles, the pi-meson, into an electron.

By the **end of November 1957** all the CERN staff, which had until then been split up between the Geneva Institute of Physics and the barracks on the edge of Geneva Airport, was installed at Meyrin.

On **19 December,** Mr. F. de Rose, French delegate, replaced Sir Ben Lockspeiser as President of the Council.

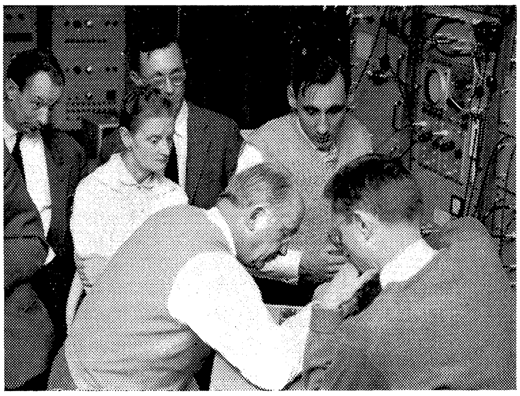
The design of the experimental equipment needed for the proton synchrotron was started at the beginning of 1958. During the summer the Group which had performed experiments on cosmic rays at the Jungfraujoch was disbanded ; during the same period an electronic computer was installed at CERN.

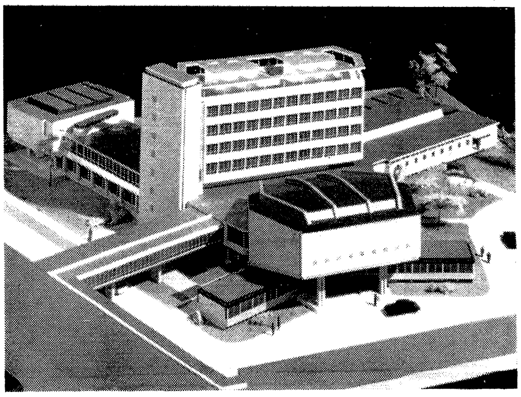
On **1 July 1959,** Austria officially became the 13th Member State of the Organization.

On **10 July** the last magnet unit of the proton synchrotron was installed in the underground ring of the big accelerator, which underwent its first pulsing tests on the 27th. On **16 September,** an energy of 24 GeV was reached. On **1 December,** the Synchro-cyclotron Emulsion Group recorded the first very high energy event to be artificially produced on earth. On **8 December,** the CERN proton synchrotron produced particles with a kinetic energy of 28.3 GeV.

In 1960, experimental research will begin on the second of the big accelerators planned by the founders of CERN.

Having thus given Europe research instruments in a field which was becoming the monopoly of the United States and the USSR, CERN will then restore the old continent to its rightful place in the field of fundamental nuclear research ●





The CERN Pro

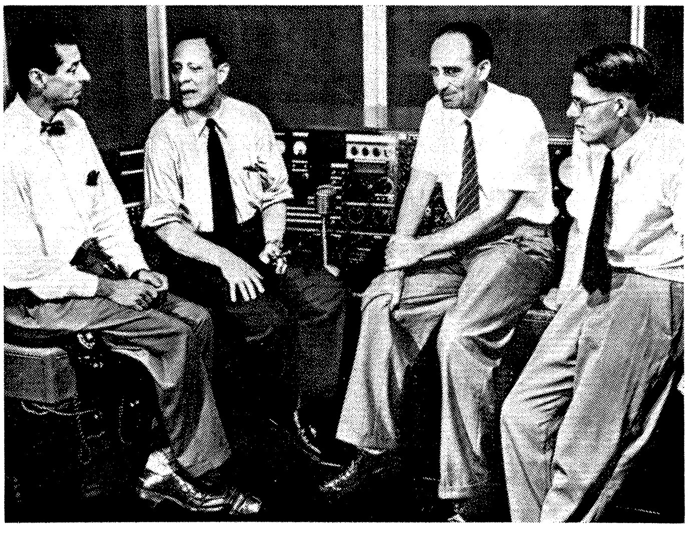
The 25 GeV Proton Synchrotron of the European Organization for Nuclear Research has now been put into operation. Towards the end of November 1959 protons were accelerated up to 24 GeV kinetic energy and a few weeks later, after adjustments had been made to the shape of the magnetic field at field values above 12 000 gauss by means of pole face windings, the maximum energy was increased to 28 GeV. The intensity of the accelerated beam of protons was measured as 10^{10} protons per pulse and there was no noticeable loss of particles during the whole acceleration period up to the maximum energy. The CERN Proton Synchrotron has thus fulfilled the expectations of its designers and the hopes of the twelve European countries that have supported the work for the past six years. It seems appropriate on this occasion to give a short account of this project together with a brief description of some of the design problems and preliminary measurements of the operating characteristics of this accelerator.

In June of 1952, at a conference in Copenhagen, the Interim Council of CERN decided to start an engineering design study of a 10 GeV proton synchrotron that was to be the principal high energy accelerator for nuclear physics research in Europe. The cost of this machine was considered to be so large in relation to other expenditures in physics research that no one European country felt justified in financing it alone. Hence several countries had combined their resources in order that physicists should have available in Europe the highest energy accelerator that was thought feasible at that time. By July 1952 a design group of three people was set up with Dr. O. Dahl in charge, and in August this group, during a visit to Brookhaven on Long Island to see the Cosmotron at first hand, learnt of a new idea for making cheaper and higher energy machines. This idea was considered so attractive that in October 1952 the CERN Council was persuaded to drop the engineering study of a 10 GeV proton synchrotron and instead to set up a theoretical study of the new principle. It seemed that a 30 GeV machine might be built for the same cost as a 10 GeV Cosmotron type of machine. It is interesting to note that at this time, and quite unbeknown to the western world, Russian scientists were planning a scaled-up version of the Berkeley Bevatron for 10 GeV.

In December 1952 the Proton Synchrotron Group was formed to augment the original staff of three and the members of this group, most of them honorary part-time members, remained in their own laboratories and institutes. Members of the theoretical section worked at A.E.R.E., Harwell and at the Universitetets Institut for Teoretisk Fysik, Copenhagen. The magnet studies were concentrated in the Laboratoire de Radioélectricité de l'Université, Paris. The radio frequency problems were studied at the Institut für Physik, Max-Planck-Institut, Heidelberg. The radiation shielding problems at such high energies were worked out using cosmic ray data at the Physikalisches Institut der Universität, Freiburg-i.B., Germany and the general engineering problems remained at the Chr. Michelsens Institutt, Bergen, Norway, where for six months two of the senior staff of the Cosmotron, J.P. Blewett and M.H. Blewett, gave invaluable assistance with the general design problems of the new machine.

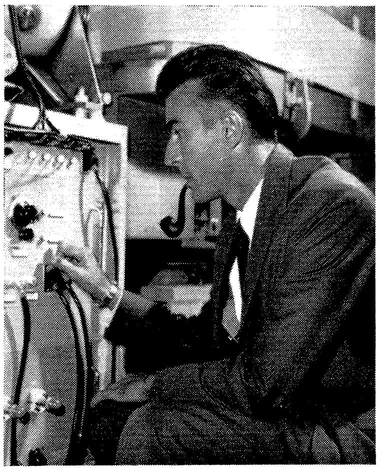
By October 1953 enough was known about the implications of the new idea to present a tentative design of an accelerator to the Council of CERN. In America, meantime, the Brookhaven group and another at M.I.T., Boston had been working on similar problems. At the end of October a conference was held at the Institute of Physics of the University of Geneva, to which were invited representatives of the American groups, the scientific members of the Council of CERN and other European scientists. The CERN Proton Synchroton Group gave a series of lectures on its work of the previous ten months and presented a design for a 30 GeV proton synchrotron using the new alternating gradient principle. It was found that the Brookhaven group had arrived independently at a very similar design.

Immediately after this conference the CERN Council fixed the energy of the machine at 25 GeV and agreed that the members of the PS Group should come together in Geneva, near which city the new European laboratory was to be sited. The State of Geneva and the University generously offered temporary laboratory accommodation and by December 1953 most of the group had moved to Geneva with their families, and the task of designing the final machine started. Soon after this move Dr. O. Dahl resigned as Director of the group, and the group suffered a fur-



O. Dahl and F. Goward, respectively second and fourth from left to right on this photograph, were the first to be in charge of designing the CERN proton synchrotron. This picture shows them in 1952 with G. Collins and R. Wideroe, in the Cosmotron control room at Brookhaven.

ton Synchrotron



by **J.P. Adams, Director PS Division**

ther loss by the sudden death of Dr. F. Goward who had been acting as Deputy Director. Despite these initial set-backs the group successfully established itself in Geneva, which for nearly all the members and their families was a foreign city. From the beginning of 1954 onwards staff was steadily recruited from all over Europe and the group was built up as shown in the following table :

End of Year	Main Activities	Total staff *
1953	Preliminary studies. . .	20
1954	Design of final machine .	75
1955	Development of component parts	120
1956	Major contracts placed for components	150
1957	Manufacturing of components in firms	163
1958	Assembly of components at CERN	176
1959	Testing of components and commissioning of CPS	180

* This includes all staff directly connected with the design and construction of the machine.

The Alternating Gradient Principle has been described many times. The original idea was published by E.D. Courant, M.S. Livingston and H.S. Snyder (1) and, quite unbeknown to these authors, was previously invented by N. Christofilos. In the conventional synchrotron the focusing of the circulating particles is achieved by arranging that the magnetic field, which guides the particles around a fixed radius, decreases slightly with radius. The amount of focusing achieved in this way is not very great, and consequently the amplitudes of the free oscillation of the particles are large and the dimensions of the magnet gap correspondingly large. Most of the cost in the original synchrotrons is in the magnet ; for example, the Russian 10 GeV Synchro-phasotron magnet, whose radius is 30.5 m, contains 35 000 tons of steel and the magnet gap is 150 cm wide and 40 cm high. Although greater focusing can be obtained in the axial direction by increasing the gradient of the magnetic field, the criterion for radial stability is then violated. It is the great advantage of the alternating gradient principle that the focusing of the circulating particles can, in theory, be made as strong as one wishes and the amplitudes of oscillation of the particles as small as desired. This is achieved by alternating the sign of the gradient of the magnetic field many times around the circumference of the machine. The net result of this stronger focusing is to reduce greatly the weight of the magnet ; for example, the CERN 25 GeV Proton synchrotron magnet has a useful aperture of 14 cm x 7 cm and contains only 3 400 tons of steel. It is 100 m in radius, that is 3 times the radius of the Russian machine and one tenth the steel weight.

These attractive advantages are realized at the price of greatly increased accuracy in manufacturing and aligning the magnet of the synchrotron. Also, once the magnet is set up with the required precision, it must remain in place and, for a machine 200 m in diameter, this presents some interesting foundation problems. The CERN Proton Synchrotron (CPS) magnet is made up of 100 supposedly identical magnet units, each about 4.3 m long. The magnetic field error between these units for the same energizing current should not exceed about one part per thousand, and the units should be set up with a precision of a few parts per million (0.3 mm in 100 m radius). The units are mounted on a free floating monolith ring of concrete 200 m in diameter and 2 m x 2 m in cross-section, and the machine is built in a subterranean annular tunnel in which the temperature is controlled to $\pm 1°$ C. As a further precaution, the concrete ring has steel pipes cast in it and water is passed round the ring to prevent any part assuming a temperature different from the rest. The technology developed for the magnet construction and the foundations has been described in various CERN reports. (2) (3)

Another advantage of the alternating gradient principle is that the amplitude of momentum oscillations is very much smaller than in the conventional synchrotron. Since these momentum oscillations result in radial movements of the particles in the synchrotron which have to be contained within the width of the magnet aperture, the alternating gradient synchrotron is again more economical in magnet aperture than the conventional synchrotron, in this case by a factor of about 60. Unfortunately, this improvement is also realized at the cost of imposing problems which, at the time of designing the CPS, seemed formidable.

One restriction concerns the curious behaviour of the machine at an energy called the "transition energy". During the momentum oscillations in a synchrotron, particles with greater momentum than the mean value swing out to a radius greater than the mean radius. The revolution time of these particles depends on two factors which work in opposition. Because these particles have a greater momentum than the mean value, their velocity is greater than the mean velocity and they take a shorter time to complete a revolution than the mean revolution time. On the other hand, since the radius at which these particles circulate is greater than the mean radius, they have a longer path to go round and this lengthens their revolution time. In an ordinary synchrotron, the "radius term" is greater than the "velocity term" and those particles with greater momentum than the mean value always take longer to go round than the mean particles. Due to the momentum compaction in an alternating gradient synchrotron, the radial displacement for a given momentum change is about a factor of 60 less than in a conventional synchrotron with the result that at low energies, at the beginning of the acceleration cycle, the velocity term is larger than the radius term. However, as the energy increases and the particles approach the velocity of light, the velocity term decreases due to relativistic effects. Consequently, there comes a time in the acceleration cycle of the CPS when the radius term equals the velocity term. The energy at this time is called the "transition energy". At this energy the frequency of the synchrotron oscillation goes to zero, phase stability is lost, and a rapid shift in the phase of the accelerating voltage has to be made so as to recapture after transition energy all the particles that have been accelerated up to that energy.

It is possible to design an alternating gradient machine so that the transition energy is higher than the maximum energy of the machine, but this can only be done by increasing the circumference of the machine by as much as 50 %, with a consequent increase in cost. In fact, two new Russian alternating gradient machines have been designed in this way. However, in the case of the CPS it was calculated that the transition energy could be passed without loss of particles, and the operational results shown by the traces on fig. 1 justify these calculations. It is possible that the Russian machines will now be modified and consequently will be capable of going to even higher energies.

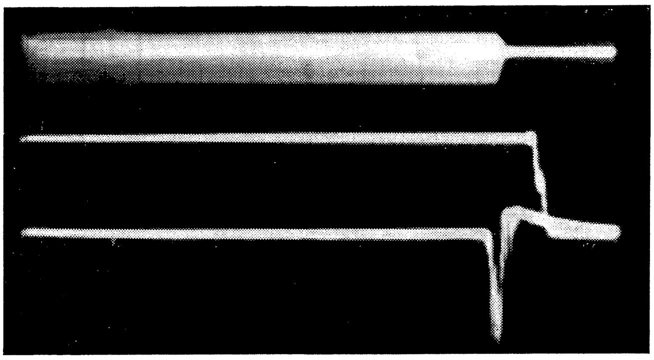


Fig. 1 : Beam accelerated to about 24 GeV with no loss

The particles in a synchrotron circulate at a fixed mean radius, and in order to keep them in the centre of the vacuum chamber during the whole acceleration cycle, the frequency of the accelerating voltage must track the steadily increasing magnetic field with high precision. The relative frequency error for a 1 cm displacement of the mean radius of the circulating particles in the CPS is given in the following table :

Kinetic Energy of Protons	Δ f/f for 1 cm Radial Displacement
50 MeV (injection)	$3.5 \cdot 10^{-3}$
1 GeV	$8.3 \cdot 10^{-4}$
2 GeV	$2.7 \cdot 10^{-4}$
3 GeV	$1.2 \cdot 10^{-4}$
4 GeV	$4.5 \cdot 10^{-5}$
5 GeV (transition)	0
10 GeV	$7 \cdot 10^{-5}$
25 GeV	$7.5 \cdot 10^{-5}$

It can be seen that another unfortunate effect of the transition energy is to impose impossible tolerances on the accelerating voltage frequency at and near that energy. This problem has been solved in the CPS in the following manner. From the injection energy of 50 MeV to about 1 GeV, the accelerating voltage frequency is automatically determined from the magnetic field by an analogue computer having an accuracy of about one part in a thousand. At an energy very much less than 1 GeV, in the 100 MeV region when the particles are firmly captured in phase-stable bunches, another frequency controlled system is switched in supplementing the analogue computer. The second system uses pick-up electrodes to detect the phase of the bunches in the machine relative to the phase of the accelerating voltage frequency and, by means of a servo system, holds this phase difference constant at a prescribed value. In addition, the radial position of the circulating bunches of particles in the machine is detected by other pick-up electrodes and, by means of another servo system, the bunches are maintained in the centre of the vacuum chamber.

Apart from these specific problems peculiar to alternating gradient synchrotrons, there are general theoretical problems concerned with non-linear stability criteria which have been studied extensively. The CPS is equipped with sextupole and octupole lenses to adjust non-linearities in the magnetic field of the machine. A complete description of the CPS is in course of preparation (2) (4) (5).

***

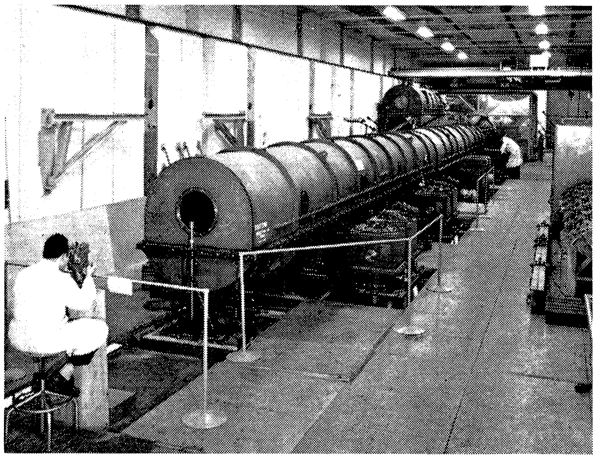
Measurements so far carried out on the CPS are necessarily preliminary and incomplete. It will take at least six months of measurement work before sufficient is known about the behaviour of the machine to exploit it as a working nuclear physics tool.

The intensity of the proton beam is surprisingly high at this early stage of operation. Protons are injected into the synchrotron at an energy of 50 MeV from a proton linear accelerator whose design closely follows that developed at the Lawrence Radiation Laboratory, Berkeley. One important difference, however, is that the CPS linear accelerator contains magnetic quadrupole alternating gradient focusing in the drift tubes, in place of the grid focusing originally used in the American machine.

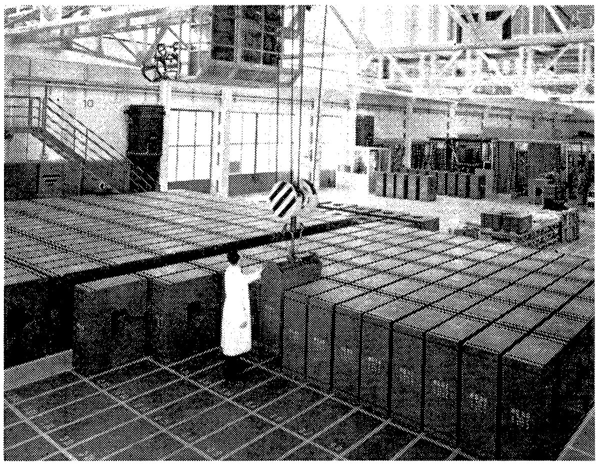
The CPS linear accelerator has produced intensities up to 5 mA peak, although for the tests so far carried out with the synchrotron a collimated 1 mA proton beam has been employed. A buncher and debuncher have been built for this linear accelerator, but neither have been used so far. With 1 mA being injected into the synchrotron and single turn injection, a capture efficiency of 20—25 % has been measured, corresponding to a circulating beam of 10^{10} protons per pulse. The pulse repetition rate at 25 GeV is 20 a minute.

The energy of the protons in the synchrotron has, so far, been calculated from the magnetic field at the time the beam disappears and the radius of the machine. The earliest operational runs were carried out without any of the correcting devices being employed, except for the self-powered pole face windings needed to correct eddy currents in the metal vacuum chamber at injection when the guiding magnetic field is only 140 gauss. The proton beam then disappeared at a magnetic field of about 12 Kgauss due to the number of free oscillations of the particles per revolution becoming an integer. As the magnet yoke saturates, the focusing forces diminish slightly, and instead of the machine working in the stable region between the unstable resonance bands, the operating point is slowly forced into a resonance and the particles are lost to the walls of the vacuum chamber. In later runs the pole face windings were energized by programmed generators designed to keep the focusing forces constant up to magnetic fields of over 14 000 gauss and it was observed that all of the proton beam then reached an energy of just over 28 GeV, limited only by the peak magnetic field available in the CPS.

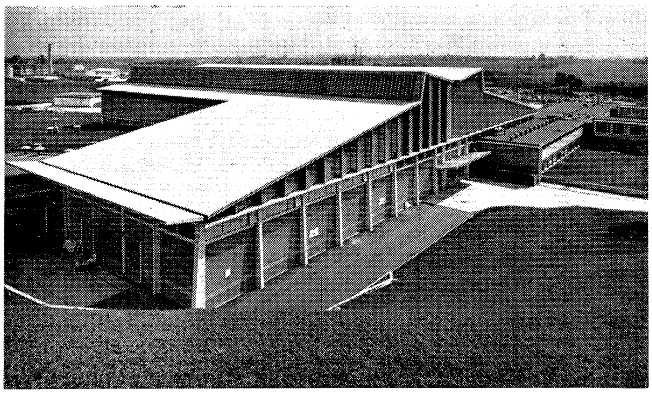
An attempt has been made to measure the number of free oscillations per revolution in both the axial and radial directions (Q_V and Q_R) during the acceleration cycle. At injection, with the pulsed inflector voltages not energized and a 2 μs pulse of protons injected from the linear accelerator, the beam spirals inwards in radius due to the rising magnetic field for over one hundred microseconds, and the fractional Q-values can be observed in the two directions by pick-up electrodes sensitive to one or the other of the two directions of oscillation. For these measurements the beam is injected in such a way as to set up either axial or radial oscillations of the particles. During the acceleration cycle the Q-values were measured by pulsing the quadrupole correcting lenses at different times in the cycle and by variable amounts, and noting when the beam was lost. The nominal Q-values are both about 6.25, and if at a certain moment the quadrupole lenses are pulsed by an amount that shifts, say,



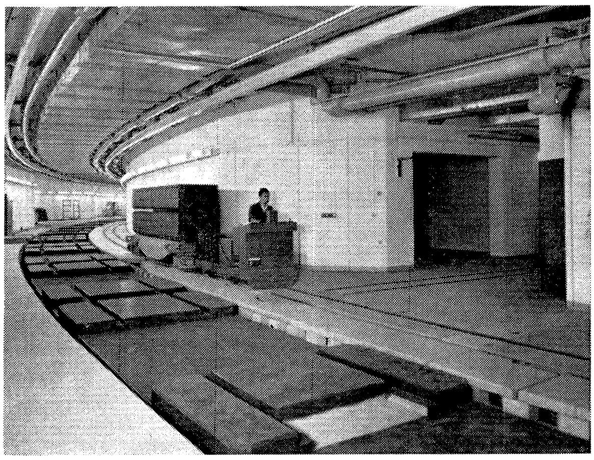
Above is a view taken during the construction of the PS, showing the ring tunnel and the linear accelerator wing (left) before the concrete structure was covered with earthfill. The photo on the right shows the 50 MeV linear accelerator tanks (30 m long) being aligned. The output end is in the foreground.



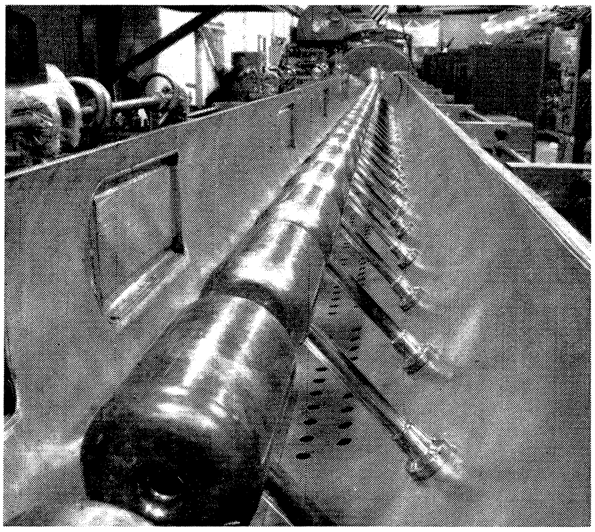
The PS magnet blocks (right) were stored in the South Experimental Hall prior to their assembling in 10-block units. Below is a view of the intricate cabling system running underground. In the PS, cable length amounts to some 3 600 km.



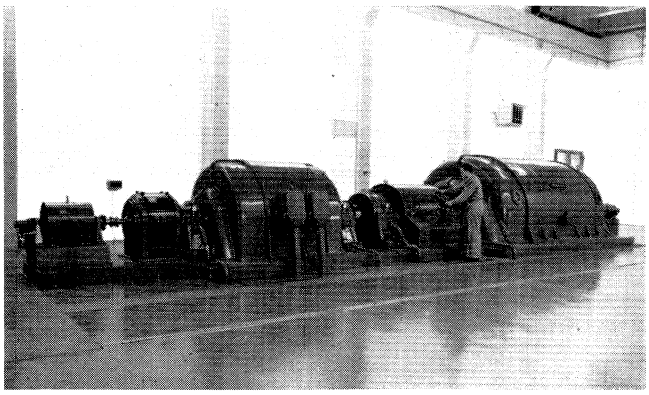
The south hall is the largest of the two intended to house the experimental apparatus to be used in connection with the PS. It covers 3 200 square metre.



A phase of the transport of a magnet unit into the ring tunnel. The unit rests on two pivoting bogies drawn by an electric tractor. The dark concrete girder designed to carry the synchrotron structure is architecturally independent of the building.



A view of the 50 MeV linear accelerator, showing the drift tubes mounted in one of the three tanks of the apparatus, before its cover was installed.



An alternating current generator driven by an induction motor at 3 000 rpm supplies 34 600 kW peak power to the magnet. An 8.6 ton flywheel (in front of operator) is used to store the energy recovered from the magnet.

the Q_R value to 6.0, the beam will be lost due to instability at a radial first resonance. Similarly, pulsing the lenses in the opposite direction by the same amount loses the beam due to instability at a radial second order resonance at $Q_R = 6.5$. Apart from the shift of the Q-values when the magnet saturates, it appears that they remain close to $Q_V = 6.3$, $Q_R = 6.2$ during most of the acceleration cycle. Using this same method, the unstable boundaries of the stable operating region, namely $Q_R = 6.0$, 6.5 and $Q_V = 6.0$, 6.5, have been measured. So far, no higher order resonances due to non-linear instabilities have been observed, although whether this is a tribute to the linearity of the machine or due to the crudeness of the measurements remains to be seen.

Measurements have been made of the closed orbit displacement at 20 points around the circumference of the machine, from which the closed orbit amplitude and shape have been computed. The closed orbit is that orbit around which all particles perform free oscillations. In a perfect machine without field free sectors it would be a perfect circle in a plane. In an imperfect machine its shape and amplitude are due to the imperfections. At injection the peak to peak amplitude of the closed orbit in the radial direction is about 4 cm, and in the axial direction it is a few mm. Later on in the cycle the peak to peak amplitude diminishes in the radial direction to about 1 cm and remains negligible in the axial direction. Since the vacuum chamber dimensions are 14 cm in the radial direction and 7 cm in the axial direction, there is therefore no danger of beam loss due to magnet misalignments.

The transition energy, which seemed so formidable a barrier during the design stage, proved to be easily surmontable in practice. The precision of phase switching needed at transition for no noticeable loss of particles was found to be about ± 3 ms, or ± 36 gauss.

Both the computer and the beam control system for determining the frequency of the accelerating voltage have proved very satisfactory after minor adjustments. During the operational runs so far carried out the beam control system has been switched in about 1 ms after injection and there seems to be no noticeable loss of particles during this switch-over. During the early acceleration studies the radial control servo acted on the amplitude of the accelerating voltage, which in principle is equally effective a means of controlling the radial position of the beam as varying the phase or frequency of the accelerating voltage. This arrangement was not successful, perhaps due to a certain amount of jitter in the phase-lock loop, and the system was modified so that the radial control servo acted on the phase of the accelerating voltage. This second method was completely successful and no particles were lost during acceleration. Preliminary measurements indicated that the beam was not moving more than 1 cm from the centre of the vacuum chamber during the acceleration cycle. The beam control system depends for its operation on the presence of a bunched proton beam, and due to noise in the servo loops, there is a certain minimum value for the circulating beam current below which the system no longer maintains control. It appears from early measurements that the system will work with about 10^8 protons per pulse.

A very important parameter of an accelerator is the mean intensity. Fig. 2 shows that at an energy of 6 GeV the mean intensity of the CPS is now nearly as high as that of the Bevatron, and at 10 GeV considerably higher than that of the Russian machine. It is hoped to increase the intensity of the CPS by an order of magnitude by bringing into operation the buncher and debuncher of the linear accelerator and allowing more protons to be injected into the synchrotron. At 25 GeV the yield of secondary particles from internal targets is considerably higher than at 6—10 GeV, and early measurements of secondary particle yields from the CPS indicate that the machine may be a strong competitor to the lower energy high intensity machines now being built from this point of view.

* * *

The significance of this accelerating machine can best be understood in relation to other proton synchrotrons. The CPS accelerates protons to an energy which is about three times the energy of the largest accelerator now functioning, namely the Russian Synchrophasotron at Dubna, and so, for a while, Europe possesses by far the largest accelerator in the world. In 1960 another machine of slightly higher energy (30 GeV) will come into operation at Brookhaven in America, and in 1962 or thereabouts the Russians plan to bring into operation a machine twice as large as the CPS (50 GeV). The possession of the world's highest energy accelerator is, and always has been, a transitory state, but the remarkable significance of this event is that for the first time for over twenty years Europe can claim this possession. Since the war a major effort has been made in Europe to equip laboratories working in high energy nuclear physics research with the necessary apparatus. The magnitude of this effort in terms of money is considerable, as can be seen in the following table :

	Maximum Energy	Cost in Million Sw. Fr.
CERN Proton Synchr.	28 GeV	120
Rutherford Laboratory Proton Synchrotron	7 GeV	84
Saclay Proton Synchr.	3 GeV	53
Hamburg Electr. Synchr.	6 GeV	60

The cost of running these laboratories and building apparatus for the experiments is equally high, and this is a recurrent cost since new experimental apparatus is continuously being needed as the experiments develop. For example, the annual budget of CERN, which in addition to the CPS also has a 600 MeV Synchro-cyclotron, is about Sw. Fr. 60 million per annum.

That Europe has made such an effort in this field of fundamental research has been due to the foresight of the physicists who have planned the laboratories and the sympathy of the governments who have supplied the money ●

Accelerator	Max. energy GeV	Mean intensity Particles per sec.	Completion date
Brookhaven proton synchrotron (COSMOTRON)	3	2.10^{10}	1952
Saclay proton synchrotron (SATURNE) .	3	10^{10}	1958
Princeton-Pennsylvania proton synchrotron	3	2.10^{12}*	1960
Berkeley proton synchrotron (BEVATRON	6	2.10^{10}	1954
Rutherford Laboratory proton synchrotron (NIMROD)	7	10^{12}*	1961/62
Russian A.G. proton synchrotron . . .	7	$\approx 2.10^{9}$*	1960
Russian proton synchrotron (Synchrophasotron)	10	$\approx 10^{9}$	1957
Australian proton synchrotron	10	10^{7}*	1962/63
Argonne zero gradient proton synchrotron	12.5	2.10^{12}*	1962
CERN proton synchrotron	28	2.10^{9}	1959
	25	3.10^{9}	
	6-10	10^{10}	
Brookhaven A.G. proton synchrotron .	30	$\approx 3.10^{9}$*	1960
Russian A.G. proton synchrotron . . .	50	$\approx 10^{9}$*	1961/62

Fig. 2 : Proton accelerators. (*) indicates target figures.

REFERENCES

(1) Physical Review, Vol. 88 (5), pp 1190-1196, 1952. « The Strong-Focusing Synchrotron, a New High Energy Accelerator » — E. D. Courant, M. S. Livingston, H. S. Snyder.

(2) CERN 59-29. « The CERN Proton Synchrotron, Part 1. Ch. I : Basic Principles of Alternating Gradient Synchrotrons. Ch. II : Design of the CPS and Choice of Parameters. Ch. III : Magnet. Ch. IV : The Radio Frequency Acceleration System. » — E. Regenstreif.

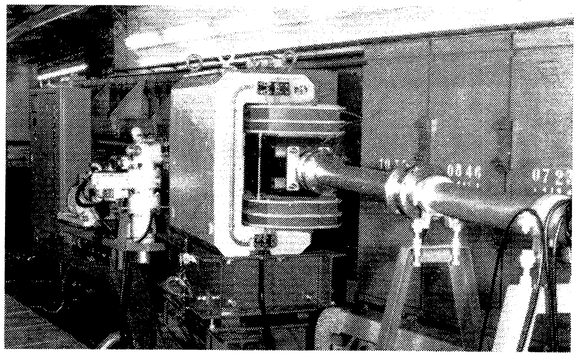
(3) CERN 56-21. « The Design of the Foundations for the Magnet of the CERN Alternating Gradient Proton Synchrotron » — J. B. Adams.

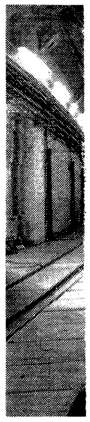
(4) CERN 59-26. Le Synchrotron à Protons du CERN, 2e partie. Chap. V : L'injection des particules. » — E. Regenstreif. (English version to be published.)

(5) CERN... « The CERN Proton Synchrotron, Part 3. » — E. Regenstreif. (To be published.)

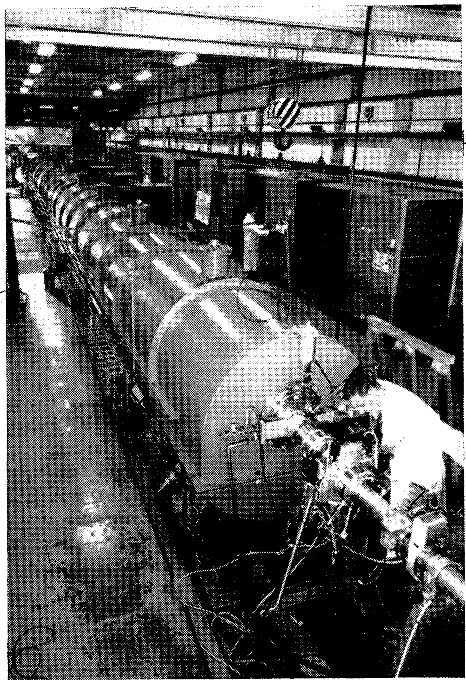
The PROTON SYNCHROTRON in pictures

3





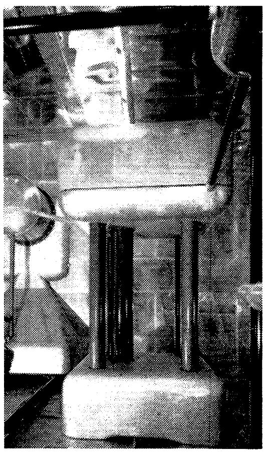
2

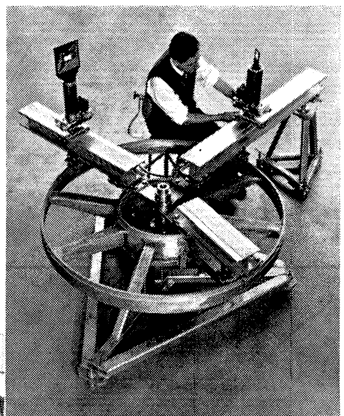


The pictures on these two pages show the working parts of the big 25 GeV proton synchrotron constructed by the European Organization for Nuclear Research (CERN) and officially inaugurated on 5 February 1960.

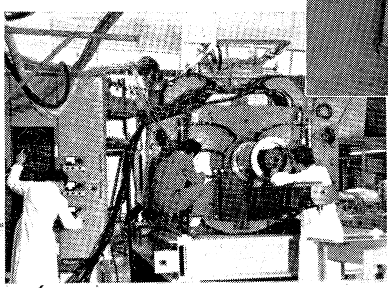
The proton synchrotron — the PS to those in the know — is a circular accelerator designed to give protons — the nuclei of hydrogen atoms — a very high kinetic energy with a view to using these submicroscopic particles as "missiles" to strike other atomic nuclei, penetrate them and give rise to events

1

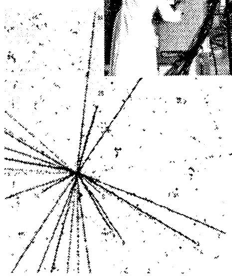




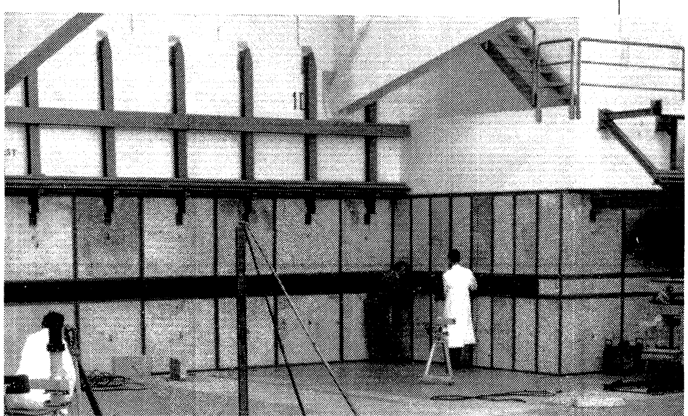
9

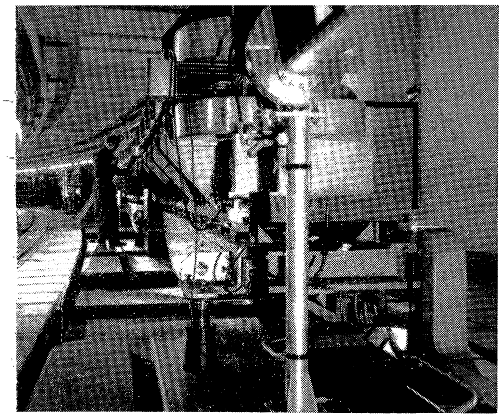


10

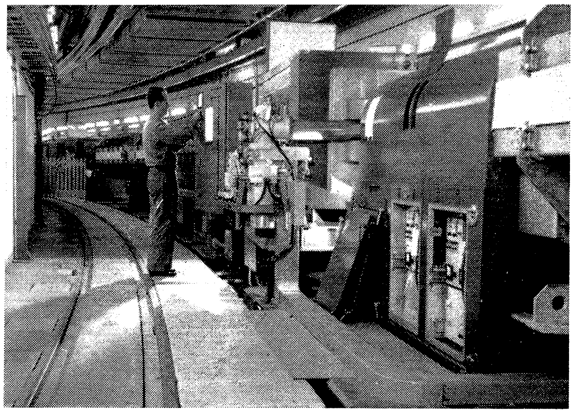


8

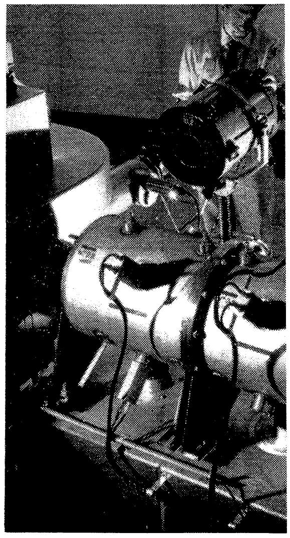




4



5



6

which provide the physicists with valuable information about the nature of matter.

The protons are produced from atoms of hydrogen gas by an ion source and then enter a "Cockcroft Walton" (**1**) pre-accelerator where they undergo initial acceleration up to 500 000 electronvolt (500 keV). After this they are again accelerated by a linear accelerator (**2**) which takes them up to a kinetic energy of 50 million electronvolt (50 MeV).

The particles thus reach the end of the injection system. In six microsecond they are injected through the inflector (**3**) into the synchrotron itself. The vacuum chamber (**4**), which is their "racecourse" is a ring-shaped structure 628 m in circumference.

There the protons are accelerated by electric fields when they go through the 16 accelerating cavities (**5**) located round the ring. In addition, a magnetic field produced by 100 magnet units (**7**) keeps the beam of particles focused on an orbit 200 m in diameter within the vacuum chamber of 14 x 7 cm cross-section.

Pick-up electrodes (**6**) contribute to this performance, which is a remarkable one in view of the above-mentioned dimensions and of the fact that in one second the protons go round the vacuum chamber 480 000 times.

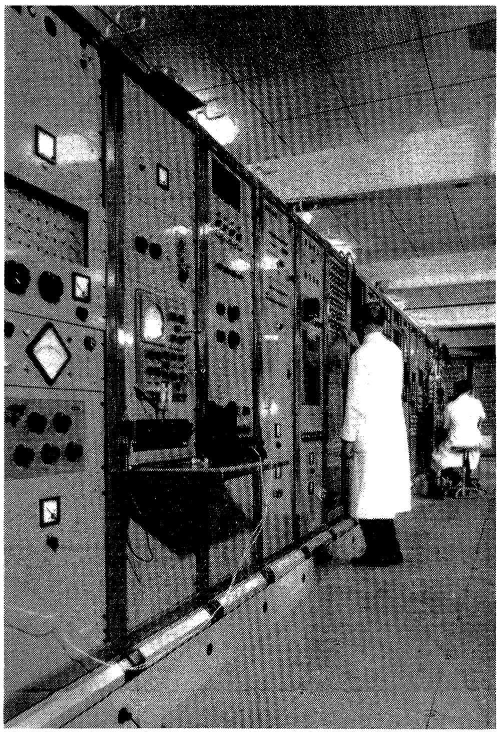
When the process of acceleration is finished the velocity of the particles reaches 99.94 % of the speed of light or about 300 000 km per second. At this point the energy is about 25 000 million electronvolt.

The beam of very high energy particles can then strike a target in the vacuum chamber itself. The remains of the atoms destroyed on impact, as well as the new particles created by the conversion of energy into mass, are observed by means of photographic emulsions.

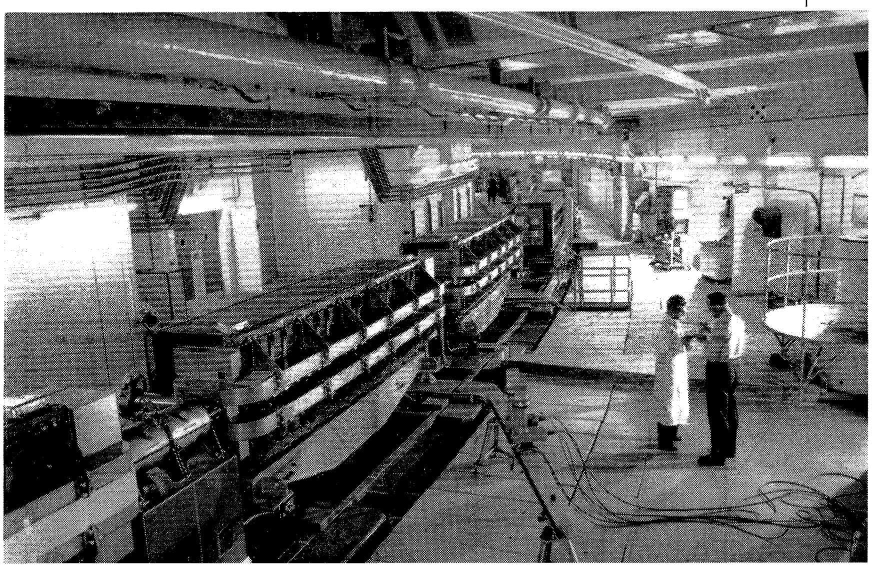
Alternatively, the beam may be ejected at a given point and guided into one of the two large experimental halls (**8**) towards the counters and the bubble chambers or cloud chambers by means of which they can be studied (**9** and **10**).

There is a certain danger in the radiation produced by the collision between the high energy protons and the atoms in their path, and strong baryte concrete shielding has therefore been installed as a protection (**8**). For the same reason, access to the machine is prohibited while it is in operation, and it is operated by remote control from control rooms (**11**) linked to the vital sections of the synchrotron by a network of cables and wires totalling some 3 600 km.

11



7



Main Features and Figures

GENERAL DATA

Maximum kinetic energy at 12 000 gauss	E_{max} = 24.3 GeV
Maximum kinetic energy at 14 000 gauss	E_{max} = 28.3 GeV
Magnetic radius	r_o = 70.079 m
Mean radius	r = 100 m
No. of magnet periods	M = 50
No. of magnet units $^1/_2$F $^1/_2$D	N = 100
No. of periods per superperiod	5
No. of superperiods per turn	10
Field index	n = 288.4
Operating mode	$\mu = \pi/4$
No. of betatron cycles per turn	6.25
Length of magnet unit	4.30 m
Length of normal straight sector	1.60 m
Length of long straight sector	3 m
No. of linear lenses	10 pairs
No. of non-linear lenses	20 pairs

MAGNET AND POWER SUPPLY

Magnetic field :	
at injection	147 gauss
for 24.3 GeV	12 000 gauss
maximum	14 000 gauss
Weight of one magnet unit	38 ton
Total weight of coils (alumin.)	110 ton
Total weight of iron	3400 ton
Rise time to 12 Kgauss	1 second
No. of cycles per minute (12 Kgauss operation)	20
Peak power to energize the magnet	34 600 kW
Stored energy	10^7 joule
Mean dissipated power	1500 kW
Magnet gap at equilibrium orbit	10 cm
Tolerances :	
Alignment tolerances vertically	0.3 mm rms
horizontally	0.6 mm rms
Tolerance on n inside the useful aperture	± 1 %
Tolerance for random errors in n between $^1/_2$F $^1/_2$D sectors	0.5 % rms

RADIO FREQUENCY

Energy gain per turn	54 keV
Stable phase angle	60°
No. of accelerating cavities	16
Length of cavity	2.3 m
Harmonic number	20
Frequency range	2.9 — 9.55 Mc/s
Power per cavity	6 kW

INJECTION

Injection energy	50 ± 0.1 MeV
Injection field	147 gauss
Length of linear accelerator	30 m
RF power	5 MW at 202.5 Mc/s during 200 μs

VACUUM SYSTEM

Vacuum chamber length	628 m
section	7 x 14 cm
Wall thickness (stainless steel)	2 mm
Vacuum pumps (Ø 10 cm)	4+67 stations
Pressure, better than	10^{-5} mm Hg

A Technical description

by **E. Regenstreif**
Division SP

This technical description of the CERN Proton Synchrotron comprises chapters on the magnet, the radio frequency accelerating system, particle injection, the power supply and survey problems. To those interested, it will provide some details on the problems involved in the construction of large accelerators of the proton synchrotron type.

The Magnet

The CERN PS magnet is an annular structure 200 m in diameter, made of 100 magnet units, each comprising a half focusing and a half defocusing sector rigidly joined together. Field free sectors are located between the units (Fig. 3). Each half-unit is composed of 5 adjacent magnets 42 cm long, called blocks. The block is a C-shaped structure of the open or closed type (Fig. 1). To facilitate the construction, the blocks are straight and provision is made for wedge-shaped air gaps between consecutive blocks. The magnet units (see p. 13) are placed on steel girders which rest on a reinforced concrete beam by means of a jack system. The concrete beam is supported by pillars cast into the sandstone rock under the site (Fig. 4).

From the beginning of the project, the efforts were centred towards designing linear fields. In theory, such a field can be obtained by means of hyperbolic pole pieces and a neutral pole. In fact, for constructional reasons the neutral pole has been dropped, but the hyperbolic shape has been maintained in the central part of the pole pieces and an effort has been made to keep the field linear over as wide a range as possible by trimming up the marginal region of the pole tips. This work was carried out on a series of models, most of them of full-scale cross-section, but reduced length.

The part played by the remanent field is negligible for medium and strong fields ; however, it raises a most serious problem for weak fields near injection where it has a major effect. It is indeed much more difficult to control and reproduce the remanent field than to make the field produced by the exciting current uniform. For proper operation of the synchrotron it is essential that the magnetic field at corresponding points of the magnetic units be the same to one part in a thousand. In the case of the CERN PS magnet, an error of 1/1000 in the guiding field from block to block corresponds at injection to a tolerance in the coercive force of about 0.1 œrsted. This is a very stringent condition to impose on a mass of iron of some 4000 tons ; it pointed to the imperative need to develop methods for the construction and assembly of the magnet so that it should be unaffected by the unavoidable lack of uniformity of the steel supply.

The magnetic field in the gap depends not only on the geometry of the magnet and the magnetic properties of the steel, but also on the rate of rise of the field. Studies on models have shown that in order to avoid field distortions due to eddy currents in the laminations, the thickness of the laminations should not exceed 2 mm ; in fact, the chosen thickness for the CERN machine is 1.5 mm.

Fringing fields at the ends of the units, transition fields between focusing and defocusing sectors and junction between blocks induce other distortions which have to be taken into account in calculating the orbits and establishing the parameters of the machine.

Finally "magnetic ageing", i.e. the changes which occur in the magnet iron as a function of time, may appreciably affect the operation of the magnet and make a delicate situation even trickier.

Manufacture of the Magnet

Even with a careful control of the steel supply, it would not be possible to construct a magnet complying with the very stringent specifications as to uniformity and homogeneity imposed by the AG principle. The problem of eliminating the effects of fluctuations in the magnet properties is therefore of primary importance. Two methods can be considered for this purpose. In the first place, the actual magnetic characteristics measured on the finished blocks may be taken into account and an attempt be made to determine the best arrangements for the blocks during the construction of the magnet. In the second place, the construction process may be so arranged as to incorporate in each block laminations from each batch of steel, thus decreasing variations in average properties from block to block. The second method proved to be quite efficient, so that the first one was used only to a small extent.

Low carbon steel, similar to that used for the manufacture of car bodies, has been chosen as the primary material. Special care was taken at the steel plant to control the chemical composition of the steel and to select the best ingots. The ingots then went through the normal hot-rolling sequence used for car body steel, and this was followed by a very carefully controlled cold reduction. The strip was then cut into sheets about 1 m square, stacked in piles and transferred to a special annealing furnace. After oiling, the sheets were packaged and sent to the block-maker. A large steel store was provided at the block-making factory, and piles

Fig. 1-2 :
The CERN proton synchrotron magnet : **1** is an "open section" block, **2** a "closed section" block. The mark **3** indicates the equilibrium orbit ; **4** is the coil window. Coils are also visible in cross-section in Fig. 2, in an "open section" block.

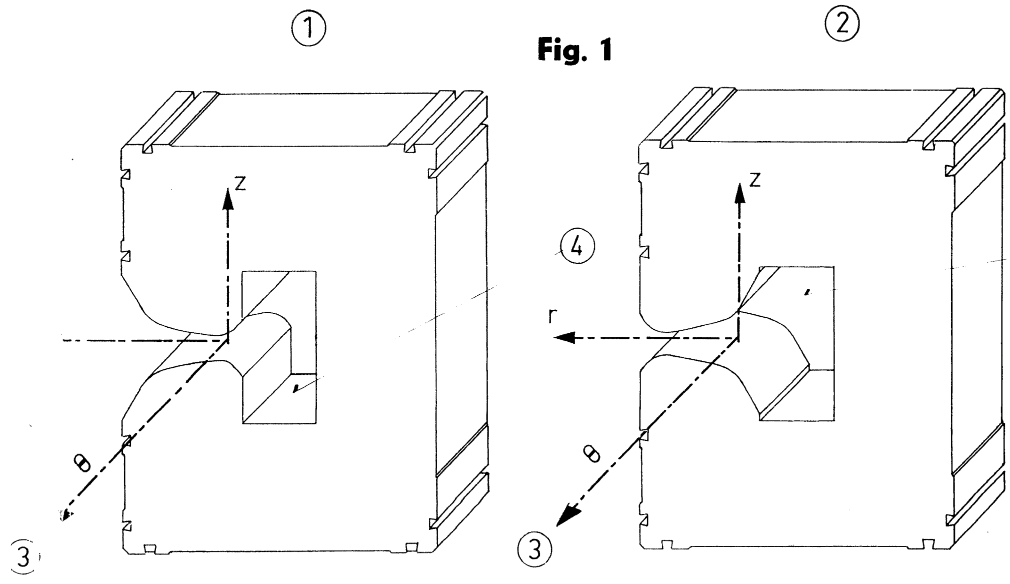


Fig. 1

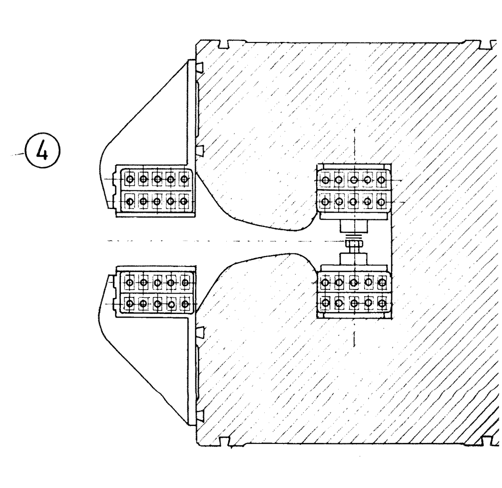


Fig. 2

of packages were built up on the floor of the store in such a way that the variation in coercive force between the packages was much less than ± 0.1 oersted, although between the piles the variations could be larger. There were the same number of piles as laminations in a block, and each block was assembled by taking the top lamination from each pile after the whole store was completely filled, passing these in order through the punching die and assembling them with paper insulation and araldite. Since each block contains one lamination from each pile and there are 264 laminations in a block, the variations in coercive force between the blocks are $\sqrt{264}$ times smaller than the spread of coercive force in a pile.

By means of very accurate measuring apparatus—a block measuring machine and a unit measuring machine—specially developed to check the magnetic properties of the steel, it has been found that for fields of 3000 gauss the r.m.s. deviation between the mean field measured along the axis of the block and the mean field measured along the axis of a reference block is 2×10^{-4}. At injection (147 gauss) the corresponding deviation is 5×10^{-4}, which is an extremely satisfactory result.

Coils

Every magnet unit is equipped with two coils, one wound on the upper pole piece and the other located on the lower pole piece. The coil consists of two pancakes (Fig. 2-4), each made of 5 turns of aluminium conductor 55 x 38 mm with a hole of 12 mm diameter for refrigerating water. The 400 pancakes of the magnet are electrically connected in series and in parallel for cooling purposes. The coils are insulated by a paper-mica-paper sandwich, vacuum impregnated with a polyester resin.

Lenses and Pole Face Windings

Deviations of the magnetic field from its ideal shape can be corrected with magnetic lenses and pole face windings.

The control of Q is effected by means of quadrupole lenses which have a purely linear effect. In order to act on non-linear effects, particularly at low energies and during the transition period, the design includes one pair of sextupole lenses and one pair of octupole lenses per super-period. These lenses are sufficiently short for a pair of them to be placed in a field free sector.

The RF Accelerating System

The main difficulty in designing the radio frequency system (fig. 5)

Fig. 3 :
Plan of the proton synchrotron and situation of the machine on the CERN site. The indications have the following meaning : **1** = central survey station and radio frequency control station ; **2** = radial tunnels ; **3** = radio frequency equipment room ; **4** = one of the 100 magnet units ; **5** = survey point ; **6** = main alternator ; **7** = laboratories ; **8** = main control room ; **9** = experimental halls ; **10** = linear accelerator ; **11** = 500 keV generator ; **12** = generator building, south, supplying power to experimental apparatus in **9**.
HF = accelerating cavity ; **T** = target ; **M** = ejection magnet ; **D** = permanent electrostatic deflector for beam injection ; **PD** = pulsed electrostatic deflector ; **P-Pd** = pick-up electrode ; **V-V'** = pumping valves ; **K_1-K_2** = double ejection magnet ; **K'_1** = simple ejection magnet ; **t_1-t_2** = ejection targets; **Q_1-Q_2** = quadrupole lenses ; **$S_{1,2}$-$O_{1,2}$** = sextupole and octupole lenses.

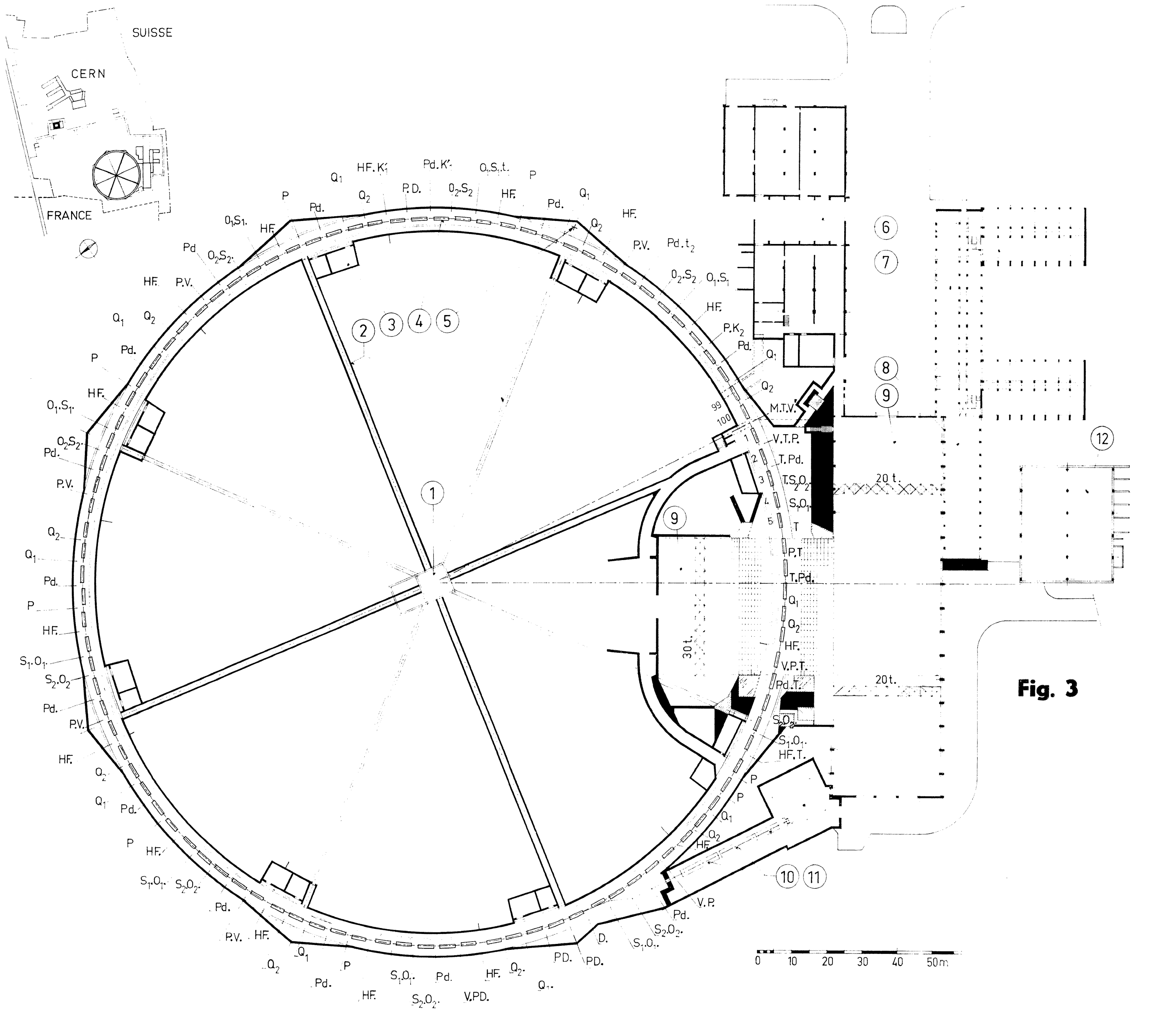


Fig. 3

to accelerate the protons in the CERN PS lies in he fact that it is necessary to ensure perfect synchronism between the motion of the particles, as conditioned by the instantaneous value of the magnetic field, and the frequency of the accelerating voltage. The accuracy required is of the order of 0.1 % at injection and 0.01 % at ejection, but in the neighbourhood of the transition energy where the phase jump occurs, the tolerance for frequency deviations is of the order of 0.0001 %. The deviations of the frequency from its theoretical value have an immediate effect on the radial excursion of the particles and once again it becomes essential to keep these within the narrow limits of the vacuum chamber.

Since the frequency programme has to follow the rise of the magnetic field, the first step in working it out consists in measuring the magnetic field in a reference magnet unit. This measurement is carried out by making use of the Hall effect and takes automatically into account the influence of the remanent field. The signal thus obtained is injected into an electronic computer which converts it into a signal corresponding to the frequency-field law. The output signal of the electronic computer acts then on the main oscillator ; this device gives a basic accuracy of the order 10^{-3} to 10^{-4} which has to be improved by a correcting signal originating from the beam. The r.f. signal obtained is then injected after adequate preamplification into the distributing amplifier placed at the centre of the machine, and from this cables of equal electric length transmit the r.f. voltage to the 16 accelerating stations placed around the ring.

Construction

At the present stage of computing techniques, analogue computers are used for accuracies up to 10^{-3}, whereas digital computers are used when the required accuracy exceeds 10^{-4}. Accordingly, there is a gap between 10^{-3} and 10^{-4} for which it is very difficult to develop analogue computers and where digital computers would not be economically justified. Moreover, in the case of the CERN PS it would be very difficult to use digital computers because of the speed of response required. The analogue computer had therefore to be used and developed to the utmost of its possibilities.

The CERN PS analogue computer is made of two main components, namely a device for the precise measurement of the instantaneous value of the magnetic field (Hall probe) and the computing system proper.

The reproducibility of this device is better than 0.1 % and the required accuracy of 1 % has been achieved. This figure can be brought down to 0.1 % by means of an auxiliary correction generator.

The oscillator contains as its frequency determining element a linear frequency-voltage converter. Fig. 6 shows the system in its basic form. The output of a conventional FM-oscillator is connected to a frequency meter giving an output voltage V' proportional to its input frequency f. This voltage is compared with the controlling voltage V produced by the Hall computer, and the difference is amplified and fed back to control the FM-oscillator.

The 16 accelerating stations distributed around the circumference comprise each : a) a resonator with an accelerating gap, b) an automatic frequency tuning device, c) a power amplifier. The resonator consists essentially of two push-pull quarter wave coaxial lines. The protons trav-

Fig. 4 :
Perspective of a ring section of the CERN proton synchrotron. **A** = magnet unit ; **B** = vacuum chamber ; **C** = screw jack ; **D** = concrete girder independent of the building and supported by **E** = elastic supports ; **F** = concrete column based on rock ; **G** bitumen ; **H** = 2 tons crane ; **I** = air-conditioning ; **K** = accelerating cavity ; **L** = octupole lens ; **M** = vacuum pump ; **N** = electrical cables ; **O** = magnet water cooling ; **P** = narrow gauge railroad track ; **Q** = earth ; **R** = rock ; **S** = temperature regulating water pipes.

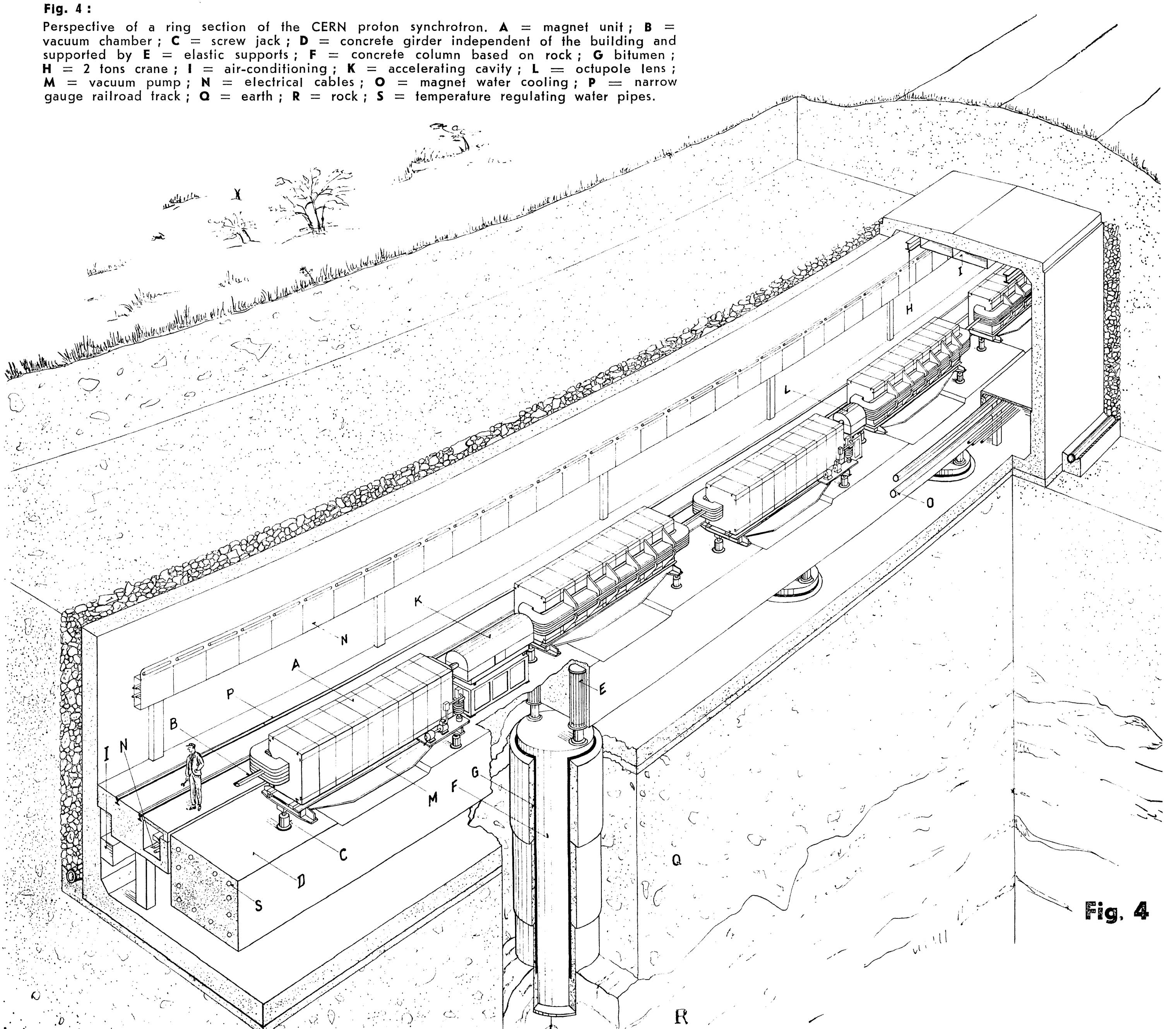
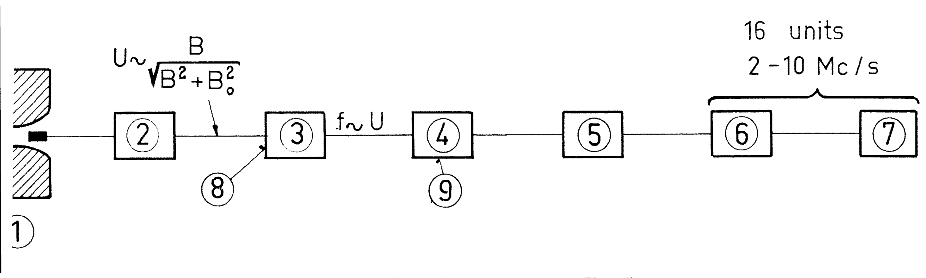
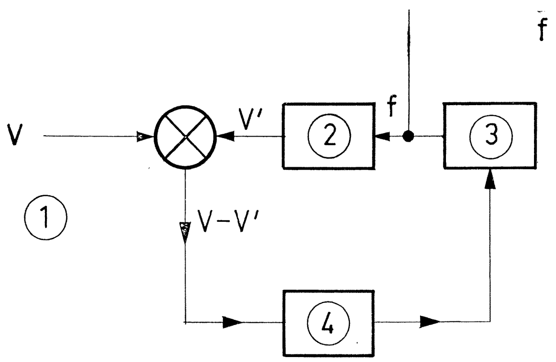


Fig. 4





el in the space enclosed by the inner conductor and are accelerated when going through the gap in the middle of the station. In order to house the resonating cavity in the section situated between two magnet units, its length must be reduced so as to fit into the available space ; this is done by loading the cavity with ferrite, which also permits automatic frequency tuning.

Fig. 8 gives a schematic cross-section of an accelerating cavity. The two quarter wave resonators are excited in phase opposition, allowing push-pull operation at the accelerating gap. One of the resonators is fed by a loop directly connected to the plate of the power supply, the excitation in phase opposition of the other resonator being effected by means of a figure of eight coupling loop. Each of the two ferrite cores contains 45 ferrite discs, 2.1 cm wide, glued together with araldite. The tuning of the cavity is achieved by means of the auxiliary magnet enclosing the cavity, the automaticity in tuning being achieved by acting on the d.c. current feeding this magnet.

The accelerating units (see p. 13) are placed in the ring, where the temperature is kept constant to ± 1° C. Under these circumstances, cooling by radiation and convection proves inadequate, and since cooling with compressed air is too complicated, the ferrite cores and all the power tubes must be water cooled.

The r.f. programme generation as described above does not work satisfactorily at high energies. The beam of particles itself has then to be used to control the frequency. If the closed orbit shifts radially due to an error in frequency, the whole beam shifts with it and radial pick-up electrodes can detect this shift. The output signal of the pick-up electrodes can then be fed into the computer as

Fig. 5 :
Basic diagram of the radio frequency accelerated system : **1** = magnetic field measurement ; **2** = Hall computer ; **3** = master oscillator ; **4** = phase shifter ; **5** = distribution amplifier ; **6** = power amplifier ; **7** = accelerating cavity ; **8** = signal from frequency corrector ; **9** = timing signal.

Fig. 6 (right) :
Basic diagram of the master oscillator : **1** = Hall computer ; **2** = frequency meter ; **3** = frequency-modulated oscillator ; **4** = d.c. amplifier.

an error signal to correct the accelerating voltage frequency. This is the principle of the "beam control". In practice, the whole system is complex, involving many servoloops using not only the beam shift as an error signal, but also the relative phase of the beam bunches and the applied r.f. voltage.

Particle Injection

Injection into the CERN PS is based on the use of a linear accelerator of the Alvarez type. The structure (Fig. 7) comprises 3 cylindrical resonant cavities, each of them consisting of a copper liner and a series of drift tubes along the axis ; these structures are placed in vacuum envelopes and fed with r.f. power. Protons produced in an ion source are first accelerated to 500 keV and then injected into the linear accelerator. The emerging 50 MeV beam is then deflected into the synchrotron proper. Injection occurs during 6 microsecond, corresponding to a single turn of the beam.

The Ion Source

The ion source is essentially made of a ceramics pot in which hydrogen is ionized by a 140 Mc/s pulse lasting 30 μs. The extraction voltage is 25 kV and lasts for about 10 μs. The required pressure inside the discharge tube is 10^{-3} mm Hg, the pressure in the accelerating region being 10^{-5} mm Hg. This led to a canal 3 mm in diameter and 15 mm long. The output current is 50—100 mA.

The 500 kV Set

The high voltage feeding the accelerating column is produced by a 600 kV, 4 mA Cockcroft-Walton generator, using a symmetrical cascade arrangement and driven by a 5 kVA 50 c/s transformer. Dry elements (selenium cells) are used in the rectifiers. The transformer as well as the cascade elements are housed in a 4 m high insulated cylinder filled with oil.

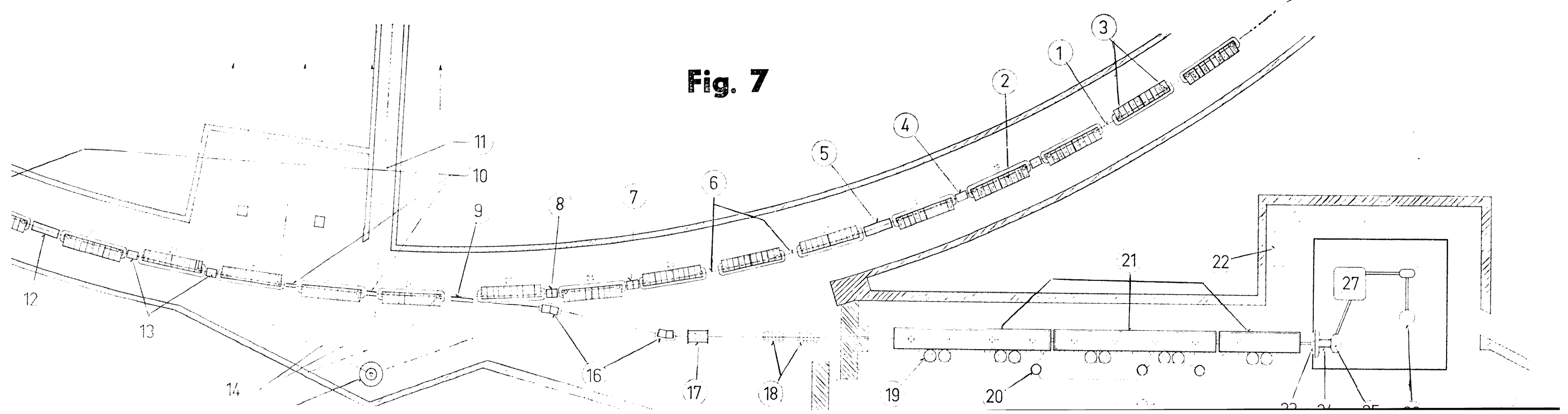
The accelerating column is made of 12 stainless steel discs, rigidly fixed to 13 porcelain rings. The length of the column is 83 cm, corresponding to a voltage gradient of 6 kV/cm. Uniformity in voltage distribution under steady state and transient conditions is obtained by means of an adequate resistor-capacitor chain. The entire 600kV set is accommodated in a Faraday cage 10.5 x 8.5 m and 6 m high.

The Accelerating Structure

Remanent field situation in the magnet, requirements of the r.f. accelerating programme and economic considerations led to the choice of 50 MeV for the injection energy into the synchrotron. It was decided to make the linear accelerator in the form of 3 cavities, respectively 6, 12 and 12 m long and giving output energies of 10, 30 and 50 MeV.

In the first tank there are 42 drift tubes of diameter decreasing from 140 to 62 mm ; the second and third tanks are provided with drift tubes

Fig 7.
Beam injection into the circular accelerator : **1** = equilibrium orbit ; **2** = magnet unit ; **3** = reference points for magnet units positioning ; **4** = quadrupole lenses ; **5** = accelerating cavity ; **6** = pick-up electrodes **7-8** = sextupole and octupole lenses ; **9** = permanent electrostatic deflection ; **10** = pulsed electrostatic deflection ; **11** = radial tunnel ; **12** = accelerating cavity ; **13** = quadrupole lenses ; **14** = magnet positioning network; **15** = survey point ; **16** = bending magnets ; **17** = debuncher ; **18** = quadrupole lenses ; **19** = vacuum pump and **(20)** = radio frequency generator for linear accelerator **21** ; **22** = controls ; **23** = buncher ; **24** = 500 keV accelerating column ; **25** = ion source ; **26** = high voltage generator ; **27** = high voltage platform.



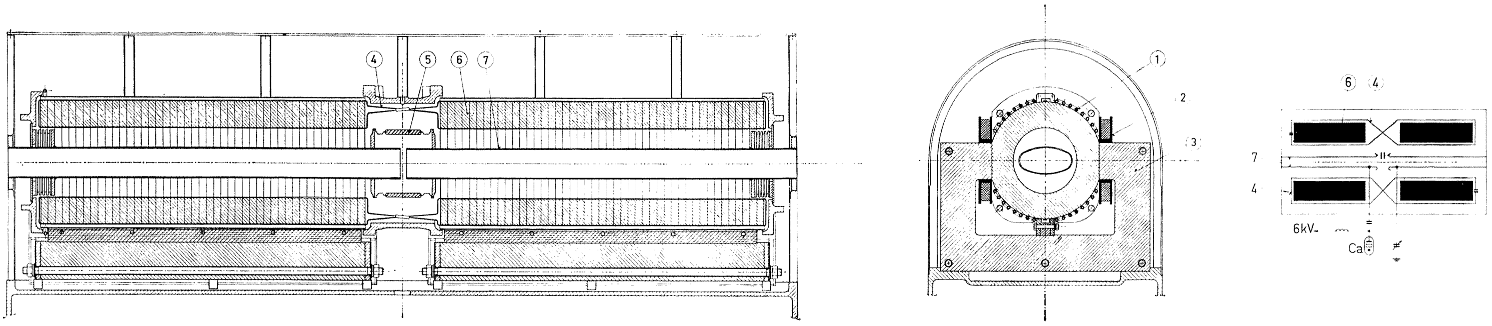


Fig. 8
Cross section and diagram of an accelerating cavity: **1** = pipes for water cooling; **2** = coils for **3** = magnet; **4** = coupling loop; **5** = insulating gasket; **6** = ferrite core; **7** = inner conductor.

of constant diameter. The lengths of the drift tubes increase towards the output in order to match the condition of synchronism.

RF Supply

The three tank design has implications on the r.f. supply problem. An amplifier system with a quartz oscillator is used as the common frequency generator. It is then reasonable to use a common amplifier up to the last stage before the output, with one output stage for each cavity.

Basic power figures are 1MW for the first cavity, 2 MW for the second, and 2 MW for the third cavity, at a frequency of 200 Mc/s, a pulse duration of 200 μs, and a repetition rate of 1 p.p.s.

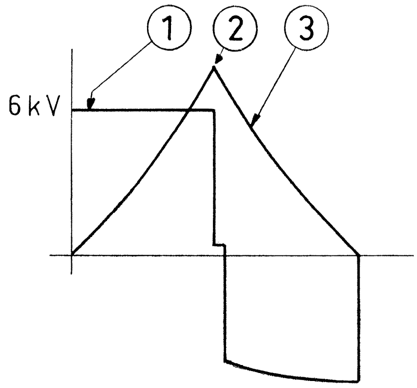


Fig. 9
Pulse cycle of the magnet: **1** = voltage; **2** = peak current: 6 400 A at 14 000 gauss, 5 000 A at 12 000 gauss; **3** = decreasing current.

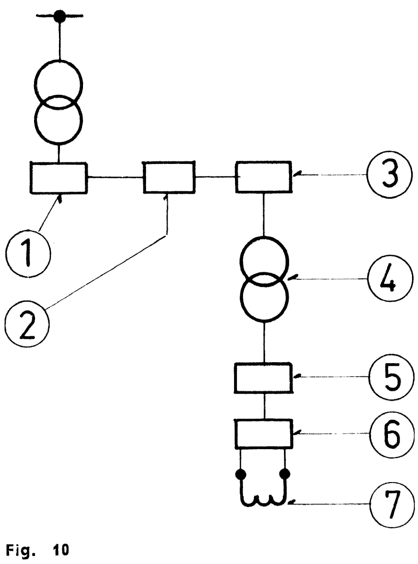


Fig. 10

Magnet power supply diagram: **1** = induction motor driving the generator **(3)**; **2** = flywheel; **4** = intermediate transformer; **5** = mercury arc power converter; **6** = filter; **7** = magnet windings.

Focusing

One of the main problems in the design of a linear accelerator is the radial defocusing of the beam associated with phase focusing.

In the CERN PS linear accelerator, focusing in the second and third tanks is provided by means of alternating gradient magnetic quadrupole lenses, operated in d.c. conditions. The first tank was initially operated with grids which have subsequently been replaced by pulsed quadrupoles.

Inflection

The difficulties in the inflection optics are due to the stiffness of the beam (i.e. its high energy), which makes its handling difficult, and to the irregular structure of the fringing field of the magnet. Moreover, the stringent tolerances on the position of the inflected beam imply equally stringent tolerances on the practical means by which inflection is effected, i.e. on the deflecting electric and magnetic fields.

Power Supply

To feed its machines in energy, CERN has a 20 000 kVA main substation installed on the site. The electrical power supply to the site. is effected by means of three 18 kV cables, each rated at 7 MVA. Power in the PS area is distributed from two substations, one of which is located in the PS power house and the other in the basement of the laboratory and office wing. The former supplies power at 6 kV to the magnet generator, at 3 kV to the r.f. system, and at 380/220 V to the experimental halls, the linear accelerator wing, the ring building and the central building.

A third substation is being built to feed the experimental apparatus and detection equipment.

The Magnet power Supply

Fig. 9 shows the desired shape of the pulse cycle in order to obtain a magnetic field in the gap rising linearly with time. The discharge of the magnet after the acceleration period should be as quick as possible, to minimize power losses and heating up of the magnet. Moreover, the discharge energy should be stored to avoid losses and large power fluctuation.

Fig. 10 shows the adopted solution An A.C. generator of the turbo type, driven by an induction motor at 3000 r.p.m., supplies 34 600 kW peak power to the magnet. A 6 ton flywheel on the shaft of the motor generator set is used to store the energy recovered from the magnet. Regulation of the driving motor is made by a Scherbius set. The development of the large mercury arc power converters has been a major task for industry.

The mean power absorbed from the feeding network is about 2000 kW at 6 kV.

Survey problems

It has been mentioned that if the magnet sectors are not correctly aligned, or the foundation of the magnet is not stable and misalignments occur, the closed orbit will be distorted from the ideal curve. If the ends of the magnet units are randomly misaligned between the limits ± 0.6 mm, the peak closed orbit deviation will reach 1 cm. In fact, the measuring tolerances for aligning the units have been aimed at 1 part in 10^6. From the point of view of the stability of the foundations, it is better to consider the spatial harmonics of the possible distortions. A second space harmonic amplitude of 3.8 cm would give a closed orbit displacement of 1 cm, and this is not very serious. The sixth space harmonic, however, is critical as an amplitude of 0.36 mm would result in a closed orbit deviation of 1 cm. This shows that the foundations of the CERN machine have to be very stable indeed.

Aligning the magnet units on the ring to an accuracy of 1 part in 10^6 is just feasible using the best modern theodolites and suitably aged invar wires. The ring building has eight radial tunnels, a central survey monument and eight survey monuments inside the building (Fih 3). A hexagonal system was deliberately avoided on account of the sensitivity of the machine to the sixth space harmonic distortion which would seriously amplify any errors in the triangulation survey. It is possible to set up the octagonal markers to the desired accuracy, and from the eight survey markers in the ring building the magnet units have been aligned using angle and length measurements ●

Questions and Answers about CERN

● **What do the initials "CERN" stand for?**

The initials "CERN" stand for **C**onseil **E**uropéen pour la **R**echerche **N**ucléaire (European Council for Nuclear Research), the interim body which has since been replaced by a permanent organization.

● **What are CERN's aims?**

CERN is devoted solely to fundamental nuclear research. In the terms of the Convention:

"The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto. The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available."

CERN also refrains from any activity aimed at the practical application of nuclear energy, such as nuclear reactors.

● **Who belongs to CERN?**

CERN now has thirteen Member States whose financial participation, according to national income, is shown in brackets:

Austria (1.93 %); Belgium (4.15 %); Denmark (1.99 %); France (21.22 %); German Federal Republic (19.52 %); Greece (1.17 %); Italy (10.09 %); Netherlands (3.85 %); Norway (1.61 %); Sweden (4.23 %); Switzerland (3.29 %); United Kingdom (25.00 %); Yugoslavia (1.95 %)

● **What is CERN's budget?**

The budgets since 1955 are given below in millions of Swiss francs:

1955 = 25.1	1956 = 39.6	1957 = 61.8
1958 = 56.5	1959 = 55.2	1960 = 65

● **How does CERN operate?**

Each Member State is represented in the Council by two delegates. The Council is assisted by a Finance Committee (one delegate per Member State) and a Scientific Policy Committee, the eight members of which are chosen for their scientific qualifications without regard to nationality. The Council takes decisions concerning the budget and general policy, but it gives the Director-General considerable responsibility for the direction of scientific work and for general administration.

● **Why was CERN established?**

The construction of a pure research institute as important as CERN, which has cost several hundred million Swiss francs, would have been too great a strain on the economy and even the technical resources of any European State which might have attempted it alone. By uniting their efforts, the Member States are able to provide CERN not only with the intricate and costly equipment required for modern physics research but also with the teams of experts no country alone could have gathered. The results of CERN's work, which is tending to push back the frontiers of science, are available to all because there is nothing secret about them.

● **What is CERN's equipment?**

CERN's basic equipment consists of two big accelerators. The first, the six hundred million electronvolt synchro-cyclotron (600 MeV) was commissioned according to plan on August 1st 1957. It is the third most powerful synchro-cyclotron in the world. The second accelerator, the CPS, is a twenty five thousand million electronvolt (25GeV) proton synchrotron. This machine is the biggest particle accelerator in the world. The two accelerators are designed to produce extremely high energy particle beams; aimed at appropriate targets, these beams give rise to nuclear reactions which afford an opportunity of accurately measuring elementary particles and help to further the knowledge of the internal structure of the atomic nucleus. Far from producing energy, CERN's machines, on the contrary, consume an enormous amount.

● **Who is the Director-General of CERN?**

Professor C. J. Bakker, formerly Director of the Zeeman Laboratory, Amsterdam, and of the Nuclear Research Institute of the same town.

● **What is the CERN staff?**

The staff is international. At 31st December of each year shown below, the total of CERN, including temporary staff and visiting scientists, was:

1953 = 30	1956 = 426	1959 = 969
1954 = 150	1957 = 610	
1955 = 286	1958 = 755	

● **What is the CPS?**

The **C**ERN **P**roton **S**ynchrotron. The CERN proton synchrotron consists basically of a huge fixed machine which accelerates nuclear particles viz protons, to a velocity very close to that of light viz 300 000 km per second. At this velocity the mass of the protons increase considerably and the accelerator in fact adds to their mass far more than to their velocity. When a proton is accelerated to 25 GeV its mass increases about 25 times. This projectile, which is at once minute, heavy and endowed with great power of penetration, is capable of breaking through the closely-knit structure of atomic nuclei and of giving rise to events which can be studied to yield valuable scientific information.

● **What is the cost of the CPS?**

The cost is estimated at about 120 million Swiss francs, or about 28 million dollars.

● **What is the maximum velocity of the accelerated particles?**

The velocity of a particle can never exceed that of light (about 300 000 km per second). When further energy is added to a particle moving at nearly this velocity, its velocity hardly increases. Instead, the energy is converted into mass, which thus becomes higher and higher, considerably. The laws of conventional mechanics then give way to those of relativity where energy and mass become synonymous in accordance with Einstein's law: Energy = mass x the square of the velocity of light ($E = mc^2$). (See also "Mass", columns on the right.)

The Physicist's Vocabulary

3×10^6: Mathematicians use this formula instead of writing figures followed by an impressive number of noughts. 10^6 stands for a million, i.e. 1 followed by 6 noughts. 3×10^6 means that 3 must be multiplied by 1 followed by 6 noughts. 10^{-6} means that one should divide by 1 followed by 6 noughts.

Alpha particle: A particle indentical to the helium nucleus. Emitted by a radioactive nucleus, it is also called an alpha-ray.

Amplifier: Electronic equipment for increasing either the size of an electric pulse or a difference in potential.

Annihilation: Disappearance of a particle and of an antiparticle e.g. an electron and a positron and transformation of their mass into energy. It is the inverse of materialization.

Atoms: Aggregates of elementary particles, viz neutrons and protons (nucleons) round which gravitate electrons whose number is equal to that of the protons when the atom is not ionized.

Beta Particle: Fast electron radiation emitted by a radioactive body.

Bubble chamber: Apparatus for detecting particles which leave a trail of bubbles as they go through a liquid which has suddenly been decompressed to make it boil.

Cloud chamber: Expansion apparatus which produces a cloud showing the trajectories of ionizing particles as supersaturated water vapour condenses on their track.

Cosmic rays: Radiation coming from all direction in space, formed of photons and various particles, some of which are very penetrating.

Decay: Transformation of a nucleus or particle into another nucleus or particle with emission of radiation.

Detector: Apparatus to detect radiation.

Dimensions of particles: The mean diameter of a nucleus is 10^{-13} cm and that of an atom is 10^{-8} cm. The size of the nucleus bears the same relation to that of the atom as a golf ball to a circle 7 km in diameter.

Electron: Negatively charged elementary particle gravitating round a nucleus, the number of electrons determines the chemical behaviour of the elements.

Electronvolt: The electronvolt or eV is a unit of kinetic energy acquired by a particle accelerated by a difference of potential of 1 volt. This energy is very small. A kilowatt hour, the usual unit of electric energy, is equivalent to 2.25×10^{25} electronvolt. In other words, about 22 billion billion electronvolt would be necessary to feed ten 100 watt bulbs for one hour... supposing that the kinetic energy of the particles could be easily converted into electric energy. In practice, multiple electronvolt units are used, particularly MeV (megaelectronvolt or one million electronvolt) or GeV (giga-electronvolt or a thousand million electronvolt). Like all other physical quantities, "electronvolt" is never spelled with an "s".

Elements: Specific atoms, for example copper, iron, aluminium, etc. There are about 100 chemical elements.

Energy: There are various kinds of energy: electrical, mechanical, thermal, etc., which can be converted into each other. Thus,

1 MeV $= 4.45 \times 10^{-20}$ kilowatt hour;
$= 1.6 \times 10^{-13}$ joule;
$= 1.6 \times 10^{-6}$ erg;
$= 3.83 \times 10^{-14}$ gramme-calorie.

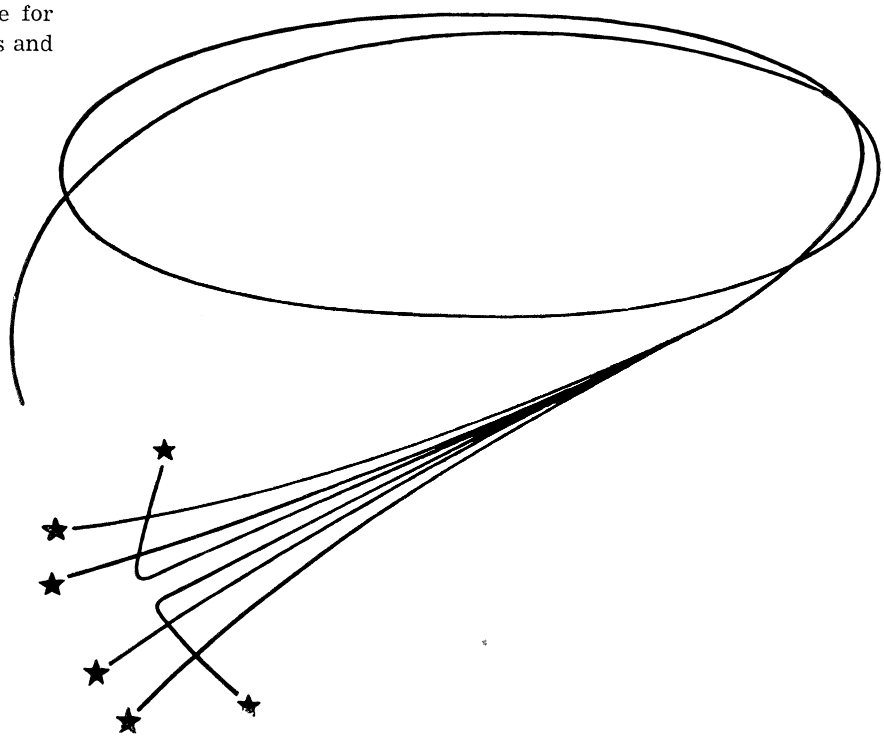
A rock at high altitude, the waters of a mountain lake, etc., possess a potential energy. Kinetic energy is due to the velocity of a body moving in relation to an axis of co-ordinates. A bullet fired from a rifle possesses a kinetic energy equal to half the product of its mass multiplied by the square of its velocity.

Equivalent energy: As a result of the above, the mass of a particle can be transformed into energy. The mass of a

The re-organization of the PS Division

The changeover in the PS Division from the construction to the research phase, which has taken effect on 1 January 1960, entailed the 1959 structure pictured on the back cover, to be replaced by four new groups until further notice :

1) **The Machine Group** is responsible for the operation, maintenance and development of the PS ;
2) **The Engineering Group** is in charge of the mechanical and electrical engineering projects associated with the machine ;
3) **The two Bubble Chamber Groups** are responsible for the design, construction and use of the liquid hydrogen bubble chambers, and the propane bubble chamber respectively ;
4) **The Accelerator Research Group** is responsible for investigating new ways of accelerating particles and studying new particle separators.



stationary proton is equivalent to about 1 GeV, exactly 931 MeV ; that of an electron to only 0.5 MeV.

Frequency : Periodicity. For wave radiation it is the quotient of the velocity of propagation (velocity of light for electromagnetic radiation) by the wavelength.

Gamma ray : Electromagnetic radiation with a very short wavelength which is very penetrating.

Geiger counter : An apparatus for detecting the number of ionizing particles that go through it.

Ion : An atom or group of atoms having acquired a positive or negative electric charge.

Ionization : The appearance of an electric charge in an atom or a group of atoms owing to either the loss of one or several electrons (appearance of a positive charge) or the fixation of one or several additional electrons (appearance of a negative charge).

Ionization chamber : Apparatus for measuring the intensity of radiation which goes through.

Mass : m_0 = the mass of a stationary particle, its relativistic mass is $m = \frac{m_0}{\sqrt{1-v^2/c^2}}$ where v is particle velocity and c the velocity of light.

It can be seen that if v = c the mass becomes infinite which would be absurd, therefore v is always smaller than c.

M : nucleon mass and, more precisely : Mproton = 1.6609×10^{-24} gramme or 1836 electron mass. Mneutron = 1.6622×10^{-24} gramme or 1839 electron mass.

Mesons : Elementary particles existing in cosmic radiation, artificially produced in the laboratory. Their masses are greater than that of an electron and smaller than that of a proton.

Neutron : Neutral elementary particle whose mass is nearly the same as that of the proton.

Nuclear : Relating to the atomic nucleus.

Nucleon : Elementary particle of the atomic nucleus which exists in two forms : neutron and proton.

Nucleus : Central part of an atom with a diameter of about 10^{-13} cm containing nucleons, viz positively charged particles (protons) and neutral particles (neutrons).

Photon : "Grain" of light of electromagnetic quantum.

Nuclear star : Nuclear decay inside a photographic emulsion ; it is only visible under a microscope.

Planck's constant : Equals $6.55 \cdot 10^{-27}$ erg. sec. The product of the constant multiplied by the frequency of the radiation is a quantum, a discontinuous quantity of minimum energy.

Photomultiplier : Apparatus including a photo-sensitive layer and an electron multiplier for detecting minute quantities of light.

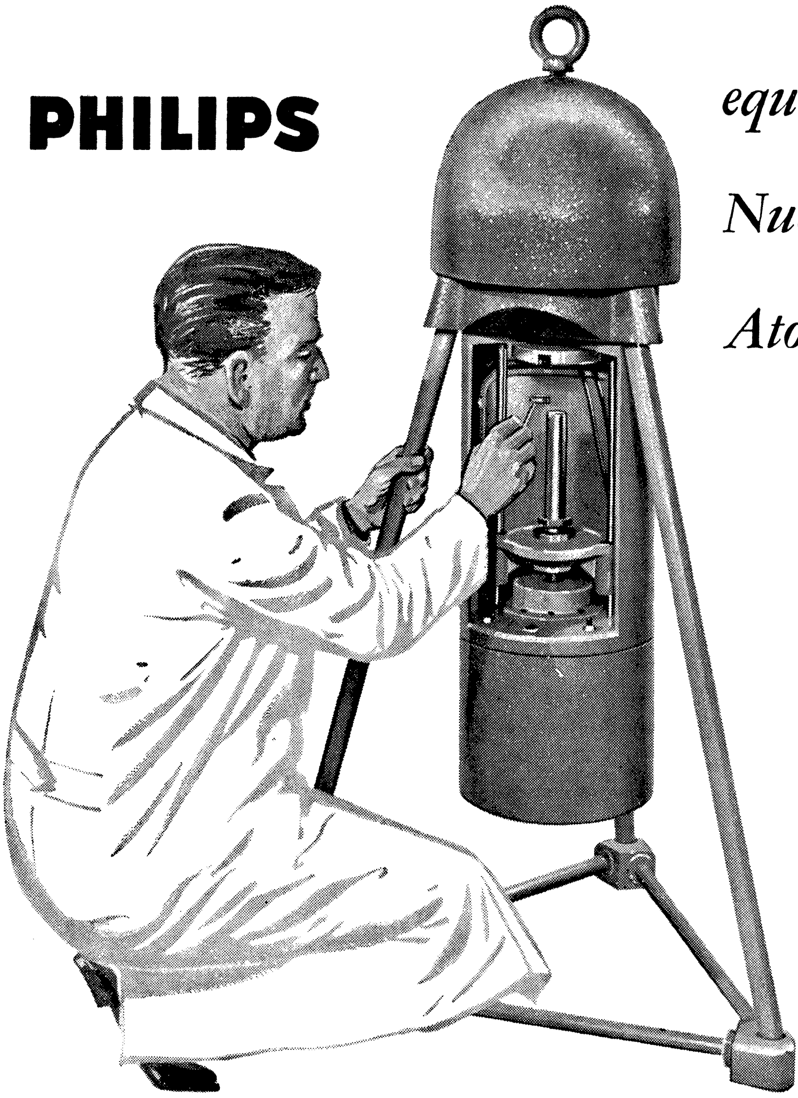
Proton : Positively charged elementary particle (hydrogen nucleus).

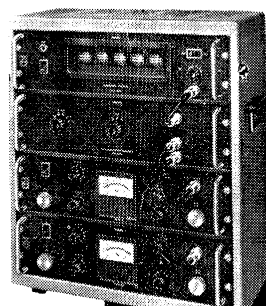
Radioactivity : Spontaneous decay of a nucleus with emission of charged particles.

Showers : Collections of positrons and electrons observed in cosmic radiation.

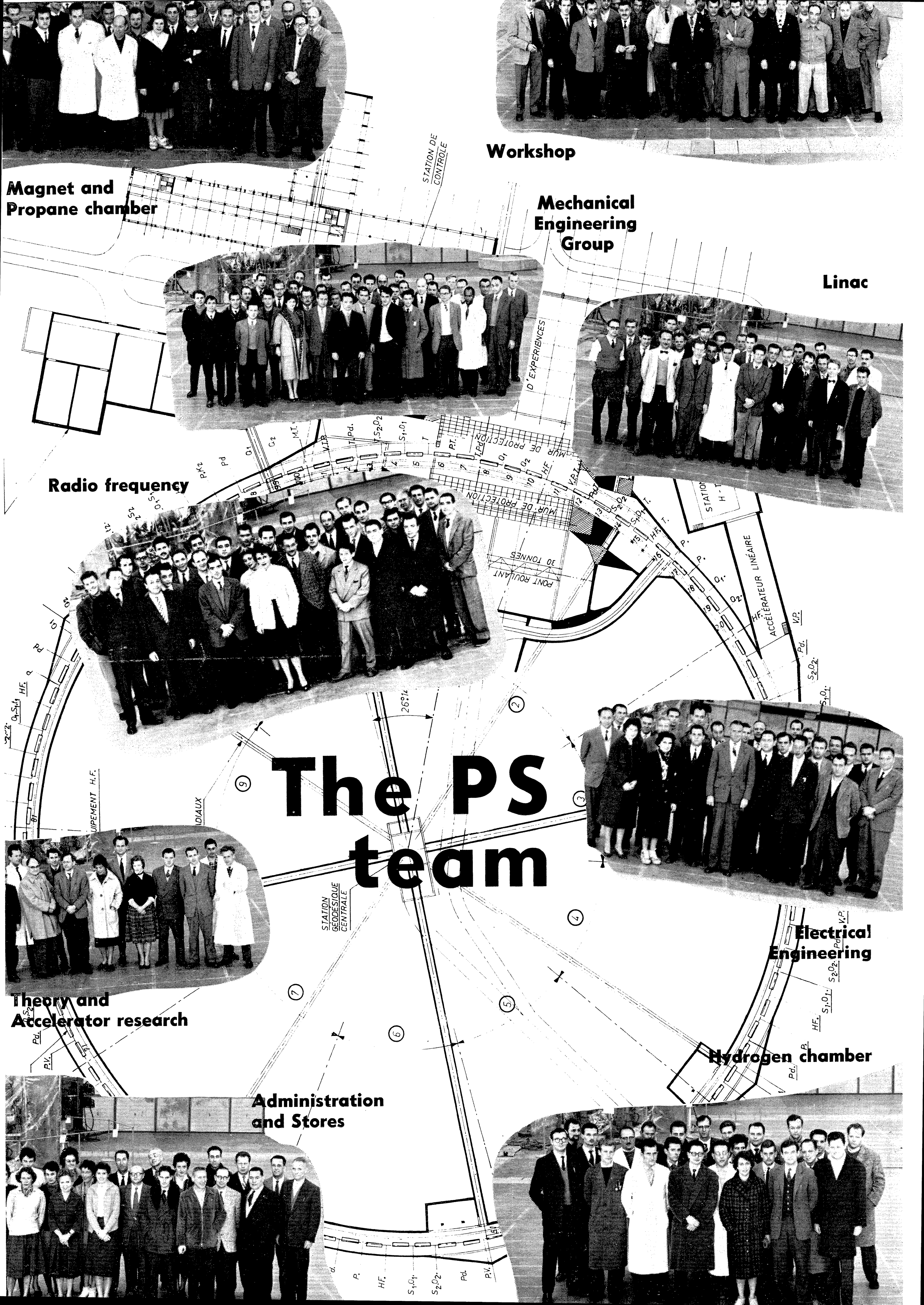
Spin : Certain particles are characterized by an angular rotation or spin momentum. This spin can only assume multiple discontinuous values of h/2 where h is Planck's constant.

X-Rays : Short wave electromagnetic radiation produced when a target is bombarded by electrons.





The PS team


Magnet and Propane chamber
Workshop
Mechanical Engineering Group
Linac
Radio frequency
Electrical Engineering
Theory and Accelerator research
Hydrogen chamber
Administration and Stores
STATION DE CONTROLE
D'EXPERIENCES
MUR DE PROTECTION
PONT ROULANT 30 TONNES
ACCÉLÉRATEUR LINÉAIRE
STATION GÉODÉSIQUE CENTRALE