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Contents

The cover photograph is an aerial view of the site for the construction of the intersecting storage rings. At the bottom of the picture can be seen some of the existing CERN buildings and, in particular, the wheel shape of the 28 GeV proton synchrotron with its experimental halls. The wedge shape of the ISR site extends to the first white buildings (top right) and is flanked on the right by the St.Genis-Geneva road and on the left by the Franco-Swiss frontier which also crosses between the ISR site and the site of the present CERN buildings.

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The European Organization for Nuclear Research, more commonly known as **CERN** (from the initials of the French title of the original body, 'Le Conseil européen pour la Recherche nucléaire', formed by an Agreement dated 15 February 1952), was created when the Convention establishing the permanent Organization came into force on 29 September 1954.

In this Convention, the aims of the Organization are defined as follows:

> **'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.'**

Conceived as a co-operative enterprise in order to regain for Europe a first-rank position in fundamental nuclear science, CERN is now one of the world's leading laboratories in this field. It acts as a European centre and co-ordinator of research, theoretical and experimental, in the field of **high-energy physics,** often known as **sub-nuclear physics** or the **physics of fundamental particles.**

High-energy physics is that front of science which aims directly at the most fundamental questions of the basic laws governing the structure of matter and the universe. It is not directed towards specific applications — in particular, it plays no part in the development of the practical uses of nuclear energy — though it plays an important role in the education of the new generation of scientists. Only the future can show what use may be made of the knowledge now being gained.

The laboratory comprises an area of about 80 ha (200 acres), straddling an international frontier; 41 ha is on Swiss territory in Meyrin, Canton of Geneva (the seat of the Organization), and 39.5 ha on French territory, in the Communes of Prévessin and St.-Genis-Pouilly, Department of the Ain.

Two large particle accelerators form the basis of the experimental equipment:

- a 600 MeV synchro-cyclotron,
- a 28 GeV proton synchrotron,

the latter being one of the two most powerful in the world.

The CERN staff totals about 2300 people.

In addition to the scientists on the staff, there are over 360 Fellows and Visiting Scientists, who stay at CERN, either individually or as members of visiting teams, for periods ranging from two months to two years. Although these Fellows and Visitors come mainly from universities and research institutes in the CERN Member States, they also include scientists from other countries. Furthermore, much of the experimental data obtained with the accelerators is distributed among participating laboratories for evaluation.

Thirteen Member States contribute to the cost of the basic programme of CERN in proportion to their net national income:

Austria (1.90 %)
Belgium (3.56 %)
Denmark (2.05 %)
Federal Republic
  of Germany (23.30 %)
France (19.34 %)
Greece (0.60 %)
Italy (11.24 %)
Netherlands (3.88 %)
Norway (1.41 %)
Spain (3.43 %)
Sweden (4.02 %)
Switzerland (3.11 %)
United Kingdom (22.16 %)

Poland, Turkey and Yugoslavia have the status of Observer.

The 1966 budget for the basic programme amounts to 149 670 000 Swiss francs, calling for contributions from Member States totalling 145 860 000 Swiss francs.

Supplementary programmes, financed by twelve states, cover construction of intersecting storage rings for the 28 GeV accelerator at Meyrin and studies for a proposed 300 GeV accelerator that would be built elsewhere.

Major construction work begins this summer on the site of the intersecting storage rings (ISR). The July issue of CERN COURIER is devoted exclusively to information about this new project for sub-nuclear physics research at CERN. The issue is divided into four main sections — a general introduction to the project; a description of the storage rings themselves; the preparatory work which has been done; the research which the project will make possible.

Why build
Intersecting Storage Rings?

Why are intersecting storage rings being built? What are they? What can they tell us which we cannot get from the existing accelerators?

This article attempts to answer these questions in a general way (without going far into the details of the project itself) and to convey some understanding of the significance of this large and unique development in the research facilities at CERN.

The scientific research at CERN, and at the many other accelerator Laboratories in Europe, the USA and the USSR, is concerned with the investigation of the nature of matter. It attempts to find out what are the basic bits and pieces of matter, what are their properties, what is the nature of the forces acting between them, what are the laws which control the way in which the basic units behave.

In less than a century, our knowledge of matter has increased almost unbelievably. First came the understanding of the atom — the, by now, familiar picture of the tiny solid core, or nucleus, surrounded by a cloud of orbiting electrons. The understanding of the properties of the electron cloud, in theory at least, explained the whole of chemistry, and opened the door to many technological developments (the electronics industry in particular) which are now part of our every day lives.

This era of 'atomic physics' was followed by the investigation of the nucleus itself. Its major constituents were identified as the proton and neutron, and considerable knowledge has been gained about how they combine to build up the various nuclei. From this 'nuclear physics' era have come the radio-isotopes in use in medicine and industry, the nuclear reactors now making a significant contribution to the electricity power in several countries, the work on thermonuclear fusion, and also, unfortunately, the atomic weapons.

At present we are in the early days of a third stage — sub-nuclear physics — where the properties of the constituents of the nucleus and of a large number of other particles on a sub-nuclear scale which have recently been discovered, are under investigation. Well over 100 of these particles have been identified (though the definition of the word particle has become a little blurred) and to describe the ways in which matter behaves, it has proved necessary to invoke four different kinds of force. There is a general feeling that this complexity, which confronts us at present, stems from our lack of understanding and that, as we probe deeper and deeper, the picture will be greatly simplified.

More energy

This increasingly fine breakdown of matter has been made possible by having available beams of particles of increasingly higher energy. The development of the techniques to build high energy particle accelerators has been the main contributor to pursuing this research.

The need for high energy can be seen in several ways. First, obviously, to get at the bits and pieces of the nucleus we must be able to provide sufficient energy to break up the nucleus. Secondly, in accordance with the famous Einstein equation, $E = mc^2$, which says that energy and matter are interchangeable, if we are to 'create' particles of high mass for investigation we must have high energy available. Thirdly, to probe matter down to smaller and smaller distances involves probes of higher and higher energy. It is possible to 'see' objects of about the same size as the wavelength of the radiation used to observe it, and the higher the energy the smaller the wavelength. For example, using ordinary light (which has an energy of a few electron-volts) it is possible to 'see' objects with dimensions greater than one tenth of a thousandth of a centimetre (10^{-4} cm); with the high energy beams of electron microscopes, distances down to 10^{-7} cm can be analysed. The highest energy accelerators now in operation (33 GeV at Brookhaven and 28 GeV at CERN) can analyse matter down to distances of about 10^{-14} cm.

Many of the questions posed by the research with the existing accelerators call for a higher energy machine to find the answers. To take just one example, which seems to have received a great deal of attention — the search for more massive particles which may underlie the present 'elementary' particles may be successfully pursued using accelerators with an energy of a few hundred GeV. The long list of particles which have been found, has, comparatively recently, been simplified into orderly groups in an analogous way to the orderly array of the elements in the Periodic Table of the chemists in the last century. We can expect to find some underlying reasons why this order prevails (as we did with the Periodic Table). One suggestion is that there exist three particles, given the name 'quarks', which generate the many particles we now observe. If the quarks do in fact exist, their mass is estimated to be at least 5 GeV (more than five times heavier than the proton) and is probably much greater. This is beyond the reach of the existing accelerators, but it may be possible to produce and observe them at a much higher energy machine.

The next step

For these reasons, the sub-nuclear physics community in Europe have been pressing for the construction of an accelerator of energy 300 GeV which was recommended in the 'Report of the Working Party on the European High Energy Accelerator Programme' (the Amaldi Report) in 1963. The CERN Council is supporting preliminary studies and possible sites for the machine are under investigation. It is hoped that approval for this project will be forthcoming in 1967 and it is regarded as the cornerstone of sub-nuclear physics research in Europe from the middle of the next decade.

Colliding Beams

The second major recommendation in the Amaldi Report was the construction of storage rings for operation in association with the existing CERN 28 GeV proton synchrotron. The project was approved at the Council Meeting in December 1965 and all the CERN member States with the exception of Greece are participating in the project. The storage rings are to be built on land, allocated to CERN by the French Government, immediately across the border from the Swiss site where the 28 GeV machine is located.

The storage rings are designed to enable two high energy proton beams to be brought into head-on collision. This process could take us into a new realm of particle phenomena.

To understand why this is so, let us consider an analogy often used in describing elementary particle interactions — colliding billiard balls. When a billiard ball (the cue ball) is fired at a stationary ball (the target ball), the stationary ball is pushed in the general direction in which the cue ball is travelling and the cue ball also continues moving in the same direction. The 'crack' as the balls collide is comparatively quiet. The energy of the cue ball goes into moving the target ball, into its own continuing motion and into the 'crack'. But if two players were able to fire two identical balls with the same speed directly at one another so that they met exactly head-on, the whole of their energy would go into a much louder crack since the balls would not take up energy by continuing in motion.

How does this relate to particle collisions? With a conventional accelerator such as the CERN proton synchrotron, particles are fired with high energy at stationary target particles. For example, a proton from the accelerator can be directed onto a stationary proton in a liquid hydrogen target. A large part of the energy of the accelerated proton goes into moving the particles which result from the collision, in the direction of the bombarding proton (like the movement of the cue and target balls after collision). A much smaller part goes into the transformation of the protons, and into the creation of other particles. It is this smaller part (the 'crack' in our billiard ball analogy) which is the useful energy for our research. At the CERN PS, from an energy of 28 GeV, about 7 GeV is useful. (An approximate equation which gives this useful energy is $E = \sqrt{(2 E_A)}$ where E is the useful energy and E_A is the energy of the particles from the accelerator. Thus a 300 GeV machine will give about 24 GeV useful energy.)

We can now see the advantage of colliding beams. If we can make two accelerated protons collide head-on, the whole of their energy will be useful energy (like the loud crack from our billiard balls hitting head-on). With the storage rings at CERN, two 28 GeV beams will be brought into collision and all of their $28 + 28 = 56$ GeV energy will be useful. To achieve such a high useful energy with a conventional accelerator the machine would have to have an energy of 1700 GeV — an accelerator 60 times as big as the PS, having a diameter of seven miles.

Obviously, there are some disadvantages in experimenting with colliding beams otherwise these enormous gains in energy would always be used and we would not pursue higher energy conventional accelerators. The first of these limitations is that only proton-proton collisions can be examined. At a conventional accelerator beams of many types of particle (π-mesons, K-mesons, etc.) can be produced and used for experiments. To look only at what happens when very high energy interactions take place between colliding protons will be useful but limited compared with what can be done with the various types of beam from the conventional accelerator, and is not expected to give a comprehensive picture of very high energy phenomena.

A further limitation is that the collisions will take place within the vacuum vessel of the machine itself. As opposed to the conventional accelerator, where beams can be extracted from the machine so that the interactions occur at a conveniently situated target surrounded by virtually any desirable configuration of particle detectors, observation of the interactions in the storage rings will be restricted by the presence of the vacuum chamber and magnets of the storage rings. Nevertheless the rings will be constructed so as to allow some space for large particle detectors to be brought close to the region where the collisions occur.

Why storage ?

Another major limitation leads us to describe why we have storage rings and don't just build another PS and fire the accelerated beams at one another.

At the conventional accelerator, the particles in the target (for example, in liquid hydrogen) are effectively packed close together, and up to a million million interactions per second can be made to occur in the target if the whole of the accelerated beam is shot into it. But when two beams are fired into one another, the particles are not packed as closely and the number of interactions is much smaller. The difference can be compared to firing a shotgun at a solid target where all the pellets hit, and firing a shotgun at the pellets coming from another shotgun where the two sprays may pass through one another with few pellets colliding.

It is to improve this situation that the protons will be stored to increase the density of the colliding beams. A pulse of a million million protons from the PS will be fed into one of the storage rings. In this ring, the magnetic field will be kept constant and the protons in the beam will, in principle, stay circling indefinitely. Many more pulses will be added to the first, a process known as stacking, until an adequate number of protons are stored in the beam. This stacking procedure will be repeated in the second ring with the protons orbiting in the opposite direction. To stack as many as 400 pulses in each ring may take up to an hour (though when the PS improvements are completed this may be reduced to nearer 5 minutes) and it should then be possible to do colliding beam experiments with these two beams for several hours. It is hoped to achieve a collision rate of about 100 000 per second. This is low compared with the million million mentioned above but it is comparable with 'secondary beam' experiments at a conventional accelerator.

Other important factors should be mentioned in connection with the storage of the particle beams. First a very high vacuum (10^{-9} torr, a thousand times lower than at the PS and about a thousand million times lower than normal atmospheric pressure) is necessary to limit the scattering and loss of particles from the beam due to collisions with gas molecules in the vacuum vessel. Even higher vacuum is needed in the regions where the beams are brought into collision, so that the experimenter has a better chance of observing the effects of genuine proton-proton collisions as opposed to collisions with residual gas molecules. Also the magnets will have to be made with extreme precision and aligned very carefully in the ring. They have to hold proton beams in a vacuum vessel about 15 cm wide and 5 cm high for, possibly, several hours. In this time the particles will travel distances of about a thousand million miles.

The two rings are concentric and are slightly distorted from a perfect circle so that they intersect in several places. It is in these intersecting regions that the collisions can be made to occur.

We now move from this general description of the ideas behind the project to more detailed, technical consideration of all that is involved in the intersecting storage rings.

Table 1: Main Parameters of the ISR

Number of rings	**2**
Circumference of rings	**942.66 m**
Number of intersections	**8**
Intersection angle at crossing points	**14.7885°**
Maximum energy of each beam	**28 GeV**
MAGNET (one ring)	
Maximum field at equilibrium orbit	**1.2 T**
Maximum current to magnet coils	**3750 A**
Maximum power dissipation	**7.04 MW**
Number of magnet periods	**48**
Number of superperiods	**4**
Total weight of steel	**5000 ton**
Total weight of copper	**560 ton**
R.F. SYSTEM (one ring)	
Number of r.f. cavities	**6**
Harmonic number	**30**
Centre frequency of r.f.	**9.53 MHz**
Maximum peak r.f. voltage per turn	**20 kV**
VACUUM SYSTEM	
Vacuum chamber material	**low carbon stainless steel**
Vacuum chamber inside dimensions	**160 x 52 mm^2**
Design pressure outside intersection regions	**10^{-9} torr**
Design pressure inside intersection regions	**10^{-10} to 10^{-11} torr**

Description of the project itself

K. Johnsen

The previous article has described the main advantages of colliding beam experimentation and explained why a set of intersecting storage rings, added to the CERN PS, is to be built. We shall in the present article give a general description of this project — its basic parameters, how it works, its expected performance — and outline some of the major difficulties foreseen in the construction.

The ISR consists of two concentric rings of magnets, each rather similar to the magnet ring of the PS itself, placed in a circular underground tunnel located about 200 m away from the PS on the land that France has put at CERN's disposal as an extension of its site (see figure 3 on pages 134 and 135). The fields in the two magnet rings are constant and of such strength that protons ejected from the PS (with a maximum energy of 28 GeV) can circulate continuously, and in opposite directions in either ring, in a very good vacuum. The rings are not exactly circular, but distorted so as to intersect in eight places. The main parameters for the rings are listed in Table 1.

Let us follow the protons from their leaving the PS till they collide with each other in the ISR where the effect of their collisions is studied. This will serve both to explain the working principle of the device, and to describe the various parts of which the whole project is composed. Frequent reference can be made to Figure 3 and to the schematic drawing of the arrangement of the rings in Figure 1.

From PS to ISR

After the protons have been accelerated to their full energy in the synchrotron, a fast ejection system, similar to the one already developed (see CERN COURIER, vol. 5, no. 10 (October 1965) p. 148) will kick the protons out of the PS a little upstream of the injection area of that machine. A beam transport system will guide the particles on to the French part of the site in the direction of the ISR. About half way, there is a fork and, depending on whether a bending magnet is switched on or not, the pulse will go left or right and thus enter one or the other of the two rings. The two beam lines from the fork not only steer the particles in the right horizontal direction, but also bend the beam upwards, as the beam level in the ISR is higher than in the PS.

In the right branch of the beam transport system there is another branching off point. This makes it possible to steer particles past the ISR and directly into an experimental area for conventional 28 GeV physics. We shall for the moment leave that part of the project and concentrate on the storage rings proper.

Let us consider only one of the rings, for instance the anti-clockwise one being fed from the right branch of the beam transport system. The beam will be deflected into the vacuum chamber of the ring so that it initially travels very near to its inside wall. To achieve this deflection, the beam will pass two septum magnets and finally a fast inflector. This inflector is somewhat different from the ejection magnet in the PS since it requires a very sharp cut-off of its fringe field in order not to cause any disturbance to the protons which are already stored in the ring. For this purpose, a movable shield will be positioned just in front of the gap when the magnet is excited. The fact that the kicker can have a rather small gap also helps to reduce the problem of the fringing field.

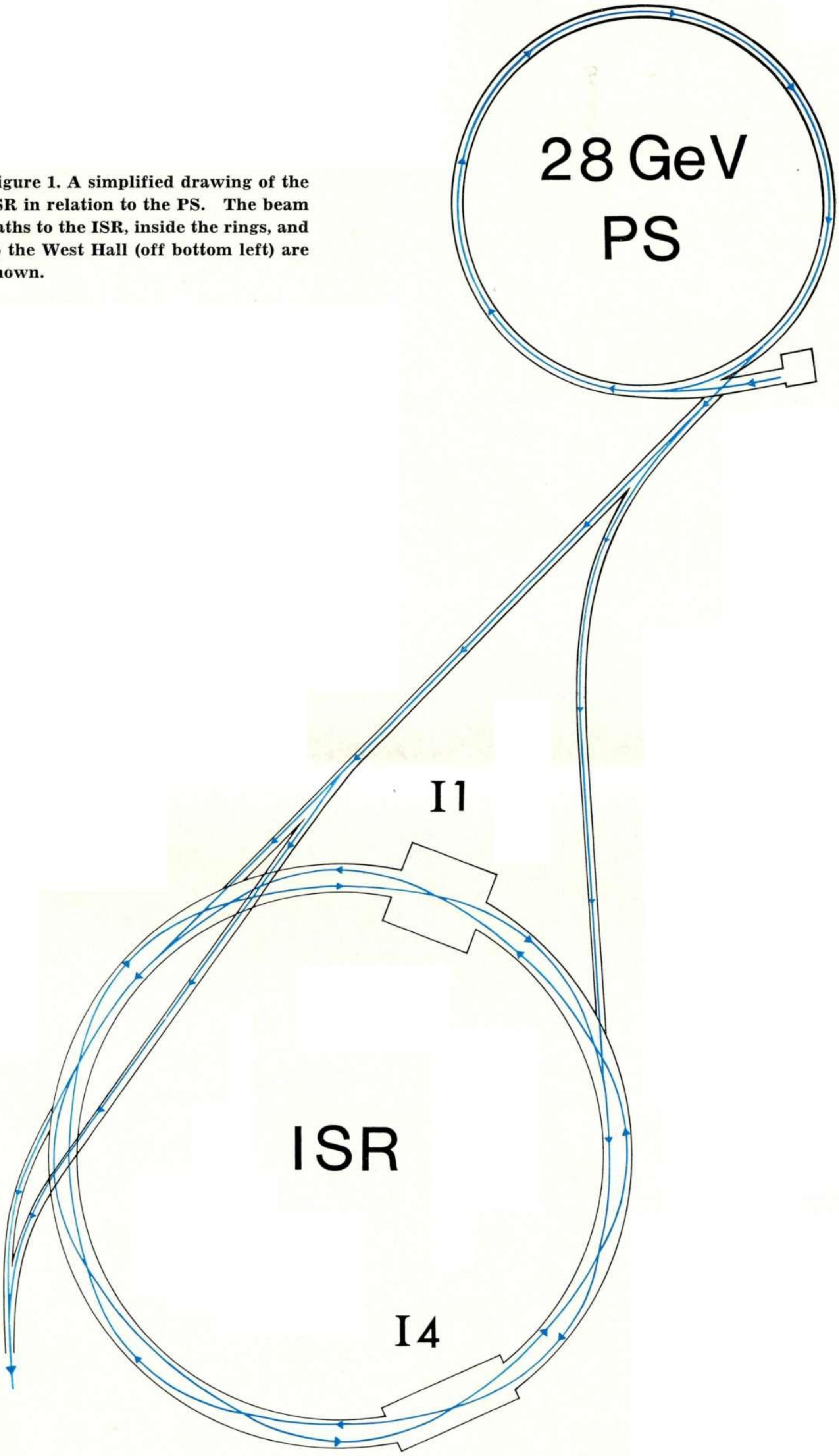
Stacking

The storage ring has a radio-frequency system that is already switched on when the protons are injected. The purpose of this system is to accelerate the particles just enough to move them from their injection orbit near the inner wall of the vacuum chamber to an orbit nearer the outside of the chamber where the particles are being stacked. The object of this stacking was explained in the introductory article: one pulse in one ring in collision with only one pulse in the other ring would give a very small proton-proton interaction rate, and many PS pulses are required in each ring to get a reasonable rate for experimentation.

When the r.f. system has moved the particles from the injection orbit to the stacking orbit, the ring is ready to take the next pulse from the PS. The r.f. system then moves these new particles to where it earlier dropped the previous pulse. In this way, the pulses are put nearly, but not quite, on top of each other. In fact there will be 0.1 to 0.2 mm between the pulses, adding up to a width of about 60 mm for 400 pulses, which is the maximum stack width provided for. This is based on the present maximum performance of the PS, and 400 pulses would mean about 4 x 10^{14} stacked protons, equivalent to 20 A circulating beam current. The improvements programme of the PS will change some of these figures. It will probably not change the maximum stacked current, but it may reduce by as much as a factor 10 the number of pulses required to reach a desirable circulating current, and thus reduce the stacking time from about one hour for the two rings to say 5 minutes.

The r.f. system will not be required to produce unusually high accelerating voltages, but the stacking process requires very large voltage variations, from about 20 kV at the beginning of the acceleration down to some tens of volts at the end. The acceleration must be slow in order to make the stacking efficient, and the stability of the r.f. system has to be very high.

Figure 1. A simplified drawing of the ISR in relation to the PS. The beam paths to the ISR, inside the rings, and to the West Hall (off bottom left) are shown.



Magnet Structure

The main guiding fields of the two rings are provided by 264 magnet units. Superficially the magnets look rather similar to the PS magnets. There are, however, a series of important differences. In particular, the magnet ring structure is basically rather different because of the strong superperiodicity (see the caption to Figure 2) of four imposed by the necessity to deform the rings to make them cross. The superperiodicity is further amplified by the need for very long straight sections for experimentation. Many possible magnet ring structures were thoroughly examined before the final choice was made. This lay between two which seemed almost equally good. One provides a 15° crossing angle between the intersecting beams and the other a 9° crossing angle. The former one has been chosen mainly on the grounds that it offers slightly more flexibility for the positioning of experimental equipment. The structure is shown in Figure 2.

In a normal accelerator, the full aperture of the vacuum vessel is needed only at injection since the beam is focused to a smaller cross-section as it is accelerated. But in the storage rings the particles are already at full energy when they are injected and we have the very strict requirement that the good field region in the magnets at maximum field must extent over the whole aperture, i.e. over 150 mm horizontally. This requirement has to be met with flux densities in the saturation region in parts of the magnet. Also, the same requirement must be met with the magnet at medium field levels in order to be able to do experiments at energies below the maximum one. The solution chosen is to put heavy pole face windings on the magnets with many possibilities for current adjustment. This also enables us to change both the field gradient and the variation of the field gradient across the gap somewhat and thus to gain flexibility in operating conditions, which may be of particular importance under conditions of space charge effects.

Vacuum requirements

The size of the vacuum chamber must be such as to accommodate the full stack and any wiggles there may be on the orbits due to misalignment of the magnet units. The chamber must further leave some room for the injection and the clearance between the injection orbit and the stacked beam. During the time between two fillings (which it is hoped may be as much as a day), there is also a small increase in the beam size due to scattering from the residual gas in the chamber. This also requires space. Taking all these requirements into consideration, we have arrived at an aperture of 150 mm horizontally and 50 mm vertically.

As described earlier the stacking process may take as long as an hour. Furthermore, in order to have a good utilization factor of the machine, the stacked beam should 'live' for a long time compared with the time it takes to produce it. This means that we want a beam life-time of the order of a day. In order to achieve this, a very good vacuum is required. (Valuable experience in this kind of ultra-high vacuum work has been gained on the electron model provided with a system evacuated down to the order of 10^{-9} torr.) This will be obtained by using an all-metal system, baked out in situ, and pumped by titanium sputter and titanium sublimation pumps.

In the interaction regions where experimentation will be carried out, the problem of background (protons interacting with molecules of gas remaining in the vacuum vessel as opposed to protons in the on-coming beam) imposes even stricter vacuum requirements and cryopumping suitable for these regions is being

The various components of the ring are as follows:

F	**focusing magnet**	**T**	**Terwilliger quadrupole**
D	**defocusing magnet**	**Q**	**skew quadrupole**
P	**pick-up station**	**S**	**sextupole**
V	**sector valve**	**H**	**horizontal field magnet**

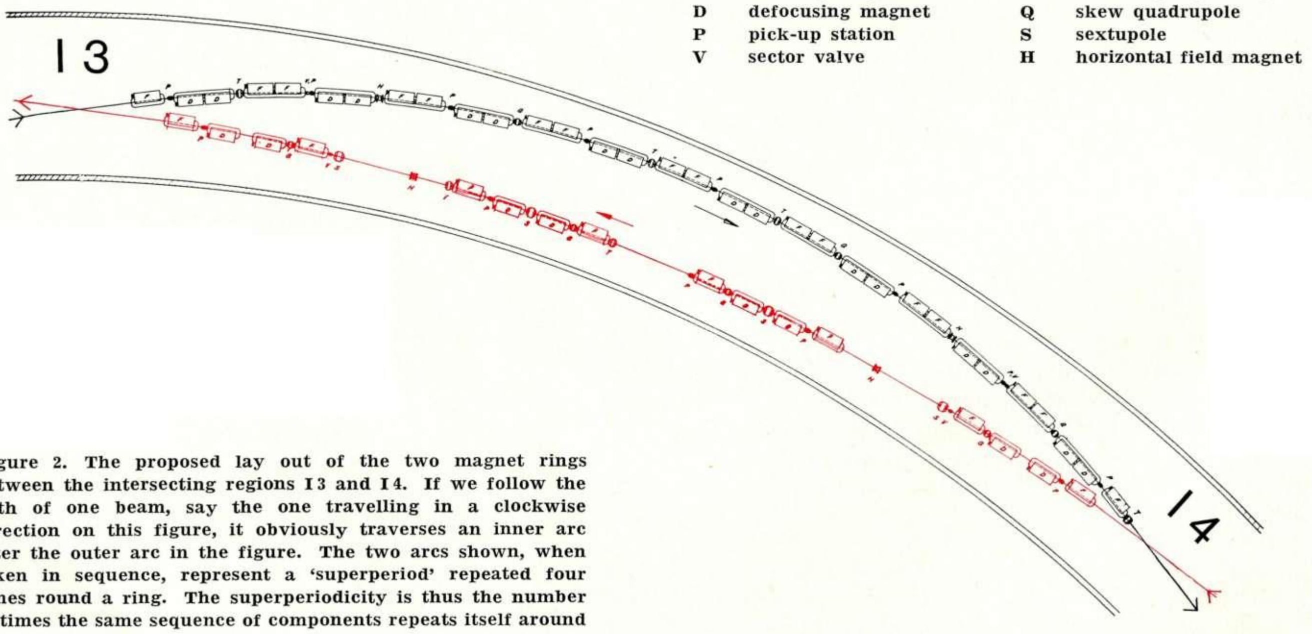


Figure 2. The proposed lay out of the two magnet rings between the intersecting regions I 3 and I 4. If we follow the path of one beam, say the one travelling in a clockwise direction on this figure, it obviously traverses an inner arc after the outer arc in the figure. The two arcs shown, when taken in sequence, represent a 'superperiod' repeated four times round a ring. The superperiodicity is thus the number of times the same sequence of components repeats itself around the ring.

developed with the hope of reaching vacua of the order of 10^{-11} torr.

Beam crossing regions

We have so far described how it is planned to stack very high proton currents in the ISR and the major requirements this imposes on the various components. Both rings are filled in the same way and we shall now have a closer look at what happens in the interaction region, in other words what the device looks like to the physicists who will carry out experiments.

When the maximum current of 20 A circulating protons has been reached, each beam looks like a horizontal ribbon of about 60 mm width and 10 mm height. These two ribbons will cross at 15°, thus forming a volume of 140 cm^3 within which proton-proton collisions will take place. In fact, taking a current of 20 A in each beam and a total p-p cross-section of 4×10^{-26} cm^2 the interaction rate inside such a volume is 10^{-5} per second. This is very low compared with a few times 10^{11} per second in a target at the PS, but is a reasonable rate when considered as taking place in a detector fed by a secondary beam from an accelerator. For experiments where the large momentum spread of the full beam is a disadvantage, it will be possible to reduce this spread considerably and still have a workable interaction rate. For instance, we could work with one tenth of the beam mentioned above, when we would have only 0.2 % momentum spread, and still have an interaction rate of 10^3 per second. In this case there is the further advantage of having reduced the volume within which the collisions occur, in other words reduced the size of the source of the interactions.

The volume can also be reduced in other ways with less reduction of the interaction rate, but involving less momentum discrimination. We shall not go further into this here. A further flexibility which is envisaged is to change the crossing angle by a system of superconducting magnets.

It is around one or more of eight such crossing points that the experimental equipment will be placed. Two of these crossing points (number 1 and number 4) will be provided with a considerable enlargement of the tunnel width, in fact they will serve as two experimental halls making room for very large experimental equipment with assembly areas attached as seen in Figure 3. A further description of experiments and experimental techniques is given on page 138 of this issue.

Performance limitations

One might ask what limits the performance of the device to the figures quoted above. It seems that the main limitation may be in the output characteristics of the PS beam. Although the improvements programme will increase the total beam current from the PS, it is much less likely to increase the phase space density appreciably. Consequently, it may not be possible to reach much higher stacked beam currents, although, as already mentioned, the stacking time will be reduced.

The design aim for the total beam current is, in any case, so high that other limitations may make themselves felt, in particular when combined with the long life-time required. For instance, if the beam neutralized itself (by producing an equal number of negatively charged electrons from the gas remaining in the vacuum vessel) the estimated space charge limit would be only around 10 A. Clearing devices to sweep the electrons away will be incorporated so that the beam will not neutralize and then the normal space charge limit will move to above 100 A. 'Resistive wall instabilities' are serious and must be avoided; Landau damping will be provided through proper shaping of the field. Also the interaction of one beam on the other is being carefully studied. The linear effect is not serious for the beam currents we are talking about, but it is more difficult to prove that long-term non-linear effects will not be serious. Life-time experiments with non-linear excitation have been performed on the PS and computations have been carried out on digital computers. Analytical approaches have been tried, and scaling laws applied to the results coming from the experiments carried out on the electron rings at Stanford and Novosibirsk.

None of these investigations have given evidence that we shall be in difficulties. Some give encouraging evidence that we can expect long life-times, certainly long enough to ensure successful experimentation on the ISR. It is nevertheless something of a problem that clear-cut stability criteria are very difficult to find.

In conclusion, the design performance figures as quoted seem feasible. We are, however, sufficiently near to basic limitations that we cannot count on much better performance.

28 GeV Hall

One aspect of the project was mentioned briefly earlier in the article: the role ISR will play in facilitating conventional 28 GeV physics. A special 28 GeV hall which forms part of the project, will about double the area now available for experiments at the PS. Proton beams can reach this area either directly from the PS (via a by-pass tunnel going under the ISR tunnel) or via one of the storage rings. The advantage of going via the storage ring lies in the great flexibility in duty cycle for all desirable mean intensities. (After storing a beam in a ring, protons can be spilled to an experiment over a long period of time or, at the other extreme, a very intense beam can be spilled in one short burst.) The advantage of having the by-pass also is that protons from the PS can be brought to the large hall when the ISR are running on colliding beam experiments or are inoperative during installation of experimental equipment, etc.

Time schedule and cost

The project is now well under way. The preparatory building work has gone on for some time and the contractor for the main civil engineering work has been chosen. He starts working this summer on the site. Model work and prototype construction is in progress for most of the ISR components and detailed specifications are being prepared to be ready for tendering for most large items during 1967. The plans foresee the commissioning of the device in the middle of 1971. The estimated cost is 332 million Swiss francs (at 1965 prices).

Preparatory Work

The following section covers some of the preparatory work which has been done on the ISR project. It includes information on the major components of the storage rings (magnet, r.f., vacuum, beam transfer and site work), research using the electron storage ring at CERN, and storage rings elsewhere.

1. Magnet

L. Resegotti

The magnet system of the ISR is in principle similar to that of the CERN proton synchrotron but has some distinctive features because of the requirements of particle accumulation and of colliding beam experiments. In particular, the gradient of the magnetic field in the gaps is a linear function of the radial coordinate and is different in focusing and defocusing magnets, which form separate units. Also, the pole face windings, besides compensating for the effects of steel saturation, have to enable a wide variety of field conditions to be set up.

The main ISR magnet is more than twice as long as that of the PS, but the construction programme requires it to be built in approximately the same time. Therefore, it was necessary to acquire the information for its design and to investigate materials and manufacturing methods at an early stage. It was also essential to ensure the interest and collaboration of manufacturers so that time schedules and budgets could be realistic.

A preliminary survey of the European steelmakers revealed several who were prepared to supply very-low-carbon steel sheet to magnetic specifications. Semi-automatic measuring equipment was prepared in the magnet laboratory at CERN and a large number of samples from seven firms have been measured. Although most of the satisfactory samples came from small scale tests rather than from the production plants, it became clear that the problem was generally understood.

Considerable interest was found among the manufacturers of large electrical machines for the construction of the magnets. Most of them favoured the use of large welded stacks of punched laminations (similar to the magnets of the AGS at Brookhaven) rather than small glued blocks; savings in cost and time are claimed. In order to gain experience with this method of construction, two full-scale model cores were built, corresponding to short magnet units, of the focusing and defocusing type respectively.

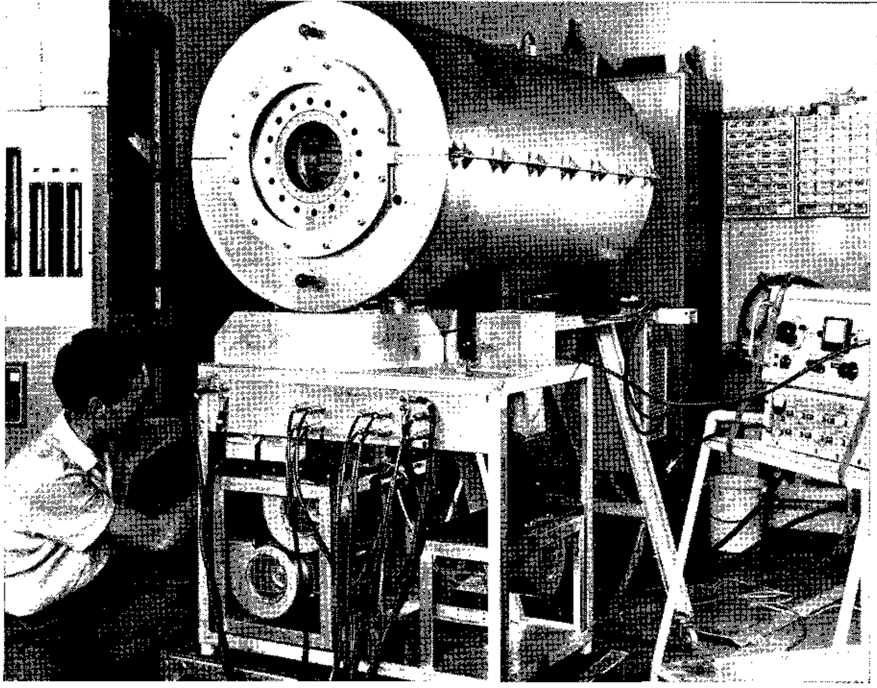
The problem of the design of the magnet profiles also had to be faced at an early stage. Computer programs were developed which could solve the two dimensional magnetostatic problem to the required accuracy by the method of successive approximations and these programs were used to arrive at the shape of the pole profiles for the two models.

In the production of the steel sheets, the influence of various treatments on the geometrical, mechanical, and magnetic properties was studied. The construction of the cores gave valuable experience on the problems of precision stacking of the laminations, of compensation for variations in thickness and of welding under pressure. The profiles of the dies had to be checked and adjusted with extreme care in order to meet the required tolerance of 0.01 mm. A measurable amount of twist appeared in both cores, but was within tolerable limits.

A set of excitation coils and one of pole face windings were ordered, and a suitable power supply was installed. The experience obtained in constructing and mounting the pole face windings, which are a rather delicate item,

CERN/PI 13.6.66

Magnetic field measurements in progress on magnet model 2 for the ISR; the model is similar to magnet model 1 (pictured in CERN COURIER, vol. 5, no. 12 (December 1965) p. 192) but is a defocusing sector. The large coils which power the magnet can be seen running along its length (2.5 m). Construction and testing of the two model magnets have provided valuable experience for the final design.



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Tests in progress on a model r.f. cavity for the storage rings. Six of these cavities will be used in each ring of the ISR to accelerate the protons from the orbit where they are injected to the orbit where they will be stored. The radio-frequency system in the ISR is different to that of a conventional synchrotron and preliminary work with the model cavity and its associated electronics is serving to develop the necessary techniques.

lead to substantial improvements in the design. Tests on radiation damage for many types of insulating resins, which could be used for the pole face windings, were carried out at a reactor centre. The tests have lead to the rejection of some types of resin and have indicated others which will probably be satisfactory.

The field distributions in the central part of the models were found to be in good agreement with the computed values. Also, end effects were measured at several excitation levels. These results provide the necessary guidance for the final design. In the near future, the two models will be mounted together on a girder and excited by a common coil, to simulate a long magnet unit of the storage rings. Methods of alignment will be tested and junction effects will be measured. Before the end of the year, all the information needed for the final design should be gathered.

Design work is now moving onto the auxiliary lenses (quadrupoles, sextupoles, etc.) while the detailed study of the lay out of the whole system is continued.

2. Radio-frequency system

W. Schnell

The purpose of the radio-frequency system is to accelerate the particles from the injection orbit to the stacking orbit where they are deposited by turning off the r.f. voltage. This stacking cycle is repeated every time a new set of particles is injected from the PS until a sufficient number of protons has been accumulated.

Two different kinds of stacking schemes are possible and there will be provision for both at the ISR. In the first scheme, the position where the particles are deposited is changed by a small amount in successive cycles, until all the space available inside the vacuum chamber (about 60 mm) is filled. In the second, the injected particles are always dropped at the same place. Those particles that have been deposited earlier are automatically displaced inwards an appropriate distance by the r.f. If the stacking process is conducted with maximum efficiency about 20 A of circulating current can be accumulated.

The r.f. system differs rather substantially from that of a normal accelerator. At the beginning of each stacking cycle, a maximum total accelerating voltage of about 20 kV per turn is required to give sufficiently rapid rates of acceleration so that the injected pulse will be stacked before the next pulse arrives from the PS. However, towards the end of the stacking cycle the voltage must be reduced to values below 100 V per turn, in order to cause the minimum of disturbance to the beam already stacked.

This large variation of voltage, which has to be carried out in a smooth and well-controlled fashion, is all the more difficult to achieve as the r.f. cavities are heavily loaded by the accelerated beam. The latter problem is overcome by means of strong negative feed-back that makes the accelerating voltage virtually independent of beam-loading.

A first high-power, full-size model has been built and tested. Full r.f. voltage has been achieved while the negative feed-back system has been working with full loop-gain. Difficulties encountered with higher order resonances in the loading capacitor of the cavity have been overcome by suitable design of the capacitor and by the use of ferrite that has little influence at the fundamental frequency of the r.f. cavity (10 MHz) but provides damping at higher frequencies.

The mechanical design of a second model, intended to be the last prototype prior to construction of the actual ISR cavities, has been completed and construction of this model is about to begin.

The requirements of precision, stability and freedom from noise of the low-power control systems for r.f. frequency and amplitude are rather stringent. The frequency may be generated either by a programming system alone or with the help of a phase-lock system similar, in principle, to the one used on the PS. But the use of phase-lock on the storage rings is complicated by the presence of the stacked beam and a method has been devised to overcome this problem. It involves leaving one or more r.f. 'buckets' empty to act as a marker.

A prototype frequency-programming system has been completed and has undergone static measurements of stability and noise which are found to be within the specified tolerance. Most basic parts of the amplitude programming system have been developed and development of the phase-lock electronics has started. So far, a prototype of the counting and frequency division unit that makes the phase-lock system lock to a predetermined bunch has been built.

3. Vacuum system

E. Fischer

Electron and proton storage rings require a much lower residual gas pressure than the conventional accelerators. While, for instance, the CERN PS works satisfactorily with a pressure of about 10^{-6} torr, the ISR require an average pressure around the rings a thousand times lower, namely 10^{-9} torr. Even the pressure of 10^{-9} torr is not sufficient for the interaction regions where it must be lower than 10^{-10} torr and if possible about 10^{-11} torr.

At these very low pressures, colliding beam experiments should be possible for many hours, perhaps even a day, without refilling the rings. Then only a small fraction of the operating time of the PS will be taken away from the conventional experiments.

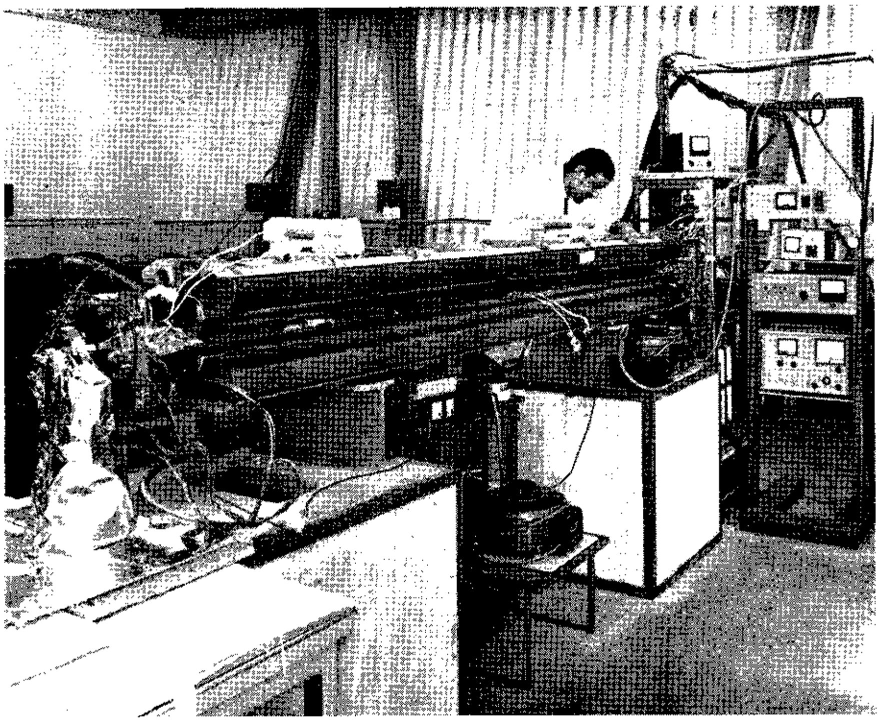
It is usual to call the pressure range 10^{-9} torr and below 'ultra-high vacuum'. Therefore, the whole vacuum system of the ISR has to be designed to use ultra-high vacuum techniques, which are distinguished from normal high vacuum techniques by two main features. Firstly, all parts of the ISR vacuum chamber must be heated under vacuum for one or two days up to 200 to 300° C in order to accelerate the release of superficially adsorbed gases from all the internal surfaces. Most of the heating elements and the thermal insulation required for this so-called 'bake-out' will remain permanently in place. Secondly, no organic components can be used in the construction of the vacuum chamber. The well-known rubber O-rings will therefore have to be replaced by copper or gold gaskets in an appropriate sealing technique.

Also, the vacuum pumps will look entirely different from those of the PS. Although rotary pumps will probably be used when the pumping starts (pumping from atmospheric pressure), at lower pressures, the pumping will be taken over by titanium getter and getter-ion pumps. In these pumps the gases to be pumped are either chemically adsorbed on fresh layers of titanium (getter pumping), or, if they are inert gases, ionized and buried deep into surfaces (ion pumping). In both cases, the gases are immobilized and cannot return to the chamber. For the very low pressure in the interaction regions, additional cryopumps using liquid helium as refrigerant will be used.

Considerable experience of the problems associated with complicated ultra-high vacuum systems has been gained on the CERN electron storage ring model (see page 135). Also laboratory tests have been carried out on titanium pumps of different design and from different manufacturers and pumps have been found which give full pumping speeds down to 10^{-10} torr. Pressures as low as 10^{-12} torr have been achieved with cryopumps.

The vacuum vessel material has to have four major properties: its presence must not affect the magnet field configuration in the rings; it must have sufficient mechanical strength to withstand the difference in pressure inside and outside the vacuum system; it must be reasonably easy to form and weld; it must have low gas desorption after bake-out. Samples of steel supplied by several firms have been tested in all these respects to choose the optimum material. Work has also been done on bellows, ceramic seals and different types of demountable gold and copper seals.

The most serious struggle during the construction of the ISR will be the fight against the old enemy of vacuum: leaks in welds and joints. It is worth remarking that the ISR, with a total length of vacuum chamber of two kilometers at a pressure of 10^{-9} torr, will be by far the biggest ultra-high vacuum system ever built in the world.



CERN/PI 56.3.66

Bake-out tests in progress on a prototype vacuum chamber. It is found that after bake-out at temperatures of up to 300° C, the gas desorption from stainless steel is about 10^{-12} torr litre/s/cm^2. This can be improved by several orders of magnitude if the chamber is baked before installation at 800 to 1000° C. About 99 % of the desorbed gas is hydrogen.

Construction of a service tunnel in progress at the beginning of June at the North East corner of the ISR site. Some of the existing CERN buildings can be seen in the background.

CERN/PI 39.6.66

4. Beam transfer

B. de Raad

The beam transfer group has the task of designing and supervising the construction of the transfer channels from the proton synchrotron to the storage rings and to the West hall, and of the fast injector magnets which will take the beams into the ISR.

The transfer channels consist of quadrupoles and bending magnets of rather conventional design such as are used in the present beam lines from the PS. Their special interest lies in the large distances over which the beam must be transported, the complicated geometry of the beam lines and the high stability, together with flexibility, required from the magnets to avoid beam losses and to preserve the quality of the beam.

The total length of the transfer channels is about 1.5 km. It is a truly three dimensional system since the level of the ISR beams is about 12 m higher than that of the PS beam (the new extension to the CERN site is about 20 m higher than the original site). Thus in the vertical plane the beam leaving the PS is first taken up across the line of the PS injector beam, continues horizontal on to the ISR site and then climbs again at an angle of about 6° near the storage rings, passing under the ring tunnel to inject from the inside of the rings. This adds complications not only in the planning of the beam lay out to follow a curved path in three dimensions but also in the mechanical problems of magnet positioning and alignment which have to be as precise as in the rings themselves. For example, in some places magnets weighing some eighteen tons will have to be manoeuvred along inclined tunnels with no crane to help, and then set precisely in position on a slope of 6°.

Since the fluctuations, in position and direction, of the beams that are injected into the ISR are required to be as small as possible, very high stability is required from all the bending magnets in the transfer channels. This involves current stabilities in the magnets of better than one part in 10^4. Also, especially in the beam lines shared between the ISR and the West hall (where the variety of beam conditions at present in use around the PS will probably be called for), it must be possible to change the magnet fields quickly. It is for this reason that a laminated construction has been chosen both for the bending magnets and the quadrupoles.

Computer programs on the beam optics have been run for some time and the lay out of the transfer channels is now well under way. The regular feature of the lay out is the positioning of focusing and defocusing quadrupoles in sequence about 9 m apart along the entire length. The bending magnets are interspersed between the quadrupoles. The magnet aperture is dictated principally by the beam requirements of the West hall experiments where it can be expected that the full beam from the improved PS will be called for. Work has started on the design of the magnet power supplies.

The injection system into the ISR is in principle the same as the fast ejection system of the PS, but there are some important differences. The fast kicker magnet must operate in ultra-high vacuum and must be baked out. This limits very seriously the choice of construction materials; the magnet is to be made of ferrite with titanium conductors and ceramic insulators. The pulse shape should be as rectangular as possible (to within ± 2 %). In particular, no transients should occur when the main pulse is switched off, since this would affect the protons when they pass through the kicker for the second time.

A lot of effort has been put into achieving this required pulsed shape. A long storage cable with an inner of copper and an outer of aluminium is being used. Prototype inflector magnets have been made and are working quite well.

5. General lay out

F. Bonaudi

The most prominent feature of the site available for the construction of the ISR is its elongated, narrow shape. Although the area (about 40 hectares) is adequate for the project as it is conceived at present, the width of the site created problems for the location of the rings. The position finally adopted for the machine (see Figure 3) just satisfies both the stringent requirements of the injection (which determines the geometry of the beam transfer tunnels between the PS and the ISR), and the

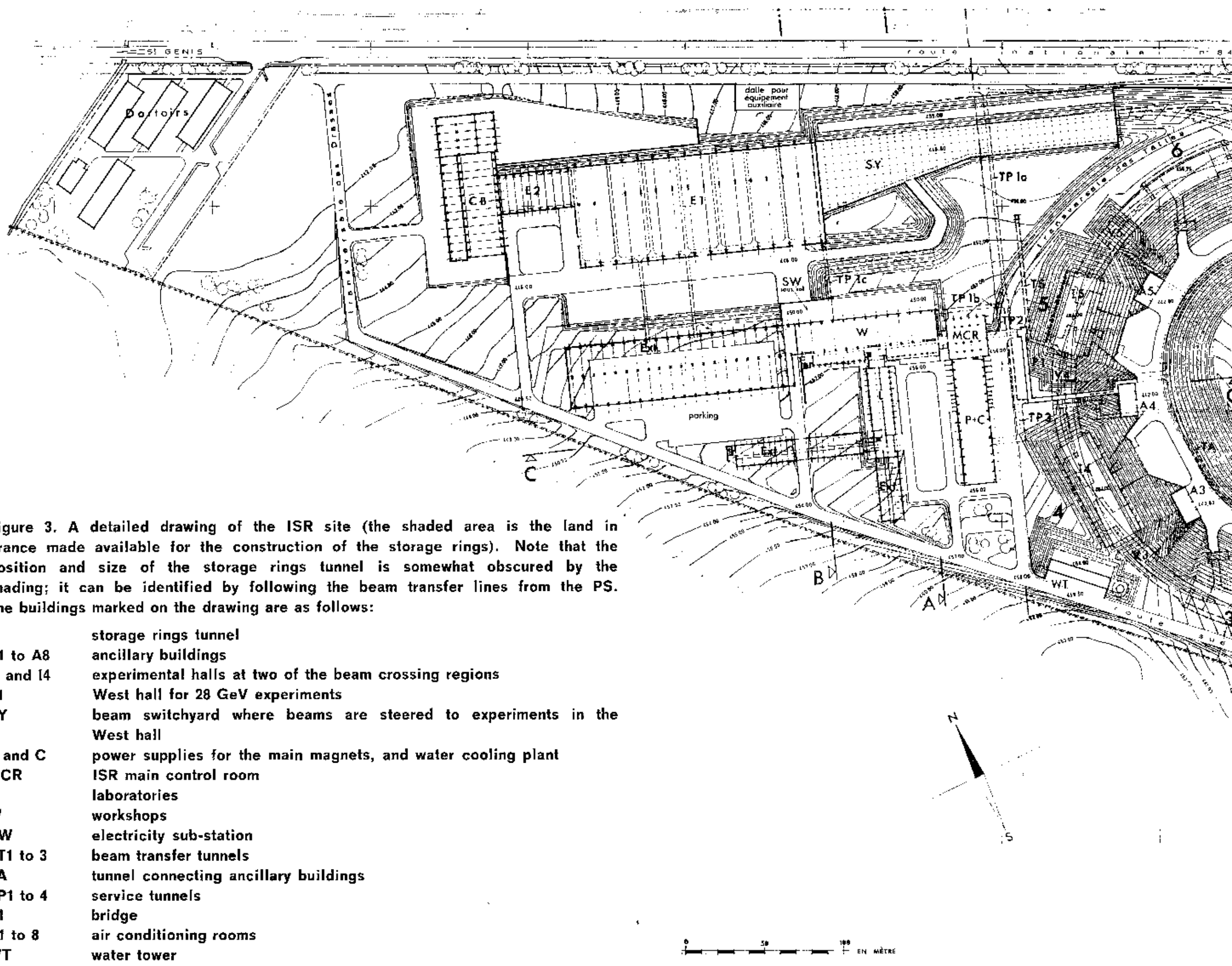


Figure 3. A detailed drawing of the ISR site (the shaded area is the land in France made available for the construction of the storage rings). Note that the position and size of the storage rings tunnel is somewhat obscured by the shading; it can be identified by following the beam transfer lines from the PS. The buildings marked on the drawing are as follows:

R	storage rings tunnel
A1 to A8	ancillary buildings
I1 and I4	experimental halls at two of the beam crossing regions
E1	West hall for 28 GeV experiments
SY	beam switchyard where beams are steered to experiments in the West hall
P and C	power supplies for the main magnets, and water cooling plant
MCR	ISR main control room
L	laboratories
W	workshops
SW	electricity sub-station
TT1 to 3	beam transfer tunnels
TA	tunnel connecting ancillary buildings
TP1 to 4	service tunnels
P1	bridge
V1 to 8	air conditioning rooms
WT	water tower

Buildings under study include: E2 — an annex to the West hall; CB — a large bubble chamber area; a new injector for the PS, and the data handling and
Buildings under study include: E2 — an annex to the West hall; CB — a large

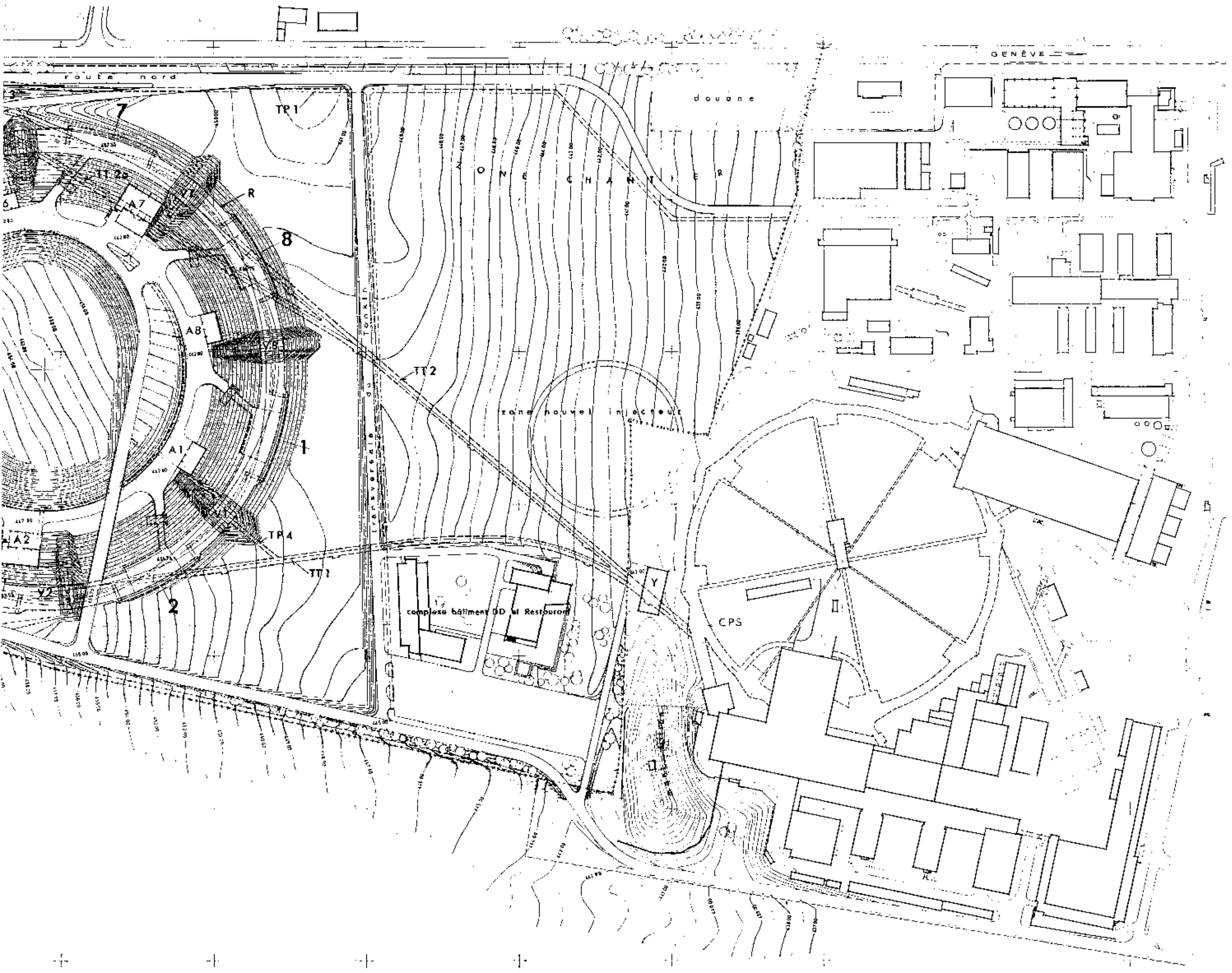
need for adequate shielding and road space on either side of the rings.

The ISR will be housed in an underground circular tunnel of 300 m average diameter, 15 m wide and about 7 m high. The width of the tunnel is determined by the fact that the two rings are housed together in it and their geometry (see Figure 2) is such that over considerable distances they are located a fair distance apart. Independent access corridors, equipped with shielding doors, lead to the intersections where colliding beam experiments can be performed. One intersection, I4, is housed in an experimental hall (25 m wide, 70 m long, about 16 m high) which is a substantial enlargement of the tunnel. Another experimental hall, at intersection I1, is designed in a different way: the rings will travel through this experimental hall in a shielded enclosure made of movable blocks. In this way we will have maximum flexibility around the colliding beam region and experiments will be able to expand beyond the fixed width which a hall similar to I4 would otherwise have imposed. There is also extra width and height at two other intersections (I2 and I8) to accommodate experiments.

The West hall for 28 GeV experiments which is located beyond the ISR ring, is 150 m long and 65 m wide. The proposed large hydrogen bubble chamber which is part of the PS improvements programme and other large chambers will be located in a complex of buildings at the far end of this hall. During the years 1968, '69 and '70 the West hall will serve as the main assembly and test area for all the components of the ISR.

The remainder of the ISR complex (equipment room, control room, workshop, laboratories and offices) is located to the South West of the rings as shown in Figure 3.

Extensive investigation of the ISR site was carried out to determine the ground stability. Samples were taken at different depths and at different positions on the site and passed to experts in soil mechanics for analysis. The outcome of the investigation indicated that there may be vertical ground movements but they are not expected to be very serious though they may involve more frequent realignment of the machine than is necessary at the PS. In positioning the magnets, we are relying on ground stability to some extent but in addition are resting the magnets on concrete beams spanning sections of the rings. This should reduce the effects of any ground movements without being a very expensive solution to the problem.



The programme for construction of all the ISR buildings is spread over 3 years (mid 1966 to mid 1969). Top priority is being given to the ring tunnel itself, due to its complexity and size, and to the West hall which is required very early by the ISR construction team to do their assembly and test work.

Preliminary site work on roads, drains etc. has been under way since last year. The main contractor for all the civil engineering work was appointed in May 1966 and will begin work this summer.

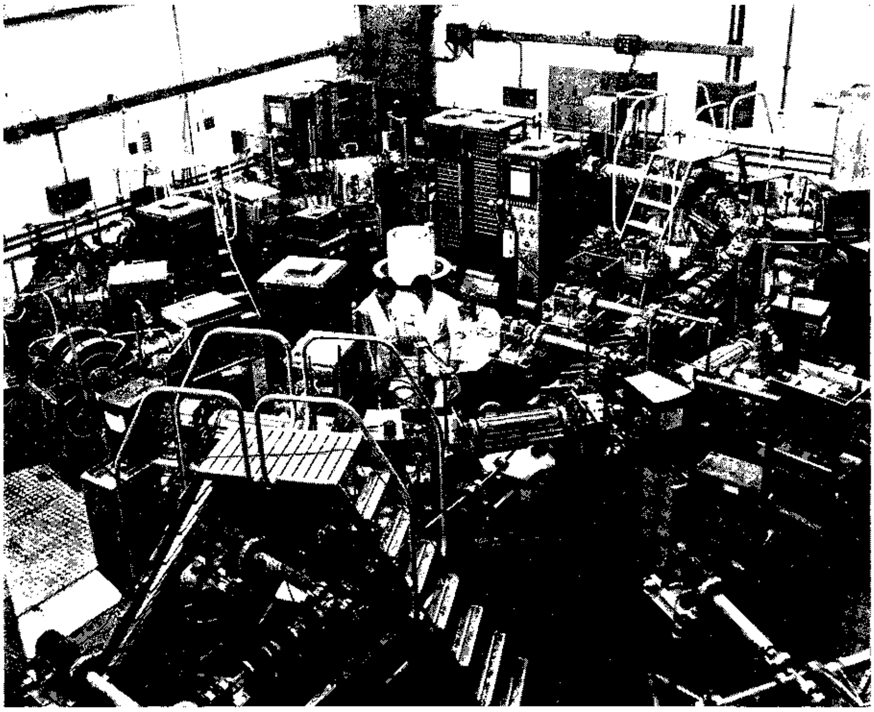
6. Storage ring model

M. J. Pentz

There was a common factor in the decision to build an electron storage ring 'model' and the later decision to build the ISR. It was essentially the large increase in the intensity of the proton beam accelerated in the PS which first opened up the prospect of adding a colliding-beam facility and which also led the Accelerator Research Division to decide to construct a storage ring model.

The model has been in operation for three years, and has acquired the name of CESAR (CERN Electron Storage and Accumulation Ring). It is not a direct model of the ISR itself, but was designed to provide experimental data on some of the basic processes of beam stacking that are essential to the efficient operation of the ISR.

Since 28 GeV protons travelling on an orbit of radius 150 m, lose hardly any energy by synchrotron radiation, the process of injecting and accumulating many pulses must involve acceleration of each injected pulse by a radio-frequency system as described on page 131. This is in contrast to the situation in a high-energy electron storage ring, in which there is an appreciable energy loss due to synchrotron radiation, which causes the electron orbits to shrink rapidly. One can then take advantage of the orbit shrinkage to shift each injected pulse of electrons away from the influence of the pulsed inflector or 'kicker' so that it is not perturbed by the 'kick' that inflects the subsequent pulse of electrons.



A view of the electron storage ring model taken during the closing stages of its construction. It is possible to make out the shape of the ring with its bending magnets, focusing magnets, r.f. units, monitoring equipment and vacuum pumps. The line of the injected beam from the 2 MeV Van de Graaff can be seen entering bottom left of centre, passing under the ladder and travelling diagonally across the photograph to join the ring.

Thus, one of the fundamental questions for a proton storage ring is: can the process of accumulating many pulses by r.f. acceleration and 'stacking' be carried out with high efficiency, that is, with little loss of particle density in the stacked beam, as compared with the density in the injected beam? This question has been well studied analytically and numerically with the help of digital computers. One can conclude from such studies that high stacking efficiencies should be attainable under certain conditions. CESAR was built to verify these predictions experimentally, and this it has done.

In order to have similar conditions to those that will apply to the ISR, CESAR stacks electrons of low energy (2 MeV) in a ring of about 4 m radius, in which the energy loss by synchrotron radiation is negligible, as in the ISR.

The first series of experiments on r.f. stacking in CESAR confirmed the theoretical predictions, but a number of unpredicted phenomena were observed, which are thought to be due to small random fluctuations, or 'noise', in the r.f. programme, and these are now being studied in a second, more refined, series of experiments.

There are two other problems in the design and operation of storage rings, on which CESAR is able to provide useful information. One is the technological problem of producing the necessary very high vacuum in a complicated vacuum chamber. CESAR was designed for a pressure of 10^{-9} torr in order that the 2 MeV electrons (which are much more easily scattered than 28 GeV protons by collision with residual gas molecules) should circulate for a sufficient length of time to allow a reasonable number of pulses to be stacked. At this pressure, the 'lifetime' of 2 MeV electrons is about 2 seconds. By injecting 50 pulses a second, one could therefore hope to do beam stacking measurements with up to 50 pulses.

In fact, we have surpassed the design aim, reaching pressures of as low as 4×10^{-10} torr, and stacking up to 100 pulses. The practical experience gained in the development of an ultra-high-vacuum system for CESAR has undoubtedly contributed something to the confidence that we have about building the very much larger ultra-high-vacuum system for the ISR. Moreover, the limit on the number of pulses that can be stacked is not so much the 'lifetime' as the stability of the 2 MeV Van de Graaff which serves as the injector for CESAR. The stability of the Van de Graaff has recently been improved by a factor of 100, and we now hope to stack up to 200 pulses.

The other problem on which CESAR is expected to provide information is that of beam instabilities. When beams of charged particles circulate in a storage ring they can interact electromagnetically with each other and with their material environment — notably with the walls of the vacuum chamber and with their magnetic 'images' in the magnet structure. Under certain conditions, these interactions can cause the beam to 'blow up' either partially (causing loss of beam density) or completely (causing outright destruction of the beam). Beam instabilities of this kind have been observed in several accelerators and storage rings. Needless to say, they have aroused considerable interest, and have been the subject of a great deal of theoretical and some experimental study.

In terms of our present understanding of the subject, none of these instabilities are expected to cause trouble in the ISR, given certain known and fairly simple precautions. It will nevertheless be desirable to check these ideas experimentally and as thoroughly as possible with the storage ring model. The design of CESAR is such that many, if not most, of the known instabilities should occur, and it is planned to exploit this fortunate circumstance in a series of experiments this year and next.

There is a further question which experiments with CESAR may be able to elucidate, given a number of improvements in its design which are now being studied. This is the question of long-term stability. In several experiments envisaged for the ISR, it will be necessary to maintain a circulating beam, without serious loss of density, for periods of several hours. In that time, the protons will make something like 10^9 to 10^{10} revolutions, travelling a distance more than double the distance from the earth to the sun. We would like to know whether there are any possible instabilities, characterized by extremely slow growth rates, that might manifest themselves in such a long time. We do not know of any at present, but that does not mean that they will not occur. Indeed most of the known instabilities were observed in practice before they were thought of, let alone understood.

There is, therefore, some interest in creating conditions in CESAR which would in a certain sense be comparable to those which can be predicted for the ISR. Since the circumference of CESAR is some 40 times smaller than that of the ISR, and since 2 MeV electrons have essentially the same velocity as 28 GeV protons (almost the velocity of light), electrons in CESAR would, in 5 minutes, make the same number of revolutions as protons in the ISR would do in about 3 hours. To achieve a beam lifetime of 5 minutes in CESAR implies improving the vacuum by a factor of 40, reaching a pressure of 10^{-11} torr. This will not be easy, and laboratory studies are now being made to see how it can be done.

This, then, is the role of CESAR in relation to the ISR project. Like most experimental devices, CESAR promises (or maybe 'threatens' is a better word for it) to raise more questions than it was originally designed to answer. We hope that it will also answer them.

7. Storage rings elsewhere

A. Schoch

Reviewing briefly the work on storage rings that has been or is being carried out elsewhere we recall that the idea of doing experiments with colliding beams was first studied at 'MURA' (Midwestern University Research Association, USA). The MURA group – which produced many pioneering ideas in the field of accelerator technology as well as outstanding contributions to the understanding of accelerators – published a scheme for colliding beam experiments using two intersecting accelerators. At about the same time, G. K. O'Neill, from Princeton, proposed the use of storage rings filled from an independent accelerator.

Further development of these ideas at MURA led to an ingenious special accelerator design, the two-way FFAG (fixed-field alternating gradient) accelerator*, and to the concept of 'stacking'. At Princeton, the idea of concentric intersecting rings, and of the delay line type of kicker magnet for beam transfer, emerged. The greater simplicity of the storage ring scheme in comparison with intersecting accelerators was more apparent than real until the efficient transfer of beams between different accelerators became technically feasible.

By the beginning of 1958, MURA proposed the construction of a two-way proton accelerator for 15 GeV. This project, estimated to cost $85 million, did not find support and was later withdrawn. The technique of electron colliding beams already opens a wide field of very specific research problems at beam energies which can be handled by devices of more modest size. Construction of the first double storage ring for electron-electron experiments at 2 x 500 MeV was started in a collaboration of Princeton and Stanford Universities. This was followed by a number of other electron devices. At Frascati, first a small single storage ring ('AdA') for electron-positron experiments at about 200 MeV was made and tested mainly at Orsay using the linear accelerator as injector. This was the first device in which collisions were shown to happen. A large electron-positron ring for energies up to 2 x 1.5 GeV ('Adone') is now nearing completion at Frascati. At the Laboratory of Orsay, an electron-positron ring for 2 x 400 MeV ('ACO') was brought into operation at the end of 1965. At Novosibirsk (USSR), two devices are operating: a double ring for 2 x 130 MeV electrons (in operation since 1963), and a single electron-positron ring for 2 x 700 MeV. Another double ring for 2 x 100 MeV electrons has been constructed at Kharkov (USSR).

These electron storage rings proved to be more difficult than had been anticipated. Apart from technological difficulties (mainly due to the need for ultra-high vacuum), the currents which could be achieved were limited by a variety of instabilities which were the main obstacles to the rapid progress of the experiments proper. Most of the instabilities were first discovered in these rings which have therefore played, and are still playing, a pioneering role in the development of colliding beam experimentation.

The most important limitations of beam currents, and consequently, of particle interaction rates, turned out to be due to: (a) forces between crossing beams, (b) interaction between the beam and the vacuum chamber and (c) collisions between particles of the same beam. Last year, however, the first colliding beam experiments which are significant from the point of view of particle physics, were achieved at Stanford (2 x 300 MeV elastic electron-electron scattering). Similar experiments published from Novosibirsk were done at considerably lower energy.

New electron storage ring projects are under study at Stanford and at DESY. Physicists at CEA are working on an ingenious way of doing electron-positron experiments in the Cambridge Electron Accelerator itself. The energy which can be reached in these future projects is not far in excess of 3 GeV, because of r.f. power requirements to compensate for the energy lost by synchrotron radiation becomes excessive at higher energies.

For proton colliding beams, a two-way accelerator using very high magnetic fields (greater than 100 kG) was proposed by the Novosibirsk group at the 1963 Conference on High Energy Acceleration at Dubna. It seems, however, that this has been abandoned in favour of a device using more conventional magnet technology but, possibly, specializing on proton-antiproton collisions.

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* The same type of design was arrived at independently by Kolowenski in the USSR, where colliding beam techniques were also under discussion.

Experiments at the ISR

Our present generation of particle accelerators has revealed an entirely new world of sub-nuclear spectroscopy which no one could have anticipated when the accelerators were planned. Beyond this observed range of resonances and unstable particles, which is the limit of our present knowledge, a new, much more simple world is expected which has been called the 'asymptotic region', since the scale of energy extends to infinity. It is believed that knowledge of this region might be the key to the understanding of sub-nuclear spectroscopy and that it might reveal more regular behaviour which will be more easily understood.

Bigger accelerators will be needed to obtain a full understanding of this region. But in the meantime we can get a glimpse at it, as if through a keyhole, by means of the ISR. We will not have beams of π-mesons, K-mesons or other particles of higher energies; the collisions between high energy proton beams will be our only tool. Yet this should give us a first insight into this new range of energy.

There are a few burning questions we can already ask which reflect our present view of this asymptotic energy range. But we might unearth some entirely new aspects when research begins at the ISR, for nature has always proved richer than our imagination.

Before describing some of the experiments which are conceivable for the ISR it is worth making a general remark to illustrate the scope of the experimental possibilities.

The so-called 'strong' interactions between particles are characterized by two important physical variables — the total energy of the colliding system, and the 'transverse momenta' of the secondaries produced in the interaction. Experimentally, it is found that, up to the highest cosmic ray energies, the chance of observing a secondary particle with a transverse momentum higher than 300 to 400 MeV/c is very small. Therefore, to study collisions in which very high transverse momenta secondaries are present demands very high intensities. The ISR will give only low numbers of collisions. Its scope is, in general, the study of proton-nucleon interactions at very high energies — about 56 GeV in the centre of mass system (c.m.s.), equivalent to a 1675 GeV beam on a stationary target — producing secondaries at quite small transverse momenta (say, less than 1 GeV/c). This is of course a rather general remark and a specific example contrary to it will be given later.

1. Elastic Scattering Experiments

The simplest (and possibly the first) experiments for the ISR are those measuring proton-proton elastic scattering, $p + p \rightarrow p + p$. Measurement of the momenta and angles of the scattered protons is sufficient to identify the reaction kinematically. It may be supposed, although it is one of most interesting features of the experiment to find out, that, even at the very high energies available, the elastic scattering cross-section will be a reasonable fraction of the total cross-section. If this is so, the elastic scattering experiments are by far the easiest which can be considered.

Information on elementary particle scattering says, roughly speaking, something about the size and character ('hard' or 'soft') of the colliding objects. More specifically, measurements of angular distributions and the energy dependence of the scattering, together with some theoretical ideas, give some clue as to the mechanism of the scattering process.

At energies in the GeV range, p-p elastic scattering is largely diffraction or shadow scattering caused by the strong absorption of the proton waves by the many possible inelastic or production processes. The angular distribution of diffraction scattering is very sharply peaked in the forward direction so that most of the scattering is concentrated in a very narrow cone, the width of which is related to the size of the interacting system. At the GeV energies so far explored (up to about 8 GeV c.m.s.) a rather small part of p-p scattering appears to be caused by a potential or billiard ball type of behaviour.

The physical interest in p-p scattering lies in the detailed shape of this forward diffraction peak, its variation with energy, and the way in which the potential type of elastic scattering changes with energy. Observations of p-p scattering at CERN in 1961-62 showed a very characteristic feature of the diffraction peak, namely that its width decreased with increasing energy. The 'shrinking' of the diffraction peak stimulated great interest both theoretically (Regge poles) and experimentally (many elastic scattering experiments subsequently done) and the ISR offers the possibility to explore the phenomenon to extremely high energies.

The potential type of scattering is studied by measuring its interference with Coulomb scattering. This is possible only at very small angles where Coulomb scattering is strong. The angles of interest even at the very high energy of the ISR are still quite reasonable from the experimental point of view. It is in fact one of the merits of the stationary centre of mass system that the interesting angular range is not restricted to impossibly small angles as would be the case for a conventional stationary target experiment at equivalent centre of mass energy.

Having measured p-p scattering at high energies, one is always interested to compare the behaviour with that of the proton-neutron system. This should be possible with the ISR provided that deuterons can be accelerated in the PS and transferred to the ISR. From the experiments it should be possible to deduce the behaviour of the p-n interaction assuming that the p-p interaction is known.

The elastic scattering measurements would use several kinds of detectors. For the very smallest angles, in the Coulomb interference region, matrices of solid state detectors inside the vacuum chamber of the machine would be conceivable. For rather larger angles, the study of the shape of the diffraction peak, wire spark chambers would seem to offer the best possibility with respect to precision of particle location and speed of operation. An array of both kinds of detectors connected on line to a computer should allow the measurement of the complete elastic scattering angular distribution up to transverse momenta of about 1 GeV/c.

The total p-p and p-n cross-sections could, in principle, be deduced from the measured small-angle scattering using a general quantum mechanical theorem called the optical theorem. However, this would still entail some assumptions, and subsidiary scintillation counter experiments observing the loss of particles from the interaction region would give direct measurements of the total cross-sections. The energy variation of the p-p and p-n total cross-section is of fundamental interest in connection with some general current theorems about the asymptotic nature of strong interactions.

2. Particle Spectroscopy

When two protons collide they may shake each other so violently that new particles are liberated from them. This phenomenon is called particle production. All the known sub-nuclear particles which can feel strong interaction forces may be created in this way. One may think of this process as the stripping off of part of a cloud from the protons. Light particles, the π-mesons, are rather easy to shake off; energies of around 140 MeV are sufficient. They are the constituents of the rim of the cloud. Other particles are produced in pairs, for example K-mesons and anti-K-mesons plus hyperons. If the collision energy is raised higher, pairs of nucleons, for instance a proton plus an antiproton, can also be produced. Such a pair of particles is very heavy, and an available energy of 2 GeV is required to create them. They come from the very heart of the cloud.

This phenomenon of particle production is then intimately connected with the structure of the proton and observations of the particles which are created in such collisions, of their relative abundance and energy, their angular distribution and their possible correlations with each other, gives us some information about the arrangement and dynamics of this cloud which constitutes the stable proton.

Every time a new energy range has opened up for particle physics, one of the first things to be investigated has been the production of particles. This has been done at the 28 GeV CERN PS and at the 33 GeV Brookhaven AGS and the overall pattern observed at these energies can be drawn quite simply: as a proton is shaken more and more violently, increasing numbers of π-mesons are stripped off. One could have imagined that instead of more and more π-mesons, fewer heavier particles could be created. This is not found at currently available energies. The colliding protons rather separate off and fly away with their clouds excited to higher energy and finally return to their normal state by emitting some π-mesons. In such collisions very little of the available energy goes into particle production. Sometimes, however, two colliding protons share the whole energy of the collision and form for a brief time something like a very hot droplet. Then heavy particles are created also and boil off from the droplet.

The picture which has been drawn here has in fact been derived from observations of the stable particles which survive long enough to be detected. The main key to this is a spectroscopy of the frequency of particles of different mass. It is going to be very interesting to carry this study to the higher energies available at the ISR.

3. A Weak Interaction Experiment

The experiments so far discussed have been concerned with strong interactions. The large energy available at the ISR suggests a search for an elusive object called the intermediate vector boson, W, supposedly the carrier particle, or field, of the weak interactions. High energy neutrino experiments at CERN and Brookhaven have searched for this object without success and their negative results suggest that, if the boson exists at all, its mass is greater than about 1.9 GeV.

An interesting property of the hypothetical W is that its strength of interaction depends on its mass. Hence, if bosons do exist with very high mass they might well become readily observable provided enough energy is available to produce them.

A possibility, then, is to search for W production in proton-proton collisions with energies up to 56 GeV c.m.s. at the ISR. The method of detection of the W relies on observing its decay into a muon and a neutrino. Muons arising from the decay of pions and kaons tend to emerge from the interaction region at small angles, following the trajectories of their parent particles which, as we remarked earlier, have small transverse momenta. The decay of a very massive, slowly moving particle, like the W, could give, however, muons emerging with high momenta at rather large angles and the experiment would rely on this to separate the W decay muons from the rest.

The experiment would use scintillation counters and spark chambers to look for muons of high transverse momenta penetrating a thick shielding wall around the ISR interaction region. Yields of wide angle muons studied as a function of incident momentum could then give some hint as to whether or not the W exists.

The Experimental Conditions

At the present accelerators, detectors have been used to make measurements at different angles around a target which is bombarded with protons. A beam of accelerated protons is brought to one of the experimental halls and directed onto a target of liquid hydrogen. In this situation, the detection equipment could be put even at 0°, a region which for an internal target is obstructed by the accelerator magnet units.

The energy of the resulting particles is selected by a magnetic field, and particles of different mass have different velocities which can be measured by Čerenkov counters or simply by their time of flight.

At the ISR the situation is quite different and more complicated. One beam is the target of the other and the collisions to be studied occur inside a vacuum vessel. Special care has been taken to provide enough free space between the magnet units at the 8 intersection points of the two beams. But the immediately forward direction is not accessible for magnetic fields which could sweep particles out, since this would also disturb the circulating protons.

The proton beams also collide with the gas which is left in the vacuum vessel. Even at 10^{-11} torr the gas density (the number of atoms per cm^3) is comparable with the density of the target beam. Moreover the beams cross over a length of some 20 cm, while the gas is present all around the rings.

How are we to distinguish a particle created in a beam-beam collision from those made in beam-gas collisions? There are several possibilities. We can use a detector which can 'see' only the region of beam-beam interaction, or we can record the tracks of particles in spark chambers and reconstruct their origin from the spark chamber readings. Also, conditions can be imposed on the particles to be recorded so that their energies add up to values which are impossible from beam-gas collisions. The detection apparatus could then, in principle, be quite similar to the ones used at present accelerators. Of course it has to cover a much wider range of angles, because the colliding protons are not pushed into one common direction as in the case with targets at rest.

Formidable detectors will have to be built to cover the whole angular region around the beam crossing points. Angles and energies of all particles have to be determined and also their mass. These detectors will grow to the size of our biggest bubble chambers and yet, as opposed to the bubble chambers, they have to select in some way the 'interesting' events. Most probably they will be a combination of wire-spark chambers and magnetic fields using a computer on-line to select and record the events.

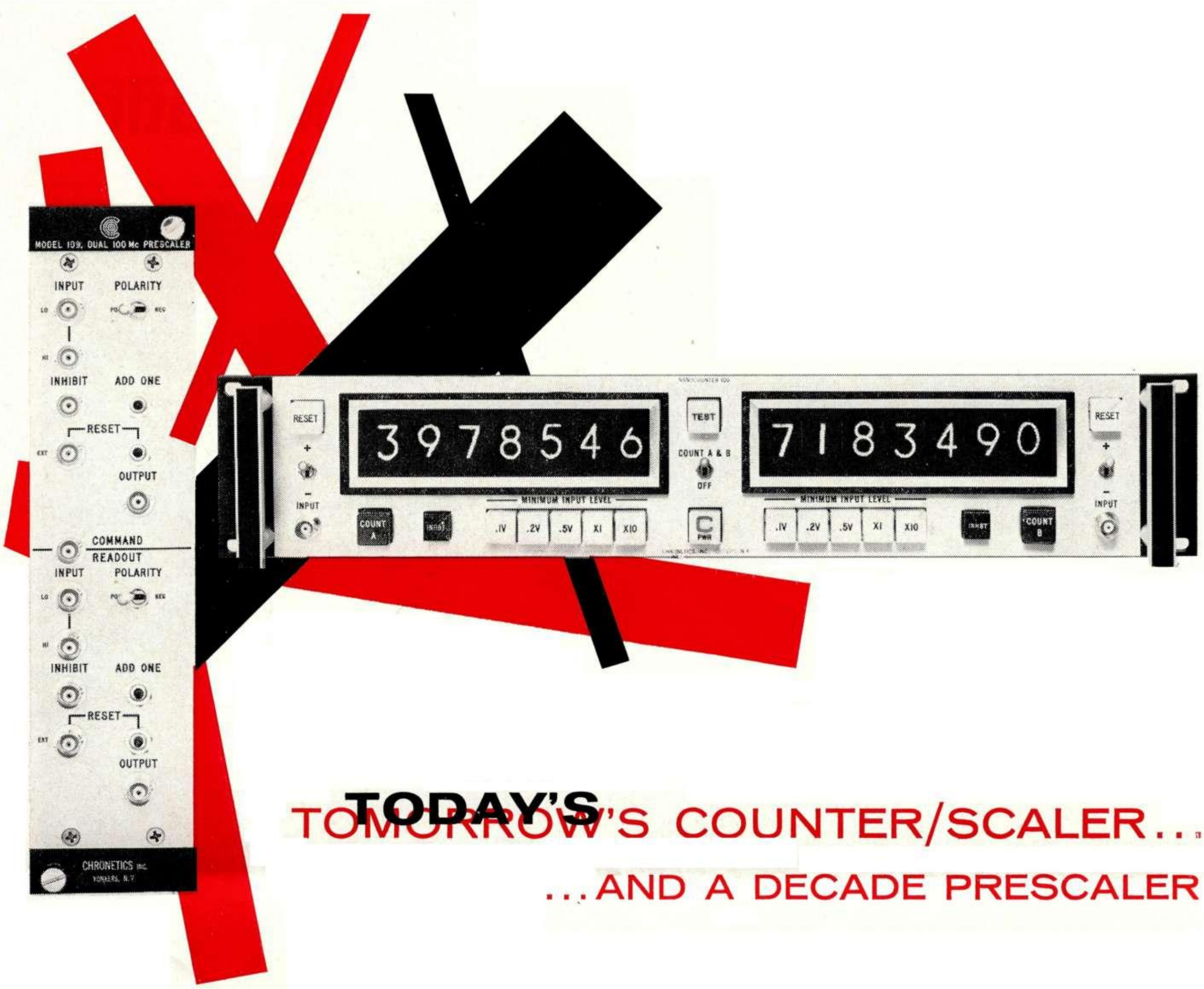
What can we expect to find in this new energy range? Is there anything we could anticipate or imagine? Can a look at the data from cosmic ray experiments help us? If the diffraction pattern in elastic scattering continues to shrink, as discussed above, this could have its origin in some changes in the production phenomena. Some unstable particle clusters, guessed at from cosmic ray experiments and christened 'fireballs', could be effective in producing particle 'jets' in a characteristic way.

One of the simplest interactions involving unstable states is the process $p + p \rightarrow p + N^*$ where N^* is an excited nucleon. This has been studied quite extensively at CERN and Brookhaven with rather simple experiments detecting the inelastically scattered proton only. From measurements of the momentum and direction of the proton, conservation of energy allows us to deduce the mass of the unobserved N^* (this has a lifetime for decay into a nucleon and pion of about 10^{-23} s). With the ISR, simple detection of the single scattered proton is probably not enough as its momentum difference from elastically scattered protons is very small (about 20 MeV/c). Hence some information on the decay of the unstable state is needed. The process then appears in the simplest class of jet events in which a very high energy proton is detected in coincidence with a rather simple jet configuration ($N\pi$ or $N\pi\pi$ for example).

The experimental programme on this type of reaction would aim to study the energy and angle dependence of the cross-section for producing the various N^* states. The details of these variations are of interest as they may be expected to depend on the quantum numbers of the states. More specifically, it is expected from certain general ideas of strong interactions, that those N^* states with quantum numbers differing least from those of the nucleon will be excited most strongly. This idea is of considerable importance and it is necessary to test it at the highest energies.

In the production of stable particles there might be new phenomena. The production of the 'cheap' π-mesons may no longer damp so strongly the production of more massive states such as nucleon pairs. Also new, as yet unknown, more massive particles may be produced.

This is the kind of physics for which we have to be prepared.



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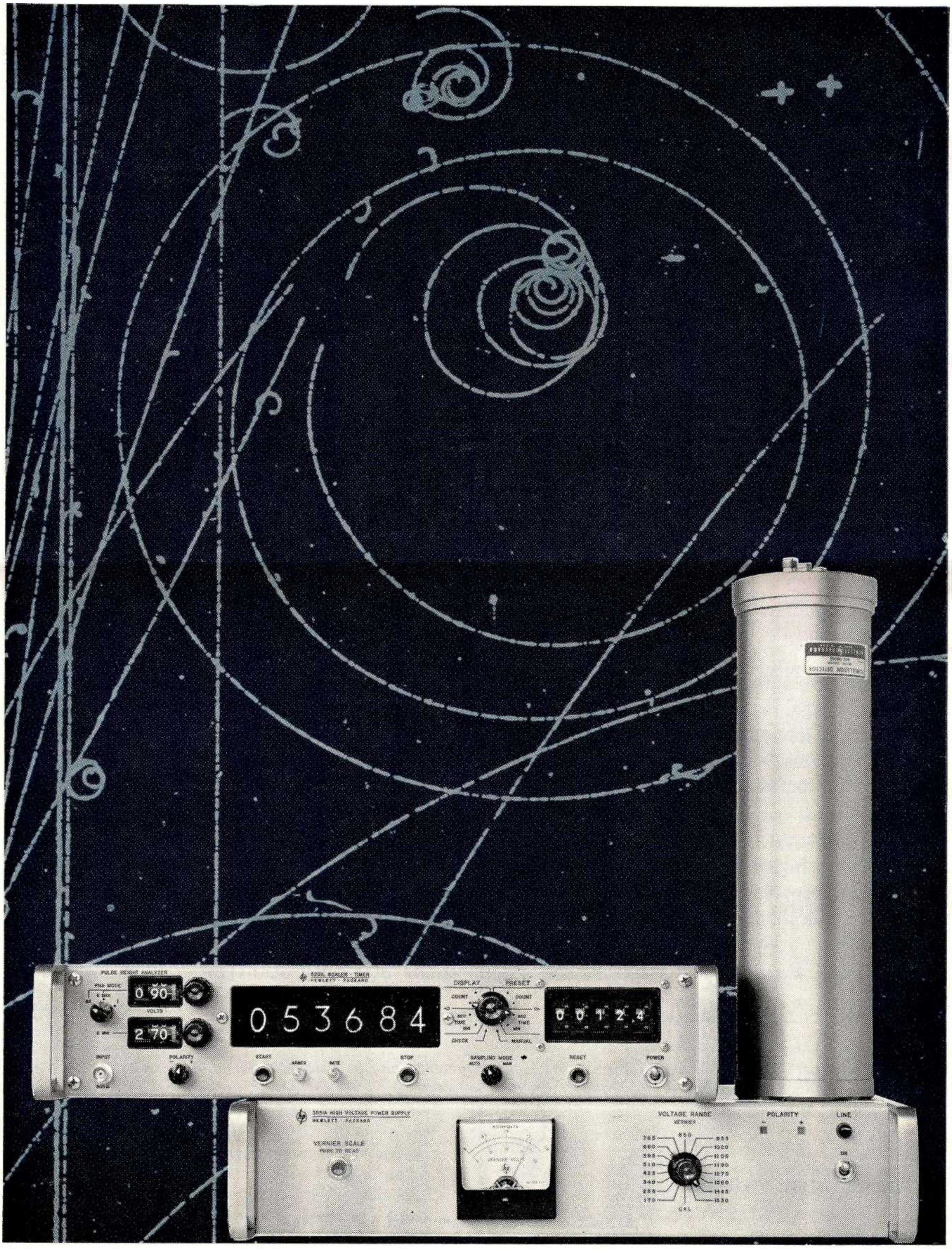

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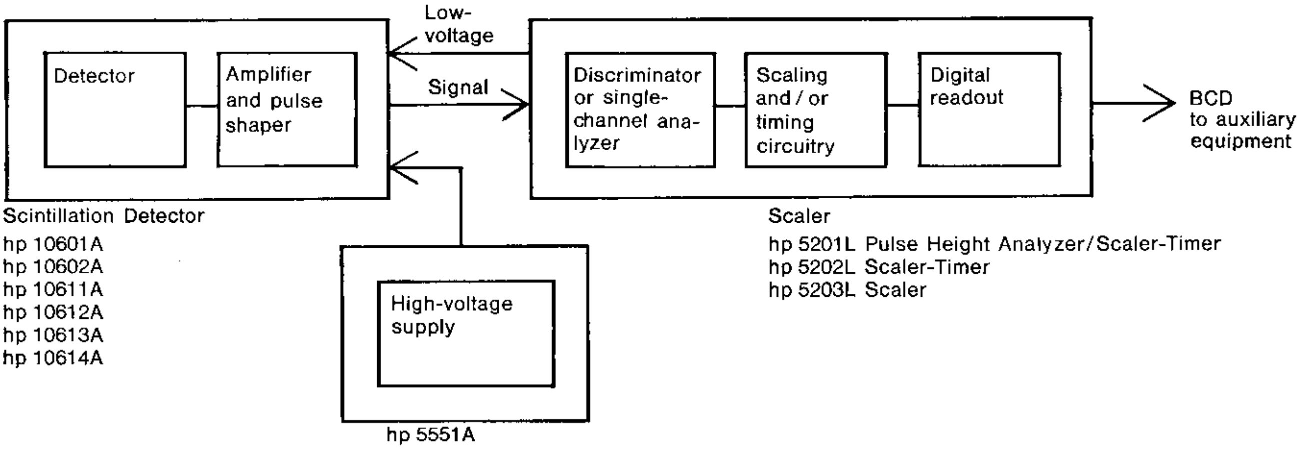

Notice that a complete scintillation detector is in one unit, single channel analyzer/scaler-timer function in a second, while a third provides stable driving voltages. Both the single channel analyzer and the scaler-timer are in a single hp module. The detector includes NaI (Tl) crystal and photo multiplier tube plus amplifier.

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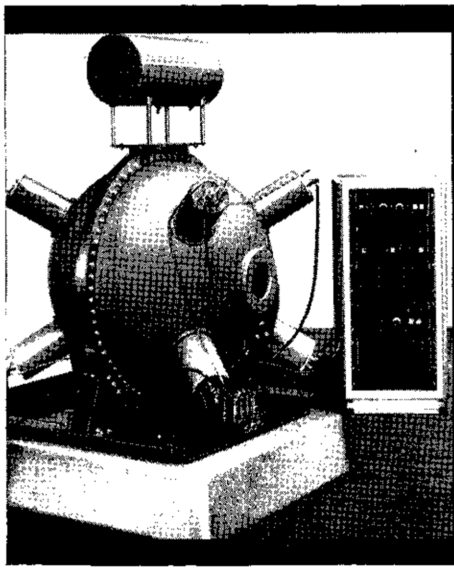

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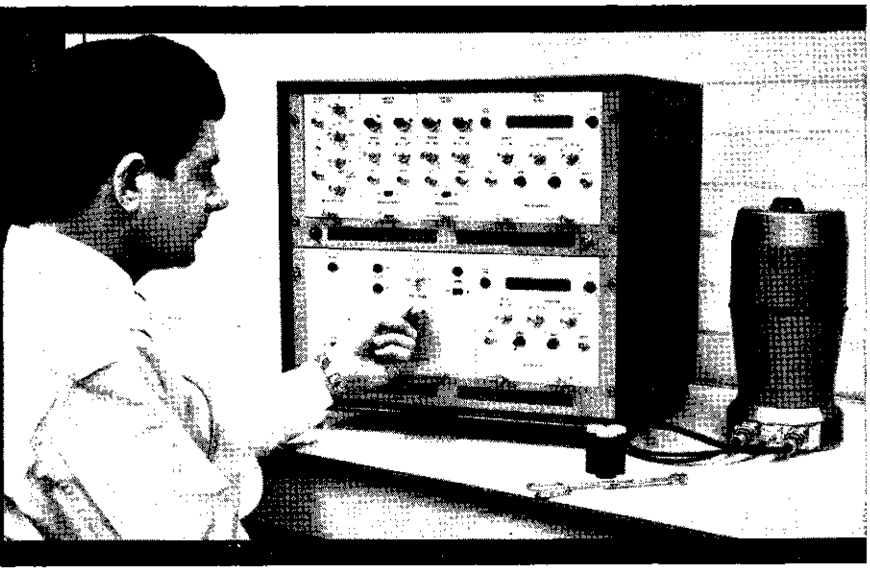

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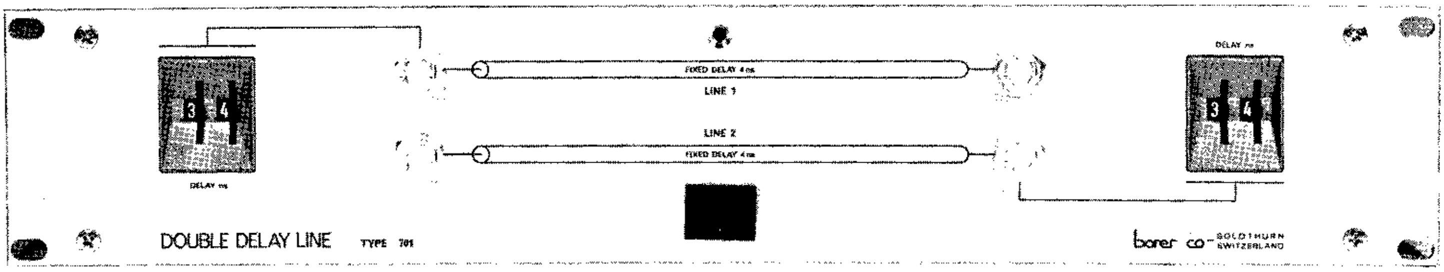

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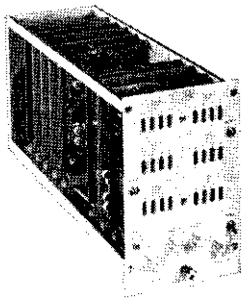

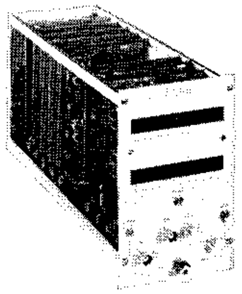

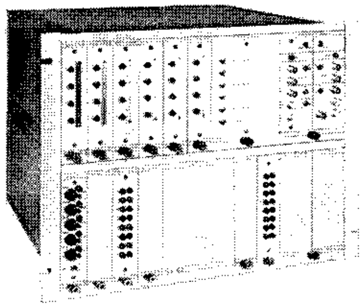


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