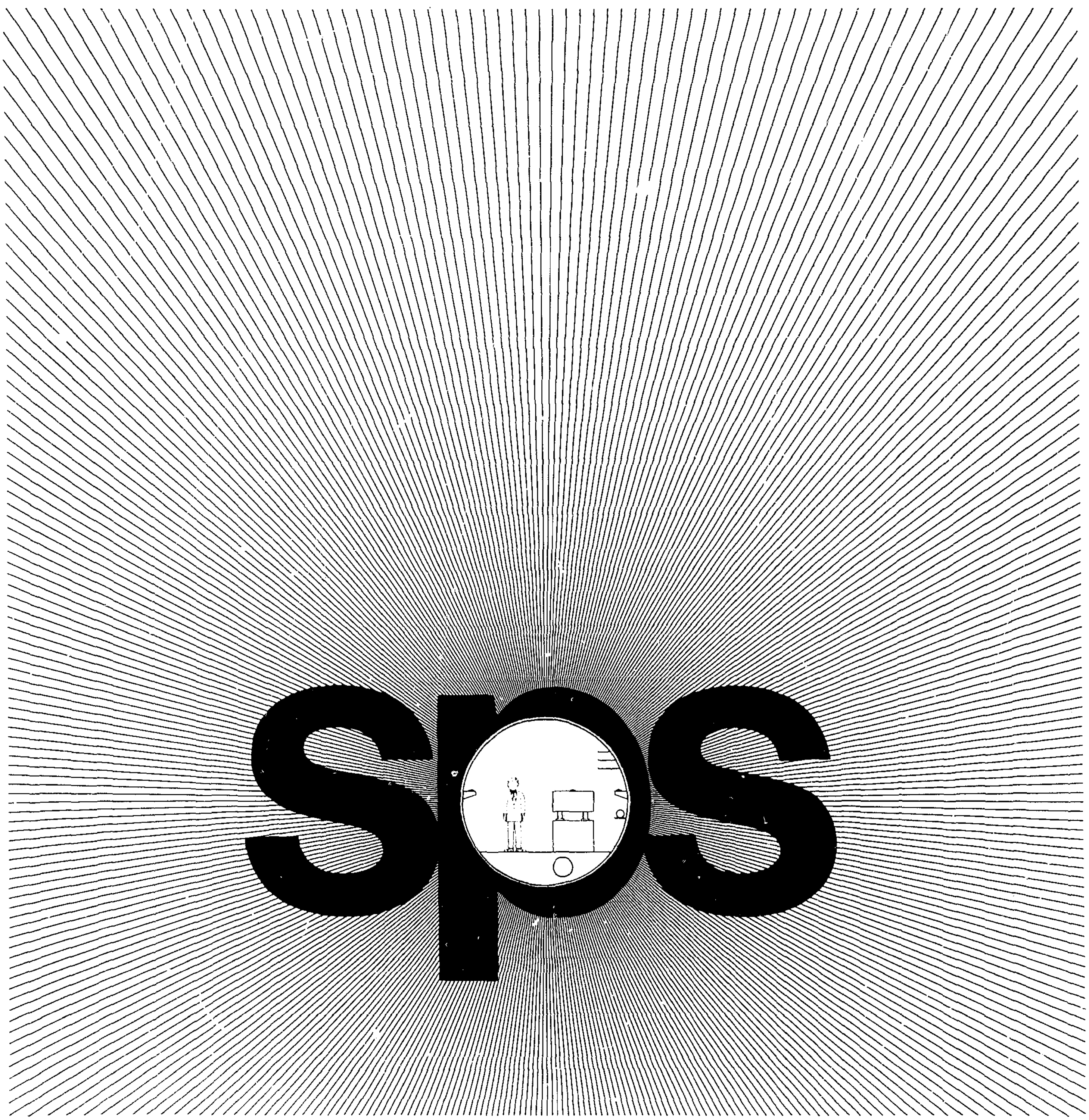
The 400 GeV proton synchrotron

CERN/SIS-PU --76-02



The European Organization for Nuclear Research, CERN, has built a 400 GeV proton synchrotron, known as the Super Proton Synchrotron or SPS. It provides the physicists of Europe with world-class facilities for research in particle physics.

Construction has been financed by eleven CERN Member States -- Austria, Belgium, Denmark, Federal Republic of Germany, France, Italy, Netherlands, Norway, Sweden, Switzerland, and the United Kingdom. The total estimated cost, spread over an eight-year construction programme which began in 1971, is 1150 million Swiss francs (at 1970 costs). Protons were first accelerated to full energy in the SPS in 1976 but provision of the full range of machine facilities, particularly in the experimental areas, is scheduled for completion at the beginning of 1979.

The accelerator is built underground on an extension of the previously existing CERN site located on the Franco-Swiss border near Geneva. The site area now comprises 109 hectares in Switzerland and 451.5 hectares in France. The ring tunnel in which the machine is built is an average of about 40 m below ground and the accelerator construction has thus caused minimum disturbance to the environment. The diameter of the ring is 2.2 km, the maximum which could be accommodated on the available site.

Although the construction programme initially envisaged a peak energy of 300 GeV, it proved possible, by using accelerator magnets with a high peak field, to increase the energy to 400 GeV. The design intensity is 10^{13} protons per pulse at a pulse repetition rate of about one pulse every 6 s. The parameters of energy and intensity are the key features of an accelerator from the point of view of the experimental programme which it can sustain.

Protons from the CERN 28 GeV proton synchrotron, PS, are injected into the SPS at an energy of 10 GeV. After acceleration they can be ejected towards two experimental areas (West and North). The West experimental area is scheduled to receive particles early in 1977, and the North experimental area about 18 months later. The areas are being equipped with a range of hadron, electron, muon, and neutrino beams, many of them of the highest energy, intensity, and quality ever achieved.

History of the SPS project

The coming into operation about 20 years ago of accelerators which could achieve particle energies in the GeV range, opened up a new era in our understanding of the nature of matter. As so often happens, this increased knowledge provoked a series of further questions, and it was obvious that many of them might be answered by access to still higher energies. In the early 1960s, following the remarkably successful operation of the CERN 28 GeV Proton Synchrotron and its twin, the 33 GeV Alternating Gradient Synchrotron at Brookhaven USA, it became clear that the techniques used in the construction of these machines could be extended to much higher energies.

In 1963 a committee (the European Committee for Future Accelerators, ECFA) was set up to study the whole field of high-energy physics in Europe and to make recommendations concerning future experimental facilities. It presented a report to the CERN Council in the same year, in which the major recommendation was the construction of "a new proton accelerator of a very high energy".

In 1964 a detailed design of a 300 GeV proton synchrotron was produced by CERN. It was envisaged that the accelerator would be constructed in a new CERN Laboratory elsewhere in Europe, and the Council invited the CERN Member States to propose possible sites. Twenty-two site offers were received, and about half of them were the object of a careful examination by CERN to see if they met the criteria laid down in the design study.

From the end of 1965 a further study was carried out by high energy physicists and accelerator experts from throughout Europe. This resulted in 1967 in a second ECFA report which strongly recommended the building of a 300 GeV proton synchrotron on the lines of the CERN design study of 1964.

By the end of 1968, letters of intent to support the project had been received from six Member States, and a Project Director was appointed by the CERN Council. The Project Director, together with experts from CERN and Laboratories in the Member States, set about revising the 1964 design to incorporate improvements in accelerator technology which had subsequently arisen. Meanwhile, the CERN Convention was ammended to take account of the existence of two separate Laboratories (the revised Convention actually coming into force in 1971). However, authorization of the project by all the Member States was not forthcoming because of difficulties in the selection of the site for the new Laboratory and because of the high costs involved in the project as it stood at that time.

In this situation, the Project Director presented in 1970 an alternative project for construction of the accelerator. The crucial change was the proposal to build the new machine alongside the existing CERN Laboratory. This circumvented the problems of site selection and, at the same time, greatly reduced the cost. The savings came from using the PS as injector, from using the existing West experimental area which already had large-scale particle detectors installed and, particularly, from using the existing "infrastructure" of the CERN Laboratory (administrative and technical services,

Aerial view of the CERN site, with the SPS accelerator picked out in white, against the background of Geneva and the Alps. The Franco-Swiss frontier which crosses the site is also indicated. (Photo Swiss Air)

etc.). The new project also included several options concerning future development of the accelerator. For example, by beginning with a "missing magnet" lattice of conventional magnets, higher energies could have been achieved later by the introduction of superconducting magnets in the gaps left in the lattice.

The new proposal was worked out in detail in the course of 1970 and presented as a two-volume report "A Design of the European 300 GeV Research Facilities". It received support from the scientific community and in political circles throughout Europe.

On 19 February 1971, ten of the CERN Member States approved the "Programme for the Construction and Bringing into Operation of the 300 GeV Laboratory". (Denmark joined at the beginning of 1972.) The project cost was set at 1150 million Swiss francs (at 1970 costs) over a construction period of eight years. A new Laboratory, known as CERN Laboratory II, with its own Director General was set up to build the accelerator. (The two CERN Laboratories were unified at the beginning of 1976.) The site, which straddles the frontier, was made available by France and Switzerland. The supply of electrical power was ensured by France and the supply of cooling water by Switzerland. The formal design description of the accelerator, entitled "The 300 GeV Programme", was published in January 1972.

The participation of the full community of European high energy physicists in designing the experimental facilities for the accelerator was ensured from the outset. ECFA organized two major study sessions in 1971 and 1972, which established the basis of the experimental hall layout, the available particle beams, and features of the major detection systems. In 1972 an SPS Experiments Committee was set up to decide on the initial experimental programme. This early start on preparing the experimental programme was necessary to ensure that the large and complex detection systems needed for physics at high energies would be built in time for the start of operation of the machine.

As the design and construction of machine components progressed at CERN, it was realized that the technology of superconducting magnets had not advanced far enough for them to be incorporated in the SPS. On the other hand, it was found possible to build the full ring with conventional magnets which, given the ring diameter of 2.2 km and a magnet design allowing peak fields of 1.8 tesla, would give the accelerator a peak energy capability of 400 GeV. The construction schedule was fixed so as to provide beams into the West experimental area in the sixth year of the construction programme and into the second (North) experimental area in the eighth year.

The SPS first accelerated protons to the design energy of 400 GeV in 1976.

General features of the SPS design

Several of the major features of the SPS design are set by the decision to locate the machine alongside the existing CERN Laboratory. The land in this area is not flat, the surface height varying from place to place by several tens of metres, and the bed rock underneath is a ridge of molasse (a mixture of sandstone and marl) whose depth varies over the site from a metre to 30 metres below ground level. Since the SPS had to be built in the bedrock for stability reasons, it was not possible to use the cut and fill method for making the tunnel to house the machine. It was decided to bore the tunnel using a full-face boring machine suitable for sand type rocks.

The molasse ridge has a width which permits a ring diameter of 2.2 km. (The maximum possible diameter is desirable since it is one of the parameters which determines the peak energy of the synchrotron.) The depth at which the tunnel lies below the surface on the circumference of this ring varies between a minimum of 18 m and a maximum of 64 m. With the minimum depth there is still more than adequate shielding by the overlying rock and morain to ensure that any radiation produced in the tunnel is reduced to a level on the surface which is well below the international tolerances for the general public.

The precise location of the ring was also dictated by the fact that the proton synchrotron (PS) provides the particles for injection and that the accelerated particles are sent to the already existing West experimental area. This fixes the positions of two long straight sections, one for injection (LSS1) and one for ejection to the West area (LSS6). The ring is divided into six arcs and six long straight sections, the other straight sections being taken up for ejection to the North experimental area (LSS2), for the radio-frequency accelerating system (LSS3), for the beam dump (LSS4), and one left free (LSS5).

Six access shafts, located at the long straight sections, are sunk to the ring, and six service buildings are constructed on the surface to house the power supplies and other equipment feeding the machine components installed in the ring tunnel underground. There is also a limited zone for office blocks and an assembly hall, and two large experimental halls in the North area. The disturbance to the existing environment has been kept to a minimum, and farming and forestry continues on most of the area of the SPS site as it had done previously.

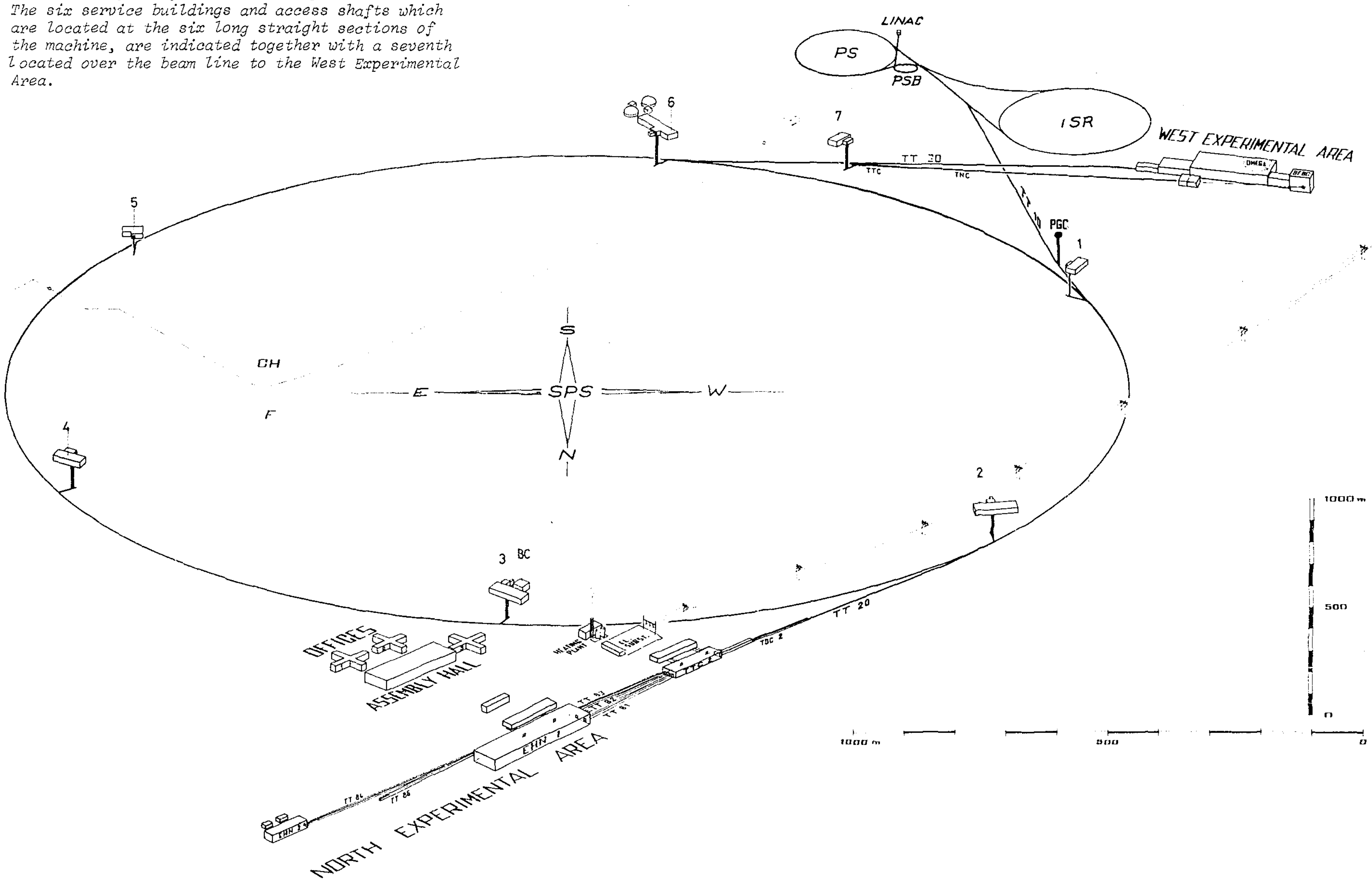
Protons are injected into the SPS from the PS with a beam intensity which will enable the SPS to reach its design intensity of 10^{13} protons per pulse. In order to spread the protons around the SPS circumference, which is eleven times longer than that of the PS (the PS diameter being 200 m), a novel method of ejection from the PS is used. It is known as "continuous transfer" and consists of debunching the PS beam and peeling it off during ten turns by a system of kicker magnets, an electrostatic deflector, and a septum magnet so that a ribbon of even intensity is ejected towards the SPS. The ejection/injection is done at a momentum which can be varied between 10 and 14 GeV/c. This is high enough to avoid problems of quality of the injection field in the SPS magnets and to limit the necessary frequency swing in the SPS radio-frequency accelerating system. It also reduces the time for which the PS is occupied filling the SPS. This keeps the time for which the PS is occupied with injection into the SPS to a minimum so that it can continue to supply protons for its own experimental programme at lower energy and for filling the Intersecting Storage Rings.

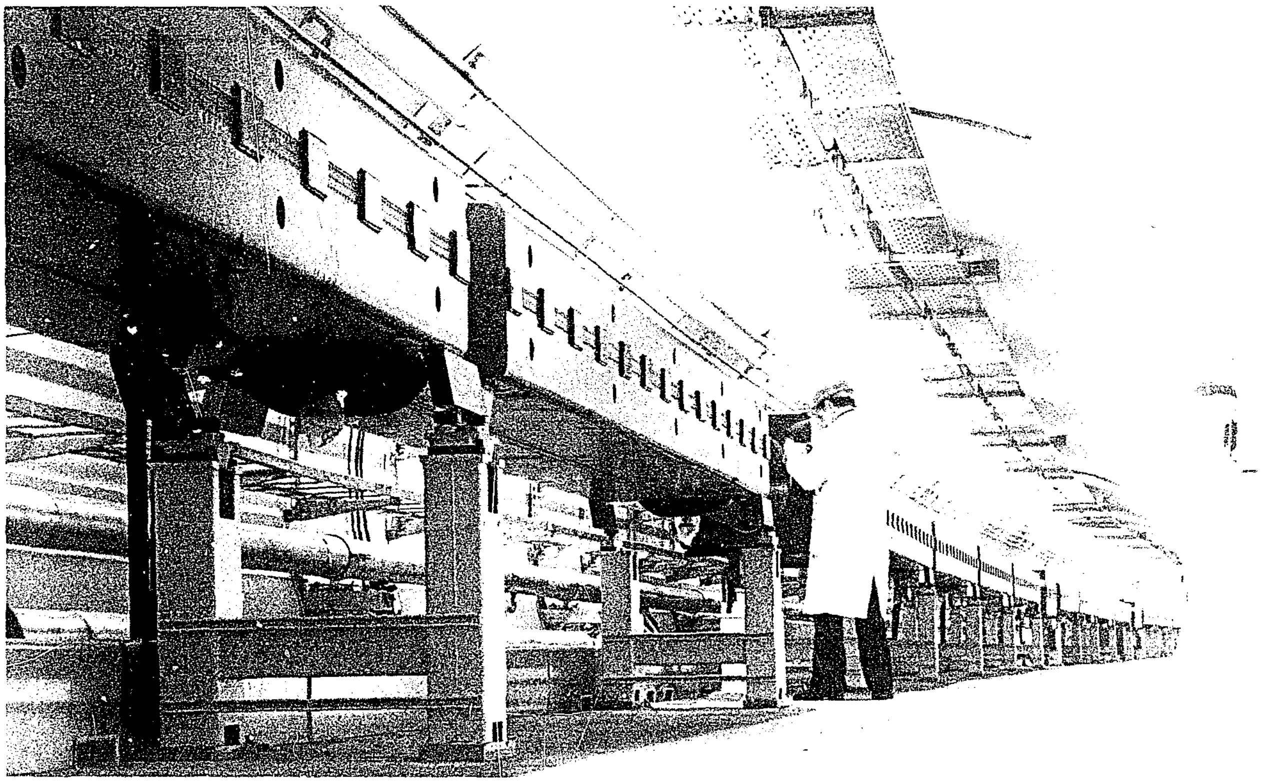
The beam from the PS first travels along a section of tunnel, TT2, which is part of the beam transfer system, towards the Ring 1 of the Intersecting Storage Rings. Two hundred metres along TT2 a switching magnet is powered to direct the beam along a new tunnel, TT10, towards the SPS (a distance of 800 m). A septum magnet and kicker magnet bend the protons onto their orbits in the ring. The ten-turn ejection from the PS gives a ribbon of protons filling 10/11 of the SPS circumference. The magnetic field in the kicker magnet can thus drop to zero before the first injected protons pass it on completing their initial turn so that their trajectories will not be disturbed by the injection field.

The magnet system into which the beam is injected has two purposes -- it has to curve the trajectories of the protons, so that they complete a near circle around the ring, and it has to maintain the beam well focused, so that the protons do not hit the wall of the vacuum vessel in which they travel. While being accelerated to 400 GeV, the protons orbit the ring about 150 000 times covering a distance of over a million kilometres. To ensure that they follow the desired trajectories throughout this journey, it is necessary that the magnetic fields be accurate to better than a few parts in ten thousand over the entire region in which the protons travel.

The magnet system is of the "separated function" type in which the tasks of bending and of focusing the beam are carried out in separate units -- dipole magnets and quadrupole magnets, respectively. This allows a higher peak energy than a "combined function" type for a given radius. There are eight dipoles and two quadrupoles in each normal "period" of the magnet lattice. The pattern of this period is repeated 108 times around the ring. The quadrupoles are arranged so that their fields are successively focusing and then defocusing giving a net focusing effect in both horizontal and vertical planes. Their peak field gradient is 21 T/m. The bending

Plan of the SPS showing the link with the PS, which serves as injector, and the two experimental areas. The six service buildings and access shafts which are located at the six long straight sections of the machine, are indicated together with a seventh located over the beam line to the West Experimental Area.





An arc of the SPS ring showing bending magnets and focusing quadrupoles in place. (CERN 10.11.74)

magnets are of the H-type in a compact design which keeps cost and power requirements to a minimum. They are 6.26 m long, and each normal period has four magnets with an aperture of 145 mm × 35 mm and four magnets with an aperture 120 mm × 48 mm. These dipoles are positioned so as to match the undulations in the beam profile determined by the focusing magnets. The dipoles are pulsed to give a peak field of 1.8 T (corresponding to 400 GeV) with a peak current of 4.9 kA.

In addition to 744 dipoles and 216 quadrupoles, there are correction magnets -- dipoles, sextupoles, and octupoles to compensate for any remaining defects in the magnet lattice and to allow refined control of the orbiting beam.

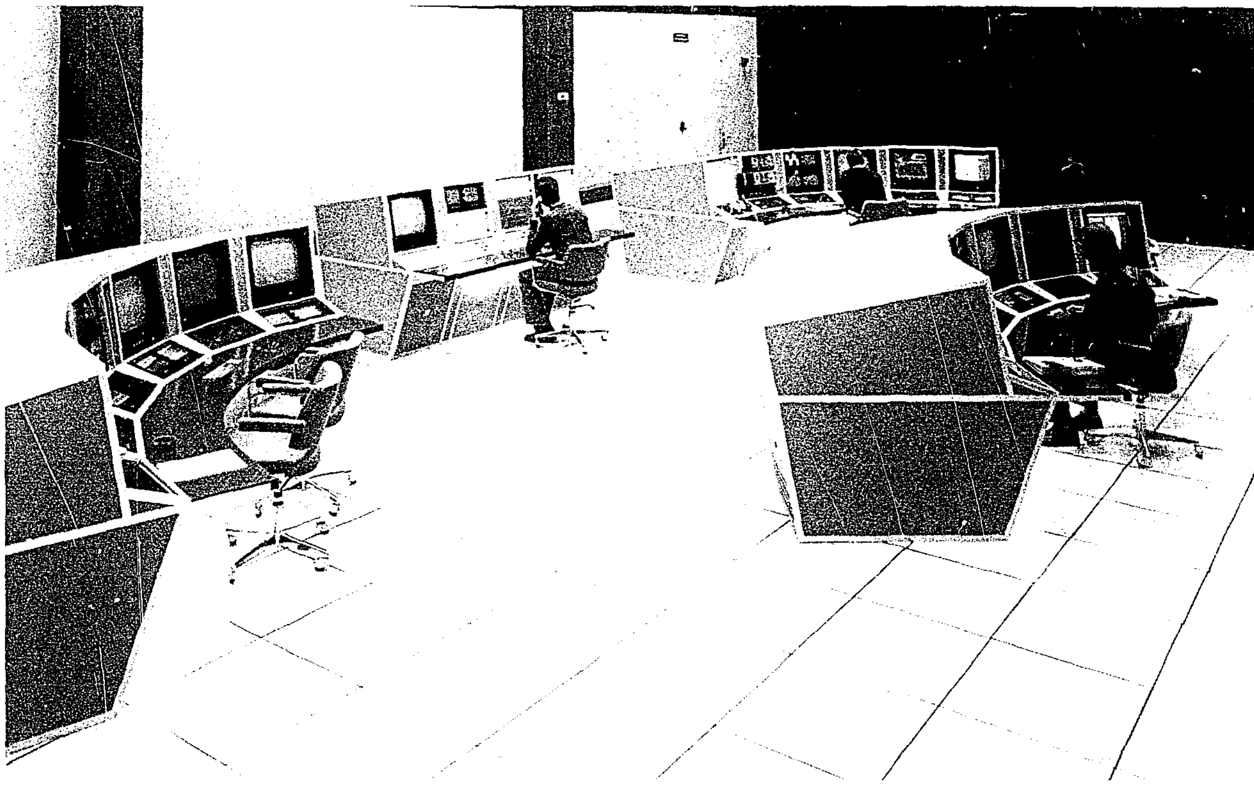
The magnets are powered using a "static power supply" rather than a motor-alternator set common in older synchrotrons. This is possible because the power generating capacity of the public electricity network is much greater than the peak pulse power required by the SPS, and the load on the generating stations can be uniformly distributed. The static supply allows the pulses of power to flow between the network and the SPS and back again without significant fluctuation of the network voltage. It is necessary to connect at an electrically strong point of the network and this is done at Génissiat in France. A 380 kV line brings the power from Génissiat to CERN.

The peak power for the bending magnets and quadrupoles is 135 MW and there is a mean power consumption of about 34 MW. This allows an SPS cycle time of about 6 s, including 0.2 s for injection, 3.7 s for magnet field rise (acceleration time), 0.7 s for a "flat-top" (during which protons can be ejected to feed the experiments), and 1.2 s for the magnet field to fall again. The power dissipated in the magnets is absorbed by a water-cooling system. Water is pumped from the Lake of Geneva (Lac Léman) and stored in two reservoirs, with a total capacity of 10 000 m^3, on the SPS site. When the machine is in operation the necessary flow of cooling water is 1000 ℓ/s.

The vacuum system is maintained at a pressure of better than 10^{-7} Torr by about 650 sputter ion pumps and 80 turbomolecular pumps. The vacuum tube, of low permeability stainless steel, changes in profile as it threads through the magnets and other machine components.

Acceleration of the protons is assured in straight section LSS3 by two radio-frequency cavities, 20 m long, each with a waveguide structure of 56 drift tubes. This form of RF structure is novel in the acceleration system of a synchrotron ring and is the most economic way of transferring power to the beam. Since the proton velocity varies very little (0.4%) during the acceleration cycle, it is possible to use an almost constant frequency of 200 MHz for the RF. This frequency divides the orbiting beam into 4620 bunches. The RF system accelerates the protons by about 2.5 MeV per turn, corresponding to an acceleration rate of over 100 GeV/s.

The accelerated beam can be extracted towards the West area and towards the North area using extraction systems located in straight sections LSS6 and LSS2, respectively. Three methods of extraction can be operated to meet the different needs of the experimental programme. Fast extraction involves bending the protons out during a few microseconds



The SPS Main Control Room. The accelerator may be operated from any of the three larger consoles, the smaller one being used for safety controls.
(CERN 137.10.75)

(all, or a fraction, of the bunches extracted during one turn) and will be used particularly to provide a neutrino beam and a RF separated beam to the BEBC bubble chamber. Medium extraction involves bending the protons out during several milliseconds, which is the maximum duration of beam that BEBC can cope with while still being acceptable to some electronic experiments. Slow extraction involves bending the protons out during times up to a second or more, providing beams best adapted to the needs of electronic experiments. Medium and slow extractions involve exciting a beam resonance which progressively increases the radial oscillations of the protons so that they enter the units of the extraction systems which deflect them out of the ring.

Each extraction system comprises four electrostatic septa 3 m long with septa made of molybdenum wires 0.1 mm thick spaced 1.5 mm apart. Outside the wire septa are electrodes at a potential of -300 kV. The field deflects the protons sufficiently so that they enter the aperture of septum magnets, of which there are four, 3 m long with septa 4 mm thick, followed by another five, 3 m long with septa 16 mm thick.

From the extraction point in LSS6 for the West area, proton beams can be taken up to the West experimental hall and split between three targets to yield secondary beams. The dimensions of the hall can accommodate secondary beams produced by protons with energies up to 200 GeV. Alternatively, protons with incident energies up to 400 GeV from the same extraction point can be used on underground targets to yield either secondary beams of a type and energy which can be selected by RF separators, or neutrino beams which are aimed at the BEBC and Gargamelle bubble chambers and counter experiments.

From the extraction point in LSS2 for the North area, proton beams can be taken almost 600 m to the surface and split between three targets to yield hadron beams in North experimental hall 1, and hadron and muon beams into North experimental hall 2. The secondary beams can be produced by protons with incident energies up to 400 GeV.

Monitoring and control of the multitude of machine components and of the proton beams themselves are carried out by a computer control system which has advanced the techniques of accelerator control in several ways. The system has 24 small computers -- 13 distributed around the ring, 8 at the Main Control Room, and 3 in the experimental areas. They are all capable of independent operation and in some cases are "dedicated" to the monitoring and control of specific components (for example, one computer looks after all aspects of the radio-frequency system). The computers communicate with one another and with three consoles in the Main Control Room by means of a high-speed message transfer system.

Much attention has been given to the control philosophy so that data can be called up easily and presented in a way which is easily assimilated by the machine operators. The operator views a number of colour TV screens which present the status of components of the machine which can be selected with a "touch screen". The screen has 16 transparent buttons backed by a TV upon which different labels can be written by a computer. Almost all the hundreds of knobs and switches of a conventional control room are channelled into a single knob whose function is also controlled by the touch screen. A specially developed computer language is used which allows changes to any computer program to be made rapidly and easily.

Published by the Publications Section, Document No.CERN/SIS-PU 76-02
European Organization for Nuclear Research
1211 Geneva 23, Switzerland *May 1976*