Chapter 5

The Super Proton Synchrotron (SPS): A Tale of Two Lives

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5.1 Introduction

In the early 1960s groups of accelerator designers on both sides of the Atlantic made plans for large proton synchrotrons based on the recently completed CPS and AGS. Each study group aimed for 200 GeV to 300 GeV, roughly ten times the energy of the existing machines, and both proposals were scaled up versions of the combined-function magnet lattice used for the AGS and CPS. Combined function refers to the ring of magnets which guide particles in a circle. The magnets combine in one type both focusing and bending of the circulating beam [Box 2.1].

A new US proposal for a 200 GeV synchrotron finally chose a different lattice in which the functions of bending and focusing the beam were assigned to separate dipole and quadrupole magnets. This choice permits a higher field in the dipoles resulting in a more compact design allowing a higher energy in a circle of a given radius. CERN considered this design but found the cost of the alternatives would differ very little and, as a “green-field site” provided by one of the CERN Member States was being considered, a 15% smaller size was not crucial and the combined-function design was retained.

The original plan of CERN had been to build both the ISR (Chapter 4) and a 300 GeV machine at the same time, but the latter was delayed by discussions among the Member States over the choice of the site and by a request to consider superconducting magnets [1].

In 1968 John Adams was invited by the CERN Council to oversee CERN’s by now well and truly stalled 300 GeV Synchrotron Project. He made two important decisions to save the project. First, the combined-function design was abandoned and the separated-function design was chosen by the new team as this reduced the size of the accelerator for the same top beam energy and allowed for a “missing magnet” option: to install all the quadrupoles but only half of the dipoles, i.e. every second dipole magnet. Although this would lead to one half of the top energy, the

initial budget would be reduced and the accelerator would be operational earlier; the missing dipole positions could be filled later — possibly with superconducting magnets, if they became available [2].

The second decision settled the thorny site problem, after years of protracted discussions. The proposal to site the new accelerator next to the existing laboratory using the PS as injector and the existing infrastructure had been put forward already in 1961. However, at that time, it was felt that (i) the new large facility should be constructed elsewhere in Europe to avoid concentration at one site; (ii) building the accelerator on the surface by the cut-and-fill method would be too major a disturbance of the local countryside; (iii) siting it in a tunnel would require expensive underground experimental areas as internal targets for the production of the secondary beams were the norm at that time. By 1968, however, tunnelling technology had advanced, the beam extraction techniques had been refined and the project team argued that experimental halls on the surface could very well be served by an underground accelerator, a novel concept and decisive for CERN's future (LEP, LHC). On top of that, the existing large West Hall including its bubble chambers would be perfect as the initial experimental area. The idea to build the new facility near to the CERN site promised substantial savings, an earlier start — not to mention an interesting perspective for the existing laboratory.

In May 1970 CERN proposed to Council to build the 300 GeV accelerator adjacent to CERN I (Meyrin) site, and to install at first only half of the magnets, in an underground tunnel of 7 km in circumference, see Fig. 5.1. Such a machine would reach 400 GeV with normal magnets installed in all the gaps. The missing magnet scheme would even permit higher energies if filled with superconducting magnets. This satisfied critics that 400 GeV was not high enough and encouraged the advocates of superconducting magnets to continue developing this technology.

Finally, the Member States, after much hesitation, accepted the new ideas and approved the machine in February 1971. During the construction it became clear that superconducting technology was developing more slowly than expected, while conventional dipole magnets proved cheaper than budgeted, and in 1973 there was a decision to build a 300 GeV machine with all normal-conducting magnets — to the great relief of the SPS construction team.

The tunnel boring in the amenable molasse (local sandstone) rock was completed on 31 July 1974, when the machine excavating the SPS tunnel returned to its starting point. The joy of achieving the important milestone of completing the boring of the 7 km long tunnel is captured in Fig. 5.2. The tunnel is situated at an average depth of 40 m below the surface and straddles the Franco-Swiss border, making the SPS the first major cross-border accelerator.

Fig. 5.1. Layout of the SPS with its experimental areas and its injector the PS. The latter is on the original Swiss site of CERN.

Fig. 5.2. Break-through moment: completion of the SPS tunnel.

The construction proceeded rather uneventfully except for the discovery in 1975 that, after about 250 dipoles had been manufactured and about 100 installed, some showed a low resistance between the insulated coils and ground which could lead to breakdowns. The SPS magnet team investigated and found the cause to be the use by the manufacturer of an inappropriate acid to clean the tag ends of magnet coils before brazing the terminals, which damaged the insulation. All suspect magnets were repaired without delaying the project. During construction the team also quietly found a way to equip the machine to be capable of acceleration up to 400 GeV. A section of the fully equipped SPS tunnel is shown in Fig. 5.3.

Five years after approval the SPS machine was operational. In the morning of the June 1976 Council meeting Adams announced the successful acceleration to 300 GeV and formally asked permission to re-programme the machine for 400 GeV operation, although Council was doubtless aware of the capability. Acceleration to 400 GeV was announced a few hours later, just before dinner.

Later in the year, the West Hall received the first extracted beams, initially limited to 200 GeV not to exceed the legal radiation background levels [3,4]. The experiments were already installed and the experimental programme could start without delay. Thanks to the careful design, the top energy could later be increased to 450 GeV at the request of particular experiments which later turned out to be a good investment for the LHC, which would benefit from a higher injection energy.

Fig. 5.3. The SPS magnet string with dipoles (red) and quadrupoles (blue). The vacuum chamber is visible before entering a sextupole downstream of the dipole.

During the construction known technologies had to be further developed and novel approaches introduced to cope with the sheer size of the facility and the high beam energy. New alignment methods had to be developed as the tunnel could only be accessed by six shafts. First, survey pillars were erected covering the site for accurately determining the position of the shafts and the position relative to the PS. The tunnelling machine was laser-guided which took its reference position from a gyro-theodolite set-up every 32 m resulting in an average error of only 20 mm at the end of a 1.2 km long sector.

Although most of the main components of the SPS were rather conventional, a high standard was applied which turned out to be a real bonus for reliability and, later, enabled the conversion of the SPS into a collider (Chapter 6). An example is the vacuum system, which though much less demanding than that of the ISR, was constructed with the same care, to maximize reliability over the 6.9 km length. It later permitted the average pressure to be reduced from 3×10^{-5} to 3×10^{-7} Pa (nitrogen equivalent) for the collider operation by the simple addition of vacuum pumps.

A major effort was devoted to develop a flexible extraction system providing both fast extraction (burst duration 1 μ s to 23 μ s) and slow extraction with a spill duration from 70 μ s to 4.8 s. Certain modes of extraction offered the option to stop the spill after extraction of part of the beam and re-accelerate the remaining beam for extraction at higher energy [5]. After an upgrade of the West area, simultaneous slow extraction to the West and North areas at up to 450 GeV became possible. To master these tasks, technology known from the PS had to be developed to accommodate the much higher beam energy. Electrostatic deflectors of 12 m length were developed to provide a deflecting field of typically 12.5 MV/m over a 20 mm gap using as septum a row of vertical 0.1 mm diameter wires of tungsten-rhenium alloy [6]. The pulsed magnetic deflectors downstream of the electrostatic deflectors provided a field of 0.47 T in a 10 cm gap with a copper septum of 4.2 mm thickness carrying 7.5 kA [7]. As all these devices operated in vacuum, they needed to be baked-out in situ to reduce outgassing. The alignment precision in the vacuum tanks of ± 0.15 mm and the fierce radiation environment imposed a strict selection of materials.

For accelerating the beam special travelling-wave structures were developed operating at a frequency of 200 MHz [8]. Lower energy synchrotrons such as the PS accelerate protons through velocities ranging from a fraction to near the speed of light. The standard way had always been to tune the accelerating cavities through a comparable range of resonant frequencies with blocks of ferrite within the cavity. These were tuned by changing the bias current in a winding around the ferrite to alter its permeability and hence the resonant frequencies of the

accelerating cavities [Highlight 3.3]. At the SPS, in which particles are already injected very close to the speed of light, a much smaller tuning range (0.5%) was needed. This led to the clever idea of using the more efficient travelling wave structure, as used in linear accelerators. Such a structure accepts a band of driving frequencies which easily covers the narrow range of velocities in the SPS. Complex and lossy ferrite tuners were not required.

When the SPS was designed, computers were used in accelerators in a stand-alone way generating, e.g., time-dependent operational functions, or for operator consoles, but were not linked. The sheer dimension of the facility and technological advance in industrial products suggested a new approach to the control system. The first truly distributed multi-computer control system was developed introducing a number of novel features, which served as a springboard for application to other accelerator projects at CERN [Highlight 5.2]. This facilitated the interaction of the operators with the system, e.g. using the operator consoles equipped with the now ubiquitous touchscreens for easy monitoring and control. A general purpose “knob” was also made available to the operator for programmable assignment of several functions to a certain task.

Another major undertaking was the construction of the long tunnels and beam lines to the experimental halls (Fig. 5.1). The North area received the first beam in early 1978 to produce a high-intensity muon beam with energy of up to 280 GeV. This muon beamline was modified a few times to match the requirements of the various experiments and is still in use today [Highlight 5.4]. A further example of the many innovative beam lines, which were and still are being constantly optimized for a particular experiment, is the line producing simultaneous and nearly-collinear K^0 meson beams. This is the most complex beam line ever constructed at CERN [Highlight 5.5].

The most dramatic change, however, to the SPS was its second incarnation as a proton-antiproton collider, which enabled CERN's Carlo Rubbia and Simon van der Meer to earn their Nobel Prize for the discovery of the W and Z (Chapter 6).

In the late 1980s, at the end of collider operation, the SPS was equipped to accelerate electrons and positrons from 3.5 GeV to 20 GeV whenever LEP (Chapter 7) required filling, interleaved with fixed-target proton or ion operation. To this end, an additional RF system was installed consisting of 32 newly developed standing-wave accelerating cavities. These were later gradually replaced by superconducting cavities, the first units being prototypes of the novel niobium-clad copper standing-wave cavities for LEP, before mass production [Highlight 7.4]. Substantial effort was devoted to shield the magnet coils in the ring against the highly directional synchrotron radiation of the circulating electrons or positrons [9].

The most recent major change occurred in a long shutdown in 2005, when this versatile accelerator was transformed into an efficient injector of protons and lead ions for the LHC. This required installing an extraction system for 450 GeV protons and 176 GeV/nucleon lead ions for the LHC anti-clockwise ring, the upgrade of the 200 MHz and 800 MHz RF systems, and rebuilding the injection kickers in order to shorten the rise-time and to reduce substantially the ripple of their pulse [10].

And so, while there were engineering innovations in the SPS which had far-reaching impact, the machine was most remarkable for its high standard of construction, which has allowed this amazingly versatile accelerator to respond to the constantly evolving demands of a dynamic physics research community.

The SPS physics programme

The SPS physics programme was discussed and detailed in workshops and meetings involving large audiences of the HEP community and providing input concerning the variety (hadronic, leptonic, charged and neutral) and characteristics (intensity, momentum resolution) of the possible beams from the SPS [11]. The locations of beams and of some of the experiments (WA for West Area, NA for North Area) are shown in Figs. 5.4 and 5.5. The flexibility, versatility and high quality provided by the SPS machine yielded a wealth of remarkable physics results [12]. In many cases the science output was only made possible by technological innovations both in the beam lines and in the detectors. A brief overview of the two experimental areas and research highlights illustrates the interplay between technology and research.

Fig. 5.4. Initial layout of beams in the SPS West Experimental Area, WA.

Fig. 5.5. Schematic layout of the North Experimental Area in 1980.

The West Area (WA), initially used as a PS area, was first to receive beams from the SPS. Operation began in 1976 with secondary beams derived from 200 GeV/c (later 250 GeV/c) primary protons. The charged hadron beam S1 led to the first SPS physics publication and was later used as a RF separated beam [Highlight 3.7]. The initial layout of the West Area is shown in Fig. 5.4.

Later the WA was transformed to receive two high energy secondary beams (H1 and H3), produced by 400 (450) GeV/c protons in an underground target station, modelled after the beams to EHN1 in the North Area. Additionally, two ‘long’ beams (N1, N3, S3) were derived from 400 GeV/c fast extracted protons targeted in underground caverns, near the extraction point from the SPS. These beams were directed towards the Big European Bubble Chamber (BEBC) and electronic detectors downstream of BEBC.

The North Area (NA), a new facility, tailor-made to receive the high energy beams, incorporated several innovative aspects. Its layout in the year 1980 is shown in Fig. 5.5. The NA features a separate underground target cavern, TCC2, and surface experimental halls, EHN1 and EHN2, joined by tunnels housing the beam lines. The layout resulted from the requirement to provide beams of well-defined momentum ($\Delta p/p \approx \pm 2 \times 10^{-4}$) up to the highest momenta. This beam layout also ensures that the main muon background is absorbed in the ground underneath the experimental hall (Fig. 5.6).

Upstream of TCC2, the slow-extracted, primary proton beam of 400 GeV/c (later 450 GeV/c) from the SPS was split three-fold, with two series of septum magnets, so as to impinge on two general-purpose target stations and one dedicated to the production of a high energy muon beam. Each of the two general-purpose

Fig. 5.6. Schematic vertical section through beam lines in the North Experimental Area.

target stations comprised horizontally-deflecting magnets, allowing the angle and position of the proton beam to be varied ('wobbled') onto the target. Thereby the momenta of two secondary beams emitted in fixed directions could be decoupled, whilst the majority of muons produced were not accepted by the subsequent vertical bends of the beams. A wide choice of particles of different momenta could be transported by the four beam lines: primary protons, attenuated in intensity, charged secondary particles and relatively pure tertiary particles, derived from neutral particles, such as polarized protons from $\Lambda^0 \rightarrow p \pi$, low-energy pions from $K_S^0 \rightarrow \pi^- \pi^+$, $e^\pm$ from $\gamma \rightarrow e^- e^+$. These beams could also transport various ions species from the SPS.

Later, an underground experimental cavern, ECN3, was added as part of the North Area High Intensity Facility (NAHIF), designed for experiments requiring the highest-intensity primary and secondary beams.

The many facets of the research landscape

Exploration of the nucleon structure

One major research activity was the exploration of the nucleon structure [Box 4.2], using the weak probe (i.e. neutrino scattering), the electromagnetic probe (i.e. muon scattering), as well as hadron scattering, producing photons and lepton pairs born from the energetic or "hard" scatter of their constituents. The use of polarized beams and targets was an important asset of these programmes [13].

Neutrino scattering [14] was performed in the WA with the WANF neutrino facility. Both wide- and narrow-band neutrino beams (N1, N3) were available, employing magnetic horns [Highlight 3.6] to focus the parent pions and kaons into an evacuated decay tunnel, followed by the hadron absorber made from iron and

concrete. These beams served BEBC and a series of ‘counter’ neutrino experiments: WA1/CDHS, WA18/CHARM, later NOMAD, CHORUS, installed on the same line, downstream of BEBC and pushing detectors to new dimensions. The heavy liquid bubble chamber GARGAMELLE (chapter 3) was installed in the neutrino beam line, downstream of BEBC. BEBC was complemented with the External Particle Identifier (EPI), which measured the energy loss dE/dx of the charged tracks leaving the bubble chamber [Box 5.2] and with the external muon identifier (EMI).

Later on, the same beam was used to search for τ neutrino interactions. No ν_τ event was observed. This was because the scale of ν oscillations (that were to be discovered later elsewhere) was too large to be detected by the contemporary experiments at CERN.

Muon scattering [15], performed in the north area, used a most remarkable muon beam. The programme started with the experiment of the European Muon Collaboration (NA2/EMC), a powerful open spectrometer, and NA4. The latter used a 40 m long liquid hydrogen target surrounded by toroidal magnetized iron discs interleaved with detectors to measure the properties of scattered μ 's. EMC was followed by an upgraded version, the New Muon Collaboration (NMC). The muon section of the beam line was rebuilt for the Spin Muon Collaboration (SMC) experiment, exploiting the high degree ($\sim 80\%$) of polarization of the muons in the beam and using a high-performance polarized target [Highlight 5.8]. The beam was again modified for the NA58/COMPASS experiment, using the M2 beam line both for a muon beam and as a high energy hadron beam. This beam line is a fine example of productive longevity!

Hard hadron scattering [16] experiments were performed with several beams and in both areas. The signal under study was either lepton pairs in, for example, WA11, WA12 (OMEGA), NA3, NA10, NA34 or energetic photons in, for example, WA70 (OMEGA). Information was obtained on the structure of both the target nucleon and the incident hadron (pion, kaon, antiproton).

The identification of beam particles was essential for this programme. This was achieved by using an RF separated beam, such as the WA S1 beam or with special differential Cherenkov counters [Box 3.2]. These ‘CEDAR’ detectors employed a mirror at the downstream end of a pressure tank filled with helium gas, and an achromatic ring-focusing lens to concentrate the Cherenkov light through an annular diaphragm onto 8 photo-multipliers at the upstream end (Fig. 5.7).

Loops

Box 5.1

Elementary particles live in a quantum world and the properties of the quantum vacuum lead to non-intuitive effects.

A particle propagating may “borrow” energy from the vacuum and turn into a pair of other particles (creating a “loop”), provided the relevant quantum numbers (electric charge, etc.) are conserved. The larger the loan, the faster it is reimbursed, in agreement with Heisenberg’s energy-time uncertainty relation. The loop disappears again and these “virtual” particles do not come to “real life”. Their existence has nevertheless an effect and modifies the rate of a process in which they occur. In the SM [Box 6.4] this effect depends on the mass and nature of the particle appearing as virtual and is precisely calculable.

In e^+e^- collisions on the Z^0 resonance (see Chapter 7), the propagating Z^0 may fluctuate e.g. into a top-antitop pair (Fig. 1a), even though the top is too heavy to be really produced. Measuring accurately the Z^0 final states at LEP1, one obtained an idea of the top mass. The effect is substantial and had to be well mastered before being sensitive to the even tinier effect of the virtual BEH (“Higgs”) boson [Box 8.2], Fig. 1b.

Fig. 1a. Top-antitop loop.

Fig. 1b. W-Higgs loop.

This effect concerns any kind of virtual particle, in particular hypothetical ones, e.g. supersymmetric particles [Box 7.2] and provides a way to search for them. This is one goal of beauty physics performed at B factories and LHC (Chapter 8).

An “indirect” hint of a virtual particle is a precious guide but “discovery” of a new particle requires producing and observing it. The agreement between the direct and indirect measurement of its mass tests the SM at the “loop” level. This confirmation of the SM was one of the major achievements of the LEP programme.

Another effect of virtual particles is the “running of coupling constants” which evolve with the energy scale of the process. The one associated with the weak force is almost constant; with the electromagnetic force it increases at smaller distance, i.e. higher energy. For strong coupling, due to the self-interaction of gluons, it does the opposite [Box 4.2]. Triple convergence of the coupling constants at very high energy is quasi-perfect with Supersymmetry.

Probing particle reactions at higher energies improves the resolving power and exhibits more details, such as higher sensitivity to fluctuations into virtual particles. These studies (violation of “scale invariance”) were one of the main topics of Deep Inelastic Scattering at the SPS (Chapter 5).

In the special underground area ECN3 the primary proton beam served to produce high intensity pion and photon beams for a series of experiments: NA10 studying muon pair production, NA14 performing direct elastic scattering of real photons on quarks, called QED Compton scattering, and NA34 searching for unconventional sources of lepton production.

There were important results on nucleon structure. Comparing structure functions measured in neutrino and lepton scattering, as well as QED Compton scattering, brought the final word about the fractional electric charge of quarks.

Another important result was the evidence that the measured nucleon structure actually depends on the resolving power of the observation, a basic prediction of quantum chromodynamics (QCD) [Boxes 4.2 and 5.1]. This is the so-called “scaling violation”, observed in particular in neutrino scattering, first by the bubble chambers BEBC and Gargamelle and subsequently, with higher accuracy, by the electronic detectors. Muon scattering revealed that the nucleon structure depends on the nucleus in which the nucleon is contained (EMC effect) and that the motion of quarks in nucleons inside the nucleus decreases for heavier nuclei. One series of muon scattering experiments used a polarized target, where the spins [Box 2.2] of the target protons and therefore also the spins of the constituent quarks were aligned along the direction of a magnetic field. Conservation of angular momentum makes muon scattering sensitive to the spin alignment and significant differences in scattering cross sections are expected depending on the direction of alignment. This was not born out experimentally and revealed that the nucleon spin is only partly carried by its valence quarks, and that sea quarks and gluons also contribute. This “spin crisis” changed our understanding of the nucleon.

For energetic hadron scattering, the observed production rates of lepton pairs or prompt photons were found to be higher than estimated at that time, by some multiplicative “K-factor”, which called for more elaborate theoretical estimates, in the framework of the then emerging QCD to which the SPS experiments contributed substantially, in particular with results from collisions of heavy ions.

Fig. 5.7. Schematic cross-section of a CEDAR detector (not to scale).

Particle Identification (PID) via energy loss (dE/dx)**Box 5.2**

A charged particle traversing a medium interacts with the electrons of the atoms, which are excited or ionized. At each collision some energy (E) is transferred. The E loss per unit distance, dE/dx , depends on the particle velocity $v = \beta c$. The average $\langle dE/dx \rangle$ is given by the Bethe-Bloch (BB) curves (Fig. 1), which show:

- a decrease $\sim \beta^{-2}$ (electric force of atomic e^- acts more briefly on faster particles);
- after a minimum, a rise $\sim \ln(\beta\gamma)$ due to the relativistic increase of the particle's transverse electric field (TEF), $\propto \ln \gamma = \ln(E/mc^2)$, increasing interaction cross-section;
- saturation at high $\beta\gamma$ due to medium polarization, shielding TEF far from the track.

E loss over a path length is the sum of E transferred in many collisions, with E fluctuating statistically about $\langle dE/dx \rangle$. Rarer large E transfers in single collisions skew the energy loss distribution to high energies (Landau distribution). Sampling dE/dx many times along the track gives an estimate of $\langle dE/dx \rangle$ with high statistical significance. Due to the skewness of the distribution, the average obtained by excluding 15–50% highest E losses (Truncated Mean, TM) is a better estimator for the energy loss than the mean. The TM distribution of many tracks of same v is centred about a value $TM(v)$ and is close to a Gaussian with variance σ_{TM}^2 . It can be related to $\langle dE/dx \rangle$ as given by the BB curves and hence to the $\beta\gamma$ (or v) of the particle. For PID, momentum p and TM are measured. Two species of particles with the same p but different m , hence different v , will produce different TM distributions. The resolution $R (= \sigma/E)$ is the relative accuracy of the TM measurement. Gaseous detectors can achieve $R < 5\%$ for a careful choice of gas mixture [1]. PID works well at low β , fails around the minimum, and is (statistically) useful in the relativistic rise region as shown in Figs. 2 and 3 [2]. Various devices have been made to provide PID. The External Particle Identifier (EPI) was installed behind BEBC [Highlight 5.7]; the large pictorial drift chamber ISIS for the European Hybrid Spectrometer achieved a TM resolution of 3.5% in the 2–80 GeV/c range. TPCs (ALEPH, DELPHI at LEP, ALICE at LHC) provide good sampling along tracks, and $R < 5\%$.

[1] I. Lehrs, *Nucl. Instr. & Meth.* **217**, 43 (1983).

[2] C. Lippmann, arXiv:1101.3276.

Fig. 1. Energy loss per cm and per $g\ cm^{-3}$.

[K. Nakamura *et al.*, *J. Phys G* **37** 0287 (2010)]

Fig. 2. Typical dE/dx of particles.

Fig. 3. Separation power of selected pairs assuming energy resolution $\sigma_E/E = 5\%$.

Heavy flavours [17]

A second major research area was the study of the heavy quarks or flavours: charm, discovered in 1974, and beauty discovered in 1977. While these discoveries came from US laboratories, CERN was very active in the study of heavy flavour spectroscopy, benefiting from the variety and quality of hadron and photon beams and pioneering the use of very accurate micro-strips silicon detectors [Highlight 5.9] exploiting the finite lifetime of charm and beauty particles. Later, pixel detectors provided even higher spatial resolution.

Micro-strip detectors were first used in the WA75 experiment. The OMEGA spectrometer performed a long series of experiments, using hadron, electron/photon, hyperon and ion beams, which included, e.g. the observation of several particles containing beauty quarks. Pixel detectors also found their place in some OMEGA experiments, such as WA89 and WA97. In the NA, silicon devices, active targets, strip detectors, pixel and CCD detectors made essential contributions in several experiments, such as NA1, 10, 11, 14, 32, 34, and 57.

The European Hybrid Spectrometer (EHS), in the H2 beam line, combined the virtues of small to medium-sized bubble chambers with those of a large magnetic spectrometer. It also housed an early dE/dx detector (ISIS) to study charm decays.

Heavy ions [18]

The SPS pioneered the study of ultra-relativistic heavy ion collisions. This programme aimed at the study of nuclear matter under extreme conditions of energy and temperature. It opened a new field of physics, initially explored with several survey experiments and a range of dedicated experiments looking for a putative “quark-gluon plasma”, characterized by unconfined quarks and leptons, whose existence is one of the “golden” predictions” of QCD.

Initially, oxygen and sulphur ions were accelerated, followed in a later phase by heavier ions, up to lead. The programme was performed in EHN1 (NA34, NA45, NA49, NA57 and now NA61) and ECN3 (NA38, NA50, NA51, NA60).

In 2000 CERN announced the discovery of a ‘new phase of matter’, consistent with the onset of the Quark Gluon Plasma.

CP violation [19]

One outstanding achievement was the accurate measurement of CP-violating processes in neutral kaon physics [Box 3.4], most notably the evidence for direct CP-violation, using elaborate and unique beam and experimental techniques.

For experiment NA31, 450 GeV/c primary protons were targeted to produce a beam rich in long-lived neutral kaons, K_L^0 , which entered and decayed in a large vacuum tank. Alternately, a K_S^0 beam was generated from a 360 GeV/c secondary proton beam, incident on a separate target. This target was mounted on a train that

could move into 41 longitudinal positions inside the evacuated decay volume. With this beam NA31 obtained the first positive indication of direct CP-violation, while a competing US experiment obtained a result compatible with no signal [20,21]. A second generation experiment, NA48, was designed to establish unambiguously and measure the direct CP-violation parameter ε'/ε in the K^0 system. The novel and decisive concept of the experiment was based on a pair of simultaneous, nearly collinear beams of K_L^0 and K_S^0 and used a state-of-the-art liquid krypton calorimeter [Highlight 5.6]. These efforts paid off: after 30 years of measurements, both the CERN NA48 and the US KTeV experiments finally proved the existence of direct CP-violation, a major facet of the Standard Model. The beam line and detectors have now been transformed for NA62 that aims to measure the ultra-rare decays of K^+ into $\pi^+ \nu \bar{\nu}$.

Recent developments

A very special muon-neutrino beam has been constructed for a tau-neutrino experiment (Fig. 5.8). The neutrino beam derived from secondary pions and kaons decaying in an evacuated decay tube approximately 1 km long, points through the earth to about 730 km away in Italy, where the OPERA detector in the Gran Sasso Underground Laboratory searched for events indicating the appearance of τ -leptons, produced by τ -neutrinos interacting in the detector. These τ -neutrinos were to appear from the transformation the original muon-neutrinos. Five events were detected from 1.8×10^{20} protons on the neutrino production target. The neutrino beam has now been dismantled and the facility is being transformed into a test bed for proton driven plasma wake field acceleration, the AWAKE project. (Chapter 12). This may in turn become a future technological highlight!

Fig. 5.8. Schematic cross section showing the CERN Neutrino to Grand Sasso (CNGS) beam line.

5.2 SPS Distributed Control System: The Emergence of Local Area Networks

Pier Giorgio Innocenti

The control system for the SPS incorporated a host of innovations. These included the first truly distributed multi-computer control system, where any action could be carried out from any part of the system, the first multi-computer operating system, the first large scale use of an interpretive language for the applications programs, the introduction of the Data Module for isolating the applications programmer from the hardware details, and the provision of simple-to-program colour graphical and other interfaces to the operator [22,23].

In the early 1970s, when the SPS design was being discussed, computers had been applied to issues relating to control in a number of accelerator laboratories, but mostly in an *ad hoc* fashion. When more than one computer was involved, they either performed independent control on different parts of the accelerator, or were organized in a master/slave relationship. For the SPS, given the large size of the ring, with its six access shafts and equipment buildings, and the need for local commissioning, it was mandatory to have the computer system distributed around the accelerator. Each of these distributed computers had to be able to operate autonomously. Instead of having them report to a single large central computer, as was normal practice for such a system, they had to be connected to a network that would allow any two computers to communicate independently of the rest. Such a network is now called a Local Area Network (LAN) [Highlight 9.3], but no such system existed at the time. Even Ethernet, for which it was early days (not yet proposed as a standard), would not have satisfied all the requirements, e.g. long range operation with cable runs of up to 6 km. Moreover, high level network protocols ensuring the cooperative working of several computers were not available. A packet-switching network was designed for this application, the specification drawn up and a contract placed with industry for its implementation. The network featured star topology, with a message handling node at the centre. Links of twisted pair cables were operating at 750 kbit/s, with repeaters every 2 km. Computers were installed in each of the six service buildings, in the experimental areas and in the control centre: in the service buildings to control the machine components, in the experimental areas to control the secondary beams and to interface with experiments, in the control centre to drive operator consoles, provide data storage for the machine data base and for program development.

A crucial decision was to use interpreted rather than compiled applications programs. It was clear that developing the applications programs for the operation of the SPS would require a very large effort in a relatively short time. The typical solution would have been for the equipment experts write detailed specifications

and to engage a large number of programmers to turn them into code, debug and modify them as the experts changed their specification. This was not the route followed, because it was thought preferable to provide a user-friendly and safe computing environment, such that the accelerator experts could write most of the applications programs themselves. The key was the use of an interpreter, a program which executes instructions in a high-level language directly, rather than compiling them and then executing the resultant machine code. Since no interpreter for a multi-computer system was available, a new one was developed, called NODAL [24]. This was the first true multi-computer operating system. Commands could be sent from any computer to a target machine for executing locally a subroutine (procedure) and returning the results to the caller: it performed what was to become standard practice — Remote Procedure Calls (RPC).

Precise timing and sequencing required for accelerator operation could not be executed by the computer network: a separate timing network distributed clock and coded “events” with microsecond precision. The clock and events were used to trigger accelerator components directly and to start programs in computers.

Another innovation was the ‘Data Module’. Until then, in most accelerator control systems using computers, the applications programmer was expected to incorporate direct references to individual hardware interface devices in his programs and carry out any necessary conversions. However, as subsequent changes to the interface might involve changes to many programs, the risk of introducing errors was large. A data module dealt with all the low level interaction needed for the control of a given type of equipment, e.g. power supplies, taking into account variations between different types. The application programs could then call the data module, only having to give the name of the power supply, the action to be carried out and values in engineering units. A change to an interface, or a modification to a power supply, only required the data module to be modified, leaving the application programs unchanged. The Data Module combined data and associated actions (methods) into a logical structure (object): it was the first example of what is now called Object-Oriented Programming (OOP).

Innovative devices were developed for presenting information to, and receiving instruction from the operator in the control room: Programmable ‘touch buttons’ on a display [Highlight 5.3] and a track ball pointing to regions of the display itself, as done today with a mouse, touchpad or joystick. In addition, a computer programmable knob could be dynamically assigned to functions more easily performed by turning such a knob. All computers in the network could be equipped with a colour graphics system which allowed computer generated displays to be incorporated in a common manner.

5.3 SPS Controls: A Part of Touch Screen History

Bent Stumpe

The choice of a distributed computer network for controlling the SPS had profound consequences for the interaction of the accelerator operator with the equipment. No direct (hard) wiring would connect the control centre to the equipment to change settings and observe signals. Every control action or piece of information would transit through the computer network via a limited number of operator consoles. The issue was to develop an “intelligent” system based on minicomputers, which would replace the thousands of buttons, switches and oscilloscopes a conventional control system would need for a machine of the size and complexity of the SPS [Highlight 5.2]. Three programmable devices were either newly designed or improved for the machine controls project: a programmable knob which could mimic a variety of hardware knobs and two devices to point at an image on a screen: a trackball, and a transparent touch screen [25]. The operator would need only a few devices to interact with the accelerator and would observe its status and performance on at most half a dozen displays. The devices and displays could be redefined quickly to select accelerator subsystems for control and monitoring, and choose from hundreds of analogue signals those to be displayed at any given time.

The trackball was invented in the 1940s for a British military research project and remained classified for a long time. The CERN design of the track ball had incremental optical encoders, working on the same principle as the ball mouse that became popular in the 1980s. Buttons with labels programmable by a computer [26] could easily be generated on a cathode-ray tube (CRT) display. How the computer would detect which button was being selected, was the question to be answered. The existing rather complicated mechanical designs were unsuitable for the SPS control system. This prompted the development at CERN of one of the world’s earliest operational capacitive transparent touch screens, and the first to be used to control a machine of the complexity of the SPS.

The transparent Touch Screen [25,27] consisted of a set of capacitors etched into a film of copper on a sheet of glass, each capacitor being constructed so that a touching finger would change the capacitance by a significant amount. In the final device, a simple lacquer coating prevented the fingers from actually touching the capacitors. The two conductors of the capacity were two interleaved flat copper combs (Fig. 5.9). The fineness of the lines, which constituted the teeth of the combs, and their pitch required a great deal of care in producing the screen, but could be achieved with techniques used to make printed circuit boards. At first, using vacuum deposition of the copper layer on the glass did not result in films

Fig. 5.9. Schematic layout of the transparent double-comb capacitor sputtered on the glass, matching the location of a button.

with reliable adherence. Ion sputtering gave better results. Ensuring that the glass was scrupulously clean and depositing the copper slowly provided films with adherence strong enough to solder connections to the sputtered layers.

The capacitance of each button was about 200 pF, increasing by about 10% under the touch of a finger. The change in capacitance was detected with a phase-locked oscillator circuit, which had become available as a single integrated circuit chip. One circuit acted as a reference oscillator, while each button had a similar circuit. The oscillator attached to a button locked into the frequency of the reference oscillator (120 kHz), so that a change in capacity altered the phase but not the frequency. The phase shift was converted into a voltage shift, indicating that the button had been touched. The circuit was very immune to noise and transients. Changing conditions would be common to all 16 “touch circuits”, so that good thermal stability could be obtained with commercial components.

A simple computer algorithm detected a “touch”: the computer could handle 16 simultaneous touches. The touch screen developed in 1972, nowadays called a self-capacitance screen, was therefore a “Multi Touch” screen and was able to react to simple gestures. The “Touch” information was then used by the software to execute the desired operation. By 1974 industry was capable of producing robust 16-button glass screens with low surface reflections. In a further development an X/Y touch screen (nowadays called a mutual capacitance screen) was constructed in 1978. When the SPS started operation in 1976 its control room was fully equipped with touch screens. Touch screens later took their place in modernized control systems for the PS, in the Antiproton Accumulator (AA) control room (Fig. 5.10), and subsequently for the much bigger LEP collider. Some of these screens continued to operate until the new CERN Control Centre took over operations in 2006. CERN touch screens were also adopted by other laboratories around the world. The commercial breakthrough for touch screens came some 25 years later, thanks to the technological progress in electronics which led to powerful microchips replacing the electronic circuits of the 1970s.

Fig. 5.10. The “Touch Terminal”, equipped with a CRT and driven by a 16-bit microprocessor.

The present CERN Control Centre (CCC), which oversees the control of CERN’s entire accelerator complex, including the PS, SPS and LHC, has no touch screens for accelerator control: the use of the ubiquitous mouse as a pointing device provides the same function. However, touch screens still play a role in the CCC, as the operators frequently communicate with colleagues by mobile phones with their capacitive touch screens and, if needed, can even control the accelerator!

The details of the practical Touch Screen, as applied in 1972 to accelerator control at CERN, were published, and following CERN policy, no patent was taken. The concept has since conquered the world with a multitude of applications, from vending machines to rail and airline ticket machines, and after further development to the ubiquitous multifunction smartphone.

5.4 The SPS Muon Beam: Energy, Intensity and Precision

Niels Doble and Lau Gatignon

The high energy muon beam M2 was designed for the NA2 (EMC) and NA4 experiments, located in experimental hall EHN2 in the SPS North Area (Fig. 5.5). These experiments required a high intensity muon flux at beam momenta up to 280 GeV/c. Muons are dominantly produced by two-body in-flight decays of pions and kaons. The lifetime of pions in the laboratory, proportional to their momentum, is about 55 m per GeV/c,^a so that pions in the 100 to 300 GeV/c range have average decay lengths of from 5 to 16 km. This led to the concept of the M2 beam design [28], which consists of a pion and a muon section (Fig. 5.11).

^a Kaons have a shorter average decay length of about 7.5 m per GeV/c.

The hadron decay section

A very high pion flux is a prerequisite for a high muon intensity. A high-intensity primary proton beam of 400 GeV/c or 450 GeV/c impinges on a Beryllium target of up to 500 mm length. Pions and kaons produced in the interactions are captured by a series of six high-gradient quadrupoles immediately following the production target. Three different beam optics were designed to achieve maximum angular acceptance in three momentum ranges. The accepted pions and kaons are then deflected by two groups of horizontal dipoles through angles of 18 and 8 mrad, respectively. In between these dipoles a collimator selects a hadron momentum band. A vertical dipole next to this collimator bends the beam upwards with a 10 mrad slope. From there the beam is matched into a ~ 600 m long decay channel, equipped with regularly spaced quadrupoles of alternating polarity, tuned to transmit the parent pions and kaons and their decay muons with high angular and very wide momentum acceptance. At the end of this section the muons are focused on a hadron absorber, which consists of nine 1.1 m long blocks of beryllium, 55 mm in diameter, encapsulated in aluminium. This absorber stops all the hadrons with minimum perturbation to the muons, which lose less than 3 GeV in energy.

The muon section

The muons traversing the hadron absorber must be momentum selected, using a vertical set of dipoles and a collimation system. The available decay length for the pions and kaons was maximized by installing the hadron absorber modules inside the first three vertical dipoles. As muons lose very little energy when traversing material [Box 3.2], classical collimators are not at all efficient, and 5 m long

Fig. 5.11. Conceptual layout of the M2 muon beam.

magnetized iron toroids ('scrapers') with adjustable gap are used as collimators. These also define the geometrical acceptance of the muon beam. After collimation and cleaning with additional toroids, the muons are transported to the surface and deflected to be horizontal for its passage through the experiments. Four planes of hodoscopes surround this vertical bend for fast and precise momentum measurements of the individual muons. The final section of the beam serves to focus the beam at the experiments.

The beam performance

At present, the beam delivers up to 5×10^8 muons at 280 GeV/c per SPS cycle of 2.4×10^{13} protons impinging on the production target, but the intensity drops rapidly with increasing momentum. The size of the beam spot at the final focus is 8 mm RMS in both planes with a RMS divergence of 0.8×0.4 mrad. The maximum muon momentum spread is 3% RMS. The momentum can be varied between 60 and 280 GeV/c. In normal operation the ratio between the central muon and hadron momenta is chosen to be of the order of (92–94)%, i.e. selecting forward muons in the decay rest frame. This ratio gives the best muon flux per incident proton, and in addition, due to parity violation in the pion and kaon decays (the spin of the μ^+ is antiparallel to its direction in the pion rest frame), gives a very high degree of beam polarization, close to -80% for μ^+ and $+80\%$ for μ^- (the spin direction flips due to charge conjugation) [Box 2.2]. The availability of polarized muon beams was (and still is) essential for studies of spin dependence of structure functions [Box 4.2], most recently by the COMPASS Experiment (Fig. 5.12) [29].

Fig. 5.12. The COMPASS experiment, showing a layout typical for fixed-target experiments. A panoply of experimental techniques is deployed for wide-ranging research. (Courtesy COMPASS).

Channelling

Box 5.3

When positively charged particles impinge on a mono-crystal at a sufficiently small angle with respect to the orientation of the crystal planes, they experience the collective effect of the electrical fields of the ions in the crystal lattice, as if the charges were smeared over the plane. The particles see therefore a potential well, in which they are trapped in case the transverse energy of the particles with respect to the plane is smaller than the depth of the potential well. In that case the particles are kept away from the nuclei and the particle is said to be 'channelled'. Depending on the particle momentum, the transverse energy limit translates into a critical angle, which for the (110) plane of a Silicon crystal is about $7 \mu\text{rad}$ for 450 GeV/c protons. The critical angle varies with $1/v_p$. Particles that directly hit a crystal plane, will most likely interact with one of the ions and be lost. This leads to a maximum transmission of particles into the bulk of the crystal that limits the ultimate efficiency for channelling.

In case the crystal is slightly bent, the transverse potential is modified by the interaction with the charged particle and the potential barrier is lowered at the outside plane, as a function of the radius of curvature. Particles that have a transverse energy lower than the reduced well depth are still channelled and will thus follow the bend. Those that have a larger transverse energy will be de-channelled. Below a critical radius of curvature R_c , no particle can be channelled any more. For a radius of curvature larger than R_c , the channelling efficiency increases with the radius of curvature. For a given crystal length and bending angle, one may compute the equivalent magnetic field that would be required to give the same deflection over the same length. In the figure below the measured deflection efficiency for 450 GeV/c protons is shown for protons along the (110) plane in a Germanium crystal. The dashed line describes the expectation from a model. A curvature of 10 mrad over the 50 mm length of the crystal in this case would correspond to a field of 300 Tesla!

One of the first applications of channelling in a bent crystal in an operational beam line was its use in the K^0 beam for the NA48 experiment [Highlight 5.5]. Recently the use of bent crystals as collimators for circulating beams has been tested in the SPS with a view to possible application in higher energy accelerators. Bent crystals are also being considered to extract fixed target beams from high energy proton colliders.

5.5 Two Very Special K^0 Beams: Discovery of Direct CP Violation

Niels Doble and Lau Gatignon

A pair of simultaneous and nearly collinear beams of long- and short-lived neutral kaons, K_L^0 and K_S^0 , formed an integral part of the NA48 experiment, aimed at studying direct CP-violation [Box 3.4] at the SPS. This study required the four decay rates, $K_L^0 \rightarrow \pi^0 \pi^0$, $K_L^0 \rightarrow \pi^+ \pi^-$, $K_S^0 \rightarrow \pi^0 \pi^0$, $K_S^0 \rightarrow \pi^+ \pi^-$, to be measured with extremely high relative accuracy in a common set of detectors [30], among which a liquid krypton calorimeter [Highlight 5.6] played an essential role. The two beams were obtained by a novel application of a bent silicon crystal.

Design Concept

Key to the success of NA48 was its concept to minimize painstakingly systematic errors in the relative decay rate measurements. The K_L^0 and K_S^0 beams were therefore designed to enter the same fiducial region simultaneously and along adjacent lines, converging at a small angle towards the NA 48 detectors.

A primary proton beam of high momentum (450 GeV/c) and high flux ($\sim 10^{12}$ protons/s) was required to produce sufficient numbers of the rare, CP-violating $K_L^0 \rightarrow 2\pi$ decays. A much lower proton flux (by a factor $\sim 10^{-5}$) sufficed to produce comparable numbers of K_S^0 decays. The high-intensity K_L^0 beam was obtained from a branch of the slow-extracted high-intensity primary proton beam from the SPS. A small fraction of these protons was shaved off using the phenomenon of ‘channelling’ in a bent crystal to derive the proton beam for the K_S^0 production [Box 5.3]. The channelling method offered three advantages: the selected protons were reduced in flux, deflected and defined to have a suitable small emittance. Moreover, the relatively low flux of protons could be detected and tagged individually, so as to attribute them to the correct K^0 beam.

Two target stations, one for high-rate K_L^0 production, the other one for low-rate K_S^0 production were used. They had to be located at quite different distances from the detectors, given the very different decay lengths of K_L^0 and K_S^0 ($\lambda_L = 3480$ m, $\lambda_S = 6.0$ m, at a mean momentum of 110 GeV/c).

The acceptances for detecting $\pi^0 \pi^0$ and $\pi^+ \pi^-$ decays were each functions of the kaon momentum (p_K) and longitudinal position of the decay vertex (z). It was therefore important that the momentum spectra of the K_L^0 and K_S^0 decays were as similar as possible over the useful range of momenta ($70 < p_K < 170$ GeV/c) and of z . To this end, the z -range was chosen taking into account the K_S^0 decay length (λ_S) and weighting factors were then applied to equalize the z -distributions and hence the detector acceptances for K_S^0 and K_L^0 decays.

Fig. 5.13. Schematic layout of the K^0 beams.

Layout

The beams were derived from protons striking two separate targets, located at 126 m and 6 m, before the beginning of the decay region, upstream of NA 48. The layout of the beams is shown in Fig. 5.13.

The K_L^0 beam

The K_L^0 beam (red cone in Fig. 5.13) was produced by the primary beam from the upstream target at a small angle to reduce the neutron flux. The beam, after emerging from the opening in a beam dump-collimator, passed through three successive collimators, designed to maximize the acceptance of the beam and to minimize backgrounds outside the central apertures of the detectors.

A vertically-deflecting dipole magnet after the K_L^0 target swept away charged particles, whereby the primary protons, which had not interacted, were deflected downwards to impinge on the channelling crystal, situated below the K_L^0 beam axis. The crystal was designed to split off the wanted, small fraction of the protons and to deflect them upward, back to the horizontal. The majority of protons and other particles, which were not deflected by the crystal, were absorbed in the beam dump-collimator.

The K_S^0 beam

The low-intensity proton beam required for the K_S^0 beam was generated with the channelling crystal (Fig. 5.14) [31]. A silicon mono-crystal was used, cut to dimensions $60 \times 18 \times 1.5 \text{ mm}^3$, parallel to the 110 plane. It was bent through an angle θ_0 (greater than the required beam deflection angle, $\theta = 9.6 \text{ mrad}$) over 56 mm of its length, by pressing it with rollers against the cylindrical surface of an aluminium block, precisely machined to have a radius of curvature, $R = 3 \text{ m}$. The

Fig. 5.14. Schematic arrangement of the bent crystal [31].

holder was mounted on a motorized goniometer, which allowed the crystal to be aligned with two transverse displacements and two rotations about axes perpendicular to the incident beam. When the crystal was rotated through an angle Φ about the vertical axis, the beam traversed the crystal from one edge to the other. The effective distance traversed in the crystal, and hence the vertical angle of the beam deflection, was controlled by adjusting Φ . With this set-up the orientation of the crystal could be chosen to adjust the deflection of the beam and its emittance.

The beam dump-collimator following the crystal contained a passage for the channelled protons, below that for the K_L^0 beam. The protons (green line in Fig. 5.13) were brought back onto the K_L^0 beam axis, passing through a ‘tagging station’ on the way. With a coincidence measurement between this station and the principal detectors of the experiment, an observed K^0 decay could be attributed or not to the K_S^0 beam. The protons were then refocused and steered onto the K_S^0 target.

The production angle of the K_S^0 beam (blue cone in Fig. 5.13) was chosen to make the ratio of K_S^0 and K_L^0 decays in the fiducial region as similar as possible over the momentum range used (70 GeV/c–170 GeV/c). After a sweeping magnet and appropriate collimation with passages for the two neutral beams, the K_L^0 and K_S^0 beams emerged into the common decay volume and converged to the centre of the detectors at a distance of 120 m from the K_S^0 target.

To count the $K_S^0 \rightarrow \pi^+\pi^-$ and $K_S^0 \rightarrow \pi^0\pi^0$ decays with the same acceptance, the beginning of the decay fiducial region had to be defined precisely. For the charged decay mode, this was done directly using a thin scintillation counter at the exit of the K_S^0 collimator to detect the $\pi^+\pi^-$. For the neutral decay mode, the photons from the quasi-instantaneous decay of the π^0 's were converted to e^+e^- in a disc of high-Z material placed immediately in front of the counter. The thickness and scattering

effect on the beam of this material was minimized by using another, carefully-aligned, crystal (iridium), which coherently enhanced the conversion probability.

This pair of beams served to establish direct CP-violation in the decay of neutral kaons by experiment NA48 from 1997 to 2002 [32]. The line was subsequently transformed to provide another pair of simultaneous beams, this time of oppositely-charged kaons (K^+ and K^-), into the same set of detectors [33].

5.6 Liquid Krypton Calorimetry: Elucidating Nature's Subtle Asymmetries

Italo Mannelli

The discovery of the violation of Charge–Parity (CP) symmetry shook the foundations of physics [Box 3.4]. Considerable experimental efforts followed, spanning more than 20 years, seemingly indicating that this effect was confined to K^0 – anti- K^0 mixing. In parallel, however, with the development of the Standard Model incorporating three families of quarks [Box 6.4], the presence of a further mechanism of CP Violation (Direct CP Violation) was predicted in kaon decays. This would manifest itself as a difference in the ratio of K_L decays into charged to neutral pion-pairs relative to this ratio in K_S decays. The effect was predicted to be subtle. Experimental searches turned out to be not sensitive enough, mostly due to the lack of adequate techniques to measure the kaon decays to two neutral pions.

First evidence for Direct CP violation was obtained at the CERN SPS by the NA31 experiment in 1987. An analogous experiment at FNAL did not support the CERN result. The need was recognized by both collaborations for new experiments, taking advantage of novel technical developments, which could achieve an order of magnitude higher statistical and systematic accuracy.

Key to the success was the quality of the measurement of the neutral pion decay into two photons with energies up to 100 GeV. This required the e-m calorimeter to be homogeneously sensitive for best resolution. It also had to locate the position of the photon showers with millimetre accuracy to reconstruct the neutral pions. The newly-formed CERN-based NA48 collaboration bet on an audacious, novel concept: the development of an ionization calorimeter with liquid krypton (LKr) as the active absorber.

Why an ionization calorimeter? Previous incarnations, using liquid argon (LAr), had demonstrated the superior control of systematic effects and long-term stability [Highlight 4.10]. Why LKr? It has three times the absorption power compared to LAr. A 100 GeV photon shower is contained in a length of 125 cm; the transverse shower size is reduced by about a factor two compared to LAr,

improving the localization of the shower. The calorimeter had a 5.3 m^2 octagonal cross-section and a depth of 127 cm. The total krypton mass was 25 t (Fig. 5.15).

The ionization charge has to be collected with electrodes. Again, ingenuity and inventions were required: the electrodes had to be nearly massless not to disturb the energy measurement, and placed with sub-millimeter precision in the 6 m^3 volume. A system of longitudinal copper-beryllium ribbons, each 1.8 cm wide and $40 \text{ }\mu\text{m}$ thick, precisely spaced to form 13248 signal cells, $2 \text{ cm} \times 2 \text{ cm}$ in the transverse direction, measured the initial current induced by the drift of the ionization charge. Every 20 cm in depth, the ribbons, with applied tension of 3 N, were held in position in a 50 mrad zig-zag geometry via slots (Fig. 5.16), accurately machined in glass-fibre-epoxy diaphragms. A slight increase in the perforation pitch vs depth made the axes of the cells converge to the centre of the observation volume of the kaon decay, 110 m in front of the calorimeter. The 1 cm spacing between ground and charge collecting electrodes had to be accurate to within $50 \text{ }\mu\text{m}$, as the initial current is inversely proportional to the gap width [34].

Fig. 5.15. The calorimeter, prior to insertion into the cryostat. On the right side, after the second mechanical support disk fibre bundles exit towards the photomultipliers.

The preamplifiers, the HV biasing and the charge injection for calibration were placed inside the cryostat immediately after the end of the ribbons to avoid signal distortion due to the inductance of long connections. The signals of each of the 13248 cells were brought out from the cryostat via $50\ \Omega$ coaxial cables through feedthroughs to the signal processing electronics, which included a 40 MHz flash ADC. The choice of placing the first electronic stages inside the LKr cryostat, practically precluding maintenance interventions, was more than compensated by the achieved time resolution and by the quality and stability of the electronic response inherent to the cryogenic operation at 120 K.

At a depth of 40 cm from the front of the calorimeter a vertical layer of scintillating fibres was placed in bundles which were brought to a set of photomultipliers operating in the LKr. Their signals were used to select the interesting kaon decays to neutral pions.

The novel calorimeter worked flawlessly, matching the design parameters. It routinely achieved an energy resolution $\sigma(E)/E = 3.2\%/\sqrt{E} + 90\text{ MeV}/E + 0.42\%$, still at world record level, 20 years later. A 100 GeV photon is measured with 0.5% accuracy. The position resolution in the transverse directions is $\sigma(x,y) = 5.5/\sqrt{E} + 0.3\text{ mm}$. The time resolution is a remarkable $2.6 \times 10^{-10}\text{ sec}$.

The bet paid off. The NA48 collaboration could unambiguously establish the existence of Direct CP Violation in kaon to two pion decays, as did their American competitors [32]. With just a few improvements to the external electronic chain to adapt it to higher data recording rates, the NA48 calorimeter has been operated without interruption since 1996, with no significant change in the energy calibration and no loss of krypton.

Fig. 5.16. Schematic drawing of the ribbon cathodes forming $2\text{ cm} \times 2\text{ cm}$ cells.

5.7 Bubble Chambers at the SPS: A Technique at its Apogee

Horst Wenninger

The story goes that in 1953 Donald Glaser observed bubble forming in his beer glass triggering him to study bubble formation in liquids traversed by cosmic rays. Glaser himself confirmed this during the discussion session of the last International Bubble Chamber Conference, at CERN in July 1993.

The era of bubble chambers at CERN lasted 30 years, and finished in 1984 with the closure of BEBC — the Big European Bubble Chamber — and of GARGAMELLE — the large French heavy liquid bubble chamber, famous for the discovery by the neutrino physics collaboration of so-called neutral current interactions, in striking support of the emerging theory of electroweak interactions. Analysis of data from experiments with bubble chambers in Europe ended ten years later with the conference cited above.

Bubble chambers reveal the trajectories of charged particle as they pass through a superheated liquid (Fig. 5.17). A string of gas bubbles produced along the path of ionizing particles form tracks that can be recorded on stereo view photographs. A magnet creating a uniform field allows to determine the momentum of particles by measuring the curvature of the tracks (Fig. 5.18). Direct visible evidence of particle interaction patterns on millions of photos were thus analysed in physics institutes around the world [35].

Fig. 5.17. Schematic showing the principle of bubble chamber operation.

Fig. 5.18. Photo of neutrino interaction in BEBC, and reconstruction of a neutrino “event”.

CERN engineers and technicians developed the technologies required for small and large, for track-sensitive, for holographic, and for rapid cycling bubble chambers, as well as for sophisticated automatic film measuring devices. The technologies required to construct and operate bubble chambers included cryogenics,^b hydraulics, vacuum, superconductivity,^c fish-eye optics, lasers, holography, and controls; the film analysis required pattern recognition algorithms and world-standard reconstruction software. Knowhow and competences acquired by CERN staff during this period provided the basis for later success of the laboratory in support for electronic particle physics experiments.

CERN-specific developments and technological highlights during the Bubble Chamber era focused on (i) increased photon conversion efficiency (e.g. photons from π^0 decays) in hydrogen bubble chambers, improved particle identification using a wire chamber Internal Picket Fence for muons (IPF) plus an External Particle Identification by dE/dx (EPI) (Fig. 5.19), and (ii) fast cycling chambers combined with tagging of selected rare events — e.g. charm decay events studied by the collaboration of the CERN Hybrid Spectrometer. Trials with holographic bubble chamber were also started in parallel.

In order to overcome the low conversion efficiency of photons in hydrogen bubble chambers the US laboratories installed iron converter plates. In BEBC, a track sensitive liquid hydrogen-filled LEXAN box was used to observe primary

^b Cryogenics and superconductivity have since assumed an important role at CERN.

^c A large superconducting magnet, providing a field of 3.5 tesla over the sensitive volume of 35 m³, the largest such magnet in the world in terms of stored energy until 1996, was built for BEBC at CERN. In addition, an External Muon Identifier (EMI), the Internal Picket Fence (IPF), the External Particle Identifier (EPI) and a Track-Sensitive Target (TST) converted BEBC into a hybrid detector.

Fig. 5.19. BEBC surrounded by External Muon Identifier EMI and External Particle Identifier EPI.

beam particle interaction, surrounded by a heavy liquid neon-hydrogen mixture, developed in collaboration with the Rutherford Laboratory, for improved photon detection [36]. The trick of this “bubble chamber inside a bubble chamber” was to find a temperature and pressure regime such that the pressure cycle transmitted from the heavy liquid to the hydrogen via LEXAN^d walls allowed to attain simultaneous track sensitivity inside and outside the transparent box, and visualize the interactions and tracks in both media of the chamber on the same photo.

The development and operation in BEBC of the LEXAN track sensitive target resulted in a second CERN invention with the construction of a high resolution fast cycling LEXAN bubble chamber (LEBC/HOLEBC) which was used for charm physics and allowed one of the first definitive studies of charm production at a proton facility [35].

Besides Neutral Currents the large bubble chamber led to other most interesting results. By comparing the structure functions of the nucleon derived from neutrino and muon scattering, it was proved at Gargamelle that quarks have indeed a fractional electric charge. The Gargamelle experiments discovered that the neutrino–nucleon cross-section rises linearly with energy. Finally, by combining their results, the BEBC and Gargamelle teams obtained the first evidence for scaling violation, namely the proof that the nucleon structure functions actually evolve with the resolution power of the observation [37].

^d A specific development was launched with an US company for an optically transparent multi-layer plastic (trade name LEXAN) keeping sufficient flexibility at 20 K to transmit the pressure from surrounding liquid neon-H₂ to H₂ inside the 3 m³ LEXAN box [36].

5.8 Polarized Targets: Pointing to New Directions

Tapio Niinikoski

In Polarized Targets (PT) nuclear spins are polarized dynamically in a solid material containing a high density of the nucleons of interest. Such targets are required for some scattering experiments where the spins of the beam and/or target particles have to be aligned with respect to a static magnetic field. To develop, build and operate solid PTs draws on several fields of physics and technology. In this highlight we address advances where CERN has made a major contribution.

Quantum statistics to describe Dynamic Nuclear Polarization (DNP)

Particles with spin have an associated magnetic moment that couples with external and internal magnetic fields. Spin polarization is observable by magnetic resonance methods, whereby a small oscillating magnetic field, transverse to a strong static field, is absorbed by the system of magnetic moments.

Spins in thermal equilibrium with the lattice have a small natural polarization because the magnetic energy levels of the moments have tiny difference in a static external magnetic field. For proton spins this is only a few tenths of a percent at 1 K temperature and 2.5 T magnetic field. Electron spins, on the other hand, under the same circumstances, have about 99% polarization, because their magnetic moment is about 1000 times higher. This large polarization can be transferred to the nuclear spins by certain types of magnetic resonance: the double resonance of electron and nuclear spin pairs, or by cooling of the whole spin system using off-resonance microwave irradiation. The former requires a strong magnetic component of the oscillating microwave field, at 70 GHz frequency, that is parallel to the steady field. The latter requires a much weaker transverse microwave field. The concept of “spin temperature” helps to understand this mechanism.

The spin temperature T_s can be seen in the populations of the magnetic energy levels E_m that are proportional to the Boltzmann factors $\exp(-E_m/k_B T_s)$, after relaxation transitions have established thermal equilibrium among the levels m . This is the classical static view. With a transverse field oscillating at a frequency close to Larmor precession, the spin system reaches a new equilibrium spin temperature that is positive, zero or negative, respectively, and can be much lower than the temperature of the lattice. We may then speak of “cooling of spin system”.

The effects are measurable and dramatic: the new “dynamic” spin temperature is transmitted to all other non-resonant spin systems by spin-spin relaxation transitions, assisted by the oscillating field. Quantum statistics must then be used to predict the thermodynamic parameters such as spin temperature, polarization and entropy. At high temperatures this is relatively easy, because the quantized

Boltzmann factors can be linearized. At low temperatures this approach does not work. It was resolved with the formalism of “Spin Temperature Model of DNP”, which gives numerically solvable formulae [38].

The development of this model was one of the major original contributions of CERN to polarized target physics. It explains the previously obtained, but poorly understood, results in hydrogen-rich materials by extending the early quantum statistical treatment of magnetic resonance saturation to electron spin systems at low temperatures where the electron polarization is high. The quantum statistical formalism was developed to properly describe and evaluate spin temperature and polarization for the regime of PT applications, where the simplifications of the so-called “high temperature” approximation are not valid. The Polarized Target team at CERN also validated experimentally [39] the key prediction of the model, namely that all nuclear spin species cool towards a common temperature. This common temperature is that of the electronic spin system under a saturating microwave field. It can be as low as one thousandth of the lattice temperature, which is typically 0.2 K to 0.7 K. This new formalism pointed the way to obtain proton polarizations over 99% and deuteron polarizations of about 90% in large targets with corresponding spin temperatures below 0.001 K.

The double resonance method was limited to small targets, owing to the high microwave power required, and to exotic single crystal materials that contain relatively few protons, the target nuclei of interest. In the dynamic cooling method, the microwave power can be reduced so much that very little heat is generated in the material, thus allowing the target to be cooled with ^3He evaporation refrigerators at 0.5 K temperature, and even lower with ^3He – ^4He dilution refrigerators, with large gains in the polarization.

The DNP described by the new model benefits from lower coolant and lattice temperatures, and can be extended to a large class of materials that are rich in hydrogen or deuterium. Importantly, the much lower temperatures available by ^3He – ^4He dilution refrigeration (Fig. 5.20) enable “freezing” the polarization. A lower and less homogeneous “holding” field of a spectrometer is sufficient to maintain the polarization of the target after DNP in an external, strong and homogeneous field. Such target technology was developed at CERN where the first frozen spin target was constructed and operated in 1974 [40].

Dilution refrigerators were first introduced to the polarized targets at CERN in the 1970s, with horizontal [40,41] and vertical [42] designs. For these targets CERN developed sintered counterflow heat exchangers [41], which have had a substantial impact on current industrial design of machines for reaching down to temperatures of 0.002 K.

Fig. 5.20. Cross-section of EMC PT cooled with a dilution refrigerator absorbing 2 W power generated by DNP. The target is split in halves polarised in opposite directions, and has 1 m total length. The superconducting solenoid magnet is not shown, for clarity.

Development of materials and magnet technology for polarized targets

DNP in hydrogen-rich chemically doped materials requires the uniform dispersion of suitable paramagnetic impurities. Such materials were initially developed by trial-and-error until the CERN team discovered that they share the common property of being excellent glass formers [43]. The glass “solidifies” by becoming increasingly viscous already at high temperature, which prevents, upon fast cooling, the phase separation of the dissolved dopant as microcrystals.

Another way of doping PT materials uniformly is to create free radicals by suitable irradiation. A technique was developed at CERN to prepare and irradiate solid ammonia, which is richer in H_2 than any hydrocarbon (except methane). Over 90% polarization was reached in the first samples tested by the CERN team [44].

Large polarized targets were designed for the deep-inelastic muon scattering experiments of EMC (NA2), SMC (NA47) and COMPASS (NA48). The NA2 PT was made of irradiated ammonia, while the NA47 target [45] used doped deuterated butanol. The low lattice temperature enabled reaching > 60% deuteron

polarization in a 2.5 T magnetic field. Even higher deuteron polarizations have been achieved in materials doped by new trityl free radicals [46], in irradiated deuterated butanol [46, 47], and in irradiated deuterated ammonia [48]. Common to these and to irradiated ^6LiD is a narrow “Electron Spin Resonance” (ESR) line that allows one to reach a low deuteron spin temperature by dynamic cooling of the spin–spin interactions of the unpaired electrons, as had been predicted in earlier studies by the PT team at CERN [49].

For the large targets an axial field geometry was required, with a field uniformity in the range of 10^{-5} . Superconducting solenoid magnets were designed with improved coil winding techniques, using rectangular wire to reduce the number of compensation and trimming coils. The rectangular wire fabrication technique was developed in collaboration with industry. The technology for achieving a uniform field in superconducting solenoids has found other applications, including magnetic resonance imaging (MRI).

While this highlight focused on technical development at CERN, clearly other laboratories also contributed to the field and CERN profited from exchanges with them. This development has now enabled us to reach over 90% polarization, positive and negative, of almost any nuclear spin. Targets can be operated in frozen spin mode in a relatively low field of any orientation, and in DNP mode for high intensity beams. Beyond experiments in nuclear and particle physics, applications of DNP are emerging in macromolecular chemistry and in MRI.

5.9 The Silicon Age: Micrometre Precision Millions of Times a Second

Erik Heijne

Silicon sensors and custom-designed integrated circuits (“chips”) are essential components in today’s particle physics experiments. These silicon devices replaced earlier tracking instruments such as spark chambers and bubble chambers which recorded the particle trajectories photographically. While gaseous wire chambers remain preferred for covering large surfaces [Highlight 4.8], they are no longer competitive in spatial resolution and signal speed for the smaller areas close to the interaction region. The characteristic features that contributed to the breakthrough of silicon (Si) detectors between 1980 and 2000 were: (i) the small, stable and well-defined dimensions of the sensor cells of typically around 100 μm ; (ii) the potential to resolve several particles, incident simultaneously on mm-size area; (iii) the short signals of less than 20 nanoseconds (ns); and (iv) the progressive miniaturization of the associated electronics for the processing of the particle signals: by 2010, 65 000 signal amplifiers, digitizers and memory could be

placed on a single substrate of Si ($15\text{ mm} \times 15\text{ mm}$), a miniaturization which was, and continues to be, driven by industry. The introduction of Si devices designed for multiple particle detection was spearheaded by scientists at CERN who exploited the advances in microelectronics technology. Si microstrip detectors were soon widely adopted in experiments that studied short-lived charm and beauty particles. Their decay-path, less than about a mm, could now be distinguished separately from traces that originate from the primary interaction vertex. Early steps in this innovation are illustrated here.

Semiconductor materials such as Si, germanium (Ge) or diamond (C) contain only few free charge carriers, contrary to metals in which a large density of free electrons easily allows an electrical current to flow. Nevertheless, a small current signal can be generated in a semiconductor by the passage of a fast, charged particle, which loses some of its energy and liberates charges. An electric field is applied between metallic contacts (Fig. 5.21) under which the charges drift to the electrodes and induce a signal, which is sensed by a connected amplifier. In Si it is necessary to provide rectifying contacts (the p+ contact in Fig. 5.21) in order to prevent a 'leakage current' which would obscure these small signal currents. Such a structure is called a 'diode', and technology has been developed to imprint a large matrix, e.g. 256×256 of adjacent diodes on the same Si substrate. In most cases, the particle generates signal currents simultaneously in two or more sensor cells and, by interpolation, it is possible to determine its position in space with a few μm precision, considerably smaller than the dimension of the sensor cell itself.

A complete reconstruction of the trajectory of a particle requires the measurement of several points in space and 'telescopic' arrangements of three to four successive Si detector planes usually surround the interaction region in an experiment.

Fig. 5.21. Schematic drawing of a segmented Si detector, with an incident ionizing particle. Segmented, rectifying contacts p+ are made by ion-implantation of boron, the continuous n+ contact is made by implantation of phosphorous or arsenic ions. A biasing voltage V_{bias} is applied across the detector, generating an electrical field E throughout the n-type bulk Si, which separates the charges created by an incident particle. The resulting signal current is sensed by the amplifiers connected to the rectifying contacts (Drawing not to scale).

In 1980 vertex reconstruction was achieved for the first time using a Si microstrip detector [50], in collaboration with the NA11 experiment at the SPS, using the setup shown in Fig. 5.22. This detector was a one-dimensional matrix of 100 metal-Si diodes, 200 μm wide gold-evaporated bands on a 20 mm $\times$ 30 mm Si substrate. The design was inspired by the earlier, so-called ‘Si checker-board’ segmented detectors used in the ‘BOL’ experiment [51] at the Nuclear Physics Institute IKO in Amsterdam, operating at their cyclotron since 1967. This IKO device had perpendicular segmentation at the front and back, hence providing 2-dimensional particle positions, while the CERN detectors had strips only on one side, and several planes were required for 3-dimensional spatial coordinates. Soon thereafter, the MPI/TU Munich and CERN collaboration perfected the exploitation of Si microstrip detectors for charm physics research. In parallel, experiment WA75 using the Omega spectrometer [Highlight 3.7] also adopted Si microstrip detectors to determine the decay point of charm and beauty particles in an upstream plate of sensitive emulsion. WA75 published the first direct observation of beauty particles decaying into charmed particles in 1985 [52].

Research into new phenomena in elementary particle physics experiments frequently needs increased energy, typically producing more particles in an interaction. However, the new phenomena tend to occur more rarely than the already known processes, so higher beam intensities and interaction rates are required, motivating development of innovative instrumentation. In Si detectors high signal rates (well over 40 MHz) can be handled, as the freed electrons move at speeds of greater than 10000 km/h: the electrical charge in a 0.3 mm thick Si

Fig. 5.22. Left: the first operational setup of a segmented, 100-element Si microstrip detector (the rectangle in the centre of the photo), on a support containing a few of the readout amplifier cards. Right: (top) reconstruction of an interaction using only the wire chamber information; (bottom) vertex reconstruction after including the signals from the Si microstrip detector. An additional particle is found as well, the broken line. (Courtesy NA11).

layer can be collected in less than 20 ns. Immediately afterwards, the diode detector is ready for recording another particle. Several particles can be measured simultaneously, even if they are as close as 0.5 mm. For these event topologies, a true 2-dimensional matrix of sensor cells is preferable to combinations of 1-dimensional microstrip detectors. In 1989 it became possible, with the help of the microelectronics team at the EPFL, to produce a first 9×12 matrix of a so-called Si pixel detector. In this case a 2-D Si sensor matrix is connected pixel by pixel to a corresponding matrix of readout cells on an integrated circuit, made in CMOS (Complementary Metal-Oxide Silicon) microelectronics technology. Each of these cells comprises a full signal processing circuit with amplifier and digitizer. In recent implementations a memory in each cell can even store the time of incidence and amplitude of a signal from one or several successive particles. In 1992 the second iteration of the Si pixel detector could resolve hundreds of particle tracks on a $6 \times 6 \text{ cm}^2$ area and was successfully used for WA94, an ion experiment in the Omega spectrometer. This demonstration helped to dispel much of the prevailing scepticism surrounding the practicality of pixel detectors. Figure 5.23, left shows the two half planes that together constituted one of the seven arrays of the Si pixel telescope. A reconstruction of an ion-event using this instrument in WA97, the successor to WA94, is shown in Fig. 5.23, right.

With the introduction of segmented Si microstrip and pixel detectors, the number of sensing elements in the experiments increased to tens of thousands or

Fig. 5.23. Left: two half-planes from the first CERN silicon pixel telescope for the WA94 Omega spectrometer ion experiment. When mounted together, face-to-face, the six horizontal Si ladders on one, white ceramic support cover the spaces between those on the other support. Also shown are the receiver board (left) and the driver module placed directly near the telescope. Right: reconstruction of tracks from an interacting ion in the WA97 experiment, using the pixel telescope with 7 double planes (Source: WA97).

even hundreds of millions. It is obvious that miniaturized, integrated electronic circuits are required for the processing of such a multitude of signals. From 1985 onward, a Si integrated circuit design expertise was established at CERN, with the 16-channel AMPLEX chip as the first outcome, used in the UA2 Si pad detector [Highlight 6.6]. Intensive contacts with experienced groups in universities such as the EPFL in Lausanne and IMEC in Leuven helped to achieve a professional level in chip design. The custom-designed circuits were then manufactured by CMOS chip processing industry, while evaluation and testing proceeded at CERN. Other particle physics institutes soon participated in concerted developments of Si circuits and detector systems. The early steps in the development of the Si pixel detectors have been described in [53, 54]. More recent achievements on electronic circuits and the development of their radiation resistance are reported elsewhere [Highlights 8.6 and 8.7]. The use of silicon detectors in particle physics experiments as well as in space-borne research has grown exponentially over three decades, as illustrated in Fig. 5.24, showing the Si detector area in an experiment as a function of the year of its first operation.

Fig. 5.24. Evolution over time of the surface area of silicon detector systems in particle physics and in recent space-based experiments (Courtesy Y. Unno, KEK).

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