The PS measurement of the anomalous magnetic moment of the muon, $g - 2$, [Highlight 2.4], successfully continued the tradition started at the SC. With a 5 m diameter storage ring experiment (1967–1970) an accuracy of 3 parts in 10^4 was reached, to be superseded with a new storage ring of 7 m (1972–76), which reached an accuracy of 1 part in 10^5. Today, higher order QED calculations, including weak and hadronic corrections, predict $g - 2$ with an accuracy of 1 part in 10^6 and ongoing experiments elsewhere are being pushed to achieve an even higher accuracy. An observed slight discrepancy between the theoretical and experimental value, if it persists, would be a "smoking gun" for new physics.

Other facilities

Besides supplying protons for the SPS and the LHC, the PS also feeds some other very important facilities, ISOLDE, n_TOF and CLOUD.

The PS Booster's high intensity 1.4 GeV proton beam is directed onto special thick targets of the ISOLDE facility [Highlight 3.8], from which beams of radioactive isotopes are obtained.

For the n_TOF facility 20 GeV/c proton pulses, 6 ns long, are directed onto a lead target producing spallation neutrons in a wide energy range [Highlight 3.9]. These neutrons travel ~ 20 or 200 m to the experimental areas depending on the flux required. The energy of the neutrons is measured by time-of-flight. Research ranges from stellar nuclear synthesis to studies of nuclear reactor fuel cycles.

An experiment involving atmospheric, cosmic ray and particle physicists, and chemists, the Cosmics Leaving Outdoor Droplets (CLOUD) project, is studying the very complex processes of cloud formation under the influence of cosmic rays. The PS supplies the particle beams that simulate cosmic ray flux [Highlight 10.7].

3.2 Extraction: Getting the Beam to Leave the Accelerator

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Originally, the PS had used only internal targets. However, high radiation damage, due to absorption of secondary particles in the accelerator components, and low efficiency motivated the development of beam extraction and external targets. Fast extraction provides a beam with a length of one turn or less in one shot for users requiring high intensity in a short pulse, e.g. for experiments with bubble chambers; slow extraction skims off the circulating beam over many turns and is the choice for counter experiments preferring a long spill length and low instantaneous intensity to match their limited time resolution [13]. In 1963, the PS was the first synchrotron with a fast extraction system in operation and equipped with a successfully tested slow extraction system, initiating a leading position of CERN in the development and improvement of these key techniques.

Fast extraction

Fast extraction has been used for experiments in the East, West and South-East experimental areas of the PS and for sending beam to downstream accelerators (ISR, SPS, AA, LEAR, AD).

The principle is that a device producing a short (in time) deflecting magnetic field, called fast kicker, imparts an oscillation to the circulating bunches to be ejected so that they enter a deflecting magnet guiding them into the downstream transfer channel. This magnet is placed just outside the central aperture reserved for the circulating beam. One of its conductors acts as septum that separates the deflecting field from this aperture in order not to perturb the circulating beam. For clean extraction of a limited number of beam bunches, kicker rise and fall times had to be less than 80 ns, well below the 105 ns separation between two circulating bunches. During its first 60 years, the PS has known two different generations of kickers. The first, installed in the early 1960s, was of limited aperture and was retracted during injection when the beam size was large, and it was hydraulically positioned after beam acceleration. A stationary full aperture kicker system was proposed in 1964. It took nine years and two successive designs to obtain a satisfactory system with 12 separate modules. The magnets use ferrite for the yoke in the machine vacuum and form a 15 Ω delay-line. Figure 3.7 shows a schematic cross-section of such a kicker magnet (left) and one module (right).

The pulse forming networks (PFN) providing the driving pulse to the kicker are made of very low attenuation 15 Ω SF_6 pressurized polythene tape cables, charged to 80 kV in less than 4 ms by a resonant power supply. The discharge of the PFNs into the kicker is controlled by hydrogen thyratrons. The full-aperture kicker system was commissioned in 1974 and is still in use with high availability [14].

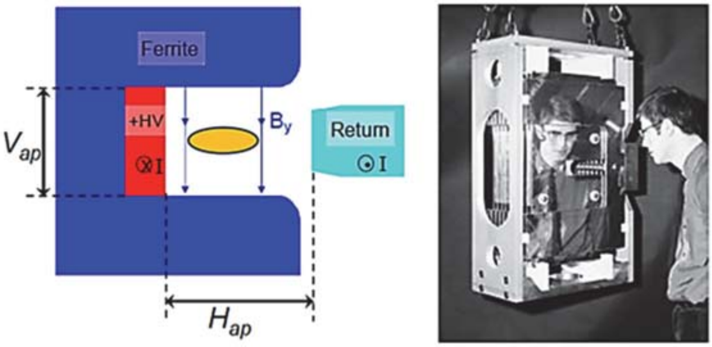

Fig. 3.7. Left: Schematic cross-section of the full-aperture kicker magnet showing the ferrite yoke, the one-turn coil (red/blue) and the beam to be deflected (yellow oval); Right: A module of this kicker with the gap for the beam seen in the middle of the shining front face.

Slow extraction

Slow extraction was introduced to provide primary beams to external targets for counter experiments. In this way external secondary beams can be produced with higher intensity and better quality than those from internal targets. During this extraction the focusing of the PS is adjusted such that the transverse oscillations of the particles grow due to a resonance driven by on-purpose installed magnetic lenses, which slowly increases the amplitudes of these oscillations until all particles have entered the deflecting field at the septum.

The first tests were conducted in 1963, reaching after improvements an extraction efficiency of 90%. In 1972 it became necessary to supply beams also to the new West hall. A new scheme was proposed based on a resonance occuring when the number of horizontal particle oscillation per turn, Q, is nudged to become a multiple of 1/3 (third-integer resonance). The resonance was driven by a standard quadrupole and a special semi-quadrupole combining quadrupolar and sextupolar fields. The scheme offered simultaneous beam sharing at will between internal targets and two external targets. The extraction efficiency reached 93% limited by the losses at the septa. The most recent scheme for proton slow-extraction was introduced in 1992 when the West hall extraction was suppressed. Taking into account that the internal targets had been eliminated by 1981 and the PS had to accelerate electrons and positrons for LEP, interleaved with proton cycles, its design used fewer and more standard magnetic elements for ease of maintenance, improved the ring vacuum, and provided component shielding against radiation from positrons or electrons. The first deflecting element of the extraction channel is equipped with a thin septum formed by an only 0.1 mm thick molybdenum foil to minimize beam loss (Fig. 3.8, left). It provides a deflecting electrostatic field of

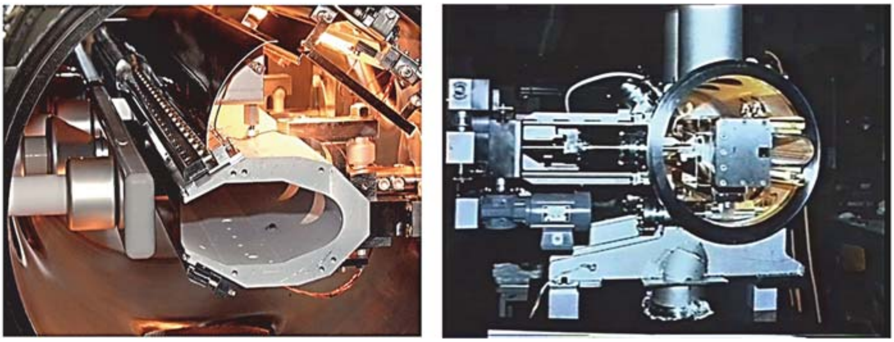

Fig. 3.8. Left: The electro-static deflector with a 0.1 mm septum in its vacuum tank; Right: Magnetic deflector with a 4 mm septum. The dark slot in the plate is the extraction channel while the aperture for the circulating beam is on the right of this slot.

10 MV/m (160 kV across a 17 mm gap) and is placed towards the inside of the ring to avoid exposure to radiation during lepton cycles [15, 16]. Further downstream, the deflected beam receives a second kick by a special magnet equipped with a thin (4 mm) septum before entering the transfer channel. This magnet also shares the ring vacuum and can be positioned remotely (Fig. 3.8, right). The extraction takes place at a particle momentum of 24 GeV/c providing 2×10^{11} protons per pulse over 400 ms (2×10^5 turns !) at the external target with an efficiency of 95%.

Multi-Turn Extraction

The development of this extraction method, called Continuous Transfer (CT), was driven by the need to fill the CERN SPS as uniformly as possible for fixed-target physics. Since the SPS circumference is eleven times that of the PS, the SPS could be filled by extracting the beam over several turns from the PS. The choice has been to fill the SPS with beam of two consecutive PS cycles, which terminate each time in an extraction over five turns at a particle momentum of 14 GeV/c. A gap of one 11th of the SPS circumference is left without beam to accommodate the fall-time of the pulsed SPS injection elements. The principle is based on a careful choice of the number of horizontal particle oscillations, on a variable-strength closed orbit bump, and on an electro-static deflector with a thin (0.1 mm) septum that peels the beam off each cycle turning it into a spill of five PS circumferences in length.

In the quest for an improved extraction mode to substantially reduce the unavoidable beam loss on the first septum, a novel approach was proposed, named Multi-Turn Extraction (MTE). In this process the beam is split in a beam four turns long (“long beam”) and a central beam one turn long. This is achieved by generating, prior to extraction, stable islands in transverse phase space inside the circulating beam by crossing a resonance produced by appropriate non-linear magnetic fields. In this process the particles get trapped inside these islands thus generating around the central beam a new, well-separated stable beam which extends over four turns and closes in itself. By a controlled drift through the resonance these islands move towards larger transverse amplitudes until the horizontal separation between two beams exceeds the thickness of the septum. The resulting configuration in transverse phase space is a central beam around which the long beam closed in itself is wound. An example of the evolution of the beam distribution in horizontal phase space at a given azimuth along the circumference is shown in Fig. 3.9. Note that it is the same beam that appears in the four islands around the central beam.

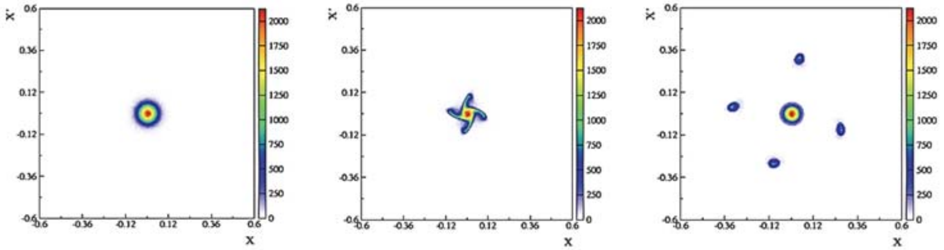

Fig. 3.9. Evolution of the horizontal beam distribution during resonance crossing in phase space (the ordinate is the horizontal momentum of the particles, while the abscissa is the horizontal position of the particles): The initial state (left); at resonance crossing particles are trapped inside the moving islands (centre); at the end of the process, the particles trapped in the islands are at larger amplitudes required for extraction (right).

Subsequently, a fast closed orbit bump created by two kickers, with a rise time short compared to the revolution time, is created with such an amplitude at the septum that the long beam enters the deflecting field region and is extracted over four turns while the central beam is not deflected. Finally, the central beam is extracted by a strong fast transverse kick creating a horizontal oscillation of sufficient amplitude making it enter the deflecting device. The timing is such that the central beam is contiguous to the long beam already transferred to the SPS.

The novelty of this method is that it replaces the brute force peeling by an intercepting device with a splitting performed by the non-linear resonance. This approach is superior as particle losses are limited to the fraction of the beam improperly deflected during the rise time of the fast orbit bump.

The proposed scheme was designed in 2006 and the first beam commissioning started in 2008. While the main concept of the beam splitting was quickly confirmed, the stability of the overall process has posed some problems. Moreover, the fraction of beam lost on the septum magnets during the rise time of the fast bump induced strong activation for which mitigation measures had to be devised [17]. This implied a major re-design of all fast extraction schemes, which were successfully commissioned by the end of 2014. This unique scheme has the welcome potential to reduce significantly the radiation dose to the equipment around the septum and, thereby, substantially increase component lifetime. As of September 2015 MTE has replaced CT as the operational extraction system from PS for SPS fixed-target physics. Thus, the PS moves closer to the ideal of loss-less extraction — the subject of a long-standing effort since its inception.