
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

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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 to16 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 perturbance 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

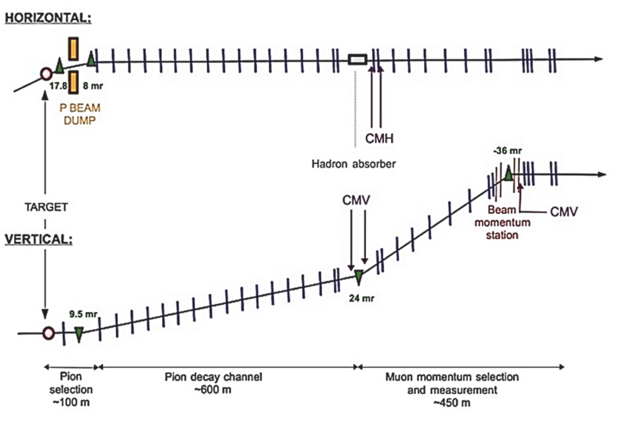



Fig. 5.11. Conceptual layout of the M2 muon beam.

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 $5 \times 10^8$ muons at 280 GeV/c per SPS cycle of $2.4 \times 10^{13}$ 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 $0.8 \times 0.4$ 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 $\mu^+$ is antiparallel to its direction in the pion rest frame), gives a very high degree of beam polarization, close to −80% for $\mu^+$ and +80% for $\mu^-$ (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].

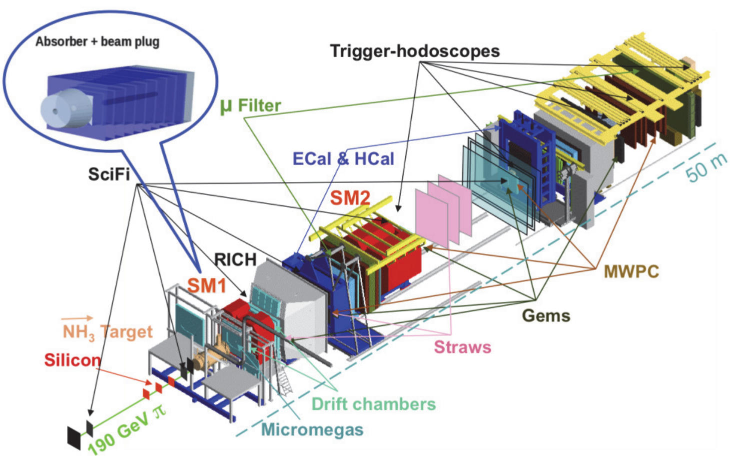
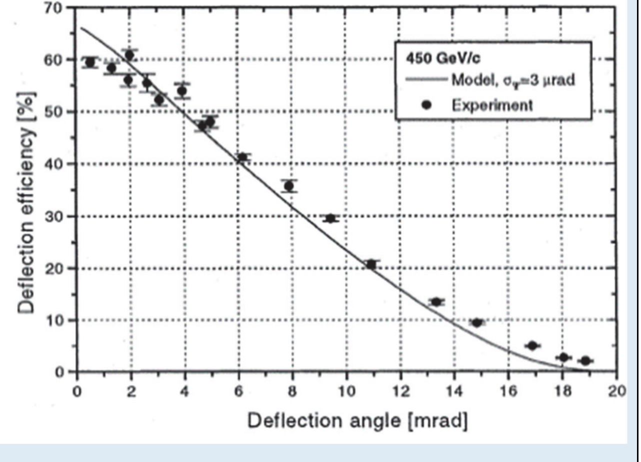



Fig. 5.12. The COMPASS experiment, showing a layout typical for fixed-target experiments. A panoply of experimental techniques is deployed for wide-ranging research. (Courtesy COMPASS).

**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 μrad for 450 GeV/c protons. The critical angle varies with $1/\sqrt{p}$. 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.