Long-Term Stability Studies for CERN-LHC

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Abstract

In the modern hadron colliders, like LHC, SSC and RHIC, the stability of the single-particle motion is basically determined by the field-shape imperfections of the superconducting dipoles and quadrupoles, especially during the injection flat bottom, when the effect of the persistent currents is maximum and the transverse size of the beam is large. The non-linear fields are at the origin of two effects: the betatron tunes change with the amplitude and the momentum of the circulating particles, and, for certain combinations of the horizontal, vertical, and synchrotron tunes, non-linear resonances are excited. These phenomena have a destabilizing influence on the particle motion, over a time-scale extending up to several million turns. Some precautions can make the motion of the particles less sensitive to the non-linear components of the guiding fields. Correcting multiplopes can be foreseen in the regular cells, to reduce the non-linear tune-shift caused by the systematic components of the field errors. The variations of the orbit functions can be limited along the insertions. The closed orbit and the linear coupling can be corrected sufficiently well. Finally the ripple of the power supplies can be reduced as much as possible. Most of these concepts have been embedded in the design of the LHC and their beneficial effects on the dynamic aperture have been extensively evaluated by computer simulations.

1. INTRODUCTION

The motion of charged particles in circular accelerators is basically governed by the magnetic field of the guiding dipoles and the focusing quadrupoles. Intentional and non intentional non-linear fields are in general also present, the side-effect of which is to induce losses at large amplitude. Sextupoles are used to reduce the chromaticity and octupoles make the tune dependent on the amplitude, which is sometime exploited to improve the current-dependent behavior. In hadron accelerators, the destabilizing action of chromaticity sextupoles is self-compensated to a large extent due to the regularity of the lattice. However, usually, a strongly focused lattice is necessary to reduce the sensitivity to field errors, and this in turn produces two adverse effects: the strength of chromaticity sextupoles has to be increased, therefore the beam stability is reduced, and the space available for dipoles along the ring is shortened with a consequent decrease of the maximum beam energy. Unintentional multipoles due to unavoidable imperfections of the guiding and focusing fields introduce additional non-linearities, which represent the greatest hazard. However, compromises are to be found between making magnetic fields as uniform as possible and keeping the magnet cost low. This is a difficult achievement especially for superconducting magnets, whose quality depends on the mechanical tolerances of the coil geometry, rather than on the shape of the poles. Both in the Tevatron and in the Hera magnets, typical deviations from uniformity have been limited to about one part in ten thousand at 2.5 centimetres from the magnet axis. Similar values, properly extrapolated with the inner coil diameter and the superconducting filament size, are expected to be reached in the magnets of the SSC, the LHC, and RHIC.

The single-particle approach provides a sufficiently simple, reliable and coherent model of the real accelerator to investigate performances related to non-linear dynamics. The key issue is to estimate the stability of the motion over the operational cycle of the accelerator. In a linear machine with irrational tunes the motion is stable and regular all around the closed reference orbit near the magnetic axis. The non-linear fields add a tune dependence with the amplitude, which shifts tunes to rational values, provoking resonant phenomena accompanied in the phase space by islands of finite area surrounded by thin chaotic layers. The islands and the chaotic layers exist through the entire phase space. However, at small amplitude, trajectories follow invariant surfaces, the KAM tori1, and remain stable for indefinite time. As amplitude increases, the islands become larger until they overlap. Beyond that point, the chaotic layers become interconnected and the particle motion is no longer bounded. This is the domain in which the non-linear forces are able to provoke particle losses, that sometimes may occur after millions of turns. The border between regular and chaotic motion is called dynamic aperture. This is analytically well defined for 1+ dimensional (1+D) systems only2. With more degrees of freedom, particles in stochastic layers, even close to the origin, may escape through the entire phase space, due to the so called Arnold diffusion. However, for all practical purposes, the border between mostly regular and mostly chaotic trajectories can be used as the dynamic aperture.

Both analytical and numerical tools are used to estimate the dynamic aperture as a function of various machine parameters. Improvements of the linear lattice and correction schemes are studied to reduce the influence of the non-linear forces, and to specify upper limits for the magnet imperfections. The final confirmation is in general performed with numerical simulations in which the particle position is tracked element by element around the machine for large numbers of turns.

Simpler dynamical systems, such as the Hénon map3, are advantageously used to investigate mechanisms of long-term losses.

Machine experiments with existing accelerators, in which non-linear perturbations are deliberately introduced, allow comparisons with predictions of numerical simulations.
In the following sections three subjects are reviewed, with special emphasis for the case of the LHC: the tools by which predictions on beam stability are formulated, the particular applications on accelerator design, and finally the outcome of the experiments performed in the CERN-SPS and in the FNAL-TEVATRON.

2. TOOLS FOR DYNAMIC APERTURE ESTIMATES

2.1. Tracking Simulations

Simulations with thin-lens approximation and symplectic integrators are considered as the master tool for quantitative estimates of particle behavior in the LHC with non-linear elements. They provide exact solutions of the equation of motion for a dynamical system approximating the accelerator. A sequence of linear transfer matrices interleaved with localized polynomial non-linearities is to be computed. Reliable results are easily obtained, since computer rounding errors can be kept under control. However a vast computing power is required to get reliable estimates of the dynamic aperture as a function of various lattice and beam parameters. A fully realistic description of the accelerator structure is difficult if not impossible. Simplifications are also imposed by limitations in computing power. Thin-lens description of guiding and focusing fields is used, and do not imply relevant changes to orbit functions. Ignoring fringing fields, and representing non-linearities with equivalent thin-lenses is also considered acceptable.

Two computer codes are routinely used to describe LHC lattice models and compute particle trajectories of given initial conditions: MAD, developed at CERN, and SIXTRACK, developed at DESY. Both of them have scalar versions to be processed in the modern farms of workstations as well as vectorized versions to make use of modern parallel processors.

2.2. Maps

In linear lattices, particle coordinates can be propagated along the accelerator azimuth by Twiss transfer matrices. The use of maps can be extended to non-linear dynamics with some precautions. This extension, originally motivated by the need to speed-up long-term tracking simulations in hadron colliders, in fact provides a powerful tool to handle dynamical quantities, like the tune dependence with the amplitude and the momentum, the distortion functions and the smear, the high-order non-linear invariants, and finally the Fourier harmonic coefficients of the resonance driving terms. Non-linear matrices can be constructed very efficiently with Differential Algebra techniques using Taylor expansion to some high order of algebraic operators. One-turn Taylor maps resulting from the composition of all the linear and non-linear elements in the accelerator, are inherently not symplectic because of the high order truncation, therefore inappropriate to preserve volume in phase space. A way to restore symplecticity, whose physical meaning, however, is not fully understood, is to replace the truncated map with a Normal Form, that is an integrable map, represented by a rotation of an angle depending on the amplitude of the orbit. In practice this is performed by a local change of coordinates in the phase space, which brings intricate orbits into circles. However, the normalized map has an optimized order of accuracy. Above it, the approximation is improved at lower amplitude and worsened at higher amplitude. The domain of convergence is limited by resonances of low order that are allowed by the truncated Taylor map. There are ways to handle the first limiting resonance, with Resonant Normal Forms, which are not yet made of practical use.

In the LHC, the mapping approach based on Taylor expansion and Normal Form is used to evaluate the dependence of tune-shift on the amplitude and the momentum due to systematic field-shape imperfections. By this it is possible to identify the multipoles that are more dangerous for the stability of the motion, taking into account the quite strong high order cross terms, and to define and optimize the most suited scheme of multipolar correctors.

High order Taylor maps are also used to estimate the dynamic aperture in a faster way than with the usual element by element tracking. However, in the LHC, this approach is non-controversial only for simulations up to few 10^4 turns. By increasing the order of the map the violation of area preserving transport can be made arbitrarily small, but the map size grows exponentially and the computing speed decreases accordingly. An interesting result is that one can correlate the accuracy of the truncated Taylor map tracking to the size of the high order terms in the map. Alternatively, one can restore the symplecticity of the Taylor map by a linear scaling transformation to the particle coordinates at each turn. The transformation is staged in three different scale transformations, two in the transverse and one in the longitudinal directions respectively, characterized by three different scaling factors chosen in a suitable manner to ensure that the Liouville's theorem is obeyed, at least in average. In fact, there is an infinite set of possibilities for the choice of the three scaling factors. The additional criterion to determine the final choice is based on the following arguments. It is assumed that Taylor maps up to order 11th are sufficient for an accurate description of the beam dynamics in the LHC, at least in the region of the phase-space where the motion is regular or only weakly chaotic. The beam trajectories are computed both with element-by-element tracking and with Taylor maps with initial values of the scaling factors. The difference of amplitudes in the phase-space of the two results are estimated in few iterations by slightly varying the scaling factors. From that one can optimize the scaling factors in such a way that the amplitude differences between the direct tracking and the iteration of the Taylor map is constant as a function of the number of turns. The comparison between direct tracking and iteration of truncated maps with and without dynamic re-scaling has been made for a large number of turns: the agreement is two orders of magnitude better with re-scaling that without.

2.3. Early indicators of chaos

Early indicators of chaotic motion have been used to speed
up the estimate of the dynamic aperture in the LHC. The exponential divergence of two initially very close trajectories is a criterion for chaos, a linear growth indicating regular motion. The exponential coefficient, called Lyapunov exponent\textsuperscript{11}, can be used to localize stochastic layers in the phase space and eventually to identify the stability border below which its value is zero. The routine way to evaluate the Lyapunov coefficient is to track simultaneously two particles with a slightly different initial amplitude, and to compute periodically and plot their mutual distance\textsuperscript{12}. An equivalent method is based on the analytical evaluation of the Jacobian in the phase space domain of interest\textsuperscript{13}. A third possibility is to compute the slow change of an action invariant\textsuperscript{14}. The predictability of all three methods is enhanced when the non-linear deformation of the phase space is removed by Lie algebraic or Normal Forms type change of coordinates. It is currently admitted that through early indicators of chaos a conservative estimate of the dynamic aperture can be obtained with about ten times less computing power than for standard tracking.

### 2.4 Figure of merit and data processing

The linear aperture, based on smear and tuneshift with the amplitude, and the short-term dynamic aperture were widely used in the past\textsuperscript{15} to estimate non-linear effects, since threshold values for detuning and amplitude distortion were considered sufficient to ensure long-term stability. However, the validity of this extrapolation has not been confirmed by deeper studies. Therefore, intensive tracking and sophisticated data processing are preferred nowadays to estimate the dynamic aperture, after a preliminary selection of rather few significant cases, on the basis of short-term simulations. Results are presented in graphical form: survival plots depict the maximum number of stable turns as a function of starting amplitude\textsuperscript{16}. These plots and early indicators of chaos provide a practical estimate of the stable region. Dense survival plots are ragged and show a large spread in the survival time close to the chaotic border, rapidly decreasing at larger amplitudes. Such an irregular shape reflects the local origin of the particle instability: at moderate amplitude in presence of weaker perturbations, the escape time is largely influenced by microscopic changes of initial coordinates; at large amplitude, instead there are only fast losses. Under the influence of non-linearities, particles migrate across different nests of resonances, which can be at least phenomenologically correlated to average lifetime. The loss mechanism is in general sudden: the particle may stay confined even for millions of turns and then diverge in a few thousand turns.

### 3. APPLICATIONS IN ACCELERATOR DESIGN

The LHC must operate with negligible loss for long periods, up to $10^8$ turns, in spite of the unavoidable field shape imperfections. An upper limit to unintentional multipoles and practical compensation strategies have to be devised for a safe operation. This implies a thorough understanding of the influence of the non-linearities on the long-term behavior of particle trajectories. Analytical methods available are not yet fully exploited. Numerical simulations are too heavy and time consuming for an exhaustive overview of all the possible situations. Nevertheless, remarkable progress has been made through heuristic approaches proposed in the recent past, based on the investigation of simplified non-linear models of the LHC lattice and on the use of empiric criteria for beam stability.

Too crude simplifications of the lattice structure itself have dramatic effects on non-linear performances. Cell lattice models with only regular cells and no interaction regions show a regular azimuthal pattern of the orbit functions and in particular of the betatron phase advance leading to unrealistic enhancement of the particle stability. They are in general used for numerical studies of simple dynamical systems as the Hénon map. A more realistic way to drop the insertions is to replace them with equivalent rotation matrices. Part of the chromatic aberration and some unintentional field errors are disregarded in this way. However, relevant informations can be gained with less computing power and complexity, especially during the injection plateau, where the stability of motion is mainly determined by non-linear perturbations in the arcs. This approach was used to determine the optimum value for the length and the phase advance of the LHC cell\textsuperscript{17}, fixed to about 100 m and 90 degrees, respectively. More advanced studies are based on models with realistic descriptions of the insertions.

The field-shape imperfections are equivalent to multipoles up to large order, which can be expressed as the sum of two parts, one systematic and the other random. The general agreement is to stop at order 11th in the multipolar expansion and to neglect correlations between random multipoles of different orders. Systematic errors are larger at injection due to persistent currents. Large low-order (3rd and 5th) values provoke a sizeable detuning with the amplitude and the momentum, which can be corrected either locally\textsuperscript{18}, as in the LHC lattice version 2, or using a clever cancellation of the detuning terms by means of Sympsson rules\textsuperscript{19}, as in the LHC lattice version 1. In the latter case, multipolar correctors are to be located near the main quadrupoles as well as at about the middle of each half cell\textsuperscript{9}. Octupolar imperfections have, in the LHC, a particular behavior related to the symmetry of the magnetic field in two-in-one magnets: the integrated value along the azimuth is expected to be zero, therefore the detuning with the amplitude is expected to be self-compensated without specific correctors. Large high-order (7th and 9th) systematic multipoles destabilize off-momentum particles and have to be minimized by design: tolerable values for the LHC have been found to be of the order of $2\times 10^{-6}$ and $5\times 10^{-7}$ units at 1 cm radius, respectively.

Random imperfections, which vary from magnet to magnet due to manufacturing tolerances, are the main source of non-linear resonances and distortion functions. Statistical distributions can be easily predicted, but are insufficient for a complete knowledge of the non-linear optics, since resonance strengths depend on the specific sequence of the random errors around the ring rather than on statistical properties. Therefore,
criteria for magnet design are to be studied on several non-
linear lattices, with different sequences of random multipoles.
In fact, there are many parameters that limit the stability of
the particle motion in the LHC, therefore the first task is to
identify the most important ones, in order to reduce to a
reasonable amount the enormous need of computing time
required for an exhaustive set of simulations. Parameters
routinely considered in the accelerator models are residual
closed orbit, linear coupling due to imperfections,
synchrotron motion, and main power supplies ripple.
Chromaticity and non-linear detuning are corrected with suited
set of correctors. Special cases with some residual
uncompensated chromaticity are considered as well. Short-
term dynamic aperture is first evaluated by tracking particles
of different starting amplitudes for $10^3$ turns. This is fast and
well suited for a first exploration of the space parameters, and
is also sufficient to reveal the most important features of the
non-linear phase space. Ten different seeds are used to fix the
test samples of the random errors. Appropriate subsets of
them are considered to disentangle the effects of the dipole
imperfections from those of the quadrupole imperfections in a
machine with a perfect closed orbit and no linear coupling. By
choosing three representative seeds in each distribution, i.e.
one with the smallest, one with the largest, and one with an
average value of the aperture, one can easily check the
combined effect of the dipole and the quadrupole errors and
identify a limited number of representative sets of non-linear
lattice models to be investigated with long-term tracking
simulations. With this strategy, beam stability has been
found to be strongly influenced by linear lattice parameters
like tune, residual linear coupling, and peak-8 values in the
insertion quadrupoles as well as by a residual chromaticity of
a few units. Instead, residual closed orbit associated to magnet
misalignment and tune ripple of a few $10^{-4}$ units showed a
weak interference with beam stability.

Particles above the stable region are expected to diffuse
towards the vacuum pipe at a speed strongly increasing with
the transverse amplitude. A set of collimators is used to
absorb them before they hit the magnets and provoke an
unwanted deposition of energy in the superconducting coils.
The transverse position of the primary collimator defines the
mechanical aperture of the accelerator. It is basically fixed
taking into account the mechanical tolerances of the cold bore
and of the thermal screen of the main magnets, the expected
peak-values of the closed-orbit, of the dispersion, and of the β-
function modulation, and, of course, the optimum value of the
separation between the primary and the secondary collimators.
For a safe operation, careful matching of physical aperture and
stability border is to be performed. With a small
mechanical aperture, trajectories with small amplitude
oscillations only are allowed, which are weakly perturbed even
in presence of large field-shape imperfections, whilst, with
larger mechanical apertures, and larger amplitude oscillations,
the non-linear perturbation becomes larger and the size of the
magnetic errors start to play a leading role for the dynamic
aperture. On the other hand, we believe that particles with
amplitudes up to the chaotic boundary are stable, although the
non-linear perturbations induce a finite smear of their
trajectories, whilst particles with larger amplitudes may
become unstable after a sufficiently large number of turns.
Ideally, the chaotic limit should be equal to the dynamic
aperture evaluated in presence of collimators, in which case
only the unstable particles will be intercepted by the
collimators. In this respect the mechanical size and the field
quality of the LHC at injection have been found to be well
matched to a value of $6 \sigma$, i.e. of 7.2 mm, which is considered
a wise choice for the needed dynamic and physical aperture.

Strategies of magnet sorting have been invented, by which
the magnets are installed in such a sequence in the machines as
to minimize the combined non-linear effects. For practical and
theoretical reasons, the sorting scheme should be as local as
possible and must refer to a limited kind of multipoles.
Different solutions have been proposed. By introducing a
quasi-periodicity of multipoles every two betatron
wavelengths, the harmonic content of non-linearities can be
shifted away from harmful frequencies. Alternatively, small
groups of magnets, typically ten, are ordered in such a way to
minimize a broad band of non-linear driving terms computed
to 2nd perturbative order, contributing to resonances up to
order 12th. The first method is used in the LHC and the SSC,
the last method is used for HERA and is still under
investigation for the LHC.

Diffusion with steady state increase of the amplitude has
never been detected in numerical simulations, even in presence
of external tune modulation, contrary to what is usually
observed with beam-beam interaction. Due to resonance
crossing and non-linear coupling, migration of particles in the
tune diagram and mixing of horizontal and vertical oscillations
are well visible in long-term tracking results. However large
increases in amplitude and particle losses are sudden and
unpredictable, even if they occur after a large number of turns.

4. EXPERIMENTS

In the last decade, experiments have been devised to study
the effect of high-order resonances under controlled conditions.
The hope is that by comparing theoretical or numerical results
with experimental ones, it may be possible to define suitable
criteria for beam stability and evaluate their predictive power.
This is an ambitious goal, since real machines are much more
complicated than models used in tracking codes or analytical
evaluations. There are many phenomena, like collective
instabilities, synchro-betatron resonances, linear imperfections
affecting the orbit functions, the linear coupling, the closed
orbit, non-linear imperfections due to fringing fields and
saturations, which may take a long time to be quantified in
order to disentangle single-particle effects from measurements.
However, analysis of operating situations provides a wealth of
informations which can be exploited to bridge the gap between
models and reality. These experiments have been performed in
the CERN-SPS and the FNAL-TEVATRON which are already
well understood, so that clear conditions could be defined,
spurious effect eliminated and phenomena under study carefully
isolated, with reasonably small effort. Having repeated similar
measurements in different accelerators is invaluable to help in
distinguishing results of general interest from those which are
just a property of the machine used. Common motivations of
the two experiments are related to the refinement of aperture
and field quality criteria for future large hadron accelerators,
like LHC or SSC. A common procedure consists in exciting
already existing sextupoles in order to introduce in a controlled
fashion non-linearities in an otherwise linear lattice. To probe
large amplitudes, a pencil beam with small emittance and
momentum spread is used, to which a large enough coherent
deflection is applied. In a few hundred turns, a ‘hollow’
distribution of charges is created around the central orbit due to
nonlinear filamentation, whose behavior is observed with
several instruments: current transformers record lifetime,
Schottky noise detectors give tune and tune-spread, flying
wires provide transverse profile, and orthogonal pairs of
position monitors are able to produce a phase space portrait.

In the experiment E778 at FNAL, sextupoles were exciting strongly the third integer resonance together with the
higher-order ones. Smear, injection efficiency and short-term
dynamic aperture were measured and compared with tracking.
The agreement is good, however long-term losses could not be
quantitatively reproduced. The existence of stable nonlinear
resonance islands was demonstrated experimentally by observing coherent persistent signals of particles captured into
them. Tune modulation effects were explored and compared
with those of 1-D forced pendulum.

In the experiments at the SPS, the sextupolar excitation
chosen so as to minimize the third integer resonance.
Detuning compensation was experimentally tested by using
existing octupoles. A 30% increase of dynamic aperture
resulted from a factor ten reduction of tune-spread. This
provides experimental guidance in devising correction schemes
for large hadron accelerators. However most of the emphasis
was put on the study of slow diffusion induced by power
supply ripple, and controlled modulation of a special
quadrupole. The diffusion coefficient was measured as a
function of the amplitude, the modulation frequency and depth,
and the tune. It was obtained by scraping the beam tail with
horizontal and vertical collimators, retracting them suddenly
by a few mm, and observing the beam lifetime to estimate the
time taken by the particles to fill the gap created by the
retraction. Diffusion immediately sets in when tune
modulation is turned on, and there is evidence that a ripple
which leads to tune modulation of $10^{-3}$ cannot be tolerated in
a machine with strong non-linearities. A tune modulation at
two frequencies is more destructive than a modulation at a
single frequency for the same overall depth. The agreement
with numerical simulations is of the order of 20%, however
the strong dependence of diffusion on modulation depth and the
dependence on frequency are not yet understood.

Recent experiments at FNAL have also addressed the
problem of ripple induced diffusion. Intensity and transverse
profile were recorded and used to deduce a phenomenological
dependence of the diffusion coefficient on amplitude. The
proposed model assumes a threshold amplitude, below which
there is no diffusion, and above which the diffusion speed
increases as a polynomial of the amplitude. A steady
reduction of beam size was pointed out which was never
observed at the SPS. This is likely to be typical of the
regime of large losses explored at FNAL.

The phenomenological model of FNAL for diffusion has
been found to be in contradiction with some results of the
CERN experiment as well as with the sudden manifestation
of fast amplitude growth in tracking. More general models
of diffusion based on Markov process with jumps, using master
equations on status transition probability are under
investigation.

5. TRENDS

Studies of theoretical aspects of the LHC related to non-
linearities are being pursued, to develop new tools for stability
estimate, and to understand diffusion in 1-D and 2-D Hénon
map models. However, the main tools to evaluate beam
stability in the design lattice will continue to be tracking
simulations and maps associated to Differential Algebra
methods, whose potentiality seems to be far from being fully
exploited. Experiments are likely to be vigorously pursued,
to compare predictions with real world in a controlled fashion,
and to clarify features of slow diffusion in presence of external
modulation and non-linear fields.

6. REFERENCES

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Proton extraction from the CERN-SPS by a bent crystal

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Abstract
An experiment is being performed at the CERN-SPS to study the feasibility of extracting protons from the halo of a 120 GeV stored beam by means of planar channeling in a 8.5 mrad bent silicon monocrystal. Two different techniques have been used to bring the protons into the crystal. In one case a kicker magnet was repeatedly energized to displace particles up to 100 microns inside the crystal front face. In the other case a continuous flux of impinging particles was obtained by powering electrostatic plates with a white noise excitation. In both cases we observed an extracted beam of channeled particles. The detection was performed with several large size scintillators, a fluorescent screen, a scintillation hodoscope, and a pair of microstrip gas chambers. Extraction efficiencies of the order of 10% were measured.

I. INTRODUCTION

Planar channeling can occur when a proton beam is sent onto a monocrystal with an incident angle relative to the main crystalline planes smaller than a given critical angle [2]. The impinging particles are confined between the atomic planes and can eventually be deflected if the crystal is mechanically bent [3]. The main features of planar channeling are now well established from the theoretical point of view [4]:

- The critical angle $\Psi_p$ varies with the beam momentum $P$ as $1/\sqrt{P}$. The surface acceptance, which is the probability that incident particles within the critical angle get initially channeled, does not depend on $P$.
- Multiple scattering on electrons can kick initially channeled particles out of the guiding potential well. The dechanneling length is proportional to $P$ in a straight crystal.
- The curvature of the bent crystal introduces additional losses due to centrifugal forces acting on particles when entering the curved region. The reduction of the deflection efficiency is function of the ratio $P/R$, where $R$ is the bending radius.

Bending efficiencies of about 50%, with a deflection of 2.4 mrad, have been measured with 450 GeV protons channelled in a silicon crystal [5]. These results were obtained on a highly parallel external beam with an angular divergence of $\pm 3 \mu$rad, less than the critical angle for planar channeling at this energy $\Psi_p(450 \text{ GeV}) = \pm 7 \mu$rad. Extraction of 70 GeV protons from an internal circulating beam was reported with a much lower efficiency of about $1.5 \times 10^{-4}$ [6].

It has been proposed to use the technique of crystal channeling to extract protons from the beam halo of both future multi-TeV colliders SSC [7] and LHC [8], allowing fixed target experiments to run in a parasitic mode. The main expected difficulty comes from a reduction of the channeling efficiency when the protons hit the crystal with small impact parameters and remain close to the surface where defaults of the crystalline structure can occur. One is also concerned about the alignment of the crystal relative to the circulating beam. The aim of the RD22 experiment [9] is to investigate these effects in the environment of a real accelerator. The experimental equipment was installed in the CERN-SPS and became operational by mid 1992.

II. EXPERIMENTAL LAYOUT

The experimental set-up, located in Straight Section 5 of the CERN-SPS, is shown schematically in Figure 1. The vacuum tank contains two silicon monocrystals, each 3 cm long, 1 cm high and 1.5 mm thick. Their upper and lower edges are clamped onto cylindrical formers to bend the crystal $\{110\}$ lattice planes by 8.5 mrad. Each crystal is mounted on a goniometer which can move horizontally into the beam and which can provide angular adjustment with a resolution of up to 4 $\mu$rad. Four beam scrapers, three in the horizontal plane and one in the vertical plane, are used for a precise positioning of the beam. Protons are extracted in the horizontal plane, towards the centre of the ring. The deflected beam stays in the vacuum pipe for about 15 meters and exits through a 0.2 mm thick stainless steel window.

The three scintillators S1, S2 and S3 form a telescope to detect and count the extracted protons. The light outputs of scintillators S4 and S5 are attenuated to operate at high fluxes. S4 is in the extracted beam line while S6 is placed on the opposite side to monitor background. TV1 is a scintillating (Cesium Iodide) screen read by a CCD TV camera providing an immediate image of the extracted beam [10]. H1 and H2 are two hodoscope planes $32 \times 32$ mm$^2$, 1 mm pitch, to measure horizontal and vertical profiles. C1 and C2 are pairs of Micro Strip Gas Chambers (MSGC) [11], $25 \times 25$ mm$^2$, with horizontal and vertical strips (200 $\mu$m pitch), spaced by 1 meter. Their spatial resolution is better than 100 $\mu$m. They are used to measure the direction and profiles of the extracted beam. Counter S3, the hodoscope and the MSGCs are mounted on a movable table to follow the position of the extracted beam and account for the parallax between the two crystals.