ISBN: 978-3-95450-254-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS1991-S18BPA03

New Controls for the CERN-PS Hadron Injection Process using Operating Tools and High-Level Accelerator Modelling Programmes

M. Arruat, M. Boutheon, L. Cons, Y. Deloose, F. Di Maio, D. Gueugnon,
R. Hoh, M. Martini, K. Priestnall, J.P. Riunaud
PS Division
CERN 1211 Geneva 23 Switzerland

Abstract

A new control system using man-machine interface tools with workstations as consoles has been successfully put into operation for the injection of hadrons in the CERN Proton Synchrotron (PS). This paper mainly focuses on specialized modelling programmes involving complex treatments for an optimum operation of the injection process. These programmes include the control of the injection timings, the measurement of the beam emittance with an estimation of how well the incoming beam is matched, and the correction of oscillations at injection. The infrastructure and the programming environment underlaying the new control system are described elsewhere[3].

The outstanding feature of the internal structure of all these modelling programmes is that they carry out three kinds of data interaction: the input, that is the measurements (e.g. beam time positions, profiles and trajectories), the physical parameters (e.g. required times for synchronization, beam emittance, beam space position and angle at injection), and the output, mainly the hardware values (e.g. preset counter settings, currents to apply to injection steering magnets).

I Structure of High-Level Modelling Programmes

A control system provides the users with centralised access to hardware control values. These values can be obtained in various ways. They can be controlled individually, for example tuning a power supply current via a knob, or globally, setting all currents of a complete beam line from a selected file. In those two cases, the final hardware values are left to the user's appreciation. Their choice is made either following the effect on the beam, as in the first case, or at the time of the file selection, as in the second. Evaluation of these control values does not require implementation of the process involved in the control system.

However, in many cases the process involved is known and several control values can be worked out from the required machine and/or beam parameters. A dedicated programme can then be used to evaluate these control values from the user's requirements. Considering the previous example of a beam line, if the relationship between the power supply currents and the energy is known, setting a complete beam line for various energies does not require as many files as energies, but only one file and a dedicated programme working out the currents from the required energy.

This trivial example can be extended to more general cases. In the example of beam steering, the trajectory of the beam in a transfer line can be taken as input, physical parameters such as angle and position of the beam at a relevant position in the line can then be worked out from this trajectory, and finally current variations in deflecting elements can be computed to steer correctly the beam in the line. More generally, controls values (output) can be computed from physical parameters (parameters relevant to the process involved) which, in turn, can be computed from measurements on the beam (input). Modelling Programmes perform such operations and take care of computations between inputs, physical parameters and outputs.

In most cases, provided they are not too large, variations of beam characteristics (ΔX, inputs) lead to variations of physical parameters (ΔP) which can be expressed in a matrix formalism. The same applies to the variations of hardware control values (ΔY, outputs) which can be expressed from variations of the physical parameters:

$$[\Delta P] = [M_1] * [\Delta X] \quad (1)$$

$$[\Delta Y] = [M_2] * [\Delta P] \quad (2)$$

Modelling Programmes can compute hardware values from physical parameters or from beam measurements, using matrix M_1 or both M_1 and M_2. If matrix M_2 is not singular, one can also work out physical parameters by reading control values. This can of course be of great help for machine tuning. In the following section we present how these considerations have been applied to the timing process of hadron injection into the PS[1].

II Injection Timing Controls

In the injection process, timing pulses have to be delivered to various equipments in order to trigger them correctly with respect to the incoming beam. Preset counters are interconnected in such a way that they can provide the necessary pulses, with the proper time resolution, at appropriate instants with respect to external time references. One can then define the required times as physical parameters and the output as the control values to be loaded in the various counters. Looking at the timing lay-out, the required times

ISBN: 978-3-95450-254-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS1991-S18BPA03

can be defined from the time of the External Starts and the sum of the various count times elapsed in the relevant counters. This can be expressed as the following matrix expression:

[Required Times] =
[External Starts] + [M lay-out] ∗ [Count Times] (3)

where M lay-out is a matrix reflecting how pulses proceed through the various counters. Its elements are null if the corresponding counter is not involved, 1 if the counter is involved and its time has to be added, and -1 in the opposite case. Count Times are simply obtained from the counters control values and their clock periods Tck:

[Count Times] = [Control Values] ∗ [Tck] (4)

If one defines as many Required Times as counters in the lay-out, M lay-out is not singular and the control value can be deduced from the preceding expressions:

[Count Times] =
[M lay-out $]^{-1}$∗{[Required Times]-External starts]} (5)

[Control Values] = [Count Times] / [Tck] (6)

Clock periods Tck can be evaluated from the hardware settings (for internal clocks) or from machine parameters (for external RF or Field-derived clocks). Therefore all control values can always be worked out from the required times, in all machine conditions.

This has been applied to the PS hadron injection timing. The system layout has been translated into a matrix M lay-out to define the required times. The resulting interactive display is shown in Fig. 1.

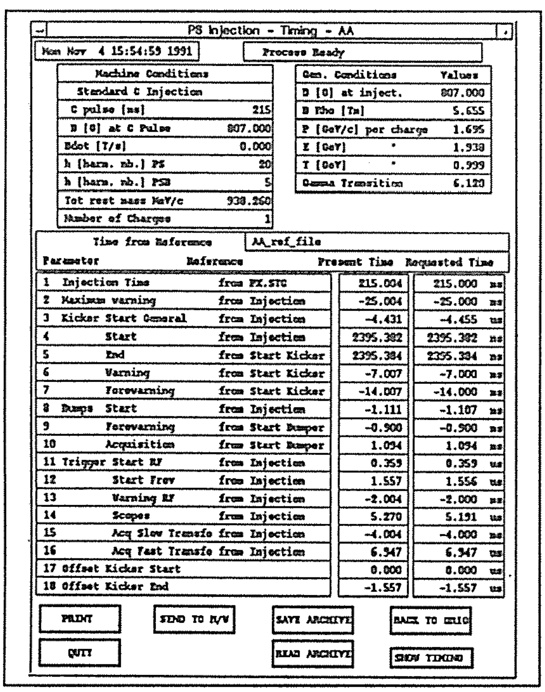

Fig. 1: Interactive display of the timing modelling programme. Present times are computed from the hardware acquisition through Eqs. (3-4). Requested times are filled in by the user and provide control values through Eqs. (5-6).

III Emittance and Matching Measurements

A method for the measurement of transverse emittance in the PS and matching of the beam between the Proton Synchrotron Booster (PSB) and the PS rings was implemented in the present control system[2]. A new version of this Application has been designed to fit the method to the framework of the new CERN-PS control system through the concept of man-machine interface and using workstations[3].

This method is based on the measurement of beam profiles at three different secondary emission monitors with known transfer matrices between them. The three monitors are located downstream of the PS injection region, each of them measuring a horizontal and a vertical profile.

With w_i the half beam widths or heights measured at the i-th monitor position and $\beta_{i\,0}$ the β-functions of the machine (i.e. of the acceptance ellipse), the beam emittance and the geometrical emittance increase due to mismatch of the incoming beam[4] may be written as

$$\varepsilon = \underline{G}_i \frac{w_i^2}{\beta_{i\,0}} \qquad (7)$$

and

$$\frac{\Delta\varepsilon}{\varepsilon} = |k| \left(\frac{|k|}{2} + \sqrt{1 + \frac{|k|^2}{4}}\right) \qquad (8)$$

with

$$k = \frac{1}{\sqrt{\underline{G}_i}}\left((\underline{G}_i - 1)^2 + j\,\underline{B}_i^2\right) \qquad (9)$$

where j is the imaginary unit, $\underline{B}_i$ and $\underline{G}_i$ are the normalized matching parameters which describe the beam emittance ellipse and k is the complex mismatch vector of the beam[2].

The mismatch vector k provides a measure for the comparison of the emittance ellipse of the incoming beam with the acceptance ellipse of the PS in the injection region. The modulus of k has to be much less than unity for good matching. For instance, |k| is equal to $1/\sqrt{2}$ when the emittance blow up reaches 100%.

From the three half beam sizes w_i measured with monitors at different positions and with the knowledge of the transfer matrices between these monitors, the normalized matching parameters at one monitor position, say $\underline{B}_1$ and $\underline{G}_1$, may be expressed as functions of the w_i, $\beta_{i\,0}$ and the phase advance difference $\Delta\mu_{i\,j}$ between monitors i and j[5].

When the beam is perfectly matched, the normalized matching parameters take the values $\underline{B}_1 = 0$, $\underline{G}_1 = 1$. Hence the beam emittance may be estimated from a unique half beam size measured with a monitor, say w_1, using Eq. (7) in which $\underline{G}_1$ is set to unity.

A convenient definition of the half beam sizes when the beam profile density is not exactly known consists in taking for w_i twice the r.m.s. value of the profile distribution.

ISBN: 978-3-95450-254-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS1991-S18BPA03

In the presence of dispersion, the pure betatron half beam width $w_{\beta\,i}$ must be used instead of the overall half beam width w_i which includes both the betatron and momentum dispersion contributions. No such correction has been implemented until now.

All acquired profiles are analyzed prior to the beam size evaluation since faulty grids, fluctuations in grid output signals and random disturbances on the beam may perturb the measurements. The treatment of the profiles are performed only on the user request, and consists of the following:

- elimination of faulty grid measurements,
- treatment of the tails (for base line detection),
- profile smoothing using spline functions.

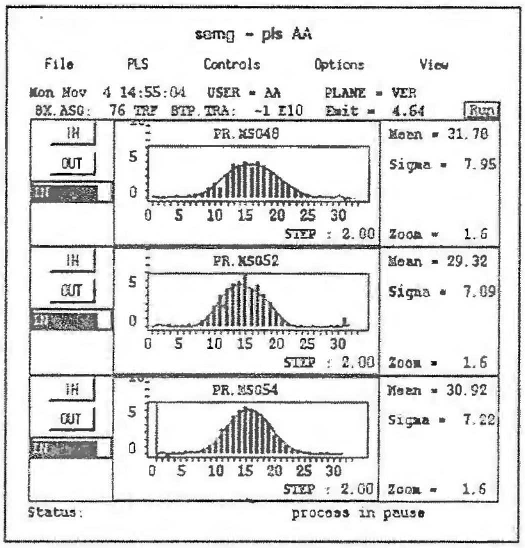

Fig. 2: Display of transverse beam profile distributions at three different monitors. The bars charts show beam profiles measured with 32 wire grid monitors. The continuous lines show the smoothed profiles after elimination of erroneous data (the smoothing coefficients are chosen by the user). Beam emittance, mean and r.m.s. values of the smoothed profile distributions are given.

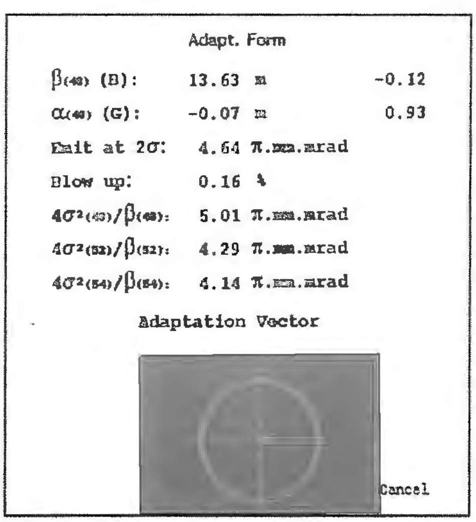

Fig. 3: Display of the mismatch vector in polar form. The area within the circle fits to emittance blow-up below 100%. The 2-r.m.s. emittance, the emittance blow-up due to mismatch, and the normalized beam matching parameters $(\underline{B}_1, \underline{G}_1)$ at the 1st monitor location, with their corresponding Twiss parameters (α_1, β_1), are shown. Estimations of the beam emittance obtained from half beam sizes measured with the three monitors, regardless to beam matching, are shown for comparison.

IV Injection Tuning

A method for the correction of oscillations at 1 GeV injection into the PS was introduced in a early version of the control system[6]. As in the case of the emittance and matching measurement process, an up-to-date version of the hadron injection process has been assembled in order to be integrated in the new CERN-PS control system.

The amplitude and the phase of the pure betatron injection oscillation when the closed orbit is unknown are derived by adjusting a sine curve to the normalized beam trajectory difference between two consecutive turns measured shortly after injection. Moreover when the machine tune is also not known, the optimum tune value which minimizes the summed-square error between the fitted sine curve and the normalized measured trajectory difference is determined by iteration. This yields a satisfactory knowledge of the betatron oscillation at injection. Hence the correcting strengths to be applied to a given pair of injection steering elements in order to cancel this oscillation are evaluated accordingly.

For the beam trajectory measurements, 40 pick-up monitors are installed around the PS ring, each measuring a horizontal and a vertical beam position with respect to the pick-up center. Trajectory position at monitor i in machine turn number n can be written as

$$x_{i\,n} = z_i + A\sqrt{\frac{\beta_i}{\beta_R}}\cos(\mu_i + \phi + 2(n-1)\pi Q) \qquad (10)$$

in which z_i is the closed orbit value at the i-th monitor location, μ_i, β_i are the phase advance and the β-function at this monitor position relative to a reference location R in the machine, Q is the tune (not an integer value), and A, ϕ are the amplitude and phase of the betatron oscillation respectively.

The normalized trajectory difference between two successive turns is then independent of the closed orbit and may be written as

$$\sqrt{\frac{\beta_R}{\beta_i}}\,\frac{x_{i\,n} - x_{i\,n+1}}{2\sin\pi Q} = C\sin\mu_i + D\cos\mu_i \qquad (11)$$

where C and D depend on A, ϕ, Q and the turn number n.

Least square approximation of measured beam trajectory difference provides estimators $\underline{C}$ and $\underline{D}$ of variables C and D by minimizing the summed-square error

$$\sigma^2 = \frac{1}{N-2}\sum_{i=1}^{N}\left[\sqrt{\frac{\beta_R}{\beta_i}}\,\frac{x^m_{i\,n} - x^m_{i\,n+1}}{2\sin\pi Q} - \underline{C}\sin\mu_i - \underline{D}\cos\mu_i\right]^2 \qquad (12)$$

3rd Int. Conf. Accel. Large Exp. Phys. Control Syst. ICALEPCS1991, Tsukuba, Japan JACoW Publishing
ISBN: 978-3-95450-254-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS1991-S18BPA03

where $x^m_{i\,n}$, $x^m_{i\,n+1}$ are the measured beam trajectory in two consecutive turns, N is the number of monitors providing reliable signal data.

In case of faulty monitors, the rejection of erroneous acquisitions is based on usual statistical criteria to decide whether the chance of occurrence of some particular measured beam position is less than some fixed number.

Hence approximate values $\underline{A}$ and $\underline{\phi}$ of the betatron oscillation amplitude and phase can be derived from the estimators $\underline{C}$ and $\underline{D}$. The position and angle variations Δx_0, $\Delta x'_0$ of the beam at injection point with reference to the closed orbit can then be obtained from Eq. (10). Finally the current variations values ΔI_1, ΔI_2 to be applied at the two correctors (septum and steering dipole) to cancel the injection oscillation are derived from these position and angle by a linear transformation written as a 2 by 2 matrix equation. The components of the transformation matrix can be either determined experimentally or from a programme for lattice design.

The summed-square error σ^2 near the real machine tune Q is well approximated by a parabola. Therefore a search procedure may be carried out to estimate the unknown tune value Q. The Fibonacci search has been considered as an optimum Q-seeking method. This procedure starts from the initial search interval, and successively reduces the subsequent search intervals by means of a sequence of numbers, which are determined from the Fibonacci numbers. The number of search steps is fixed by advance. The Fibonacci search is the most effective one-dimensional search strategy available. An accuracy of 0.01 is then achieved with 8 search steps within an initial tune search interval of 0.5.
However, in some cases fluctuations in the monitor acquisitions may be distributed in such a unpredictable way that the tune calculated in this way is irrelevant. Assuming that the trajectory measurements are done in the 1st and 2nd turns, the tune error is inversely proportional to the signal to noise ratio. For instance, rough estimate shows that when the amplitude of the oscillation at injection is lower than 5 mm, the tune accuracy cannot be kept within 0.04.

Consequently the tune search is mostly reliable at the first stages of the correction process, when the injection oscillations still have large amplitudes. Once an adequate estimation of the tune has been found during the first few corrections, the latter Q-value can be frozen and further corrections may be carried on to refine the injection tuning. Simulation from the trajectory data has shown the validity of the above algorithm.

At any stages of the tuning process, no automatic corrections will be performed, the computed corrections are merely proposed to the user, who decides whether they have to be carried out. Fig. 4 shows the proposed Workstation window for the horizontal and vertical interactive corrections of betatron oscillations at 1 GeV injection into the PS.

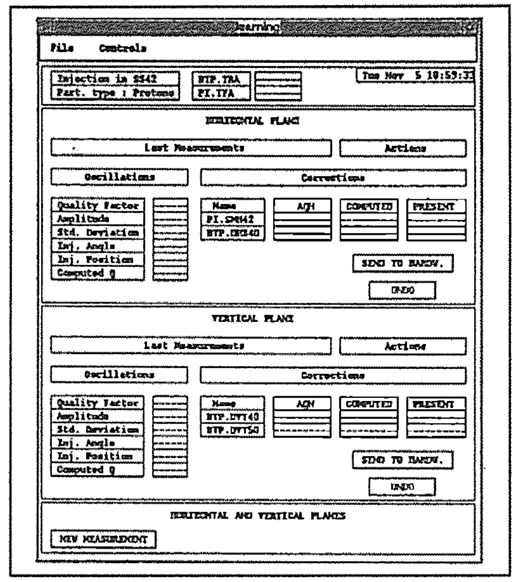

Fig. 4: Display of the interactive window used for the injection tuning. For every two single turn trajectory measurement, the computed tune, the fit quality and the characteristics of the derived betatron sinewave are anticipated. The appropriate currents to be applied to each pair of correctors will be displayed for possible user action.

V CONCLUSION

The injection timing control and the emittance and matching measurements are presently implemented within the new CERN-PS control system and are used in current operation to the user satisfaction. The third application, optimization of the betatron oscillations at injection into the PS, although well under way, is not entirely set up. The search of the optimum tune and the calculation of the two corrections which will cancel the oscillations are finalized, but the final stage, on-line connection to the beam trajectory measurements, is in the process of being implemented.

VI REFERENCES

[1] J.P. Riunaud, "Modelling of a Timing Process", Internal Report CERN PS/PA Note 91-21, November 1991.
[2] M. Martini, "Calcul de la désadaptation dans la ligne d'injection à 800 MeV du PS", Internal Report CERN/PS 84-12 (OP), August 1984.
[3] M. Boutheon, F. Di Maio, A. Pace, "General Man-Machine Interface used in Accelerator Controls: Some Applications in CERN-PS Control Systems Rejuvenation", these Proceedings (ICALEPS, Tsukuba, Japan Nov. 1991).
[4] K. Schindl, "Increase of 95% Emittance due to Missteering and Mismatch", Internal Report CERN MPS/BR Note/75-25, November 1975.
[5] P. Brummer, "The Method of Measurement of the Emittance and the Betatron Phase Space Parameters in the Beam Transfer System of the ISR", Internal Report CERN-ISR-OP/72-6, January 1972.
[6] M. Martini, J.P. Potier and T. Risselada, "Automatic Injection Tuning Using Two Successive Single Turn Trajectory Measurements", in European Particle Accelerator Conference EPAC 90", Nice, France, June 1990.