MONITORING BEAM QUALITY IN THE PS COMPLEX DURING THE LHC ERA

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Abstract
Continuous monitoring of beam intensity and beam losses is provided today at the PS complex with beam current transformers and beam loss monitors. The beam intensity is continuously displayed over a video network, together with relevant information concerning the machine status. In the future, during the LHC era, further important beam quality parameters will be brightness, bunch length and momentum spread.

For maximum beam brightness, any increase of emittance must be avoided, and its value should be monitored continuously. Transverse coherent beam position oscillations, due to injection steering errors, can be measured with conventional pickups. A new system, using two quadrupole pickups, will allow continuous monitoring of both position oscillations and beam size oscillations, the latter caused by injection matching errors. Beam size, after smear-out consequent to any injection errors, is measured with fast wire-scanners on a daily basis. The possibility of monitoring it non-invasively and continuously using the signals from the quadrupole pickups will be explored.

A longitudinal phase space plot can be created on-line by applying phase space tomography to bunch shape data from a longitudinal pick-up. This allows many important longitudinal parameters - among them emittance and momentum distribution - to be deduced with unprecedented precision.

We discuss the problems associated with i) automating all these measurements, ii) the limits of the different systems and iii) how the results can be used for on-line beam quality monitoring.

1. INTRODUCTION

The PS Division is responsible for the operation of seven accelerators which deliver beams of protons, antiprotons, lead ions and electrons either directly to the users, or to the SPS for further acceleration. Four areas are fed with beam directly: the East Hall where there is an experiment (DIRAC) and numerous tests of experimental equipment, the ISOLDE facility, the new AD area and the LEA and SLF areas where tests of detector and vacuum components take place. During 2001, the Division took over responsibility for operating the ISOLDE facility. The breadth of the CERN physics programme requires that normally several of the different particle beams operate simultaneously, which requires pulse-to-pulse modulation of the machines and a complicated interweaving of different machine cycles in a supercycle. The accelerators operate for close to 6500 hours per year, which requires the reliable operation of all the component parts of all the machines for extended periods. In general the many different users have high requirements on beam quality, but with different emphasis on particular beam characteristics. In this paper the monitoring of the future LHC beam will be discussed. In particular, the issue of providing on-line beam quality data for the subsequent machine in the injector chain will be addressed.

2. ON-LINE BEAM MONITORING FOR THE PS USERS

At present a display showing the actual magnetic cycle in the PS, the ejected beam intensity and the beam destination is broadcast over a video network to experiments and subsequent machines (the Users). Measurements of transverse and longitudinal beam characteristics are done on a daily basis at all machines by the PS operation crew, by some experiments and at injection into the next machine in the chain. The PS operators correct for all irregularities and work on improving general aspects of the beam quality. Such general aspects can be a poor beam profile or a undesired beam halo. Irregularities observed by the Users which cannot be verified or understood by the operation crew are discussed in specially arranged meetings. Weekly meetings are also held to inform the Users about the machine programme and status, and the work in progress.

3. THE LHC BEAM

The emphasis at the PS division has historically been on high-intensity beams. Major investments have been made to increase the intensity over the years with impressive results. The LHC beam is of low intensity but high brightness. This translates into a small emittance beam with a high longitudinal and transverse particle density. To enable the control and observation of such a beam, a project was launched in 1993 to adapt the machine hardware, the longitudinal and transverse beam control, and the instrumentation of the PS machines forming part of the LHC injector chain.

4. MONITORING TRANSVERSE LHC BEAM CHARACTERISTICS

In order to verify that the beam emittance is not blown up by bad matching between machines, a new measurement system has been developed to monitor PS injection (since the Booster uses multiturn injection, matching is not as much of an issue there). This system is currently being installed and consists of two quadrupole pick-ups positioned in consecutive straight sections of the machine. A quadrupole pick-up is a non-intercepting device that measures, apart from the beam position, the quadrupole moment of the beam. The PS pick-ups [1] have been designed [1] so that κ can be measured on a turn-by-turn basis for each bunch separately (see Fig. 1).

$$\kappa = \sigma_x^2 - \sigma_y^2 = \varepsilon_x \beta_x - \varepsilon_y \beta_y + \sigma_p^2 D_x^2 \tag{1}$$

Any oscillatory part of κ as a function of machine turn is due to mismatch. If the lattice dispersion is non-zero (as in the PS case), beam size oscillations due to injection errors in β_x and D_x^2 develop differently as a function of turn. Consequently, it is possible to separate these two effects in the horizontal plane. The vertical dispersion mismatch cannot, however, be easily distinguished from a vertical betatron mismatch, but it is expected to be very small.

Since the ratio of β values (horizontal to vertical) are different at the the two pick-up locations, the system of equations given by Eq. (1) for the measured κ values can be solved for the emittances. This requires a knowledge of the β's, which may be oscillating due to mismatch. However, by using the values of β and κ averaged over many turns, the filamented emittance can be calculated. This is theoretically very straightforward, but has yet to be demonstrated experimentally. Since σ is the rms beam size, the result is the true rms emittance, independent of distribution.

The momentum spread, which is needed to quantify the dispersion part of the signals, is calculated from the cavity voltage and the bunch length. The latter can also be determined from the pick-up data. Thus, the measurement system is self-contained in the sense that it will not require any additional input of measured beam parameters by the user. Therefore, it can employ a very simple user interface, or even run continuously in the background as an emittance watchdog, alerting the operator when correction is needed. The application program for this system will be integrated with the ABS (Automatic Beam Steering and shaping) one developed for the PS Complex [2], allowing the simple correction of detected injection errors.

Since the quadrupole pick-up system was developed primarily with injection studies in mind, some of its components (hybrids and amplifiers) are bandwidth-limited to about 30 MHz. This means that it is not possible with the present configuration to make single-bunch measurements in the very last part of the cycle, when multiple splitting has significantly shortened the bunch length to fit the SPS requirements. An increase of the bandwidth is possible if required, but the emittance at PS ejection will anyway be monitored using the Optical Transition Radiation (OTR) screens [3] in the transfer line towards the SPS.

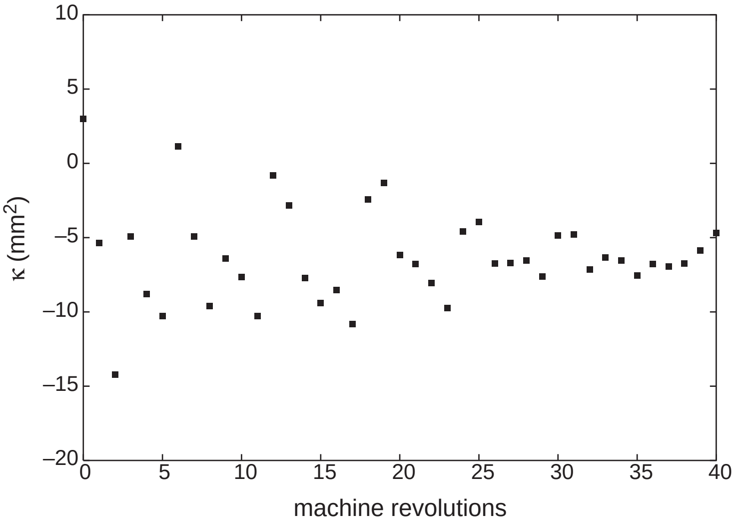

Fig. 1: Quadrupole moment of a proton bunch in the PS measured with a quadrupole pick-up over several machine turns.

Apart from the on-line monitoring of the injection using the quadrupole pick-ups, it is foreseen that the operators measure the emittances at different times in the cycle on a daily basis using the wire scanners [4]. This will provide a valuable cross-check of the on-line results, verify the beam profile that cannot be studied with the pick-ups, and provide day-by-day emittance statistics.

5. MONTORING OF LONGITUDINAL LHC BEAM CHARACTERISTICS

The main longitudinal beam characteristics can be determined from a measurement of the longitudinal bunch shape. The longitudinal pick-ups in the PS and the PS Booster can be read with a digitizing oscilloscope and the resulting image can be displayed for one entire turn. It is also possible to acquire turn-by-turn data with an oscilloscope triggered by a revolution train synchronous with the bunch, or bunches, in the accelerator. The software for the first system permits the operator to save reference images, which can be compared to the present image yielding information on the phase and bunch shape. This is particularly important for the LHC beam where there is a second bunch-to-bucket transfer which must be synchronised at the energy of the first batch waiting in the PS. The on-line software for the turn-by-turn system includes a tomographic reconstruction algorithm [5] which permits the measurement of longitudinal phase space density (see Fig. 2). Additional input of some machine parameters, e.g. the RF voltage and the magnetic field, is necessary for the reconstruction. The longitudinal rms emittance together with the momentum distribution can easily be deduced from the resulting tomograms. Our tomography algorithm has proved extremely robust for errors in the input data [6]. An example of the on-line display is shown in Fig. 3 where the Booster beam was captured at the wrong frequency.

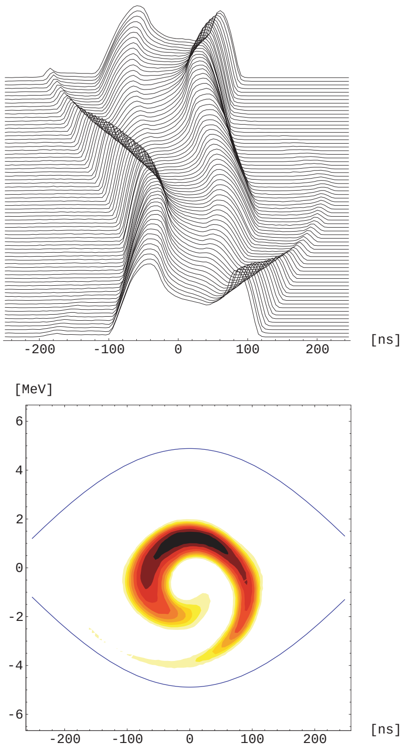

Fig. 2: A tomographic reconstruction of an unusual bunch distribution. Without tomography it would not be trivial to visualize the longitudinal phase space distribution from the turn-by-turn data.

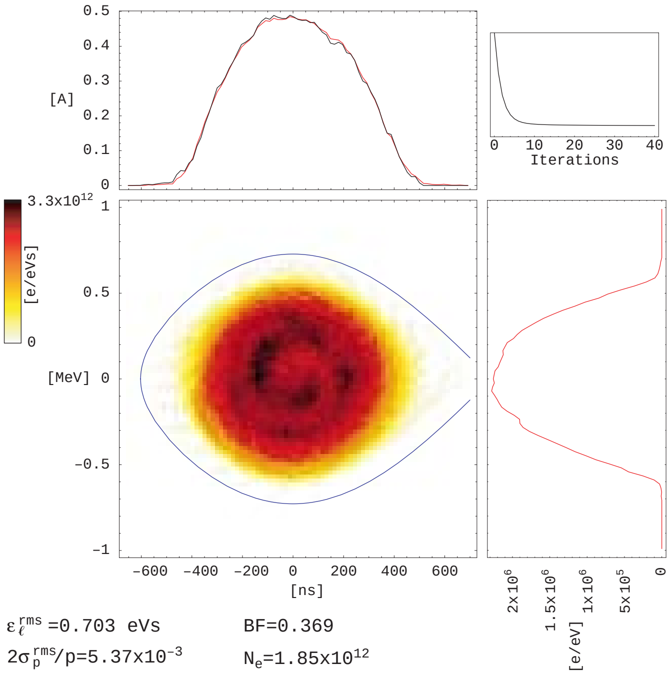

Fig. 3: A small error in the RF capture frequency at injection caused this phase space distribution. From the profile data alone it would not be possible to diagnose this fault.

6. CONCLUSIONS

The LHC beam is more sensitive to a deterioration of the beam quality than the present beams. The new instrumentation developed for this beam will, as we have shown, yield reliable on-line data for the beam characteristics. This can be used for on-line alerts (and correction) but it can also be directly broadcast to the subsequent machine. This would enable the crew at that machine to monitor and even store the initial beam conditions and relate that to observed abnormalities in their accelerator. This would require a different form of broadcast compared to today, which will need a common control structure (under study). It would also differ from the present situation due to the type of data that is being monitored and broadcast e.g. longitudinal and transverse beam emittance, beam shape and longitudinal phase shift (compared to a given reference). Maybe the most important difference is that, with this new type of monitoring, the operator of the subsequent machine would not have to rely on a manual intervention to have important beam characteristic data at hand.

Longitudinal tomography not only yields emittance data, but it could also serve as a powerful visual aid to see small longitudinal beam perturbations. The present style of video screens with a summary of the most important machine data will probably continue to be broadcast over the existing, or an improved, video network. The tomograms are visually attractive and would form a natural focus on such a screen. The present progress in computing power should permit us to compute on-line tomograms for every machine cycle at the LHC start-up in 2006.

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