CERN PS HIGH BRIGHTNESS OPERATION FOR LHC

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The paper is a short description, for non specialists, of some of the main machine physics issues concerning the production and the conservation of high brightness beams in the pre-injector chain of the LHC machine.

1 Introduction

1.1 The PS Complex

The PS Complex is an ensemble of many machines, see Fig.1. Three of these will be used as pre-injectors for the LHC: the 50 MeV LINAC2, the 1 GeV PS Booster (PSB) and the 26GeV/c PS. Note that the modifications to obtain the required LHC proton beam will be completed already before the year 2000 in order to study and prepare the SPS beam. This conversion will not jeopardise the present machine operations and performance.
1.2 The LHC filling scheme

The LHC filling scheme is shown on Fig. 2. On three consecutive 3.6 s long cycles at 26 GeV/c the PS will transfer to the SPS a beam of 80 bunches. Each bunch will have an intensity of $N_b = 10^{11}$ p/bunch (nominal beam) and a r.m.s. normalized transverse emittance $\varepsilon_x \equiv \varepsilon_y \equiv 3.5 \mu$m. The SPS will accelerate and extract the beam at 450 GeV/c to the LHC. The operation will be repeated 12 times per LHC ring.

![Figure 2: The LHC filling scheme](image)

1.3 The LHC requirements

The LHC luminosity can be determined from the following expression:

$$L = \frac{N_b \cdot N_b \cdot k_b \cdot f \cdot \gamma \cdot F}{\varepsilon_{x,y}^2} \cdot \frac{\beta^*}{4\pi}$$  \hspace{1cm} (1)

where:

- $k_b$ is the number of bunches
\( f_0 \) is the revolution frequency

\( \gamma \) is the usual relativistic factor

\( F \) is the crossing angle reduction factor (~0.9)

\( \beta^* \) is the betatron function at the interaction point

The nominal design value of LHC luminosity is \( L = 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \), while the ‘ultimate’ or so-called beam-beam limit corresponds to \( L = 2.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) (obtained with a beam of the same emittance but with higher intensity: \( N_b = 1.7 \times 10^{11} \text{ p/b} \)). All the following considerations will refer to this ultimate performance.

Note that the luminosity is directly proportional to the term \( \frac{N}{\varepsilon_{x,y}} \), the so-called beam brightness or more precisely the normalized transverse phase space density. For the ultimate LHC luminosity, the beam brightness to be achieved by the injectors has to be more than doubled when compared to the present best performance.

This paper is a succinct description of the methods and modifications adopted in the present machines in order to attain and preserve such a high beam brightness.

2 Beam issues

2.1 Space charge

Space charge effects are one of the first obstacles to obtain high density beams. The space charge defocusing forces have multiple contributions (e.g. coherent, incoherent, image fields, etc.) but for the machines we are considering, the so-called self field incoherent tune spread \( \Delta Q_{x,y} \) is dominant. The particles are defocused differently depending on their position inside the bunch, therefore their betatron oscillations will have different frequencies. Considering, for simplicity, a round Gaussian beam and only the vertical plane (results in the horizontal plane are similar), \( \Delta Q_y \) is given by the following expression:
\[ \Delta Q_y \equiv -\frac{3r_p}{4c} \frac{R}{\tau_p (\beta \gamma)^2} \frac{N_p}{\varepsilon_y} \]  

(2)

where:

- \( r_p \) is the classical proton radius
- \( R \) is the machine radius
- \( c \) is the speed of light
- \( \tau_p \) is the total duration of a parabolic bunch
- \( \beta \) and \( \gamma \) are the usual relativistic parameters

Note the direct proportionality of the tune spread with the beam brightness.

The larger the tune spread the more betatron resonances are overlapped by the beam, yielding, after some time, an emittance blow-up and eventually beam losses. The tolerable tune spread depends on the distance of the machine working point from dangerous resonances and how long the beam remains in these conditions. As an estimate, if this time is counted in milliseconds, seconds or minutes, \( |\Delta Q| \) should be less than 0.5, 0.2 or 0.01 respectively. Note that futuristic machines, e.g. for nuclear fusion, have been designed with \( \Delta Q \) of several units since their beam remains in these conditions only during few microseconds.

The PSB is injecting protons at 50 MeV and is staying close to this energy for about 10 ms, consequently it can hardly accept a \( |\Delta Q| \) larger than \( \sim 0.5 \). In other words if the beam has the right LHC emittance (say \( \varepsilon_{x,y}^* \sim 2.5 \mu \text{m} \)) it can have only half of the desired intensity. Note that an H injection would suffer the same limitation. To overcome this missing factor the proposed solution is to inject in two batches into the PS machine.

The total circumference of the 4 PSB rings is equal to the PS circumference. In order to squeeze the PSB beam into one half of the PS ring the PSB RF harmonic number has to be changed from the present \( h=5 \) to \( h=1 \). Finally, eight (4+4) bunches are injected into the PS machine.

The first batch of 4 bunches has to circulate in the PS at the injection energy of 1 GeV during 1.2 s, awaiting for the second batch. The space charge tune spread is \( |\Delta Q| \sim 0.4 \), enough to induce a too large emittance blow-up of \( \sim 30\% \). The remedy is to increase the PSB energy to 1.4 GeV, in that case the tune spread decreases to less than 0.3 and experiments have proved that no emittance blow-up takes place when the working point is carefully chosen.
2.2 Brightness conservation

Once the beam with the right brightness has been obtained the subsequent problem is how this brightness can be conserved.

In transferring the beam from one machine to the following one, matching and injection errors can be very harmful particularly if the beam emittance is small. An injection error $\Delta x$ produces an emittance increase of $\varepsilon_x = \frac{\Delta x^2}{2\beta_x^\gamma}$ independent of the beam emittance, i.e. the consequences are proportionally larger the smaller is the emittance.

For instance, an error at the PS injection of $\Delta x \sim 2$mm will increase the emittance by $\sim10\%$ i.e. half of the total emittance blow-up budget allowed to this machine. Having minimised and corrected all systematic errors, the pulse to pulse variations must be eventually cured by transverse dampers.

Moreover, transverse instabilities of many kinds are also good candidates as brightness destroyers. An illustration is the head-tail horizontal instability observed in the PS at low energy7, see Fig.3.

![Figure 3: Evidence of a horizontal head tail instability in the PS at 1GeV. The signal coming from a radial pick-up is observed on ~15 consecutive turns. The 5 nodes are the signature of a $m=5$ mode of oscillation (Sacherer-Zotter theory). Time base: 20 ns/d.](image)

Figure 3: Evidence of a horizontal head tail instability in the PS at 1GeV. The signal coming from a radial pick-up is observed on ~15 consecutive turns. The 5 nodes are the signature of a $m=5$ mode of oscillation (Sacherer-Zotter theory). Time base: 20 ns/d.
Transverse feedbacks are typically employed to cure such instabilities, however octupoles can also be used to stabilise the beam by increasing Landau damping, as shown on Fig. 4.

Figure 4a: Some PS signals showing, during the first part of the acceleration, some consequences of octupoles on the beam transverse instabilities. Here the octupoles are OFF. S1: is the beam intensity. Note the ~20% loss due to the transverse instabilities at ~50 ms after injection. S2: is the current in the octupoles (now OFF). S3: is a signal proportional to the bunch peak current (bunch height). S4: is the main magnetic field. Time base = 50 ms/d.

Figure 4b: Same as before but now the octupoles are ON, providing a Landau damping which stabilises the beam. The losses are practically disappeared.

Mismatch conditions can occur as well at extraction. The PS beam during the transfer to the SPS and in the very first part of its trajectory, is traversing a region of non-linear stray fields from the nearby PS main bending magnet, see Fig.5. Preliminary measurements seem to indicate strong mismatch conditions for the particles having large momenta (\(dp/p \approx \pm 2 \times 10^{-3}\)). These effects could generate an emittance blow-up of ~30% for the beam entering in the SPS machine. Possible solutions to this problem are at present still under study.
In the longitudinal plane, emittance conservation is also a challenge\textsuperscript{9}. The eight 200 ns long bunches coming from the PSB are adiabatically split into 16 already at low energy. After being accelerated to 26 GeV/c, an adiabatic debunching-rebunching gymnastic transforms the 16 bunches into 84 using a new 40 MHz cavity. Finally, just before extraction, a non adiabatic bunch rotation, employing two new 80 MHz cavities, squeezes the bunches even more to a minimum length of 3.8 ns to be captured by the 200 MHz SPS RF system. A very stable beam is required to make these gymnastics totally reproducible. This is achieved by a controlled longitudinal blow-up applied to the beam, already at low energy, to increase Landau damping. Such a longitudinal blow-up can also be profitable for reducing the space charge tune spread by diluting the particle density in the bunch core. See Fig. 6.
Figure 6a: Some PS signals showing, during the first part of the acceleration, the consequences of a controlled longitudinal blow-up on the beam longitudinal instabilities. Here the blow-up is OFF. S1: is the beam intensity. Note the ~10% loss due to longitudinal instabilities ~50 ms after injection. S2: is the current in the 200 MHz cavity used for the controlled longitudinal blow-up (now OFF). S3: is a signal proportional to the bunch peak current (= bunch height). The ‘grass’ on the signal is the signature of longitudinal instabilities (quadrupole at al.). S4: is the main magnetic field. Time base = 50 ms/d.

Figure 6b: Same as before, but now the controlled longitudinal blow-up is ON. The signal S3 is ‘clean’, no longitudinal instabilities are observed and also no losses.
Figure 6c: PS bunch shape measurement at a given time during the acceleration. The controlled longitudinal blow-up is OFF. The irregular contour is the actual bunch measurement while the regular profile is a Gaussian fitting of the bunch measurement. The bunch is very unstable. Time scale: 10 ns/d

Figure 6d: Same as before, but now the controlled longitudinal blow-up is ON. The bunch is slightly longer (larger longitudinal emittance) but very stable. Time scale: 10 ns/d

3 Conclusion

Beam brightness conservation is one of the major problems and a constant concern in the design and operation of high energy hadron colliders. We have listed here only some of the main causes of brightness deterioration, many other secondary effects exist and their integrated action can be very harmful. They are in fact difficult to correct. The problem can only be solved by a meticulous and rigorous tracking of all possible sources of emittance blow-up. The remedies are not always obvious nor trivial, but they are mandatory to obtain a high performance. A very powerful beam
instrumentation is an absolute necessity, not only a desire. After all we can try to improve only what we can measure.

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References

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