PERFORMANCE OF NOMINAL AND ULTIMATE LHC BEAMS IN THE CERN PS-BOOSTER

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Abstract

The requirements for nominal and ultimate LHC beams in the CERN PS-Booster were specified in 1994 and served as input for the definition of the “PS conversion for LHC” project. Already during the upgrade project and also after its completion in 2000, the beam intensities to be provided from the PS Booster were increased in order to compensate for changes on the LHC machine, the beam production scheme in the PS and for non-anticipated beam losses along the injector chain. In order to improve the beam brightness, to be compatible with the increased requirements, extensive machine studies have taken place on the PS-Booster. The working point was changed to reduce the influence of systematic resonances and the injection line optics was re-matched to improve the injection efficiency.

The paper summarizes briefly the evolution of the performance requirements. The various measures undertaken to improve the LHC beam quality are outlined and the present performance achieved in the PS Booster is presented.

INTRODUCTION

Over the last decade, the proton injector chain for the LHC was upgraded to be able to provide the beams required by the collider. This upgrade was mainly performed in the framework of the “PS for LHC” and “SPS for LHC” projects [1, 2] and based on requirements defined in 1994 for “nominal” and “ultimate” 25 ns LHC beams [3]. These requirements are outdated, since several LHC design parameters were modified in the meantime [4] and also the bunch train production scheme in the PS had to be changed [5]. In addition, the initial intensity requirements assumed zero beam losses or 100% efficiency from capture in the PS-Booster (PSB) throughout the complete injector chain (and also the LHC), which turned out to be too optimistic. To compensate for beam losses and design changes, the injectors have to provide accordingly more intensity (within the same transverse emittances) so as to keep the LHC luminosity at the desired level.

EVOLUTION OF REQUIREMENTS

The different ingredients that have lead to an increased demand on beam brightness from the injectors were on the LHC side:

- Crossing angle change from 200 to 285 μrad (1995): intensity increase by a factor 1.1.
- β* change from 0.5 to 0.55 m (2003): intensity increase by 1.05.

On the PS side:

- Change from debunching-rebunching to multiple splitting scheme (2000): intensity increase by 1.14, only relevant for PSB and PS.

It is important to note that compensation of crossing angle and β* changes is only required for the nominal beam and not for the ultimate, where the intensity is fixed by the LHC beam-beam limit. The factor 1.14 in the PSB is required for both beam variants to compensate for the scheme change in the PS.

Transmission efficiencies along the injectors

In addition to the factors mentioned above, even more intensity is needed to compensate for beam losses along the injector chain. Extensive beam tests with nominal intensity during the last years have permitted a detailed beam loss inventory to be established. Table 1 quotes the transmission efficiencies along the injector chain for the nominal 25 ns beam and gives an extrapolation for the ultimate beam, based on first beam tests approaching ultimate intensities*.

Table 1: Transmission efficiencies along the injector chain for the nominal 25 ns beam (measured) and ultimate 25 ns beam (extrapolated).

Machine/process	Nominal beam	Ultimate beam
PSB after capture to PS transition	0.96	0.95
PS transition to 25 GeV	1.0	0.97
PS before extraction to TT2/TT10	1.0	1.0
TT10 to SPS including injection	1.0	1.0
SPS after injection to 450 GeV	0.9	0.85
Total transmission efficiency PSB capture to SPS 450 GeV	**~ 0.85**	**~ 0.80**

A few percent of losses appear during transfer of the beam from PSB to PS, at start of acceleration in the PS and during PS transition crossing. All together these can be kept around 5% by constant optimisation of PSB recombination line trajectories, energy matching and phase synchronisation between the two machines, flat bottom and low energy working point settings of the PS, bunch triple splitting in the PS and transition crossing settings. For intensities higher than nominal, some more losses are observed in the PS during transition crossing. The major part of the beam losses (up to 10% for nominal and up to 15% for ultimate intensity) appears at start of acceleration in the SPS; efforts were made to understand the mechanism leading to these capture losses and to hopefully reduce them [6].

* For 25 ns beams with intensities above nominal, the transverse emittances increase with intensity and are outside the LHC emittance budget.

As a consequence of the beam losses, the ultimate 25 ns beam which is the most demanding in terms of brightness N_b/ε_n (where N_b is the number of protons per bunch and ε_n the transverse normalised emittance), could no longer be produced by the PSB due to space charge limitations at injection. The nominal 25 ns beam was produced within specifications, i.e. with normalised transverse rms emittances below 2.5 µm for $(\varepsilon_h\&\varepsilon_v)/2$, but there is no longer a comfortable emittance margin, rendering operation more critical. Table 2 summarises the present requirements.

Table 2: PSB and LHC bunch intensities for nominal and ultimate beams in 1994 and 2003.

25 ns LHC beams	1994	2003	Intensity increase
LHC nominal bunch	1.00×10^{11}	1.15×10^{11}	1.10·1.05 = **1.15**
PSB nominal bunch	10.50×10^{11}	16.29×10^{11}	1.10·1.05·1.14/0.85 = **1.55**
LHC ultimate bunch	1.70×10^{11}	1.70×10^{11}	**1.00**
PSB ultimate bunch	17.85×10^{11}	25.50×10^{11}	1.14/0.80 = **1.42**

RECENT DEVELOPMENTS

As a reaction to the increased LHC requirements, efforts were undertaken in the PSB to better understand existing limitations and to possibly improve the brightness of LHC type beams.

New working point studies

Since the 1980's the operational working point of the PSB was set to $(Q_h, Q_v) = (4.17, 5.23)$. A dynamic variation of the tune during injection and at the beginning of the ramp was used to deal with the large space charge incoherent (>0.5) and coherent (~0.15) tune shifts. At the beginning of acceleration the single-particle vertical tune was set to $Q_v = 5.6$ and, thanks to a good and easier than expected compensation of the resonance $2 \cdot Q_v = 11$, at least the inner rings were able to accelerate more than 1×10^{13} particles, resulting in a total number of more than 4×10^{13} protons accelerated with the 4 PSB rings. This performance was achieved even though the beam "sits" over many low-order resonances, since the incoherent tune spread is about 0.5. The systematic resonance $3 \cdot Q_v = 16$ was the most difficult to compensate and caused some beam losses, mainly in the outer rings. Surprisingly, the small-emittance and high-brightness LHC beam was produced without too many difficulties.

Despite the fact that the high working point was assumed to be the best compromise with the existing hardware [7], efforts were invested to test a lower vertical working point $(Q_h, Q_v) = (4.17, 4.23)$ that was supposed to be less efficient in terms of space charge but avoids crossing the systematic vertical third-integer resonance. Already after a few hours of adjustment, similar performances as with the high working point were obtained.

The LHC nominal beam was produced with slightly larger emittances, especially in the vertical plane, but still within the 1994 specifications [3]. For high intensity beams, the rings 1, 2 and 4 showed quite similar performances, all exceeding 1×10^{13} protons accelerated. Ring 3 is however suffering from an unknown problem, limiting its performance to less than 8.5×10^{12} protons. Some of the higher-order resonances were measured for the two working points [8]. Their strengths were found to be typically 2 to 5 times smaller for the low working point, explaining the improved performances for the outer rings. The larger vertical emittances found for the LHC beam can be well explained by the more important effect of space charge and probably also by the integer resonances, where the low amplitudes particles "sit" during the early acceleration phase.

Improved injection line optics

The transfer line from the CERN proton linac to the PSB comprises two horizontal bending dipoles which introduce horizontal dispersion. In order to minimize the injection mismatch and to improve the injection efficiency into the PSB, simulations of the injection line have been performed using the code TRACE 3-D [9]. This code takes into account space-charge and allows for simultaneous dispersion and Twiss parameter matching. The TRACE 3-D model was used to match both D and D' to zero at the exit of the second bending magnet in the line resulting in an overall achromatic optics. With both D and D' nullified at the exit of this dipole, the dispersion function is zero all along the rest of the line. The quadrupoles downstream the second bending magnet were then used to re-match the Twiss parameters at Booster injection without perturbing the dispersion matching. A solution for a dispersion-free, achromatic optics could be found from simulations, but implementation was only possible after tedious debugging of the transfer line hardware. The measurement of the dispersion was done by varying the beam momentum and measuring the displacement of the beam center at the pick-ups along the transfer line.

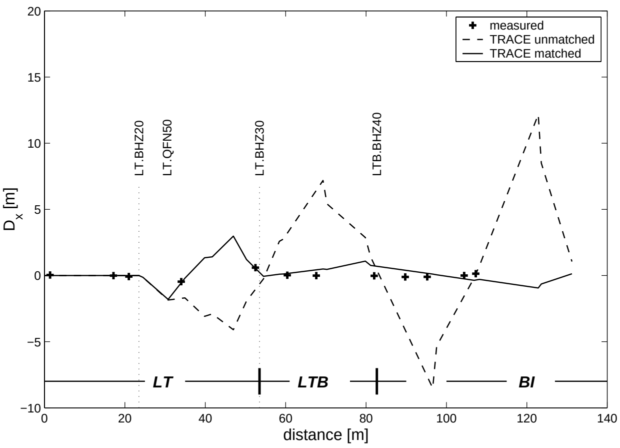

Figure 1: Horizontal dispersion along the PSB injection line for unmatched and matched optics.

Figure 1 shows the simulated and measured dispersion along the beam line for the old optics as well as for the new, matched optics [10, 11].

Putting into service the matched optics improved significantly the injection efficiency into the PSB. For high-intensity beams, the injection efficiency went up from about 60% in the past to values around 75%, for low-intensity beams, with fewer turns injected, from about 40% to values around 50%. The improved injection efficiency was found to be also beneficial for high-brightness LHC-type beams, where a given intensity can now be injected using fewer turns and hence occupying a smaller transverse phase space area [10,11].

RESULTS FROM BEAM TESTS

During 2005 and 2006 several measurements series were made to quantify the effect of working point and injection line changes on the LHC beam performance. Table 3 quotes normalised transverse rms emittances as a function of beam intensity. The last column indicates the values that were obtained during routine operation in 2000, before the changes [12].

Table 3: Transverse normalised rms emittances $(\varepsilon_h \& \varepsilon_v)/2$ as function of bunch intensity for LHC beams in the PSB.

	1.5×10¹²	**2.0×10¹²**	**2.5×10¹²**	***1.4×10¹²***
R 1	2.0	2.6	3.5	-
R 2	1.9	2.9	3.7	*2.0*
R 3	2.3	3.5	4.1	*1.9*
R 4	1.9	2.9	3.9	*2.2*

Figure 2 shows the corresponding measurements for the single PSB rings and also the average of horizontal and vertical emittances. The target value of 2.5 μm is also indicated.

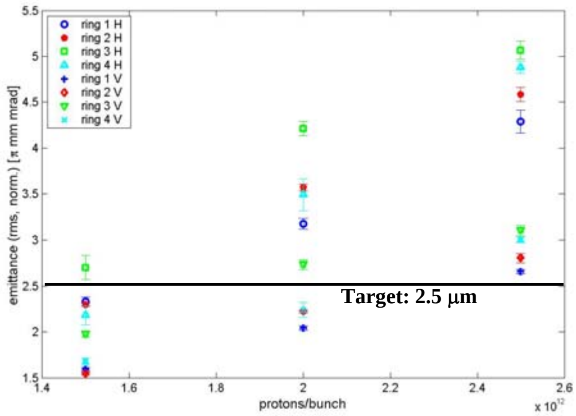

Figure 2: Transverse normalised rms emittances as function of bunch intensity for LHC beams in the PSB.

As can be seen, the transverse emittances for the new nominal LHC bunch intensity in the PSB (1.7×10^{12}) are just met whereas the new ultimate bunch intensity (2.6×10^{12}) is still far out of reach.

CONCLUSIONS

The intensity requirements for nominal and ultimate LHC beams in the PSB have increased over the last years due to various changes on the LHC and the injector complex. In order to improve the PSB performance the working point and the injection line optics have been changed. The new injection line optics has clearly a beneficial effect on the beam brightness which is less evident for the working point. Even though there is some overall improvement compared to the initial situation, the ultimate LHC beam is still far out of reach. As a next step it is planned to perform measurements with the new injection line optics and the old working point to clearly separate both effects.

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