HIGH INTENSITY BEAMS FROM THE CERN PS BOOSTER

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Abstract

The CERN Proton Synchrotron Booster (PSB) has been running for more than 30 years. Originally designed to accelerate particles from 50 to 800 MeV, later upgraded to an energy of 1 GeV and finally 1.4 GeV, it is steadily being pushed to its operational limits. One challenge is the permanent demand for intensity increase, in particular for CNGS and ISOLDE, but also in view of Linac4. As it is an accelerator working with very high space charge during the low energy part of its cycle, its operational conditions have to be precisely tuned. Amongst other things resonances must be avoided, stop band crossings optimised and the machine impedance minimised.

Recently, an operational intensity record was achieved with >4.25×10^{13} protons accelerated. An orbit correction campaign performed during the 2007/2008 shutdown was a major contributing factor to achieving this intensity. As the PSB presently has very few orbit correctors available, the orbit correction has to be achieved by displacing and/or tilting some of the defocusing quadrupoles common to all 4 PSB rings.

The contributing factors used to optimise performance will be reviewed.

INTRODUCTION

Four superimposed rings constitute the PSB, a unique design aiming at a reduction of space charge effects in particular during the low-energy part of the cycle. The PSB is served with protons at 50 MeV from Linac2 that are distributed into the four PSB rings. To optimise the capture efficiency for high intensity beams, an h=1 and h=2 component are added to yield the highest possible bunching factor (more than 0.5; see Fig. 1).

INTENSITY LIMITATIONS

There exists a long list of potential intensity limitations, but we focus here on a selection of those.

The main characteristics of a low-energy accelerator like the PSB is the large incoherent tune shift due to space charge. The injection energy of Linac2 being 50 MeV, the working point has to be optimised along the acceleration cycle. In Fig. 2 the dynamic tune diagram for a typical high intensity user is shown. At injection, the tune for the horizontal and vertical plane is roughly set to Q_h=4.27 and Q_v=4.65, evolving to a tune of Q_h=4.17 and Q_v=4.20 before extraction. The tune change in the vertical plane is therefore close to -0.5. To avoid large beam losses it is necessary to carefully compensate for the unavoidable resonance crossings (of particles and beam ensemble).

Injection into the PSB is performed on a magnetic field ramp to quickly leave the space charge dominated region.

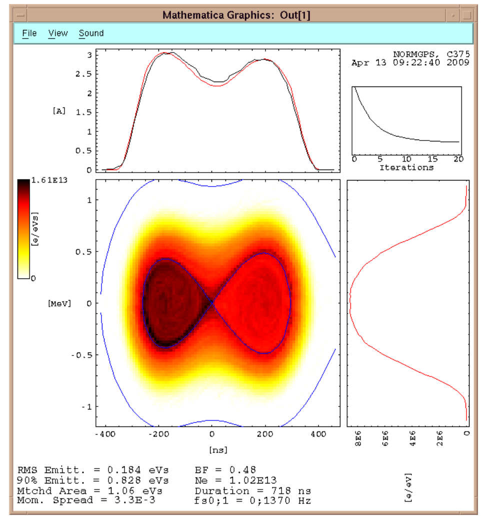

Figure 1: Tomographic reconstruction of the longitudinal phase space of an ISOLDE beam 100 ms after injection; a bunching factor BF close to 0.5 is achieved combining h=1 and h=2 systems.

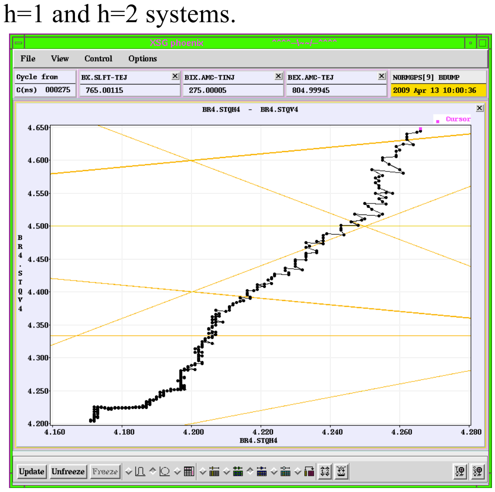

Figure 2: Dynamic tune diagram of ring 4 along the cycle.

Space Charge

To limit space charge effects, the multi-turn injection is carefully adjusted to minimise losses during capture. This is done by painting the horizontal phase space through off-centred injection and by adding some linear coupling to decrease the vertical central density. During the bunching process the longitudinal density is kept as small as possible, compatible with a good capture (lower possible voltage, double harmonic system, adjustments of frequencies and radio-frequency loops). The tune is programmed to leave a maximum of free space in the tune diagram to accommodate particles with large tune shifts.

A measurement was done to evaluate the incoherent tune shifts for large and small beam densities. To achieve small beam densities, a sieve was inserted in the injection line yielding a density reduction by a factor of 5 to 6. The number of injected turns was varied from 1 to 13 while all the other injection parameters were kept constant. The transverse emittances were recorded and the maximum tune shift computed with the Laslett formulae for the two cases [1]. Subtracting these tune shifts from the programmed tune yields the tunes for the small-amplitude particle (0,0) of Fig. 3 that is most affected by space charge. Finally, when extrapolating the 'zero-amplitude' tune for the low-density case to higher number of particles (taking the tune shifts with sieve and the number of particles without sieve), it can be seen that the tune for the small-amplitude particles will be lower than the two systematic resonances Q_h=Q_v=4 and the space charge coupling resonance $2(Q_h-Q_v)=0$. This indicates that the linear coupling resonance and possibly the integer resonances are responsible for the vertical emittance increase we observe with increasing particle densities (~a factor of 2 for 13 turns injected) [1].

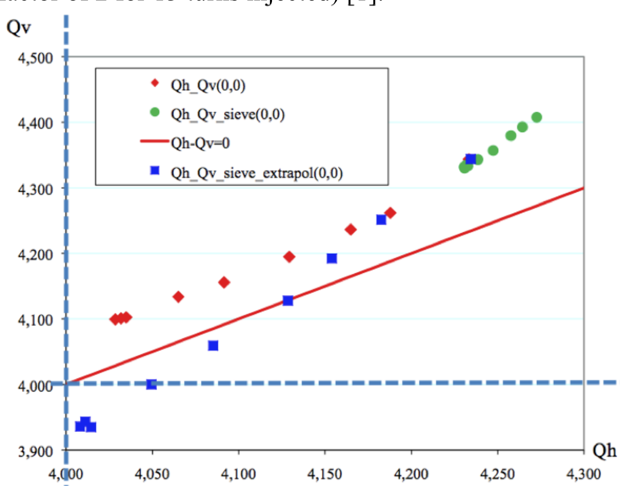

Figure 3: Tunes for particles having only small amplitude oscillations at the start of acceleration. Lozenges: without sieve; circles: with sieve; squares: extrapolated tunes using the number of particles without sieve and the emittances obtained with sieve. The solid line represents the linear coupling resonance $Q_h–Q_v=0$, the dotted lines the integer resonances.

Systematic Resonances

For many years, the PSB working point had been set to around (Q_h, Q_v)=(4.2, 5.4). The tune diagram area the particles covered during the first part of acceleration due to tune spreads and shifts was full of resonances. Amongst these, one resonance ($3Q_v$=16) was systematic. This led to different performances of the four rings by more than 20% despite a good compensation of these resonances. It was decided to change to an area on the tune diagram where no systematic resonances were present (Q_h, Q_v)=(4.2, 4.4). This proved beneficial as the performance of each of the rings converged, therefore this new working point was adopted for operation. No systematic resonances remained except for the integer resonance at the edge (systematic 3rd order due to space charge) and the Montague resonance $2(Q_h-Q_v)=0$. Figure 3 shows that these resonances are the limiting factor as the tune obtained after losses and/or evolution of the beam distribution is forced to the corner of all the systematic resonances.

Measurements made at 160 MeV (the future injection energy with Linac4) show that there is space to accommodate within this tune area 1.6 times the number of particles actually accelerated at this energy with the same emittances. The ultimate LHC beam will require 1.5 times the intensity within the same beam parameters as the nominal LHC beam.

Matching, Machine Acceptance and Alignment

In 2005 new optics for the Linac2 to PSB transfer line were put in operation. Improved matching resulted in a substantial increase in injection efficiency of ~15% [2].

Another intensity limitation is given by the machine acceptance. In the PSB the main aperture restriction is the beamscope window yielding an acceptance of 337/130 π mm mrad for the horizontal/vertical plane. The horizontal acceptance needed is in practice even smaller (~274 π mm mrad at injection) due to the acceptance of ~40 π mm mrad of the extraction line.

In the PSB there are very few orbit correctors operational, therefore an orbit correction has to be performed by displacing the main quadrupoles. This displacement in both planes affects all 4 PSB rings (it is also a mean correction as the tune is varying along the cycle) as the quadrupoles are fixed in a stack, individual ring corrections can only be achieved through appropriate tilt and displacement of the magnets. The last orbit correction dates back to 1996; since then the vertical tune of the machine has been lowered and the orbits have in general degraded over the years. In addition, each ring exhibited a different orbit leading to (more than usual) individual tunings for each ring.

Table 1: Peak-to-peak orbits before (O) and after (fO) correction for both planes, measured for different tunes at 3 periods (c-timing) in the cycle (just after injection, after capture and before extraction).

c [ms]	E_{kin} [MeV]	Tune h/v	O_h/fO_h [mm]	O_v/fO_v [mm]
301	63	4.08/4.13	17.2/11.2	21.2/7.3
		4.17/4.23	10.4/7.6	13.4/4.8
		4.21/4.30	9.4/7.1	11.0/4.1
		4.28/4.58	8.6/6.7	9.2/4.9
500	403	4.17/4.23	12.2/6.3	15.0/6.2
790	1377	4.17/4.23	13.6/6.5	14.6/7.2

Orbit measurements were thus performed at the end of 2007 and magnets displaced during the shutdown. The original peak-to-peak orbit values and the data after orbit correction in 2008 are presented in Table 1. In addition to an average orbit improvement by 59% in horizontal and 145% in vertical, all rings display since similar orbits (for details see [3]).

A direct effect of this orbit correction was a new PSB intensity record in 2008; an intensity of >1000×10^{10} protons per ring (>4200×10^{10} in total) could be extracted (see Fig. 4).

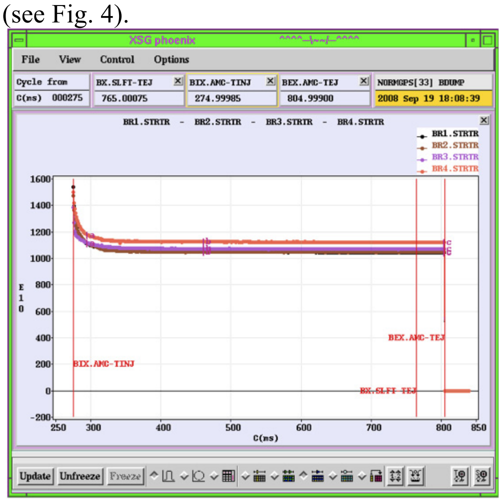

Figure 4: 2008 intensity record where almost 4300×10^{10} protons were extracted for an ISOLDE beam and 13 injected turns.

Impedance

Studies were conducted during the 2008 operation with the aim of understanding losses observed at two well-defined locations in the cycle (103 and 203 ms after injection) in the case where the transverse damper is switched off. These horizontal instabilities show similarities to head-tail modes. The observed rise-time and the fixed location of these instabilities suggest that they are excited by a peaked narrow-band impedance. The detailed analysis of the excitation frequency points to the extraction kickers as source of these instabilities [4].

In addition, the coherent tune shift as a function of intensity has been measured for three different energies. In the horizontal plane, no clear trend is visible contrary to the vertical plane. These measured vertical tune shifts cannot be explained by space charge alone. The total coherent tune shift can be written as

$$\Delta Q = \Delta Q_{SC} + \Delta Q_{RW} + \Delta Q_{BB}$$

where the three contributions are due to space charge, resistive wall (RW) and broad band (BB) impedances. Values for the individual impedance contributions were calculated [4], and it was found that the RW contribution is negligible and that the PSB has a low-frequency BB impedance in the order of a few MΩ/m.

Other Effects

In order to determine the difference in the oscillation damping time of a high- or low-density beam injected with an offset, only a fraction of a turn was set and the sum and difference signal of a pickup observed. Normally, with the high chromaticity present (Qξ~-5), the amplitude of the trace at injection would decrease by simple filamentation in phase space with a time constant of about 100 turns. However it was observed (Fig. 5) that with higher space charge the decrease is much slower (about 500 turns). This means that space charge effects keep the beam as a rigid body without filamentation. This is probably one of the reasons that the nominal LHC beam is not too difficult to realise (brilliance $N/\varepsilon_{norm.}$=0.65×10^{12} p/μm) with only 3 turns injected.

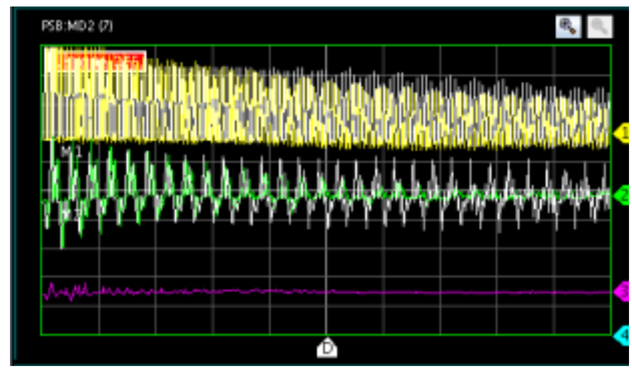

Figure 5: 0.7 turns injected with an oscillation of ~25 mm peak-to-peak. Top: sum signal; below: difference signal. The stored larger amplitude signal is for a beam without sieve; the superimposed smaller amplitude signals are measurements for a beam with sieve (~5 times less dense; vertical scale of scope was changed). Note the significant difference in signal damping.

CONCLUSIONS

During the last years a number of actions have been undertaken to allow the PSB to deliver beams with steadily increasing intensity and brilliance. Space charge forces dominate the injection process and resonance compensation is essential during operation. The vertical working point has been changed to avoid a systematic resonance, a machine alignment was performed and impedance contributions were evaluated. All these actions led to the intensity record achieved in 2008.

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