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SPACE CHARGE MEASUREMENTS AT THE PSB

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Abstract

The PS Booster (PSB) is an accelerator working under very high space charge during the first part of its cycle. After the change of tune, it was necessary to revisit the space charge effects to try to understand and possibly improve the situation. In addition, the Linac2 will be replaced by the Linac4 providing an H^- injection in the PSB at 160 MeV. This energy is chosen to reduce by a factor 2 the space charge effect with the same beam characteristics. It was then needed to make some measurements at this energy, not only to find the limits but also to benchmark some simulation with available programs [1].

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THE PSB, INJECTION AND ACCELERATION

The PS Booster [2] is composed of four superposed rings. The lattice is a sequence of sixteen periods BFoDoFoB. The PSB is feed with protons by the LINAC2 at 50 MeV through a classical multi-turn injection (thin magnetic septum and decreasing local bump). A maximum of 13 turns are injected from the 160 mA proton beam leading to more then 1.4 10^{13} protons circulating into the PSB (injection efficiency~70%). During the injection the magnetic field is already varying at a rate of 0.5 T/s. Then the beam is immediately bunched with a two harmonic system [3] (h=1+h=2) providing the best possible bunching factor (Bf~0.5) to decrease the space charge effects (see Tomoscope [4] on figure 1). The beam is finally accelerated to 1400 MeV in 530ms. During the first 30-40 ms, part of the beam is lost due to large Laslett tune shift (ΔQ_0~-0.5), tune spread and coherent tune shift (ΔQc~-0.15). To compensate for these shifts, the tune is set to (Qh=4.28, Qv=4.60) during the injection process (figure 2) and restored back to the operational tune (Qh=4.17, Qv=4.23) in about 150 ms. It allows most of the particles to stay within an area of the tune diagram free of dangerous resonances (integer, coupling or excited by space charge). To limit the losses, all the resonances which could affect the particles movement are compensated at the best, even the second order, 2 Qv=9. Nevertheless, about 25% of the particles injected are lost during the first part of acceleration. The performances obtained so far are indicated in table 1 and figure 3.

Table 1: PSB performances

N accelerated to 1.4 GeV	1.02	10^{13} p/ring
Normalised emittances (H/V)	12/7	μm(1σ)
Brightness for high intensity beams (N/ε*)	0.8	10^{12}/μm
Beam for LHC (nominal/ultimate)	1.7/2.5	10^{12} p/ring
Brightness for LHC beam (nominal/ultimate)	0.6/0.7	10^{12}/μm

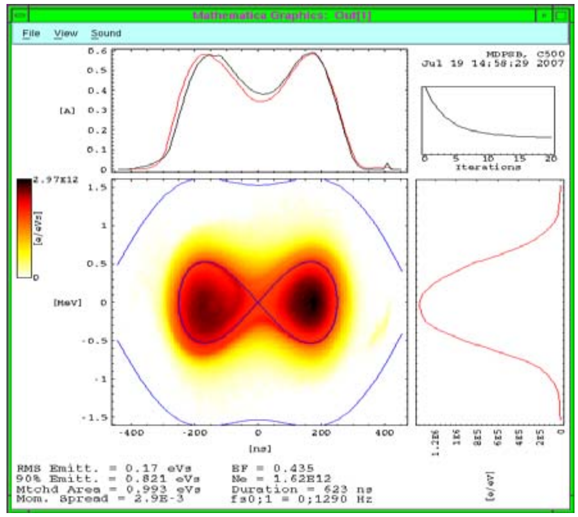

Figure 1: Tomoscope representation of the longitudinal phase space and projected distributions.

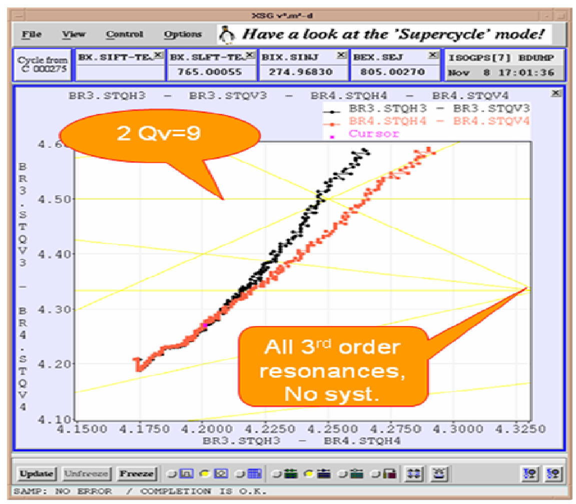

Figure 2: Tune diagram showing the dynamic tune along acceleration for rings 3 and 4

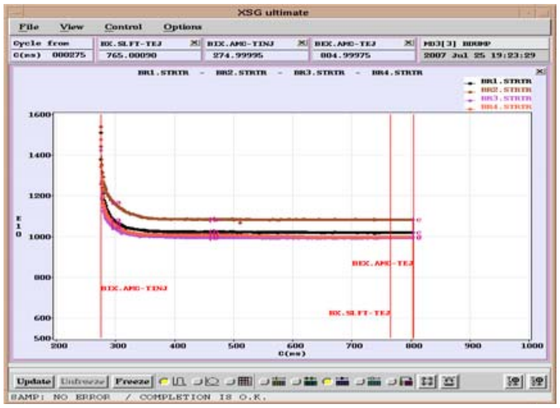

Figure 3: Number of protons accelerated for the 4 PSB rings

MEASUREMENTS

Due to the extreme conditions for the particles at the beginning of acceleration, it was decided to perform measurements of the beam characteristics varying different parameters, like tune, intensity and density. The tools used where:

- A sieve in the injection line which allows the reduction of the Linac2 proton beam density by a factor 5 to 6.
- Transformers in the machine to measure the currents.
- Tomoscope to evaluate the longitudinal emittances and the momentum distribution.
- Wire scanners in the machine to measure the emittances. They were not operational for some of the measurements.
- Semgrids in the extraction line to measure the emittances after acceleration and extraction.

The first measurements concerned the emittances obtained for different number of turns injected with and without sieve.

As the PSB machine will be fed in 2012 by the Linac4 [5], it was important to observe the beam behaviour on a 160 MeV flat top after acceleration from 50 MeV. The effect of the integer resonances was studied at this energy as the beam was particularly stable compared to a 50MeV flat top,

EMITTANCES WITH AND WITHOUT SIEVE

The emittances, after acceleration and extraction, were measured for 1 to 13 turns injected with and without the sieve (Figure 4). In the horizontal plane there is no effect of the sieve while the vertical emittance is strongly affected (a factor 2 at high intensities).

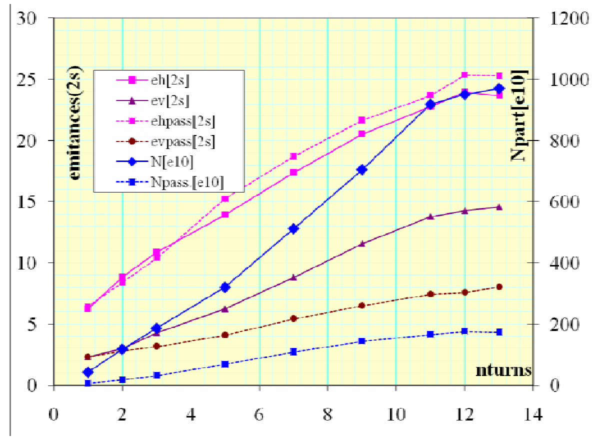

Figure 4: Emittances and number of particles accelerated and extracted versus number of turns injected without (plain) and with sieve (dashed)

Then we compute using the usual Laslett formulae and the measured parameters the tune under space charge for the zero-amplitude particle (the one which is the most affected by the space charge). We also extrapolated this zero-amplitude tune to the case where the emittances are the one obtained with sieve and the number of particles is the one without the sieve (Figure 5). We observe that the linear coupling resonance and possibly the integer resonances are responsible for the vertical emittance increase. It should be noted that the vertical emittance obtained without the sieve corresponds to the vertical acceptance of the PSB at low energy.

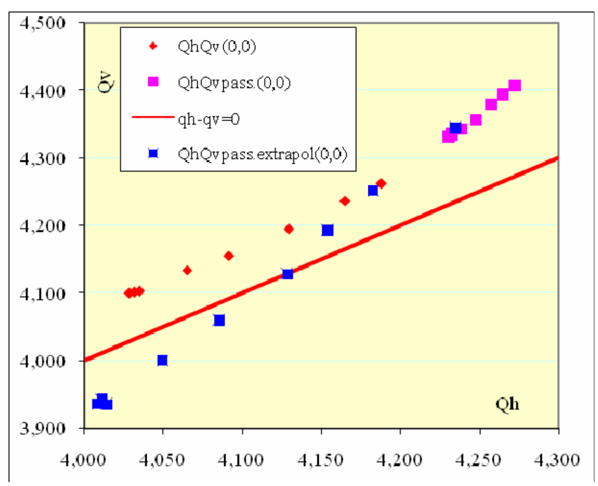

Figure 5: Tunes for particles having oscillations of zero amplitude at the start of acceleration. Red lozenges: without sieve; magenta square: with sieve; blue square: computed with the number of particles without sieve and the emittances with sieve. The red curve is the linear coupling resonance Qh–Qv=0.

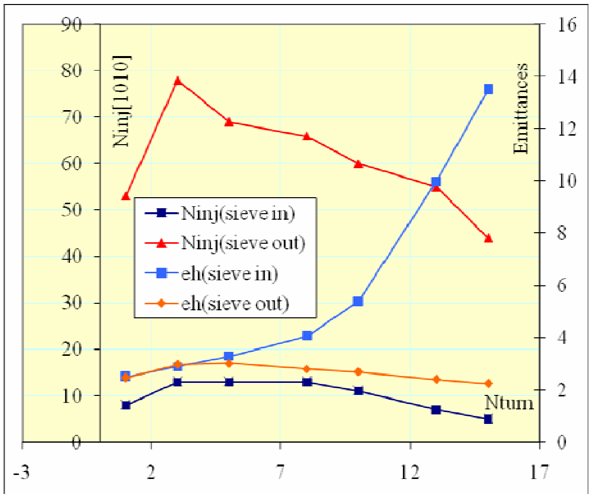

Figure 6: Injection of one turn with the same oscillations as the injected turn number 1 to 14, with and without the sieve.

We have also very often observed that, for only turn injected, the obtained emittance was very much related to the Linac2 emittance and not affected by the large horizontal oscillations during the injection process. To verify this observation, we have injected one turn with horizontal oscillation corresponding to the first, second...thirteenth turn, and with and without sieve (Figure 6). With the sieve, the final horizontal emittance increases indicating a filamentation in phase space. At the contrary, without the sieve, the final emittance is the same whatever is the original injection oscillation. This can be interpreted as a frozen phase space by the space charge forces, which don't allow filamentation. The beam is then a rigid body which oscillates for long time until the oscillation is damped through the interaction with the environment. Long damping time was also observed during the measurements. In term of beam stability, it is interpreted as large space charge impedance which drives the beam close to instability. Fortunately, the PSB is working below transition which helps the beam to not undergo instabilities through this process.

BEAM ACCELERATED TO 160 MeV

The beam was accelerated from 50MeV to 160MeV in the same way the acceleration to 1.4GeV, except for the last part just prior to the flattop. The beam was also partly decelerated back to 50MeV. It was possible to accelerated and maintain 1.08 10^{13} protons along the 200ms flattop with only small evolution of the beam emittances and number of particles (case 1). To evaluate the limits of the space charge, the second harmonic cavity voltage was first set to 2kV (instead of 8kV)(case 2) and then 8kV(case 3) but in phase with h=1 instead of being normally out of phase (Table 2).

Table 2: beam evolution along the 160MeV flattop depending of the bunch characteristics. Note that density is the bunch relative bunch peak density.

cases	1	2	3	units
V(h=1)	8	8	8	kV
V(h=2)	8	2	8	kV
Relative phase	π	π	0	rad
Qh	4.21	4.21	4.21	
Qv	4.35	4.35	4.35	
density	1	1.35	1.64	
N begin ft	1.05	1.05	1.03	10^{13} p
$\varepsilon_h/\varepsilon_v$ (2 σ)beg.	100/47	91/45	126/47	πmmmrad
N end ft	1.05	0.99	0.9	
$\varepsilon_h/\varepsilon_v$ (2 σ)end	93/52	91/53	133/48	πmmmrad

First, we should note that the normalised emittances are larger (a factor 1.2) than the emittances obtained when the beam is directly accelerated to 1.4 GeV. It surely means that, arriving on the flattop, the emittances have increased due to the proximity of several resonances. In the case 1, along the flat top only the vertical emittance increases, indicating a possible coupling effect leading to small losses. The case 2 is very similar to case 1 despite the loss increase. This indicates a possible 35% bunch peak density margin. To minimize the losses for case 3, the vertical tune was increased to 4.46. Nevertheless, the horizontal emittance and the losses are much larger than for the other cases. It was possible to restore the same horizontal emittance as for cases 1 and 2, but at the expense of the losses along the flattop. In conclusion, it is possible to further increase the peak density, but probably not more than 35%, with the same beam characteristics. Nevertheless, the resonances compensation at 160MeV should be reviewed to possibly increase the margin.

INTEGER RESONANCES

During the above measurements, it appears that the coupling resonances (Qh-Qv=0) and the integer resonances play an important role when the beam is under strong space charge. To understand these phenomena, we have changed the tune, approaching the integer resonances and finally crossing them. We have recorded the number of particles, the evolution of emittances and orbit. These measurements were taken on a 160MeV flattop as the beam with high number of particles is much more stable. Again, we compared the measurements with and without sieve.

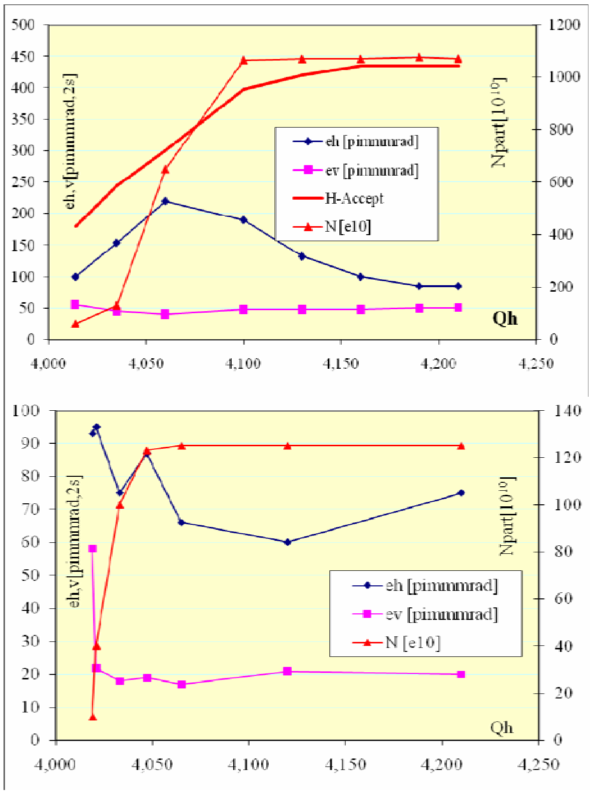

Figure 7: Evolution of different beam parameters when the horizontal working point is moved toward the integer resonance Qh=4. Top: without sieve i.e. high intensity beam; bottom: sieve in, lower intensity and ~5 times less beam density.

Resonance Qh=4

While keeping the vertical tune at 4.30, the horizontal tune is moved to the resonance Qh=4. We observe(Figure 7] that the horizontal emittance is first growing up to a maximum value (~200 πmmmrad) while the peak to peak orbit increases, and then reducing the horizontal acceptance. Losses occur when the dynamical acceptance is reached. Note the constant difference between the 2 sigma's emittance and the machine acceptance computed from the mechanical aperture, the peak orbit and the lattice Twiss parameters. When the sieve is inserted into the injection line, the losses start at a later time, i.e. closer to the integer resonance. The emittance increase is not as important as for the strong space charge case (without sieve). It probably means that the integer resonance is also excited by the octupole's like effect derived from high density beam (in addition, at the PSB, the resonance 4 Qh=16 is a systematic resonance). The effect of the horizontal integer resonance has been used to send to the PS a beam with a larger horizontal emittance, easing the island formation for the 5 turn's extraction [6].

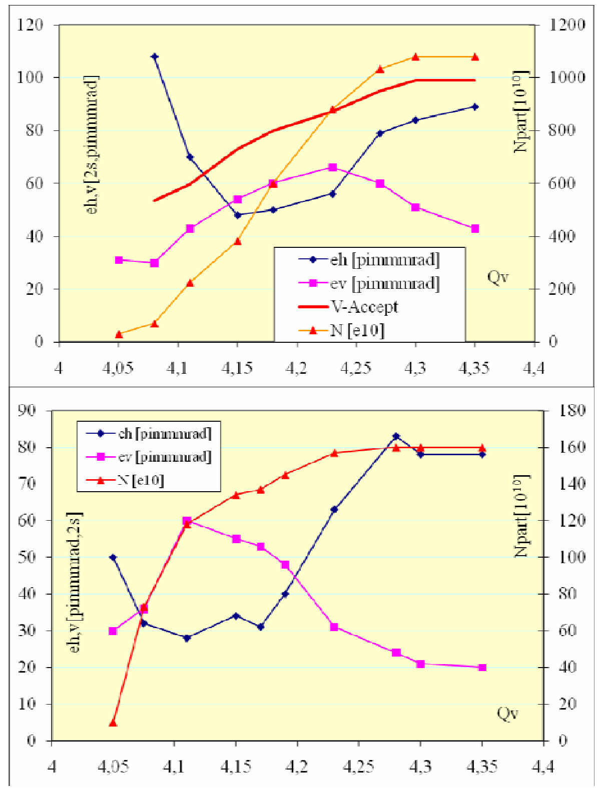

Figure 8: Evolution of different beam parameters when the vertical working point is moved toward the integer resonance Qv=4. Top: without sieve i.e. high intensity beam; bottom: sieve in.

Resonance Qv=4

While keeping the horizontal tune to 4.21, the vertical tune is moved to the resonance Qv=4. On the way, the working point crosses the coupling resonance Qh-Qv=0. During this crossing, emittances are exchanged (at least partially), and then losses occur {Figure 8] as the vertical emittance reaches the vertical acceptance. Otherwise, the same conclusions as for the horizontal plane can be drawn. In the strong space charge regime, the two resonance effects are mixed which renders the analysis more difficult.

OUTLOOK

The measurements have shown a very large orbit increase when approaching the resonance. Then a program has been launched to better correct this orbit during the coming shut down by displacement of quadrupoles.

We have also seen interesting evolutions of the distributions. This has to be measured systematically and compared with simulations, trying to find corrective solutions.

CONCLUSIONS

We have extensively measured the beam behaviour in the PS Booster and tried to disentangle different observed effects. The strong space charge doesn't allow filamentation which is one of the reasons for the easiness we have had to produce the small emittances for LHC in the PSB, despite a multiturn injection. The tune diagram space is just sufficient at 160 MeV to allow a beam of allow 10^{13} protons having emittances suitable for the PS to survive for long time on a flat top. Of course the problematic could be different if the beam is accelerated as soon it is injected.

ACKNOWLEGMENT

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