ACHIEVABLE SPACE-CHARGE TUNE SHIFT WITH LONG LIFETIME IN THE CERN PS AND SPS

E. Métral and H. Burkhardt (CERN, Geneva)

Abstract

In the CERN Proton Synchrotron (PS), a slow beam loss of few percents is still observed on the long injection flat-bottom with the nominal beam for LHC after fine tuning of the working point. The understanding of space-charge effects is therefore of paramount importance to try and alleviate this limitation. This is why controlled benchmarking space-charge experiments were performed in the last few years. The results are presented in detail with a particular emphasis on the maximum achievable space-charge tune shift with long lifetime.

On the contrary, space-charge effects usually play a minor role in high-energy machines like the CERN Super Proton Synchrotron (SPS). However, they could potentially become a limitation for the heavy ion beams needed for the LHC. Therefore, experimental studies on space-charge limitations were also performed in the SPS in the last few years. The results are discussed in detail in the present paper. Furthermore, it is worth mentioning that observations similar to the ones done in the PS in the presence of space-charge were also done in the SPS with electron cloud.

INTRODUCTION

Two different space-charge issues are observed at injection energy (1.4 GeV kinetic) in the PS (where the integer part of the transverse tunes is 6 in both planes and the chromaticities are uncorrected at ~ -1 in both planes), depending on the beams which need to be produced:

- **Beam for LHC** [1]: It is almost round, much smaller than the vertical aperture, it has the highest incoherent direct space-charge tune shift (~ -0.25), it has to stay more than ½ million turns at low energy without emittance blow-up, and linear coupling between the transverse planes is used to damp a horizontal single-bunch head-tail instability due to the resistive-wall impedance [2].
- **Beam for CNGS** [3]: In this case, the situation is quite different. The beam almost fills the mechanical aperture and it is flat (ratio of a factor ~ two due to the elliptical shape of the vacuum chamber). Therefore a good injection trajectory is required to minimize the losses and particular attention should be paid to the Montague resonance, which can transfer part of the horizontal emittance to the vertical one and produce beam losses on the (usually more critical, as smaller) vertical aperture. Furthermore, the horizontal emittance should be kept small as it will become four times the vertical one in the SPS (after the 5-turn CT extraction, which decreases the horizontal emittance by a factor four, and the emittance exchange in the transfer line TT10 [4]), otherwise losses are observed on the SPS vertical aperture.

In the SPS (where the integer part of the transverse tunes is 26 in both planes and the chromaticities are corrected or increased up to ~ 0.5 in the vertical plane to combat the fast single-bunch vertical instability induced by the electron cloud on the nominal LHC beam), space-charge is generally not an issue (alone) for proton beams, even if the interplay with other mechanisms (e.g. electron could for the nominal beam for LHC) still has to be analyzed in detail. However, few years ago space-charge was identified as a potential limitation with the LHC ion beam, where an incoherent direct space-charge tune shift of ~ -0.1 was foreseen for ~ 40 s [5,6].

The main space-charge studies performed in the PS over the last few years are reported in the first section, while those of the SPS are discussed in the second one, before concluding on the maximum achievable space-charge tune shift with long lifetime in both the CERN PS and SPS.

SPACE CHARGE STUDIES IN THE PS

Over the years the intensity per bunch in the PS beam for the LHC increased for several reasons: (i) The initial scenario foresaw a debunching/rebunching (with 84 bunches (b) of 1.15E11 p/b on h = 84 at top energy), and 8 bunches on h = 8 at injection; (ii) Then, triple and double splittings were proposed as replacement to prevent a longitudinal microwave instability from developing during the debunching procedure and create the gap for the extraction kicker (72 b of 1.15E11 p/b on h = 84 at top energy were required and 6 b on h = 7 at injection with more intensity per bunch; (iii) Finally, to compensate for the losses in the SPS, 72 b of 1.3E11 p/b on h = 84 are required at PS extraction, i.e. 6 b on h = 7 at injection with again more intensity per bunch. As a consequence losses of few percents on the injection plateau are now observed (without emittance growth) [7]. It should be noticed that in 2000, with a smaller intensity leading to an incoherent direct space-charge tune shift of ~ -0.21, the losses were almost not visible [8].

Crossing the integer (or ½ integer) resonance

Few years go, when the number of protons per bunch for the LHC beam was smaller than now, the working point was optimised to (6.18,6.21). Increasing the intensity per bunch increased the space-charge neck-tie and one of the basic space-charge mechanisms took place, namely the overlap between the space-charge tune footprint and the integer (or ½ integer) resonance. This led to a regime of loss-free core emittance blow-up, which was studied in Refs. [9,10]. The working point was slightly increased to its current value (6.22,6.25), to avoid the emittance blow-up.

Why decreasing the horizontal tune on the high-intensity beam for CNGS?

For several years it has been observed by the operation team that during each run the horizontal tune has “the tendency to decrease” to values as low as ~ 6.1 on the very high-intensity beam for CNGS. This does not go in the good direction for the classical space-charge effect (as it pushes the bunch closer to the integer resonance). Another (space-charge) mechanism had to be found and this is why the Montague resonance was revived [11] as a possible limitation (see next Section). Finally, it seems that by changing the trajectory in the injection transfer line as well as the injection process parameters, it was possible to keep a high horizontal tune (~ 6.20) with the same amount of losses [12].

Montague resonance

As mentioned in the previous section, this study was initiated to try and explain why the horizontal tune had (has) to be decreased on the high-intensity beam for CNGS. The idea was that if the horizontal tune is too close to the vertical one some (intensity-dependent) emittance exchange between the transverse planes could take place, and as the beam fills the vacuum chamber, some beam losses could be expected on the vertical aperture.

The Montague resonance was studied in detail in both static [13] and dynamic [14] regimes and these measurements triggered a huge benchmarking campaign between many space-charge codes [15].

Space-charge driven resonance phenomena

By lowering the working point towards the resonance 4 Q_x = 25 (excited by a controlled octupole), a gradual transition from a regime of loss-free core emittance blow-up to a regime dominated by continuous beam loss has been observed, as expected from simulations [16]. The emittance growth regime was rapidly in good agreement with predictions, while the observed maximum losses (~30%) were much larger than predicted (~8%) without including chromaticity in the analysis [17]. Including chromaticity brought the beam loss prediction to 50% of that found in the experiment [18].

This mechanism is sometimes observed in the PS with the LHC beam when the tunes are not correctly set [19].

Decoherence at injection without and with space charge

Space-charge has usually detrimental effects. However, sometimes it can also have beneficial effects. One of them is the increase of the decoherence time at injection [20], which can be explained by a loss of Landau damping [21]. A (total) decoherence time of ~ 2 ms was measured with the nominal beam for LHC. This time is quite long compared to the decoherence time which can be computed (or simulated) from chromaticity alone, which is ~ 0.1 ms. Without space-charge the transverse damper would have to damp the injection oscillations much faster than ~ 0.1 ms (to avoid emittance blow-up through filamentation), whereas with space charge much more time is available. Therefore, as mentioned before, space charge is really a beneficial effect in this case. Note that it was observed that with the transverse damper ON, the damping of the injection oscillations is performed in ~ 0.6 ms [19].

Resistive-wall instability with the beam for LHC without and with space charge

The nominal bunch for LHC is unstable at PS injection due to the resistive-wall impedance. For almost ten years, it has been stabilized by linear coupling only (i.e. without Landau octupoles nor feedbacks). One of the proposed mechanisms is the sharing of the head-tail instability growth rates (which depends on the chromaticities) [22]. This mechanism was checked with simulations in Ref. [2], with neither Landau damping nor space charge. Another mechanism which can happen in the presence of linear coupling is the sharing of Landau damping [22]. Therefore, the next step (challenge) would be to simulate the “real case”, i.e. the resistive-wall instability with both linear coupling (used to stabilize the beam) and space charge, during ~ 0.6 million turns! This would help us to understand better all the mechanisms involved, and in particular to distinguish between the cases where the coherent and incoherent tune shifts have the same sign (as in the vertical plane) or opposite sign (as in the horizontal plane), i.e. if the coherent tune is inside the incoherent space-charge tune spread or not.

SPACE CHARGE STUDIES IN THE SPS

Beam lifetime studies with protons and large space-charge tune shift (~ -0.25)

In view of a future operation with ions for LHC, where the bunches will have to wait for ~ 40 s on the injection flat-bottom with an incoherent direct space-charge tune shift of ~ -0.1, space-charge studies were performed in the SPS with an almost nominal proton bunch (1.2E11 p/b) but at a lower energy (14 GeV/c instead of 26 GeV/c) [5,6]. An incoherent direct space-charge tune shift of ~ -0.30 (with initial parameters) could be achieved but then fast losses were observed at injection. Measuring the beam parameters after 1 s, where a stable situation was reached, an incoherent direct space-charge tune shift of ~ -0.24 was still obtained with a beam lifetime larger than 50 s. It was therefore concluded that no major problems should be expected with the ions.

Working point studies with a pencil proton bunch

This study was performed to evaluate the integer (or ½ integer) stopbands and identify the most stable operation region in the tune diagram [23]. For this aim, a LHC pilot bunch (5E9 p/b) was used at injection energy (26 GeV/c) and the measured integer (or ½ integer) stopbands were 0.015 in the horizontal plane and 0.020 in the vertical one. The best operation region was identified as the region between 26.11 and 26.14 for the horizontal tune and between 26.16 and 26.18 for the vertical one. Note that the actual working point on the nominal LHC beam is (26.13,26.185).

Results from early ion (Pb^{82+}) commissioning in 2007

By the end of 2007, 4 bunches of 9×10^7 ions (Pb^{82+}) were extracted and seen at the beginning of one of the extraction lines towards the LHC (TT60/TI2) [24]. This corresponds to 90% of the design intensity, which is 295.2×10^8 charges. The corresponding measured transverse emittances were 25% smaller than the design values (the smaller the better!), which are 1.2 μm (rms, normalized). Note that the best working point was found at (26.13,26.25) and that a much smaller injection plateau was used (~ 7 s instead of ~ 40 s in the nominal scheme).

Similarity between space-charge-induced and electron-cloud-induced bunch shortenings

One of the characteristics of the beam losses due to the space-charge trapping/detrapping mechanism discussed above is that they are associated to a bunch shortening as the particles with large synchrotron oscillations are lost [16]. Indeed, the synchrotron oscillation causes a periodic tune modulation due to space charge, and leads to trapping and detrapping on the resonance islands. For working points very close to the resonance this induces a beam halo with large radius, which in conjunction with the reduced dynamic aperture is the source of beam losses.

Few years ago bunch shortening was also observed in the SPS at the end of a bunch train in the presence of electron cloud [25]. The idea that similar incoherent effects as with space charge could arise from the electron cloud has been around for some time. Recently, the similarities and differences between space charge and electron cloud were summarized in Ref. [26].

CONCLUSION

Few percents of beam losses are observed during the long (1.2 s = 0.6 million turns) injection flat bottom in the PS with the LHC beam for LHC (where the incoherent direct space-charge tune shift is ~ -0.25). Almost no beam losses were observed in the previous years when the PS did not have to compensate for the SPS losses (the incoherent direct space-charge tune shift was ~ -0.21). Note that the (high) chromaticities are not corrected in the PS at injection, which is good for the head-tail instability (slower rise-times) [2], but which is not so good for the beam lifetime [18]. The next challenge as concerns simulations would be to simulate the PS low energy resistive-wall instability with large chromaticities (~ -1), linear coupling (used to stabilize the beam), image charges from the almost flat vacuum chamber, and direct space charge over 0.6 million turns! This would help us to understand better all the mechanisms involved, and in particular to distinguish between the cases where the coherent and incoherent tune shifts have the same sign (as in the vertical plane) or opposite sign (as in the horizontal plane), i.e. if the coherent tune is inside the incoherent space-charge tune spread or not. The effect of space charge on head-tail modes still has to be fully understood.

In the SPS, detailed studies performed in 2007 at low energy with Pb^{82+} ions revealed that although the space-charge detuning was as high as ~ -0.1, almost no transverse emittance blow up was observed over periods of the order of one minute, confirming the expectations based on studies with protons [6].

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