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LIU SPACE CHARGE STUDIES FOR THE LHC PRE-ACCELERATORS

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Abstract

In 2011 a working group has been started to study performance limitations due to Space Charge (SC) in the four LHC pre-accelerators, LEIR, PSB, PS & SPS, in view of the LHC Injector Upgrade (LIU) project [1]. To this end external and in-house simulation tools have been benchmarked for the LIU study cases with the long-term goal of providing a full sequence of tested CERN Space Charge tools. It became clear that SC studies must be combined with trustworthy models of the machines, including linear and non-linear errors. In particular, an effective s-dependent non-linear model is required. Recent studies indicate that also the low frequency ripple spectrum due to conventional power supplies might play an important role for the beam dynamics in presence of space charge in the pre-injectors.

THE CERN SC WG

At the start of the LIU project it has become clear that for significantly increasing the beam brightness in the LHC proton injectors a good understanding of SC effects in conjunction with the linear and non-linear models of these machines would be required. Therefore a program has been started to gain the required understanding and prepare computing tools. The main points of this program are:

- For all machines linear and non-linear lattice models are being developed including modeling of the most relevant magnets with the help of our magnet experts. Additionally, we are now investigating the effect of substantial power supply ripple and trying to minimize their effects with the help of power supply experts.
- The developments and benchmarking of several SC simulation tools.
- The computing resources have been upgrades by a High Performance Computing (HPC) cluster at CNAF [2] and CERN and as well as a high-end multi-GPU server.
- Collaborations have been started to perform beam experiments at CERN and with several institutes.
- A series of biennial SC workshops have been started and convened at CERN [3], Oxford [4] and Darmstadt [5] as well as some collaboration meetings [6, 7].

SC STUDIES AT THE LHC INJECTORS

The goal of the SC studies in the LHC injectors is to understand the performance limitations both in terms of emittance blow-up as well as beam losses in view of reaching the challenging beam parameters of the LIU project, which are defined by the performance goals of the High-Luminosity (HL)-LHC upgrade. For protons, this implies doubling the intensity per bunch for the 25 ns beam compared to today's operation for the same transverse emittance. In other words, also the beam brightness has to be doubled. For the Pb-ion chain, the main concern is reaching the target intensity at SPS extraction. The issues and challenges of the different machines of the injector chain are summarized in the following.

LEIR

The Low Energy Ion Ring (LEIR) is the first synchrotron of the LHC ion injector chain. In the past, the achievable intensity of Pb54+ ions after accumulation of 7 injections from Linac3 was strongly limited by losses after RF capture. Extensive machine studies in 2015 and 2016 indicated that periodic resonance crossing induced by SC is one of the main ingredients for the losses encountered [8]. In fact, the incoherent SC tune spread easily exceeds 0.2 after RF capture. Significant improvements of the extracted intensity were achieved by flattening the longitudinal bunch profile and by optimizing the machine settings, so that LEIR is now able to produce the LIU target intensity [9]. Figure 1 shows a comparison of the intensity along the LEIR cycle between 2015 and 2016. Recent studies show that the resonances limiting the performance of LEIR are, at least partially, excited by the space charge potential of the transverse Gaussian beam itself [10]. An overview of recent beam dynamics studies performed in LEIR can be found in [11] and [12].

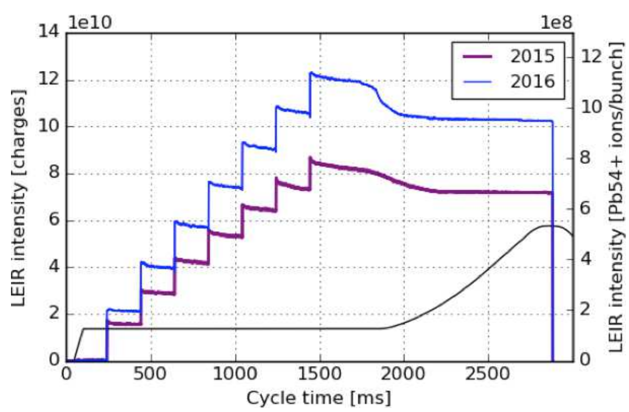

Figure 1: LEIR Intensity along its machine cycle [9].

PSB

The Proton Synchrotron Booster (PSB) consisting of four independent rings is the first synchrotron of the proton injector chain. In the present configuration, Linac2 delivers protons for multi-turn injection into the PSB at 50 MeV. Figure 2 shows the rather dramatic SC tune spread for LHC beams at injection. In fact, space charge determines the brightness achievable in the PSB: for increasing intensity the transverse emittances are observed to increase proportionally as shown in Fig. 3. Increasing the injection energy to 160 MeV with the connection of Linac4 will allow reaching the LIU target of twice higher beam brightness considering the scaling of the space charge tune spread with energy. This is also

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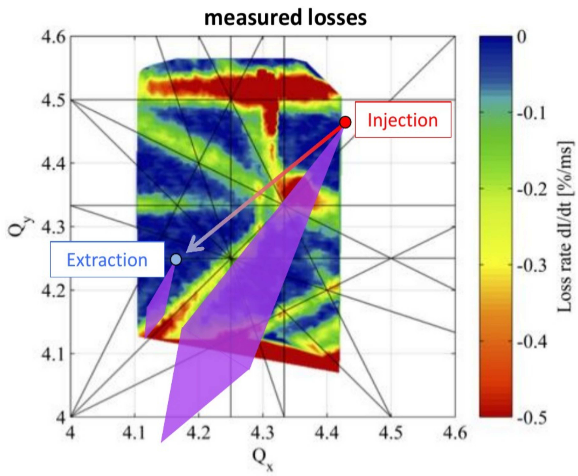

Figure 2: PSB Tune diagram showing the losses measured in a dynamic tune scan with a low brightness beam together with a schematic representation of the space charge tune spread at injection and extraction in the PSB for the high brightness LHC beams.

predicted by space charge simulations as discussed in more detail in [13]. Nevertheless, resonance compensation will be critical for reaching the target parameters. This concerns in particular, the correction of the beta beating induced by the new injection chicane dipoles for the H^--charge exchange injection with Linac4 as the working point at injection is close to the half integer resonance [14]. This is the focus of an ongoing machine study campaign. A benchmark of losses on the half integer resonance is described in [15].

PS

The Proton Synchrotron (PS) is part of both the ion and the proton injector chain. For ions the PS does not impose a critical performance limitation. For the LHC proton beams on the other hand, some of the bunches have to be stored at injection energy for 1.2 s to wait for the remaining bunches

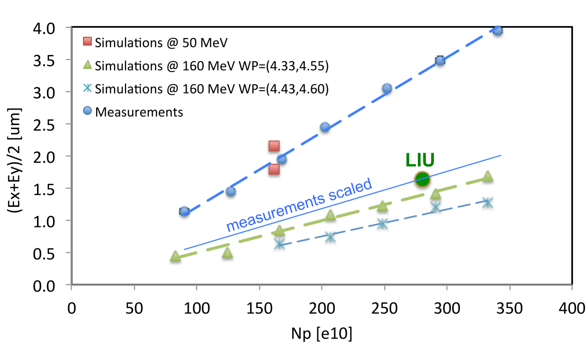

Figure 3: 2016 PSB brightness curves including measurements at the present injection energy of 50 MeV and extrapolations to the new 160 MeV injection energy based on scaling laws or simulations. Shown is the average normalized emittance versus number of protons per ring. The LIU target parameters are indicated by the green marker [13].

to be produced in the PSB. Periodic resonance crossing induced by space charge is imposing a limit on the achievable brightness for the budget of emittance growth and losses.

Figure 4 shows the blow-up and losses as a function of the intensity dependent incoherent space charge tune spread in the PS for two different working points [16]. Losses are caused by the 8th order structure resonance $8Q_x = 50$ excited by the modulation of the Gaussian space charge potential with the dominant harmonic of the PS lattice functions (which is 50) [17]. Therefore vertical tunes above 6.25 are avoided for normal beam operation. On the other hand, the integer resonance results in unacceptable blow-up when the vertical incoherent tune spread at injection exceeds 0.3. In order to allow reaching the LIU target of double beam brightness, the PSB-to-PS injection energy will be increased from the present 1.4 GeV to 2 GeV as part of the LIU project [1]. In addition, injecting larger longitudinal emittances [18] and potentially even flat bunches with hollow phase space distributions [19] into the PS will further mitigate space charge.

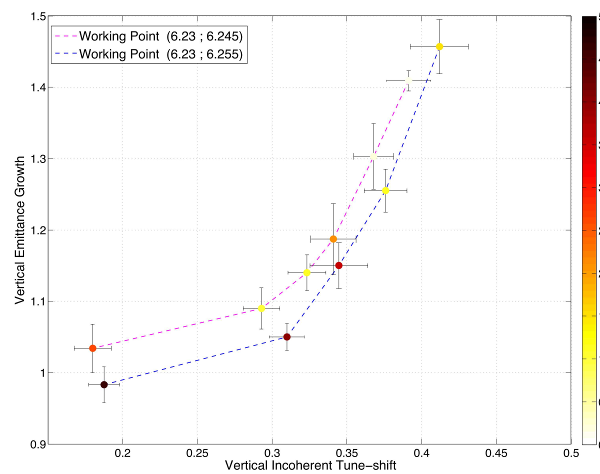

Figure 4: PS Performance limitation due to SC [16].

Recent studies on further characterization of the resonances in the PS are reported in [20, 21]. Correct modeling of the linear and non-linear optics of the PS lattice, which is built with combined function magnets, is also an essential ingredient for understanding the beam dynamics in presence of SC. A significant effort is therefore put on optics measurements, including dynamic effects of tune and chromaticity variation during the fall of the injection bump [22].

SPS

The Super Proton Synchrotron (SPS) is the last accelerator of both the proton and the ion injector chain. In the LIU era the SC tune spread for proton beams at SPS injection will reach up to 0.2 and the beam needs to be stored for more than 10 s to accumulate four injections from the PS [1]. Although challenging, this has been demonstrated within the emittance growth and loss budgets (10%) for single bunch high brightness beams. However, it should be pointed out that recent studies indicate that the tune modulation induced

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by power converter ripple can play an important role in the beam degradation during the long storage in presence of space charge [23]. Figure 5 shows the emittance growth and transmission for different working points in the SPS close to the resonances (Q_x = 20.33 deliberately excited using a single sextupole and at Q_x = 20.4 mostly driven by SC). These measurements could be reproduced in frozen SC simulations only when taking into account the tune ripple induced by the power converters for the main quadrupoles. Detailed studies on this subject are ongoing. This might also help understanding the strong beam degradation encountered on the injection plateau for the ions, where the beam has to be stored for more than 40 s and the SC tune spread reached up to 0.3 at injection [24]. In this case also the interplay of intra-beam scattering and space charge induced resonance crossing might need to be studied in more detail in order to understand the experimental observations. In any case, even the presently achieved performance is sufficient for reaching the LIU target parameters for Pb-ions when the momentum slip stacking will become available with the upgrade of the SPS RF [25].

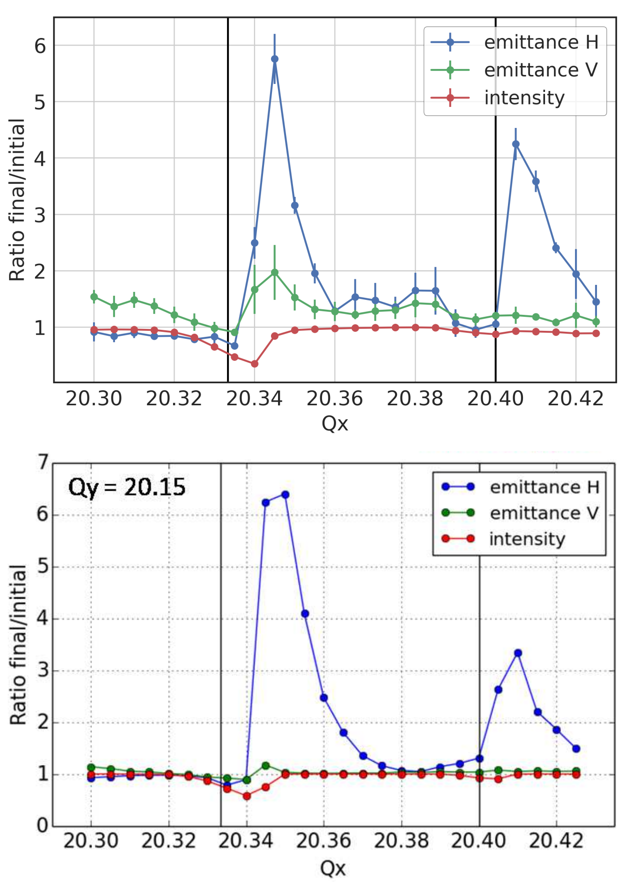

Figure 5: Relative emittance growth and intensity as a function of the working point in the SPS as obtained from experimental studies (top) and from simulations using a frozen SC model including the tune ripple from power converters (bottom) [23].

Tools

Together with our collaborators from Fermilab and BNL [26] we have introduced SC into the MAD-X code [27]. For self-consistent SC studies we started to use PTC-ORBIT [28] from SNS. But in the meantime the pyOrbit code [29] had been developed to allow for a better modular structure of the code via Python. At CERN the benchmarking between the two codes has been initiated and successfully completed [30].

Another development has been the speeding up of the purely frozen SC by implementation in the SixTrack code [31]. The goal is to reach a speed-up by a factor of 100 compared to the MAD-X code. The implementation is expected to be benchmarked in the near future [32].

In addition, the PyHEADTAIL simulation library [33, 34] has been extended with a space charge suite [35]. The included GPU-accelerated 2.5D and 3D self-consistent PIC algorithms reach speed-up factors above 100 on the new GPU server at CERN compared to single CPUs.

OUTLOOK

The LIU SC studies are entering the critical phase of just one more year of measurements at the LHC pre-accelerators till the two year shutdown (LS2) will begin in 2019. Various experiments will be conducted in order to refine our understanding of the performance limiting mechanisms in the different machines. After the implementation of the LIU upgrades during the shutdown, the machines have to be recommissioned with the new hardware for producing the challenging target beam parameters required for the HL-LHC era. To this end, the consolidation and further development of the simulation tools will be very important. The collaboration with colleagues from various labs has been key for the progress made so far and we hope to continue in this spirit in the future.

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