CHALLENGES IN UNDERSTANDING SPACE CHARGE EFFECTS

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Abstract

Space charge effects in high intensity and high brightness synchrotrons can lead to undesired beam emittance growth, beam halo formation and particle loss. A series of dedicated machine experiments has been performed over the past decade in order to study these effects in the particular regime of long-term beam storage (10⁵-10⁶ turns) as required for certain applications. This paper gives an overview of the present understanding of the underlying beam dynamics mechanisms. In particular it focuses on the space charge induced periodic resonance crossing, which has been identified as the main mechanism causing beam degradation in this regime. The challenges in further progressing with the understanding, the modelling and the mitigation of these space charge effects and the resulting beam degradation are discussed. Furthermore, an outlook for possible future directions of studies is presented.

INTRODUCTION

Space charge effects in high intensity and high brightness synchrotrons can lead to undesired beam emittance growth, beam halo formation and particle loss. Some accelerator projects require long-term storage (up to several seconds) of high brightness bunches at injection energy in order to allow accumulating several injections from an upstream machine. This is the case for the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) at CERN, which are part of the injector chain for the Large Hadron Collider (LHC). In preparation for the High Luminosity era of the LHC (HL-LHC), the injector chain at CERN is in the course of being upgraded in the framework of the LHC Injectors Upgrade (LIU) [1]. In simplified terms, the aim of this project is to enable the injectors to deliver twice higher intensity at equal emittance, i.e. twice as high brightness, as compared to today's performance. Table 1 shows an overview of the required storage times, the space charge tune shifts and the loss and emittance growth budgets for the various machines of the proton injector chain at CERN. For the heavy ion injector chain, space charge is critical in the Low Energy Ion Ring (LEIR). In the SPS, a space charge tune shift of up to $\Delta Q_v = -0.3$ is achieved and storage times of up to 40 s are required. In this case the beam quality is subject to strong degradation, which has been taken into account for the projection of the LIU-ion target parameters [2].

At the Facility for Antiproton and Ion Research project (FAIR) at GSI, the future SIS100 is required to store high brightness beams with a maximum space charge tune shift of about $\Delta Q_y \approx -0.3$ for about 1 s to accumulate several injections from SIS18 with losses on the percent level [3]. In this case, the tight constraint on beam losses is (at least

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Table 1: Target Parameters for LIU Project at CERN

Machine	ΔQ_y	Storage time	Budget for losses / Emittance growth
PSB	-0.5	-	5% / 5%
PS	-0.31	1.2 s	5% / 5%
SPS	-0.21	10.8 s	10% / 10%

partially) imposed by dynamic vacuum issues stemming from the large ionization cross section of U^{+28} ions with the residual gas.

Keeping the beam degradation within tight tolerances for long storage times can be quite challenging in presence of large space charge tune spread. A detailed understanding of the underlying beam dynamics mechanisms is required. A series of dedicated machine experiments has been performed over the past decade in collaboration between CERN and GSI in order to study the space charge dynamics in this regime. The aim of this paper is to give an overview of the present understanding, discuss the challenges faced and provide an outlook for future directions of study.

OVERVIEW OF STUDIES AND PRESENT UNDERSTANDING

One-dimensional Resonances

The first systematic experimental study of long-term space charge effects in presence of non-linear resonances was performed at the CERN PS in 2002-2003, as reported in [4] and [5]. In this experiment, the fourth order horizontal resonance $4Q_x = 25$ was deliberately excited by a single octupole. A bunched proton beam with a horizontal (vertical) incoherent direct space charge tune shift of -0.075 (-0.12) was stored at injection energy for about 1 s for different working points. Depending on how the space charge tune spread overlaps the resonance, two regimes of beam degradation could be clearly identified. For bare machine working points only slightly above the resonance, beam loss dominates. At the same time a reduction of both the horizontal emittance as well as the bunch length are observed. For higher machine tunes, losses are reduced but a large halo is formed in the horizontal plane leading to an enlarged emittance.

The beam degradation observed in the PS experiment was explained by trapping and scattering of particle trajectories during the periodic resonance crossing induced by space charge in a bunched beam, as anticipated by a simplified simulation model in 2002 [6]. This picture was refined in the following years [7–9], describing the main features of the phenomenon as follows:

• Space charge couples transverse and longitudinal planes: due to the change of line charge density along

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the bunch, the instantaneous transverse Coulomb force depends on the particle location in the longitudinal plane. Therefore, the longitudinal motion induces, via space charge, a variation of transverse tunes.

- The presence of a relatively small tune shift compared to the machine tunes $(\Delta Qx/Qx_0 \text{ of a few percent})$, does not destroy the validity of standard transverse non-linear dynamics, but rather induces a slow modulation of transverse tunes according to twice the synchrotron frequency.
- The transverse-longitudinal space charge coupling determines, via the depression of tunes, the transverse position of the fixed-points generated by the 1D resonance.
- The strength of the resonance determines the tune of particles around the fixed-points and also the resonance island size. The island size is also determined by the detuning created by space charge: a stronger gradient in the amplitude dependent detuning leads to smaller islands,
- The synchrotron tune determines the speed of the resonance crossing. A figure of merit on the speed of the resonance crossing is given by the adiabaticity parameter *T*, which is obtained as the ratio between the speed of migration of the fixed-points to the maximum speed of rotation of the particle in the island. If this ratio is small ($T \ll 1$) the motion is adiabatic and the particles remain locked to the island. As a consequence, the particle gains large amplitudes (trapping). If instead T > 1, a single resonance crossing results in a "kick" to the particle invariant (scattering).
- Particles that periodically cross the resonance will slowly diffuse to large amplitudes to form a halo. Its density and extension depend on the number of particles that cross the resonance, and on the outer position of the islands. If the outer position of islands intercepts the beam pipe or reaches the dynamic aperture, beam loss occurs according to a rate which is function of the distance from the resonance. When the accelerator is tuned close to a resonance (and above it), only particles with large synchrotron amplitude may cross the resonance and therefore become trapped or scattered into a halo and eventually be lost. This leads to a correlation between beam loss and longitudinal beam size such that only particles with large synchrotron amplitude will be lost resulting in a reduction of the bunch length.
- The space charge induced tune modulation due to longitudinal particle motion has twice the synchrotron frequency. The tune modulation introduced by chromaticity, instead, has the same frequency as the synchrotron motion. When maximum space charge detuning and maximum chromaticity detuning are comparable, the resulting slow modulation of the transverse tunes is

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the composition of these two effects with different frequencies. Consequently, the position of the fixed points is different in the two synchrotron half-periods. The overall effect is that islands are pushed further out (during half of the synchrotron period) and the halo size is increased.

This mechanism was confirmed in a systematic measurement campaign performed at the GSI SIS18 in 2007, where the horizontal third order resonance $3Q_x = 13$ was studied for both coasting and bunched beams with different beam intensities and space charge tune spreads [10]. The strong emittance growth was only observed for the high intensity bunched beam but not for the coasting beam with the same space charge tune shift, since for the coasting beam there is no periodic resonance crossing.

Two-dimensional Sum Resonances

While all the studies reported above concentrated on onedimensional non-linear resonances, an experiment in 2012 at the CERN PS was dedicated to studying the beam behaviour close to the third order coupled sum resonance $Q_x + 2Q_y =$ 19 deliberately excited by a sextupole magnet [11]. The beam was stored for about 1 s. Also in this experiment the loss dominated and the emittance growth dominated regimes were observed depending on the working point. However, the halo formation measured with wire scanners was observed to be very asymmetric between the horizontal and vertical planes. In particular, the beam developed much larger tails in the vertical plane. This observation could not be explained by a naive extension of the one-dimensional model developed earlier, since the particle trajectory on the coupled resonance follows resonant tori in phase space rather than fixed points. These resonant tori, in this context referred to as "fixed lines" [12-14], have a peculiar shape in the 4 dimensional phase space of horizontal and vertical coordinates. In the case of the $Q_x + 2Q_y$ resonance, the projection of the single particle trajectory in the physical x - y space has a larger excursion in the vertical plane and, depending on the phase advance from the driving sextupole to the observation point, follows either a figure-of-eight or a C-shape. This explains the larger vertical halo observed in this experiment at the PS.

It should be mentioned that there is an experimental campaign ongoing at the CERN SPS to study the fixed lines on the $Q_x + 2Q_y$ resonance in the "zero" space charge limit [15]. Furthermore, a general theory of space charge dynamics in the presence of non-linear coupled sum resonance of arbitrary order is being developed [16].

(REMAINING) CHALLENGES

Macroparticle Simulations

Space charge in a synchrotron is usually modelled by alternating space charge interaction ("space charge kicks") with particle tracking in the magnetic guide field. As the space charge forces depend on the transverse beam sizes, the rule of thumb is that about 10 space charge kicks per beam size variation period (sometimes referred to as betatron wavelength) are needed.

The brute force way of calculating the space charge forces is based on the Particle-In-Cell (PIC) algorithm [17]. In this approach the real number of particles is represented by macroparticles (usually about 10^6), where the total beam intensity is equally distributed to the charge of each macroparticle. The charge distribution is binned onto a spatial grid and the Poisson equation is solved numerically on the grid points to obtain the space charge kicks through the electric field. This method is self-consistent, i.e. the evolution of the particle distribution as a function of time is fully taken into account. However, a large number of macroparticles is needed to reduce emittance growth due to numerical noise in the particle distribution [18]. This approach is therefore very demanding in terms of computational power, necessitating the implementation of parallel computing. In addition, there is some artificial emittance growth induced by the grid ("grid heating") [19] and special care needs to be taken to make the calculation symplectic [20], which comes at additional computational cost.

To avoid the issue with noise, simulations with a so-called "frozen" space charge potential are commonly used for longterm simulations. In this approach, the space charge kicks are computed analytically for a chosen (fixed) particle distribution. A closed analytic expression for the electric field generated by a bi-dimensional Gaussian transverse distribution was derived by Bassetti and Erskine [21]. For each particle in the simulation, this formula is evaluated at the position of the particle using the actual horizontal and vertical beam sizes at the location of the space charge interaction and taking the local longitudinal line density into account. Simulations with this approach require only a few thousand particles to study the emittance growth and losses statistically. The drawback of this approach is that coherent collective effects cannot be taken into account. Furthermore the evolution of the particle distribution is not treated self-consistently.

The latter is partially overcome by adapting the beam parameters such as intensity and transverse emittances periodically and recomputing the frozen potential, as implemented in MAD-X [22] and in PyOrbit [23]. PyOrbit allows furthermore to partially account for the generation of halo by representing the beam by two transverse Gaussian distributions with different weights and different transverse emittances.

Some years ago a code-to-code benchmarking suite has been put in place in order to check the space charge induced particle trapping phenomenon [24]. In addition to MICROMAP [25] and SIMPSONS [26], this benchmarking case has been successfully passed by MAD-X [22], PTC-ORBIT [27] and lately also SYNERGIA [28, 29]. It should be highlighted that SYNERGIA is a PIC code and all the features observed in the frozen space charge codes could be reproduced. Even the long term emittance evolution test case was in very good agreement, once a sufficient number of macroparticles was used [30]. Work is presently ongoing to check the frozen space charge module of PyOrbit against this benchmarking case.

A more general overview of space charge code benchmarking can be found in [31, 32].

Quantitative Agreement Between Measurements and Simulations

Achieving quantitative agreement between machine experiments and space charge simulation codes is challenging. In fact, reproducing the evolution of the particle distribution during long-term storage requires several ingredients:

- Accurate measurement of beam parameters The measurement of the transverse beam profiles in synchrotrons is particularly challenging, because a high signal to noise ratio is required in order to resolve the beam halo.
- Good knowledge of machine linear and non-linear errors The long-term evolution of the particle distribution in the presence of space charge is very sensitive to machine errors and non-linearities. Having a good model of the machine is crucial. In general, the information on magnet errors for machines, which have been in operation for more than two decades, is sparse. In this case an effective non-linear model of the machine can be established from beam-based measurements, as done for example at the SPS [33].
- Accurate aperture model including misalignments Reproducing losses relies critically on a good model of the machine aperture, including element misalignments and the closed orbit. This information is unfortunately not always readily available, especially concerning the alignment data.
- Properly identifying and accounting for interfering effects To achieve quantitative agreement with simulations it is crucial to identify any effects that contribute to emittance growth and or losses in the machine under study. If these effects cannot be suppressed in the machine, they need to be quantified and eventually taken into account in the simulations. In some cases the interplay between space charge and other effects requires a study on its own. This might become more and more relevant in the future, when the accelerator performances will be pushed further. This aspect will be addressed in more detail later in this paper.

An example where a good quantitative agreement between measurements and simulations could be achieved is the PSB. As reported in [34], a benchmark experiment was performed for a working point slightly above the $2Q_y = 9$ half integer resonance. The beam loss evolution over about 200 ms was studied on a constant energy plateau when switching off the half integer correctors. To reproduce the observed losses in PIC simulations, a very accurate machine model of the

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linear errors had to be developed using beam-based measurements. In the end, even the evolution of the longitudinal bunch profile measured in the experiment was in very good agreement with the simulations.

A similar level of agreement has not yet been reached for the PS. Studies performed in 2013 have shown that high brightness beams suffer from losses for machine working points above $Q_v = 6.25$, while practically no losses are observed for beams with low brightness [35]. Further studies have shown that the non-linear space charge potential of the Gaussian particle distribution drives the 8th order resonance $8Q_v = 50$, because 50 is the strongest harmonic of the PS lattice functions [36, 37]. More recent campaigns concentrated on tune scans in different experimental conditions. However, simulations using a frozen adaptive model in PyOrbit for the ideal PS lattice do not explain the observed losses quantitatively (about a factor 3 higher losses in the measurements for high brightness beams) as shown



Figure 1: Relative emittance growth and losses as a function of the vertical machine tune in measurements (top) and in simulations (bottom) [38]. The horizontal tune was set to 6.2 in all cases.

in Fig. 1 [38]. The space charge tune shift of the beam used in this study was about $\Delta Q_{\rm v} = -0.25$. As the discrepancy between measurements and simulations is relatively large, detailed investigations on this subject are ongoing. In particular, the interplay with some residual, but yet to be quantified, magnetic resonance excitation at $Q_{y} = 6.25$ (e.g. octupole components) is being studied. A direct measurement of such residual resonance excitation is however difficult. Furthermore, the aperture model of the machine is being refined (e.g. comparison of model aperture with direct measurement of the effective physical aperture). Finally the importance of other effects like indirect space charge, as recently proposed in [39], and coherent space charge effects is being investigated. It should be mentioned that, since the beam loss at these working points is observed only for high brightness beams, the studies need to be performed with a relatively large tune spread. It could therefore be that multiple resonances are contributing to the beam degradation, which is an additional complication for these studies. In fact, driving term calculations have shown that there are also 8^{th} order coupled sum resonances excited by space charge [40], in addition to third order (skew) resonances in the tune space investigated (as indicated in the top of the graphs in Fig. 1).

Mitigation of Beam Degradation

In view of pushing the accelerator performance further, an important aspect to be addressed is the mitigation of the space charge induced beam degradation. On the one hand, individual non-linear resonances excited by magnetic errors can be compensated in case appropriate corrector magnets are available in the machine (at the expense of possibly further exciting other resonances or reducing the dynamic aperture). Typically two independent correctors with adequate phase advance are needed in order to control the resonance driving term in the complex plane. This has been tested in the PS for third order normal and skew resonances, see for example [38, 40, 41]. Experimental studies in the SIS18 on this subject are summarized in [42]. It seems that after the compensation, some minor residual resonance excitation left. It is not yet clear if this is related to the space charge detuning or to non-ideal resonance compensation settings, or due to another reason.

The other approach could be to try compensating the space charge detuning in the first place. A study in this direction was performed recently based on using electron lenses [43].

FUTURE DIRECTIONS

As described above, the main mechanism for beam degradation of high brightness bunches in the long-term storage regime has been attributed to periodic resonance crossing. Future study efforts could focus on identifying and better understanding the interplay with other collective effects or beam dynamics mechanisms such as:

- · Tune modulation induced by power converter ripple
- Intra Beam Scattering (especially for ions)

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- Electron-cloud
- · Indirect space charge and impedance

which are encountered in some operational conditions in the CERN injectors. A good example is the SPS, as discussed in more detail below.

Reaching the LIU target beam parameters requires injecting 25 ns beams with unprecedented intensity (about twice compared to today's nominal) and beam brightness. In the past, coherent and incoherent electron cloud effects were encountered in the SPS already with the nominal intensity. Over the years this effect was slowly reduced by beam induced scrubbing. In recent machine studies with high intensity beams (not yet LIU intensity) a strong incoherent emittance growth was observed when storing the beam for about 20 s at injection energy. However, a clear improvement of the beam quality could already be observed after running the machine in this scrubbing configuration for two days [44]. Nevertheless, some residual electron-cloud might always be present in future operation and the interplay with space charge effects could become important.

Other recent studies at the SPS indicate that the tune modulation induced by power converter ripple can play an important role in the beam degradation during the long storage in presence of space charge [45]. Figure 2 (top graph) shows the relative emittance growth and transmission for different working points in the SPS close to excited resonances $(Q_x = 20.33$ deliberately excited using a single sextupole and at $Q_x = 20.40$ most likely driven by space charge itself). Simulations using a frozen potential are far from the experimental observations (middle graph) unless the measured tune ripple induced by the power converters for the main quadrupoles of the SPS is taken into account (bottom graph). Detailed studies on this subject are ongoing.

It should be pointed out that the tune ripple might also play a role for the strong emittance growth and losses observed for the Pb⁸²⁺ ion beam on the SPS injection plateau. This beam has to be stored for more than 40 s for accumulation of several batches from the PS to reach the LIU ion target parameters [2] and the space charge tune shift at injection reaches up to $\Delta Q_y = -0.3$. On the other hand, Intra Beam Scattering is also contributing to emittance growth [46] and the interplay between space charge and Intra Beam Scattering needs to be studied.

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Figure 2: Relative emittance growth and losses as a function of the measured horizontal machine tune in measurements (top), in simulations (middle) and in simulations including the tune ripple induced by power converters in the SPS (bottom).

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REFERENCES

- J. Coupard *et al.*, "LIU Technical Design Report Volume I: Protons", CERN, Geneva, Switzerland, Rep. CERN-ACC-2014-0337, Dec. 2014.
- [2] J. Coupard *et al.*, "LIU Technical Design Report Volume II: Ions", CERN, Geneva, Switzerland, Rep. CERN-ACC-2016-0041, April 2016.

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- [3] "Facility for Antiproton and Ion Research", https:// fair-center.eu
- [4] E. Métral *et al.*, "Observation of octupole driven resonance phenomena with space charge at the CERN Proton Synchrotron", *Nuclear Instruments and Methods in Physics Research* A, vol. 561, pp. 257-265, 2006, doi:10.1016/j. nima.2006.01.029
- [5] G. Franchetti, et al., "Space charge and octupole driven resonance trapping observed at the CERN Proton Synchrotron", *Phys. Rev. ST Accel. Beams*, vol. 6, p. 124201, Dec. 2003, doi:10.1103/PhysRevSTAB.6.124201
- [6] G. Franchetti and I. Hofmann, "Modeling of Space Charge Induced Resonance Loss", in *Proc. of High Intensity and High Brightness Hadron Beams 2002*, AIP Conf. Proc. No. 642, AIP, New York, 2002, p. 260, doi:10.1063/1.1522641
- [7] G. Franchetti and I. Hofmann, "Particle Trapping by Nonlinear Resonances and Space Charge", in *Proc. of High Intensity Beam Dynamics - COULOMB'05*, Senigallia (AN), Italy, 2005.
- [8] G. Franchetti and I. Hofmann, "Resonance Trapping due to Space Charge and Synchrotron Motion, in Theory, Simulations and Experiments", in *Proc. of High Intensity and High Brightness Hadron Beams 2006*, Tsukuba, Japan, 2006.
- [9] G. Franchetti and I. Hofmann, Nucl. Instrum. Methods Phys. Res., Sect. A, vol. 561, p. 195, 2006.
- G. Franchetti *et al.*, "Experiment on space charge driven nonlinear resonance crossing in an ion synchrotron", *Phys. Rev. ST Accel. Beams*, vol. 13, p. 114203, 2010, doi:10. 1103/PhysRevSTAB.13.114203
- G. Franchetti *et al.*, "Space charge effects on the third order coupled resonance", *Phys. Rev. Accel. Beams*, vol. 20, p. 081006, 2017, doi:10.1103/PhysRevAccelBeams.20. 081006
- [12] F. Schmidt, "Untersuchungen zur dynamischen Akzeptanz von Protonenbeschleunigern und ihre Begrenzung durch chaotische Bewegung", PhD thesis, DESY HERA 88-02, 1988.
- [13] G. Franchetti and F. Schmidt, "Extending the Nonlinear-Beam-Dynamics Concept of 1D Fixed Points to 2D Fixed Lines", *Phys. Rev. Lett.*, vol. 114, p. 234801, June 2015, doi:10.1103/PhysRevLett.114.234801
- [14] G. Franchetti and F. Schmidt, "Fix-lines and stability domain in the vicinity of the coupled third order resonance", April 2015, http://arxiv.org/abs/1504.04389
- [15] H. Bartosik, G. Franchetti, F. Schmidt, M. Titze, private communication.
- [16] G. Franchetti, "Sum Resonances with Space Charge", presented at HB2018, Daejeon, Korea, June 2018, paper WEA1WA01, this conference.
- [17] R.W Hockney and J.W Eastwood, "Computer Simulation Using Particles", ISBN9780852743928.
- [18] F. Kesting and G. Franchetti, "Propagation of numerical noise in particle-in-cell tracking", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 114201, Nov. 2015, doi:10.1103/ PhysRevSTAB.18.114201
- [19] A. Bruce Langdon, "Effects of the spatial grid in simulation plasmas", *Journal of Computational Physics*, vol. 6, Issue 2, October 1970, pp. 247-267, doi:10.1016/ 0021-9991(70)90024-0

- [20] J. Qiang, "Symplectic multiparticle tracking model for self-consistent space-charge simulation", *Phys. Rev. Accel. Beams*, vol. 20, p. 014203, 2018, doi:10.1103/ PhysRevAccelBeams.21.054201
- [21] M. Bassetti and G.A. Erskine, "Closed Expression for the Electric Field of a two-dimensional Gaussian Charge", CERN-ISR-TH/80-06, Geneva, March 1980.
- [22] Y. Alexahin *et al.*, "Adaptive Space Charge Calculations in MADX-SC", in *Proc. NA-PAC'16*, Chicago, IL, USA, Oct. 2016, paper THPOA15, doi:10.18429/ JACoW-NAPAC2016-THPOA15
- [23] Andrei Shishlo *et al.*, "The Particle Accelerator Simulation Code PyORBIT", *Procedia Computer Science*, vol. 51, pp. 1272-1281, 2015.
- [24] G. Franchetti, "The GSI Bench-Marking Suite", http://web-docs.gsi.de/~giuliano/research_ activity/trapping_benchmarking/main.html
- [25] G. Franchetti *et al.*, "MICROMAP Library", http://web-docs.gsi.de/~giuliano/micromap_ manual/micromap_reference_manual.html
- [26] S. Machida, "The Simpsons program 6-D phase space tracking with acceleration", *AIP Conference Proceedings*, vol. 297, p. 459, 1993, doi:10.1063/1.45344
- [27] J. Galambos *et al.*, "Orbit A ring injection code with space charge", ibid, p. 3143.
- [28] E. Stern et al., "SYNERGIA", https://cdcvs.fnal.gov/ redmine/projects/synergia2/wiki
- [29] J. Amundson *et al.*, "High Performance Computing Modeling Advances Accelerator Science for High Energy Physics", *IEEE Comput.Sci.Eng.*, vol. 16, no. 6, pp. 32-41, 2014.
- [30] E. Stern, "Studies on space charge compensation", 2nd CERN Space Charge Collaboration Meeting, March 2018, https: //indico.cern.ch/event/688897
- [31] S. Machida, "Benchmarking and Application of Space Charge Codes for Rings", in *Proc. IPAC'15*, Richmond, VA, USA, 2015, pp. 2402-2407.
- [32] F. Schmidt *et al.*, "Code Bench-marking for Long-term Tracking and Adaptive Algorithms, in *Proc. HB'16*, Malmö, Sweden, 2016, paper WEAM1X01, pp. 357-361, ISBN978-3-95450-178-6
- [33] H. Bartosik *et al.*, "Improved Methods for the Measurement and Simulation of the CERN SPS Non-linear Optics", in *Proc. IPAC'16*, Busan, Korea, 2016, paper THPMR036, pp. 3464-3467.
- [34] V. Forte *et al.*, "CERN Proton Synchrotron booster space charge simulations with a realistic model for alignment and field errors", *Phys. Rev. Accel. Beams*, vol. 19, p. 124202, 2016, doi:10.1103/PhysRevAccelBeams.19.124202
- [35] R. Wasef, "PS Experiments and Simulations", 1st CERN Space Charge Collaboration Meeting, CERN, Geneva, May 2014, https://indico.cern.ch/event/292362
- [36] S. Machida, "Space charge simulation for 4th order resonance", CERN Space Charge Collaboration Meeting, CERN, Geneva, May 2014, https://indico.cern.ch/event/ 292362

61st ICFA ABDW on High-Intensity and High-Brightness Hadron Beams ISBN: 978-3-95450-202-8

- HB2018, Daejeon, Korea JACoW Publishing doi:10.18429/JACoW-HB2018-M0A1PL01
- [37] R. Wasef, "Space charge in the PS", Machine Studies Working Group meeting, CERN, Geneva, July 2015, https: //indico.cern.ch/event/433250/
- [38] F. Asvesta et al., "PS: Studies on Qy=6.25 and other resonances", 2nd CERN Space Charge Collaboration Meeting, CERN, Geneva, March 2018, https://indico.cern.ch/ event/688897
- [39] S. Machida, "About indirect space charge driven resonances", 2nd CERN Space Charge Collaboration Meeting, CERN, Geneva, March 2018, https://indico.cern.ch/event/ 688897
- [40] F. Asvesta *et al.*, "Resonance Identification Studies at the CERN PS", in *Proc. IPAC'18*, Vancouver, BC, Canada , 2018, paper THPAK056.
- [41] A. Huschauer *et al.*, "Identification and compensation of resonances in the CERN Proton Synchrotron", presentation at Space Charge 13 workshop, CERN, Geneva, April 2013, https://indico.cern.ch/event/221441/

- [42] G. Franchetti, "Resonance Compensation for High Intensity Bunched Beam", in *Proc. IPAC'15*, Richmond, VA, USA, 2015, paper MOPWA028, pp. 159-161.
- [43] O. Boine-Frankenheim and W. Stem, "Space charge compensation for intense ions beams in booster synchrotrons", arXiv:1705.01057
- [44] G. Rumolo, "Beam Dynamics Challenges for the LHC and Injector Upgrades", presented at HB2018, Daejeon, Korea, June 2018, paper MOA1PL02, this conference.
- [45] H. Bartosik *et al.*, "SPS: Power converter ripple and space charge driven resonance", 2nd CERN Space Charge Collaboration Meeting, CERN, Geneva, March 2018, https: //indico.cern.ch/event/688897
- [46] A. Saa Hernandez et al., "Characterization of Losses and Emittance Growth for Ion Beams on the SPS Injection Plateau", in Proc. IPAC'18, Vancouver, BC, Canada, 2018.

MOA1PL01