ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRA2I1

SUMMARY OF THE WORKING GROUP A: BEAM DYNAMICS IN RINGS

H. Bartosik*, G. Rumolo, CERN, Geneva, Switzerland
J.-L. Vay, LBNL, Berkeley, CA, USA
N. Wang, IHEP, Bejing, China

Abstract

The HB-2023 workshop at CERN from October 9 to 13, 2023 is the continuation of the series of workshops, which started in 2002 at FNAL and rotates every two years between America, Europe and Asia. This contribution summarises the main highlights from Working Group A, Beam Dynamics in Rings, in terms of progress and challenges in the achievement of ever higher intensity and brightness hadron beams in accelerator rings around the world.

INTRODUCTION

The HB-2023 workshop at CERN from October 9 to 13, 2023 is the continuation of the series of workshops, which started in 2002 at FNAL and rotates every two years between America, Europe and Asia. This contribution summarises the main highlights from Working Group A, Beam Dynamics in Rings, in terms of progress and challenges in the achievement of ever higher intensity and brightness hadron beams in accelerator rings around the world. The following main themes have been treated during the Working Group A sessions:

- Understanding and mitigating space charge effects;
- Studies for characterizing luminosity;
- Understanding and mitigating beam instabilities;
- The pursuit for more powerful simulation tools.

A short summary of the main highlights from each of these themes will be given in the following, and the main challenges ahead will then be discussed.

UNDERSTANDING AND MITIGATING SPACE CHARGE EFFECTS

Losses and emittance growth due to space charge effects in combination with resonances, lattice driven or space charge driven, remain among the most prominent performance limitations for high brightness and high power circular hadron machines.

Careful optimization of the tune working point for avoiding resonances (e.g. Montague resonance and half integer resonances) allows reaching large space charge tune spreads at injection with losses below the percent level. This was shown for the case of the CSNS rapid cycling synchrotron, where a tune variation along the cycle ("tune pattern") through a modulation of the quadrupole fields was developed to mitigate space charge effects at injection and suppress beam instabilities during the ramp [1]. Like this, loss levels could be maintained at a minimum for the nominal 100 kW beam power (and beyond) when combined with correlated injection painting [2]. However, foil heating remains a big challenge. A new painting scheme using a pulsed injection chicane, combining the injection chicane and the painting bump, was developed for CSNS-II in order to reduce the foil temperature and the edge focusing effects from the injection chicane [2]. This scheme saves one set of bumper magnets, and reduces the optics distortion and resonance excitation, which in turn allows for smaller transverse emittances and higher intensities.

As shown in several contributions at the workshop, the compensation of lattice or injection chicane driven resonances through dedicated corrector magnets is nowadays standard practice in many machines. Identifying the magnetic errors through beam-based measurement of resonance driving terms from turn-by-turn beam position data has proved quite successful, as demonstrated for example in the studies at Fermilab [3]. These beam-based measurement techniques are particularly relevant for existing machines, for which detailed magnetic modelling is not available.

Another method for identifying magnetic errors through beam-based measurements has also been presented, the so-called "Deep Lie-Map Networks" [4]. This method builds an improved accelerator model with magnetic errors such that simulated tracking of single particles through Lie Maps reproduces the measured turn-by-turn beam position data along the machine. A first proof-of-principle experiment was performed at GSI to identify sextupole errors from trajectory data, and further experimental campaigns are planned. During the workshop, it was suggested to extend the method by including also the tunes and chromaticity as objectives for the algorithm.

The compensation of resonances excited by the nonlinear potential of the space charge force itself is particularly challenging, but was successfully demonstrated at the J-PARC main ring [5]. In particular, minimizing the driving term of the $8Q_y = 171$ structure resonance through the optimization of the arc phases advance while maintaining the overall tunes of the machine through adjustments of the straight section optics resulted in reduced beam loss in operation.

In the context of discussing resonance compensation schemes in different machines, A. Oeftiger proposed to formulate the efficiency of resonance compensation in the sense of "how much intensity could be gained by resonance compensation for a given amount of acceptable losses".

An open question raised by V. Lebedev at the workshop concerns the maximum achievable space charge tune shift in a real machine with a highly super-periodic lattice operating above the half-integer. While this question was not answered at the workshop, the maximum tolerable space charge tune

* Hannes.Bartosik@cern.ch

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRA2I1

shift depends on several factors, in particular for how long the strong space charge regime needs to be maintained during the machine cycle (e.g. difference between rapid cycling synchrotrons and beam accumulation in injector rings).

Progress has also been shown on the side of the theoretical understanding of space charge effects. In particular, a two-particle model for space charge and chromaticity effects in a coasting beam has been studied, showing a coupling and exchange between the motion of the centre of mass ("coherent") and the motion with respect to the centre of mass ("incoherent") similar to the classical linear coupling description [6]. This behaviour was confirmed also in multiparticle simulations and in experimental studies a the CERN PSB. The aspect of exchange between coherent and incoherent motion was not yet addressed as such in past studies using a particle-core model [7], and it was suggested by E. Métral at the workshop to extend the model to include also impedance effects in the future.

Concerning the impact of dispersion on the coherent motion in presence of space charge, previous studies for coasting beams have been extended to the 3D case [8]. It has been shown that, in this case, sidebands appear around the envelope modes, and that the split of dispersion mode is coupled to the envelope modes.

STUDIES FOR CHARACTERIZING LUMINOSITY

Luminosity calibration is of fundamental importance for the precision of high energy particle physics experiments in high brightness colliders and a few studies related to this aspect have been treated in the workshop.

The observation of non-factorizable distributions in LHC van der Meer scans actually triggered space charge studies in the LHC injector chain. It was demonstrated experimentally that space charge induced periodic resonance crossing can generate statistical dependence between the transverse planes for the case of coupled resonances, as shown experimentally through profile measurements in both planes for different amounts of scraping in one plane after the beam was exposed to different resonances (one dimensional or coupling resonances) [9].

Another example concerns the impact of beam-beam effects on luminosity during precision luminosity measurements using van der Meer scans. It was shown that beam-beam effects in the LHC introduce a luminosity bias due to a change in orbit and a change in optical properties and a crosstalk due to multiple experiments being in collision. A benchmark experiment was performed at the LHC, which was reproduced in self-consistent tracking simulations within few percent of the experimental observations [10]. The good modelling of this effect can thus be used for correcting the luminosity values in the experiments in operational conditions based on the low intensity single bunch van der Meer scans.

UNDERSTANDING AND MITIGATING BEAM INSTABILITIES

The beam coupling impedance induces tune shifts (coherent and incoherent) and drives coherent beam instabilities. A good theoretical understanding and minimization of impedance contributions is thus crucial for maximising the intensity reach of circular hadron accelerators.

For existing machines, the observation of instabilities or beam quality degradation typically triggers studies to identify through modelling and measurement, and modify (if possible) the responsible impedance source in the machine. This was shown nicely for the example of the J-PARC main ring, where a longitudinal microbunch structure developing during slow extraction could be successfully cured by reducing the impedance of the eddy current extraction septa through the addition of plates to ensure the continuation of the beam pipe inside the septum tank so that the mirror current flows smoothly, as well as the impedance reduction of other extraction septa [11].

In the case of the SPS at CERN, the impedance induced coherent tune shifts attain large values for the bunch intensities requested for the High Luminosity LHC era, requiring a good tune correction to ensure that the transverse damper is efficient for mitigating transverse coupled bunch instabilities [12]. This tune correction compensates for the average tune shift of the newly injected bunch train and so far this was sufficient for reaching the required beam quality (i.e. emittance growth between batches within budget). At the workshop it was proposed to investigate if a reactive damper configuration could be used to actually compensate the bunch-by-bunch coherent tune shift that builds up along the train in the vertical plane.

Significant progress has been reported on the theoretical treatment of longitudinal instabilities as demonstrated for examples from the LHC and the SPS at CERN from both numerical calculations and beam-based measurements [13]: It was shown that the instability threshold for the loss of Landau damping for a binomial distribution is inversely proportional to the cut-off frequency, a generalized threshold due to loss of Landau damping and coupled bunch instabilities was developed, and the important role of the RF non-linearity on the potential well distortion was demonstrated resulting in lower radial mode-coupling instability threshold compared to the threshold for azimuthal mode-coupling instability expected from the classical Sacherer theory [14].

An aspect not fully resolved yet concerns the role of space charge in transverse beam instabilities. In particular, experimentally measured rise times can be usually reproduced in simulations without space charge, but there is no good agreement of the intrabunch motion, as reported for the case of the CERN PS for the studies of horizontal instability driven by kicker cables and their external circuits [15], and for the case of the vertical instability observed at ISIS [16]. A comparison with the predictions from convective instabilities [17], and with the predictions from the dispersion integral includ-

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRA2I1

ing detuning as suggested by X. Buffat during the workshop, should be performed.

One proposition was to solve the "inverse stability problem of beam dynamics", i.e. to determine the particle distribution function from measurements of the stability diagram [18]. This could still be challenging in actual practice, considering a number of uncertainties introduced by the space charge, the impedance, and the nonlinearity of the optics. However, this method could be of particular interest in experimentally measuring the tails of the particle distribution, which is usually challenging using available beam instrumentation techniques due to noise.

THE PURSUIT FOR MORE POWERFUL SIMULATION TOOLS

Accurate predictions of high intensity induced beam halo, losses, emittance growth and collective instabilities require more and more powerful simulation tools. The integration and modernization of a large body of legacy codes is a path towards faster and more capable code suites, as demonstrated in different contributions at the workshop. The trend goes to porting codes to GPUs, as this allows for the simulation of more particles, higher resolution, larger systems, longer integration time. On the integration side, emphasis is put on more efficient co-development and reuse, more physics at hand to explore all possible couplings, not "miss anything", increase realism toward digital twins and open design capabilities beyond "what we can compute", and a gateway to community ecosystems with standards. In many cases a programmable (Python) frontend is chosen, as it is user-friendly with shorter learning curve and flexibility for extension, exploration and coupling with Artificial Intelligence (AI)/Machine Learning (ML) tools, and coupling with other codes and experiments.

The CERN legacy codes are being upgraded and combined into a modern, integrated suite called Xsuite [19]. It combines features of MAD-X, Sixtrack, COMBI, pyHEADTAIL, and others, into a modular and extensible suite with unified and flexible Python interface, CPU and GPU support, and it is open source. Although the development has started not long ago, there are already various users and applications to date.

The simulation codes from Berkeley Lab (WarpX, ImpactX, etc.) are also being modernized and combined into the Beam, pLasma & Accelerator Simulation Toolkit (BLAST) [20]. It combines a triple acceleration approach (i.e. exploiting GPU, Mesh Refinement, and AI/ML) with a flexible Python frontend, and is also open source. This is part of a larger effort to develop a Community Ecosystem based on standardized inputs/outputs.

The CISP-GPU is a new code with many features for end-to-end simulations for the HIAF/BRing (IMPCAS) [21]. It is applied to nonlinear lattices and space charge effects and their mitigation. It is planned to be embedded into LACCS to provide high level features for commissioning and online beam dynamics research.

MAIN CHALLENGES AHEAD

Several challenges were highlighted at the workshop at different occasions, such as:

- Loss control at the sub-per-mill level to allow for multi MW beam power (e.g. ISIS II [16])
- To demonstrate space charge compensation by pulsed e-lenses (FAIR-SIS100)
- Crab cavities for hadron colliders (such as HL-LHC [22] and EIC) pose particular challenges as the low noise levels and feedback requirements to limit emittance growth are beyond the state of art.
- Accurate impedance modelling at very low frequencies (particularly concern for machines with small transverse tunes) when the electromagnetic fields of the beam penetrate out the beam pipe and see the outside boundaries. The transverse feedback system at too low frequency can also be challenging.
- The mitigation of e-cloud effects at the LHC remains a big challenge, as the surface condition of the beam screens degrades after each long shut down and the resulting e-cloud generation further and further limits the maximum number of bunches in the machine. This issue needs to be addressed at the root cause and developments of Plasma-assisted CuO reduction and carbon recovery (PE-CVD) or carbon coating (10 nm to 20 nm) by sputtering are being followed in view of the High Luminosity LHC upgrade [22].
- Being creative for proposing new accelerator applications for interesting physics cases is clearly a challenge for the entire particle accelerator and high energy physics community. In this respect, a nice example of a predominantly electric "E&m" storage ring with nuclear spin control capability to study "rear-end" d-p collisions was shown at the workshop [23].

CONCLUDING REMARKS

The conveners of the Working Group A would like to thank all the speakers for the excellent and very interesting presentations, and all workshop participants for their active contribution and fruitful discussion. We are looking forward to an interesting HB workshop in 2025.

REFERENCES

[1] S. Xu *et al.*, "Tune Optimization for Alleviating Space Charge Effects and Suppressing Beam Instability in the RCS of CSNS", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper WEA2C1.

[2] M.-Y. Huang *et al.*, "Performance and Upgrade Considerations for the CSNS Injection", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper THA1I1.

[3] C. Gonzalez *et al.*, "Compensation of Third-Order Resonances in the High Intensity Regime", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper WEA2I1.

[4] C. Caliari *et al.*, "Identification of Magnetic Field Errors using Deep Lie Map Networks", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper WEA1C2.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRA2I1

[5] T. Yasui *et al.*, "Space Charge Induced Resonances and Suppression in J-PARC MR", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper WEA2I2.

[6] G. Franchetti *et al.*, "Analytical and Numerical Studies on Kicked Beams in the Context of Half-Integer Studies", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper WEA1I2.

[7] I. Karpov, V. Kornilov, and O. Boine-Frankenheim, "Early Transverse Decoherence of Bunches With Space Charge", *Phys. Rev. Accel. Beams*, vol. 19, p. 124201, 2016. doi:10.1103/PhysRevAccelBeams.19.124201

[8] Y. Yuan *et al.*, "Coherent Dispersion Effects in 2-D Coasting Beams and 3-D Bunched Beams in High-Intensity Hadron Synchrotrons", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper TUA1C2.

[9] E. Lamb *et al.*, "Effects of Statistical Dependence in the Transverse Planes for Non-Gaussian Beam Distributions", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper WEA2C2.

[10] T. Pieloni *et al.*, "Beam-Beam Effects: Modelling, Measurements and Correction Strategy on the Luminosity Calibration Measurements at the Large Hadron Collider Experiments", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper TUA2C1.

[11] A. Kobayashi *et al.*, "Major Longitudinal Impedance Sources in the J-PARC Main Ring", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper TUA1C1.

[12] I. Mases Sole *et al.*, "Bunch-by-bunch Tune Shift Studies for LHC-type Beams in the CERN SPS", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper WEA1C1.

[13] I. Karpov *et al.*, "New Understanding of Longitudinal Beam Instabilities and Comparison With Measurements", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper TUA1I2.

[14] F. J. Sacherer, "Methods for Computing Bunched-beam Instabilities", CERN, Geneva, Switzerland, Rep. CERN-SI-BR-72-5, 1972.

[15] S. Joly *et al.*, "Recent Advances in the CERN PS Impedance Model and Instability Simulations", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper TUA2C2.

[16] R. Williamson *et al.*, "High-Intensity Studies on the ISIS RCS and their Impact on the Design of ISIS-II", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper THA1I2.

[17] A. Burov, "Convective Instabilities of Bunched Beams With Space Charge", *Phys. Rev. Accel. Beams*, vol. 22, 034202, 2019. doi:10.1103/PhysRevAccelBeams.22.034202

[18] A. Burov , "Inverse Stability Problem in Beam Dynamics", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper TUA1I1.

[19] G. Iadarola *et al.*, "Xsuite: An Integrated Beam Physics Simulation Framework", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper TUA2I1.

[20] C. Mitchell *et al.*, "Community Modeling Tools for High Brightness Beam Physics", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper TUA2I2.

[21] J. Liu *et al.*, "Development and Application of High-performance CISP-GPU Code for High Intensity Effects in Hiaf", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper WEA1I1.

[22] N. Mounet *et al.*, "High Intensity Beam Dynamics Challenges for HL-LHC", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper THA1C1.

[23] R. Talman, "Predominantly Electric Storage Ring with Nuclear Spin Control Capability", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper THA1I3.