SUMMARY OF WORKING GROUP A

Wolfram Fischer, BNL, Upton, NY, USA
Giuliano Franchetti, GSI, Darmstadt, Germany
Yong Ho Chin, KEK, Ibaraki, Japan

The working group A, Beam Dynamics in Rings, was structured with the following 6 sections:

1) Collective effects (4 talks),
2) Space charge - beam-beam (4 talks);
3) Code development and benchmarking (4 talks);
4) New machines / New Concepts (4 talks);
5) Theory (4 talks);
6) Emerging talents (6 talks).

A few highlight are given below.

COLLECTIVE EFFECTS

Elias Metral, CERN has presented a status of the collective effect at CERN [1]. The talk concluded that in a machine like LHC, not all the effect can be understood separately. Instead all the possible interplay between the several phenomena need to be analyzed in detail, these effects should include: beam-coupling impedance (collimators, crab cavities); linear and nonlinear chromaticity; Landau octupoles; transverse damper; space charge; beam-beam; electron cloud; linear coupling; tune separation between transverse planes; tune split between the two beams; transverse beam separation between the two beams; noise effects.

Giovanni Rumolo, CERN reviewed the state of the art of the electron cloud effects in the LHC and SPS [2]. The comprehensive talk showed that because of intensive measurements and new simulation tools, a deeper knowledge of the electron cloud in the different CERN accelerators has been reached. For the present 25 ns beam parameters PS and SPS can deliver the required beams within the original specifications. The LHC still suffers from electron clouds. Scrubbing mitigates the electron cloud, and allows for LHC operation, but it is not known up to which point one can rely on scrubbing. Future parameter studies include: in PS e-cloud instabilities should be prevented by transverse feedback system; SPS relies on scrubbing, and relevant chambers will be a-C coated; the HL-LHC will also require studies on scrubbing.

SPACE CHARGE – BEAM-BEAM

Hannes Bartosik, CERN has presented a study of the beam loss in LEIR for high intensity bunched beams [3]. The intensity limitation at LEIR are found experimentally to happen during and after the RF capture. It has been identified that the mechanism driving the beam loss is the interplay of space tune-spread with betatron resonances. It is also found that the vertical emittance is enlarged after RF capture. The mitigation of the beam loss happens by reducing the bunching factor and thereby the space charge tune-spread, and by reducing the excitation of chromatic sextupoles (resonance reduction). These steps have provided a significant reduction of beam loss in LEIR. Plans to further increase the intensity aim at increasing the repetition rate to 10 Hz, the development of a new optics that reduces the strength of low order resonances.

Shinji Machida, STFC presented a study on the effect of space charge on the multi-turn extraction scheme presently running at CERN [4]. The study is motivated by the experimental studies reported in [5, 6], where it appears that the fixed-points in the four islands drift outwards in the phase space when the beam intensity is increased. Simulation studies tracking beam in free space have highlighted that the effect of space charge on the fixed-points is reverted (they move inward in phase space when increasing the beam intensity). The study shows that the effect of the image charge created by the pipe plays the crucial role for unraveling the reverted pattern of the fixed-points. The talk has presented the slope of the fixed-point/intensity for each beam-let when the boundary is included.

CODE DEVELOPMENT AND BENCHMARKING

Frank Schmidt, CERN has presented a code-code benchmarking based on previous HB work [7]. For several codes that implement frozen or PIC space charge algorithm, a comparison of emittance growth over 10^5 turns is made. The physics case is the periodic crossing of one SIS18 resonance. The result of the benchmarking showed that the codes MICROMAP, SIMSONS, MADX and SYNERGIA agree well especially considering the differences in space charge calculation methods, and lattice modeling. In the talk it was shown that code-experiment benchmarking has been performed using the PS experiment data showing a good agreement also for a storage time of half million turns.

Oliver Boine-Frankenheim, GSI has presented a new development in PIC solvers [8]. The issue of simplecticity in particle tracking, which uses PIC is of relevance for long term tracking. In fact, artificial emittance growth is the result of un-physical modeling of the beam dynamics. The talk has presented a review of the methods for avoiding grid heating and artificial noise. A test example using a spectral solver has shown that artificial emittance growth due to grid heating can be avoided. This removes artificial emittance growth at the expenses of heavier computational load. Also Ji Qiang [9] has discussed in WGB a similar integration scheme.

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NEW MACHINES / NEW CONCEPTS

Sergei Nagaitsev, FERMILAB reviewed IOTA [10]. The project is advancing, building space is ready, and the main components of IOTA includes: 20 x/y skew correctors, 8 correctors in dipoles, 20 button BPMs, 30 deg and 60 deg dipoles with synch-light ports, electron-lens sections, and an optical stochastic cooling section.

A very exciting IOTA research program will be centered around nonlinear beam dynamics and advanced beam cooling, in particular on

1) nonlinear integrable optics;
2) space charge compensation;
3) optical stochastic cooling;
4) beam collimation technology development with hollow electron lenses;
5) electron cooling advanced techniques.

Studies for a high intensity proton FFAGs at RAL were presented by **Christopher Prior** [11]. The talk reviewed the ISIS Upgrades option. ISIS has long-served as neutron and muon facility operating at 160-180 kW, with two target stations. There is a continuous program of maintenance, replacements and upgrades with ongoing studies to upgrade to the MW level beam power. ISIS Upgrade options are:

1) a 70 MeV Linac with new tank;
2) replacement of injector with a 180 MeV Linac;
3) phased upgrades for 2.5-3 MW with: a) addition of a 3.2 GeV RCS, b) addition of a new 800 MeV H–ĹŠ Linac.

The future multi-megawatt proton driver aimed specifically at a spallation neutron source (short pulse), including a small test ring that might also have a practical application. FFAGs may be a good choice for a high intensity machine. The main options for the upgrade are:

1) RCS Pumplet, and
2) the DF-Spiral FFAG.

The associated experimental program includes an MoU with Kyoto University (FFAGs at KURRI), and an MoU with Hiroshima University (Paul trap studies of particle accelerators).

THEORY

In the theory section **Ingo Hofmann, GSI/TUD**, attempted to give a global view on the space charge resonances introducing a "typology" of the resonances [12]. The talk categorized two main groups of resonant space charge effects:

1) "Single particle" resonances with driving terms due to the initial space charge profile, the "usual" resonance diagram; and
2) Parametric "half-integer" resonances, which are equivalent to instabilities with driving term pumped from initial noise "stability diagram".

He also concluded that parametric resonances are characterized by coherence in density, hence frozen space charge simulation cannot include these type of effects.

This development should stimulate more experiments to further advance the understanding, which necessarily has to include the synchrotron motion. The discussion of the 3rd order resonance effect has shown, however, different conclusions between Ingo Hofmann [12], and Dong O Jeon [13]; one author called it 3rd order instability, and the other 3rd order parametric resonance. The unraveling of the discrepancy is left to future HB.

Alexei Burov, Fermilab presented a review of head-tail modes with strong space charge [14]. The review started with the work of M. Blaskiewicz on the fast head-tail instability with space charge, and the further development addressing the head-tail modes for strong space charge (A. Burov). Coupled-beam and coupled-bunch instabilities have been treated in the presentation (former work of A. Burov).

Then the presentations addressed numerical work by **V. Kornilov** and **O. Boine-Frankenheim** on head-tail instability and Landau damping in bunches with space charge. The review also discusses the threshold of head-tail instabilities in bunches with space charge (V. Kornilov et al.), and conclude with the latest results on simulation of transverse modes with their intrinsic Landau damping for bunched beams in the presence of space charge (A. Macridin et al.).

A lively discussion followed the talk by **V. Kornilov** on head-tail instability and Landau damping in bunches with space charge [15]. The audience had several comments and an additional early morning session organized Friday from 8:00 to 8:45 has been requested to discuss the topic further. Extra presentation by **Elias Metral** on constant inductive impedance, and by **Alexy Burov** on why there is no Landau damping for the rigid bunch mode have take place during the extra session.

EMERGING TALENTS

The section on emerging talents have covered a broad spectrum of topics such as the space charge effect in FFAGs [16], and how to use electron lenses to compensate space charge [17]. Contribution on nonlinear optics experiment from university [18], and strip-line BPM with improved frequency response [19] have been discussed. The special use of RF quadrupole to enhance stability has been part of the session as well [20].

FINAL CONSIDERATION

The history of space charge effects in ring traces back to prior 1985 at the time when incoherent tune-shift was understood by Lastlett, and the KV distribution was invented. From 1985 to 1990 studies on emittance preservation were performed, especially it started the advent of multi-particle simulations. Theory benefited of Frank Sacherer's innovative work. In the years from 1990 till 2000 the studies developed particle core models, and simulation codes have become more complex and capable. The decade 2000 – 2010 marks the start of the HB workshop series. There is a renewed interest incoherent effects, and systematic machine

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studies started at a number of laboratories including CERN, GSI, J-PARC, and ORNL. The machine modeling has significantly improved. In this decade the beam dynamics analysis also started to include the interplay of several effects.

What are the new trends and the new challenges for this decade?

1 "The computational paradox". From the previous decade the computer power have grow larger and lager, and the advent of new computer languages have allowed the creation of codes that can model accurately a complex accelerator. However, the increase of modeling power leave open all the challenges for understanding the beam dynamics. A new effort for extracting the beam physics from simulation is necessary to give new input to theoretical development.

2 "Coherent vs. Incoherent". In the previous decade a rise of the incoherent effect gain importance in relation with space charge and machine nonlinearities interplay. However it is not clear how coherent and incoherent effects interplay each other, and which beam parameters favor one with respect to the other.

3 The "Transverse - Longitudinal" connection. Transverse, and longitudinal dynamics are often treated as separated areas of studies. However, the trends in the past decades, especially the interplay of effect intertwine these two community. Challenges are in some context arising from the necessity of studying the full 3D dynamics. The experience accumulated in each community is a starting point for a new approach to beam physics in accelerator (also helped by simulation and machine experiment insight).

4 Role of "machine experiment" and the beam dynamics in rings. It is now time for the community to redefine the role of the machine experiments. Some question remain open:
   a) What machine experiments are needed to clarify beam physics this is not well understood?
   b) What is the new beam physics to be addressed?
   c) What machine-code-theory benchmarking is necessary to validate the models?
   d) Is it the beam physics progress uniquely a function of operational needs, or can we progress with new ideas or schemes for advancing the field?

OUTLOOK

The working group A leaves open for the next HB a basket of topics of high relevance:

- What are the machine limits and how can they be addressed? The standard approach to overcome a space-charge limits in rings is still to build a higher energy Linac (the exception to this approach is IOTA).
- After decades of research the community still has no unified language to describe the space charge phenomena.
- There are a number of simulations codes available, and the question arises if the communities efforts should concentrate on fewer codes with more collaborators.

REFERENCES

[1] E. Métral, "General Formula to Deduce the Space Charge Tune Spread From a Quadrupolar Pick-Up Measurement", presented at HB2016, Malmö, Sweden, June 2016, paper MOPR024.

[2] G. Rumolo, H. Bartosik, E. Belli, G. Iadarola, K.S.B. Li, L. Mether, A. Romano, and M. Schenk, "Electron Cloud in the CERN Accelerator Complex", presented at HB2016, Malmö, Sweden, June 2016, paper TUAM4X01.

[3] H. Bartosik, S. Hancock, A. Huschauer, and V. Kain, "Space Charge Driven Beam Loss for Cooled Beams and Mitigation Measures in the CERN Low Energy Ion Ring", presented at HB2016, Malmö, Sweden, June 2016, paper TUAM5X01.

[4] S. Machida, S.S. Gilardoni, M. Giovannozzi, S. Hirlaender, A. Huschauer, and C.R. Prior, "Intensity Effects in the Formation of Stable Islands in Phase Space During the Multi-Turn Extraction Process at the CERN PS", presented at HB2016, Malmö, Sweden, June 2016, paper TUAM7X01.

[5] A. Huschauer, J.C.C.M. Borburgh, S. Damjanovic, S.S. Gilardoni, M. Giovannozzi, C. Hernalsteens, M. Hourican, K. Kahle, G. Le Godec, O. Michels, and G. Sterbini, "Transverse Beam Splitting Made Operational: Recent Progress of the Multi-Turn Extraction at the CERN Proton Synchrotron", presented at HB2016, Malmö, Sweden, June 2016, paper MOPR009.

[6] S. Gilardoni, M. Giovannozzi, and C. Hernalsteens, *Phys. Rev. ST Accel. Beams* **16**, 051001 (2013).

[7] F. Schmidt, Y. I. Alexahin, J. F. Amundson, H. Bartosik, G. Franchetti, J. A. Holmes, A. Huschauer, V. V. Kapin, A. Oeftiger, E. G. Stern, and M. Titze, "Code Bench-Marking for Long-Term Tracking and Adaptive Algorithms", presented at HB2016, Malmö, Sweden, June 2016, paper WEAM1X01.

[8] O. Boine-Frankenheim, "PIC Solvers for Intense Beams: Status and Future Prospects", presented at HB2016, Malmö, Sweden, June 2016, paper WEAM2X01.

[9] J. Qiang, L. Li, and Z. Wang, "A New RFQ Model and Symplectic Multi-Particle Tracking in the IMPACT Code Suite", presented at HB2016, Malmö, Sweden, June 2016, paper THPM7Y01.

[10] S. Nagaitsev, "Nonlinear Focusing in IOTA for Space-Charge Compensation and Landau Damping", presented at HB2016, Malmö, Sweden, June 2016, paper WEAM7X01.

[11] C.R. Prior, "Studies of High Intensity Proton FFAGs at RAL", presented at HB2016, Malmö, Sweden, June 2016, paper WEAM6X01.

[12] I. Hofmann, "Typology of Space Charge Resonances", presented at HB2016, Malmö, Sweden, June 2016, paper THPM1X01.

[13] D. Jeon, J.-H. Jang, and H. Jin, "Resonances and Envelope Instability in High Intensity Linear Accelerators", presented at HB2016, Malmö, Sweden, June 2016, paper THPM4X01.

[14] A.V. Burov, "Head-Tail Modes With Strong Space Charge: Theory and Simulations", presented at HB2016, Malmö, Sweden, June 2016, paper THPM2X01.

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[15] V. Kornilov, O. Boine-Frankenheim, “Head-Tail Instability and Landau Damping in Bunches with Space Charge”, presented at HB2016, Malmö, Sweden, June 2016, paper THPM3X01.

[16] M. Haj Tahar, F. Méot, “Space Charge Effects in FFAG”, presented at HB2016, Malmö, Sweden, June 2016, paper THPM6X01.

[17] W.D. Stem, O. Boine-Frankenheim, “Using an Electron Cooler for Space Charge Compensation in the GSI Synchrotron SIS18”, presented at HB2016, Malmö, Sweden, June 2016, paper THPM5X01.

[18] K.J. Ruisard, H. Baumgartner, B. Beaudoin, I. Haber, T.W. Koeth, and D.B. Matthew, “Early Tests and Simulation of Quasi-Integrable Octupole Lattices at the University of Maryland Electron Ring”, presented at HB2016, Malmö, Sweden, June 2016, paper THPM8X01.

[19] Y. Shobuda, Y.H. Chin, K.G. Nakamura, K. Takata, and T. Toyama, “Stripline Beam Position Monitors With Improved Frequency Response and Their Coupling Impedances”, presented at HB2016, Malmö, Sweden, June 2016, paper THPM10X01.

[20] M. Schenk, A. Grudiev, K.S.B. Li, and K. Papke, “Use of RF Quadrupole Structures to Enhance Stability in Accelerator Rings”, presented at HB2016, Malmö, Sweden, June 2016, paper THPM7X01.

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