# SUMMARY OF GENERAL SESSION OF WORKING GROUPS A+B+D ON CODE BENCHMARKING *

J. Wei†, Brookhaven National Laboratory, New York, USA
E. Shaposhnikova, F. Zimmermann, CERN, Geneva, Switzerland
I. Hofmann, GSI, Germany
for the working group A, B, and D participants

*Abstract*

This is the summary of the joint session among working groups A, B, and D of the HB2006 Workshop on computer codes benchmarking.

## INTRODUCTION

Computer simulation is an indispensable tool in assisting the design, construction, and operation of accelerators. In particula, computer simulation complements analytical theories and experimental observations in understanding beam dynamics in accelerators. The ultimate function of computer simulation is to study mechanisms that limit the performance of frontier accelerators.

There are four goals for the benchmarking of computer simulation codes, namely debugging, validation, comparison, and verification [1]:

- Debugging: codes should calculate what they are supposed to calculate;
- Validation: results generated by the codes should agree with established analytical results for specific cases;
- Comparison: results from two sets of codes should agree with each other if the models used are the same;
- Verification: results from the codes should agree with experimental measurements.

Adequate debugging is the first goal that established codes should meet. In the following, we summarize the status of validation, comparison, and verification, and provide suggestions for each topic discussed.

Speakers in the code benchmarking session were G. Franchetti (GSI), F. Zimmermann (CERN), V. Kornilov (GSI), I. Hofmann (GSI), A. Burov (FNAL), K. Ohmi (KEK), and A. Fedotov (BNL). Authors whose presentations in other sessions are quoted in this summary include V. Danilov (ORNL), S. Cousineau (ORNL), J. Holmes (ORNL), L. Prost (FNAL), J.-L. Vay (LBNL) and E. Benedetto (CERN).

## CODES BENCHMARKING STATUS

Four topics were covered by this session: space charge, electron cloud, instability driven by external impedances, and electron cooling. Each topic contains one or more tasks for codes benchmarking.

Information on many codes as well as some benchmarking examples can be found in the CARE-HHH accelerator physics code web repository [2].

### *Space Charge*

**Montague resonance and emittance exchange** The aim is to compare the evolution of horizontal and vertical emittances as the transverse tunes are varied so as to cross the Montague resonance of $2\nu_x - 2\nu_y = 0$.

- Validation with 2D analytical theory is performed for most codes. Validation with 3D theory is performed only for a few cases.
- Comparison is performed [3] between the codes ACCSIM [4], IMPACT [5], MICROMAP [6], ORBIT [7], SIMBAD [8], SIMPSONS [9], and SYNERGIA [10]. Good agreement is achieved using 2D models, tracking for $10^3$ turns, and observing emittance evolution when the transverse tunes are swept to cross the Montague resonance.
- Verification is performed with IMPACT3D [5] against experiments on the CERN PS. When the vertical tune is fixed and various horizontal tunes are selected, the agreement is excellent on resonance but poor off resonance. The agreement is poor when one tune is dynamically varied over a time period of $4\times10^4$ turns.
- Suggestion: Longitudinal synchrotron motion needs to be added, and lattice nonlinearities need to be included in all simulation codes.

**Resonance trapping with sextupoles** The present aim is to compare space charge induced trapping of particles in the presence of sextupole magnets during long-term storage. The final aim is to determine halo density and beam loss during long-term storage of high intensity beams.

- No quantitative analytical predictions are available for validation.
- Comparison is performed [11] between codes MICROMAP [6] and SIMPSONS [9]. The comparison is satisfactory on space charge detuning and third-order resonance trapping. However, at the time of the workshop there was about a factor of 2 difference in the full bunch emittance growth for $10^5$-turn simulation using

* Work supported by the auspices of the US Department of Energy.
† jwei@bnl.gov

$10^3$ macroparticles. This factor has recently been resolved and the two codes now are in nearly perfect agreement [12].
- Verification is performed with MICROMAP against experiments on the CERN PS with satisfactory agreement.
- Suggestion: More comparison is needed with fully self-consistent codes like ORBIT [7].

### *Electron Cloud*

**Electron build-up** The aim is to compare the electron density in the beam and vacuum chamber and the electron flux on the chamber wall under beam induced electron multipacting.

- Validation is limited to some special models of multipacting.
- Comparison is performed [13, 14, 15] between the codes POSINST [16], PEI [17], ECLOUD [18], CLOUDLAND [19], EPI [20], CSEC [21], and MEC [22]. The result is sensitive to often unknown and time dependent surface parameters including the incident angular dependence of secondary emission yield $\delta_{max}(\theta)$ and zero-energy reflectivity $R$. The agreement is typically within a factor of 2 to 3 in electron density.
- Verification is performed with ECLOUD [18] against SPS experimental data [23]. Fixing the vaccum pressure and using two fitted parameters ($\delta_{\max} = 1.35$, $R = 0.3$), good agreement is achieved for all measurements (two types of bunch train spacing). Verification is also performed with the codes POSINST [16] against APS and PSR experimental data; good agreement is reached also here using two fitted parameters.
- Suggestion: Benchmarking study on surface scrubbing is needed. More bench measurements are needed on the secondary emission yield and the secondary-electron energy spectrum their dependence on the angle of primary incidence.

**Multi-bunch instability** The aim is to study multi-bunch instability induced by the electron cloud in a positively charged beam.

- Some model validation is performed against analytical predictions based on simulated wake fields generated by the electron cloud.
- No comparison is performed between codes, since only one code, PEI-M [17, 24], is available.
- Verification is performed with code PEI-M [17] against KEKB experimental data [24]. Qualitative agreement is obtained on the mode frequency. On the other hand, when the solenoid is turned on, a good agreement is obtained only if a factor of 5 adjustment is made on the solenoid field.
- Suggestion: It is preferable to combine multi-bunch electron cloud instability codes with single bunch instability codes. PEI-M [17] is the only example so far.

**Single bunch instability** The aim is to study single bunch instability induced by electron cloud in a positively charged beam.

- Two-particle and broadband resonator models are used to validate the codes with satisfactory agreement (within about 30% in predicted emittance growth).
- Comparison is performed between the codes PEHT [25], PEHTS [26], HEADTAIL [27], and QUICKPIC [28] with qualitative agreement on the predicted transverse emittance growth [29, 13, 30]. Different from the other codes, PEHT [25] contains a micro-bunch model.
- Verification is performed with the codes PEHTS [26] and HEADTAIL [27] against KEK-B experimental data [25, 31] and with code the ORBIT [7] against SNS experimental data [32]. The intensity threshold for electron-proton instability is correctly predicted for the SNS ring [32]. The upper sideband phenomenon found in KEKB has been understood and reproduced [31] in simulations with PEHTS [25] and HEADTAIL [27].
- Suggestion: Simulations should consider realistic electron distribution.

**Incoherent effects** The aim is to study incoherent effects related to electron cloud including emittance growth caused by periodic resonance crossing due to electron-cloud induced tune shift and electron-cloud induced resonance trapping or scattering.

- Validation against analytical model is not yet performed.
- Some comparison is performed between codes HEADTAIL [27], Franchetti's codes [12], CLOUD_MAD [33], and PEHTS [26] with qualitative agreements [34].
- Verification is performed with codes HEADTAIL [27] against SPS experiments with good agreement [34].
- Suggestion: KEKB observations below the electron cloud instability threshold need to be bench-marked. Effects due to numerical noise caused by finite number of seed electrons and due to slicing interpolation could further be checked. Analytical estimate needs to be developed for the emittance growth.

**Self-consistent modeling** The aim is to develop a self-consistent model incorporating both the electron generation and the interaction between electrons and beam particles.

- Analytical validation is not performed.
- No comparison is performed between the available codes: ORBIT [7], WARP/POSINST [35, 16], PARSEC [36], and PEI-M [17].
- Verification is performed with codes WARP/POSINST [35, 16] against experimental observation at HCX [37, 38]. Good agreement is obtained for a “coasting” beam.

- Suggestion: Careful comparison needs to be performed between codes. It is highly desirable to develop self-consistent codes addressing performance limiting mechanisms like transverse emittance growth in LHC, beam losses in RHIC, SPS, PSR, and SNS, and vacuum pressure rise in RHIC.

### *Instability Driven by External Impedances*

**Transverse instability** The aim is to study the threshold and growth rates of transverse instability induced by external beam coupling impedances.

- An attempt has been made to validate PATRIC [39] with the dispersion relations of Moehl and Laclare [40]. However, large discrepancies are found in the stability area.
- No code comparison has been presented at the workshop. PATRIC [39] and ORBIT [7] are available for such activities.
- Verification is performed with the code ORBIT [7] against experimental observations on the SNS ring [32]. Instabilities due to the resistive wall impedance and the extraction-kicker broadband impedance are predicted at observed intensity thresholds and frequencies.
- Suggestion: Comparison needs to be performed between codes like PATRIC [39] and ORBIT [7]. Codes need to be compared with more comprehensive theories, e.g., one by M. Blaskiewicz [41].

**Longitudinal instability** The aim is to study the threshold and growth rates of longitudinal instability induced by external beam coupling impedances.

- No validation results have been presented at the workshop.
- No comparison between codes has been presented at the workshop. Codes like ESME [42] and ORBIT [7] are available.
- Verification is performed with ORBIT against observations at PSR [43] and with ESME against observations at SPS [44], in both cases with good agreement.
- Suggestion: Codes for multi-bunch longitudinal instability study are needed.

### *Electron Cooling Friction Force*

The aim is to study the cooling friction force in both magnetized and non-magnetized electron cooling.

- Code VORPAL [45] is validated with Parkhmochuk's expressions for magnetized cooling [46].
- Comparison is performed between codes BETACOOL [47] and VORPAL [45] with good agreement [46].
- Verification is performed with codes BETACOOL [47] and VORPAL [45] against experimental data from CELSIUS for magnetized cooling [48], and with BETACOOL [47] against experimental observations at the FNAL recycler for non-magnetized cooling [48].
- Suggestion: None.

## SUMMARY

"Everybody believes in experiments except the experimentalist; Nobody believes in simulation except the simulationalist." The recent success at SNS predicting instabilities (resistive wall, broadband, electron-proton) [32] on a newly built machine gives us hope that such rules may be violated!

## REFERENCES

[1] M. Furman, HHH-2004 workshop, CERN, Geneva, Session 6B (2004).

[2] *http://oraweb.cern.ch:9000/pls/hhh/code_website.startup*

[3] I. Hofmann et al, "Benchmarking of Simulation Codes Based on the Montague Resonance on the CERN Proton Synchrotron," PAC'05 Knoxville (2005).

[4] F. W. Jones, G. H. Mackenzie, and H. Schönauer, Part. Accel. **31** (1990) 199.

[5] Contact: J. Qiang (LBNL), R. Ryne; J. Qiang et al, J. Comp. Phys. **163** (2000) 434.

[6] Contact: G. Franchetti (GSI), S. Rambaldi, G. Turchetti, A. Bazzani, A. Orzhekhovskaya, Web site: http://www-linux.gsi.de/ giuliano/micromap/manmimac_tmp.html

[7] Contact: A. Shishlo, J. Holmes, S. Cousineau (ORNL), Web site http://www.ornl.gov/ jzh/JHolmes/ORBIT.html; *ORBIT Users Manual*, J. Galambos, J. Holmes, D. Olsen, A. Luccio, and J. Beebe-Wang, SNS/ORNL/AP TN 0011, (1999), http://www.ornl.gov/sns/APGroup/Codes/ ORBITUserMan1_10.html

[8] Contact: A. Luccio and J. Beebe-Wang.

[9] Contact: S. Machida (ASTEC), Web site: http://hadron.kek.jp/ machida/simpsons/; S. Machida, Nucl. Instr. Meth. **A 309** (1991) 43.

[10] J. Amundson, P. Spentzouris, "SYNERGIA: A Hybrid, Parallel Beam Dynamics Code with 3D Space Charge," PAC 2003 Portland (2003) 3195.

[11] *http://www-linux.gsi.de/g̃iuliano/research_activity-/trapping_benchmarking/main.html*

[12] G. Franchetti, S. Machida, I. Hofmann, THBW01, these proceedings.

[13] E. Benedetto et al, Proc. EPAC 2004, Lucerne (2004) 2502.

[14] G. Bellodi, CARE-HHH-APD HHH-2004 workshop, CERN-2005-006 (2005) 281.

[15] *http://conf-ecloud02.web.cern.ch/conf-ecloud02/CodeComparison/ecsimbu.htm*

[16] Contact: M. Pivi (SLAC), M. A. Furman (LBNL), Web site: http://www-project.slac.stanford.edu/ilc/testfac/ecloud/elec_cloud.html; M. A. Furman and M. T. F. Pivi, Phys. Rev. ST-AB, **5** (2003) 124404.

[17] Contact: K. Ohmi (KEK); K. Ohmi, Phys. Rev. Lett. **75** (1995) 1526.

[18] Contact: F. Zimmermann (CERN), D. Schulte, G. Bellodi, G. Rumolo, O. Bruning, X.-L. Zhang, Web site: http://wwwslap.cern.ch/collective/electron-cloud/Programs/Ecloud/ecloud.html; G. Rumolo, F. Zimmermann, *Practical User Guide for ECloud*, CERN-SL-Note-2002-016 (2002).

[19] Contact: L. Wang (SLAC); L. Wang, H. Fukuma, K. Ohmi, et. al., Proc. PAC 2001 (2001) 701.

[20] K. Ohmi et al, "Simulation of Ep Instability for a Coasting Beam in Circular Accelerators," EPAC 2004 Lucerne (2004) 2107.

[21] Contact: M. Blaskiewicz (BNL).

[22] U. Iriso, S. Peggs, "Maps for Fast Electron Cloud Simulations at RHIC," EPAC 2004 Lucerne (2004) 2870.

[23] D. Schulte et al, PAC 2005 (2005) 1371.

[24] S.S. Win et al, Proc. ECLOUD'02, Geneva, CERN-2002-001 (2002) 199.

[25] K. Ohmi, F. Zimmermann, "Head-Tail Instability Caused by Electron Cloud in Positron Storage Rings," Phys. Rev. Lett. **85** (2000) 3821.

[26] K. Ohmi, "Particle in Cell Simulation of Beam-Electron Cloud Interactions," PAC 2001 Chicago (2001) 1895.

[27] Contact: F. Zimmermann, G. Rumolo (CERN); *Practical User Guide for HEADTAIL*, G. Rumolo and F. Zimmermann, CERN-SL-Note-2002-036 AP (2002)

[28] Contact: B. Feng (USC), A. F. Z. Ghalam, C. Huang, V. Decyk.

[29] G. Rumolo et al, "Electron Cloud Studies for KEKB," PAC 2001 Chicago (2001) 1889.

[30] *http://conf-ecloud02.web.cern.ch/conf-ecloud02/CodeComparison/modelinst.htm*

[31] K. Ohmi, E. Benedetto, J. Flanagan, private communication; and K. Ohmi, HB2006, THBW04 (2006).

[32] V. Danilov, S. Cousineau, TUAX01, these proceedings.

[33] D. Chen et al, "Single Bunch Electron Cloud Effects in the NLC Beam Delivery System", SLAC-TN-03-051, LCC-0126 (2003).

[34] E. Benedetto et al, Phys. Rev. Lett. **97** (2006) 034801.

[35] A. Friedman (LBNL), D.P. Grote, J.-L. Vay, Web site: http://hif.lbl.gov/theory/WARP_summary.html

[36] Contact: A. Adelmann (LBNL) and M. A. Furman; Proc. PAC 2003 (2003) 3524

[37] J.-L. Vay, HB2006, THAW01 (2006).

[38] A. Molvik, HB2006, THAW02 (2006).

[39] Contact: O. Boine-Frankenheim (GSI).

[40] V. Kornilov, TUBX02, these proceedings.

[41] M. Blaskiewicz, Phys. Rev. ST-AB **1** (1998) 044201.

[42] Contact: J.A. MacLachlan (FNAL); J.A. MacLachlan, FERMILAB TM-1274 (1984).

[43] S. Cousineau, J. Holmes, C. Beltran et al, "Benchmark and Threshold Analysis of Longitudinal Microwave Instability in the PSR", EPAC 2004 Lucerne (2004) 2224.

[44] E. Shaposhnikova, TUBX05, these proceedings.

[45] Contact: D. Bruhwiler (TX-Corp), C. Nieter, J. Cary, Web site: http://www.txcorp.com/products/VORPAL/ and http://www.txcorp.com/pdf/VORPAL/ VORPAL_UsersGuide.pdf; C. Nieter and J. Cary, J. Comp. Physics **196** (2006), 448; D. Bruhwiler et al., AIP Conf. Proceed. **773** (2005), 394.

[46] A. Fedotov, WEAY04, these proceedings.

[47] Contact: A. Sidorin (JINR), A. Smirnov (JINR), E. Syresin, G. Trubnikov, I. Meshkov, I. Seleznev, Web site: http://lepta.jinr.ru and http://lepta.jinr.ru/betacool/doc.zip; A. Sidorin et al., Nucl. Instru. Methods, **A 558** (2006) 325.

[48] A. Fedotov, FRAP05, these proceedings.