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<u>Transcript (final discussion session):</u>

<u>Unknown:</u> Do we need to update the list of computer codes? (there was this excel list in the past …)

<u>Oliver Boine-Frankenheim:</u> I think it is not so useful, but it would be better to build a collaboration and a combination of modules of different codes; we could have custodians like for MADX, for example for filters to minimize noise in simulations (what is the best filter, ...)

<u>Ingo Hofmann:</u> 3 important aspects:

- *physics content* or what creates emittance growth or beam loss; there are some physics mechanisms that are not really understood.
- *noise*, which is still a complicated story especially for very long terms simulations.
- *statistics*, there was a review on the balance between the noise of the computer system and statistics from different seeds to make sure that we are not noise dominated, but we can see the difference between noise and statistics.

For benchmarking we have to keep in mind these 3 aspects and we have to start our benchmarking with the cases where we are pretty sure to understand the physics.

<u>Giuliano Franchetti:</u> What are now the physics that can be benchmarked? In this moment it is important to understand which are the “believable physics cases”?

<u>Ingo Hofmann:</u> this physics case could be a resonance line that is constantly crossed by particles at the synchrotron oscillation and the space charge effects, or a collect of dynamic apertures

<u>Oliver Boine-Frankenheim:</u> We could also look at the noise.

<u>Giuliano Franchetti:</u> Yes, but yesterday it came out from the discussion that according to how you change your system you get different results, so it is important to know the physics.

<u>Leonid Vorobiev:</u> Last slide of my presentation during workshop: possible way to organize. Can classify in single pass systems and multipass systems, properties that should be taken into account for the two kinds of systems (symplecticity, complex boundary and so on)

<u>Kazuhito Ohmi:</u> we have to study the frozen potential if we want to study the relevant physics.

<u>Frank Shmidt:</u> We should not demotivate the efforts already going on in the

benchmarking. We can start with SIS18, as we already do with Synergia and Orbit and people come with other machines and projects they want to test and we build up a benchmark.

Ingo Hofmann: There is no problem with a specific machine. My understanding is that we mostly discuss the beam physics issues that happen in different machines.
If we concentrate on a specific machine this means that the non-linearity and the lattice of the specific machine is the dominant issue that actually we don't know.

Stephen Webb: We have all these different codes and we have to benchmark with different machines, there are a lot of complexities in the machine that can mask some sort of bugs or imprecision in the code, so perhaps we should come up with a set of test problems for that we have analytical solutions, we have to test the single elements: quadrupoles, sextupoles, space charges .. You have to test every components of your code individually …

Giuliano Franchetti: This is what everyone in this room has done, to verify basic elements like courant-snider invariants.

Stephen Webb: Not talking about this but about to compute quadrupole kicks, if you consider the basic elements you have can compare the codes at the very basic level.

Giuliano Franchetti: But for the wonderful theory of Courant Snider if the beta functions of 2 codes are the same, I am pretty sure that the optics are the same, and I think that this is the first test that everybody is doing.

Stephen Webb: What I want to emphasize is that in long term tracking differences are accumulated and become evident, but it is more difficult to find the origin at this point, so we have to consider and find the differences between different codes starting from basic elements like quadrupoles, …

Ingo Hofmann: Somebody is the coordinator in this benchmark effort. Of course everybody has a different angle. Years ago when we started to study this space charge Montague coupling, we started with pure physics and when we included the machine nonlinearities the codes diverged quite a bit. Of course you can spend a year on getting the codes giving you the right non-linear map. I think you should start from the linear lattice. I don't think it is a good idea to consider the full machine lattice with all the sextupoles and errors and so on …

Oliver Boine-Frankenheim: I think that considering the linear lattice with space charge you have already enough non-linearity to study …

Giuliano Franchetti: In 2006 with Shinji Machida we started with the benchmarking since Ingo doubted the results ;-). Shinji was invited to GSI to start to collaborate and than the problem was to set up an example that it was relevant for the machine but it was kind of controllable, which is was what we are discussing now. The codes were obviously different the benchmarking was done to get some steps, which allow to test any bad case, to verify for example that the emittance growth is reasonable. Now as Oliver emphasized it is not the full real machine but it is the simple lattice with the structure of the machine and we worked to find consistent results. This is one example of what I think we have to do.

Ingo Hofmann: So there are at least two roads to follow. One is the space charge free modeling of the non-linear machines, the other is the noise issue for that it is important not to take too complex machine and it is useful to concentrate on a linear machine. These are parallel roads to follow at the moment and in the end will be combined somewhere;

Oliver Boine-Frankenheim: for the noise there are 2 trends. One is to take more and more particles, the other is to reduce the number of particles and do some filtering

Unknown (Ingo?): We have to remember that in plasma physics people are worried about short wavelength issues that are not important for us, we are worried about leading order multipole components of the space charge, so we have a different situation; we learn from plasma physics but we need our specific tools.

Jeff Holmes: Let's discuss the SNS linac: for H- we have intrabeam scattering, intrabeam stripping, ionization losses …

Shinji Machida: losses are much higher than in proton linac, so why to take care about noise from the code, when the noise due to the physics, like the one due to the scattering effects is higher?

Oliver Boine-Frankenheim: Maybe the solution is to move the noise below the level of the intrabeam scattering noise.

Jeff Holmes: On Wednesday 2 talks related to lattices:
- for PSB regarding the resonance correction and a new working point
- LHC database for errors: a huge and useful work; we should take advantages from this

Elias Metral: when doing simulations, we should profit from these kind of databases especially in the future when building new machines, when we can measure all magnets

Unknown: People want to go on with the benchmarking that they already started. Why don't take care of the lattice as linear lattice then take a 3D bunched beam, consider a practical phase advance, load with an amount of space charge and then perform a noise test? We have to think that if we are not at any resonance which we can control, than the single particle invariant should be roughly conserved and we can verify the noise effects on a single particle, and from that the noise effect for global quantities like the rms emittance. This can be the starting ground to consider after all the non-linear effects.

Unknown: We consider macroparticle because we want a distribution.

Unknonw: At Fermilab we looked into these single particle issues in SYnergia and we learnt a lot from this.

Shinji Machida: In fact this space charge effect in these ring machines like synchrotrons is really tiny, it's not like the space charge effect in a linac; we can understand some physics simply looking at the single particle. For example single particles can be trapped by 4th order resonance excited by space charge. So single particle it's really the way to see where the physics is going on, maybe we are in this moment ignorant about this, but I think this is the good time to do these studies.

Unknown (Stephen ... brown t-shirt): Problem is that we are concerned to conserve the J, but how about the phi? Maybe we are introducing errors there, so looking to a single particle should be good, but I want to warn that it will not be so precise, because there for example to calculate space charge force for each particle we can not do it with enough accuracy.

Jeff Holmes: 2 talks on diagnostics;
Interesting to look what happens inside the bunch! Could diagnostics be improved towards that?

Elias Metral: What are our requests? Maybe scrapers for halo could be interesting for studying halo; or a quadrupolar pick-up.

Simone Gilardoni: They were removed in the PS because they were not working.

Elias Metral: For example this could be used to measure the tune spread and understand if the necktie is extending over the integer in the PS …
There are limitations due to intensity, for example with wirescanners.

Oliver Boine-Frankenheim: Would be very useful to compare different methods for measuring beam profiles or methods for measuring tune shifts, …

Unknown: Starting from our experience in the halo measurements in the Fermilab booster, sometimes one can start from measurements, find something unexpected and then try to analyze and understand the physics behind.

Oliver Boine-Frankenheim: for benchmarking, need to use a lattice that can be used also for measurements, which is well equipped to look into all the details of the beam.

Elias Metral: SPS in this sense is simple

Hannes Bartosik: Yes, but the beam instrumentation is not so easy

Jeff Holmes: 2 presentations that investigate the space charge starting from the lattice.; A couple of talks that presented modern codes that handle many physics effects. There are a couple of talks that benchmarked Patrick and Orbit. Then there is the talk about the GPUs, it is fast but hard to program, and it is necessary to not communicate more than needed…

Stephen Webb: The problem is that you have CPU and GPU but not a good integration between the 2: very slow bus and this is why you have to reduce the communication. There is a new architecture coming which is integrating that, that is shared memory for example you can pass a pointer from CPU to GPU with shared memory.

Jutta Fitzer: At the moment it is still a bit hard to program in GPU, but there are efforts ongoing to create libraries to make the programming easier and more abstract.

Unknown: But still at the beginning simple problems seem to be handled efficiently with GPUS, for big and complex codes we are investigating if GPU is the best solutions.

Unknown (Stephen ... brown t-shirt): I agree, for small problems the GPU is ok, but for complex programs ... if you don't want to communicate and you use abstract libraries you finish to rewrite the entire code on the GPU. So if the shared memory comes it would be great.

COFFEE BREAK …

Elias Metral:
Summary of the topics discussed during the workshop

- The micro scale instability should be understood, even if it could be argued that the micro-scale might not be important for macro-scale effects, but we have to test and to understand better - so there is still work to do in simulation. Also at the moment what we can understand and do with simulation is more advanced compared to what we can do in the machine.

- For the presentations on Thursday: can we disentangle between coherent and incoherent effects? A lot of progress was made in the last 10 years for space charge and impedance, obtaining a better understanding. Also for the measurements we made in these 10 years a lot of progress, for example in the Booster also if in this case the work is not finished yet. I emphasize that space charge can also be beneficial.
- There is a new proposition to define the halo, to better follow the different behavior of beam core and halo. From the measurement side it is important to understand how we can measure better the halo, to benchmark the studies about the transfer of the halo from longitudinal to transverse - maybe the PS could be good ...
- What we really need is a better description of the machines; our simulations codes are more or less fine; The question is how we can improve the nonlinear description of our machines? What are the possible methods?
    - linear and nonlinear chromaticity
    - resonance driving terms (correct chromaticity, kick in both planes,)
        - some data in PS, PSB: hard time, only 1 family of sextupoles,
    - experience in other labs:
        - chromaticity, DTA
        - ISIS: turn-by-turn
        - octupolar components by local bumps

<u>Elena Benedetto:</u> Concerning the booster what was done by Peter was really great and this was part of the reason why the working point was changed, but now Megan and Rojelio have a hard job because they need to find the nonlinearities which are not systematic …

<u>Elias Metral:</u> What about the other machines?

<u>Simone Gilardoni:</u> In the PS this moment we have a magnetic model to take care about all the non-linear components of chromaticity. So we have at the moment two methods: beam based measurements and simulations of the magnetic field.

<u>Unknown:</u> the need for the knowledge of the non-linearites depends also on the storage time!

<u>Elias Metral:</u> Prepared question 2)
Experience from the LHC - start with some scaling laws for guidance, but then one needs to go into the detail with simulations; we should not just say: it's complicated - so let's try to get some important parameters so that we can try to transport the experience from one machine to another

Vincenzo Forte: could we think about automatic tune optimization, so that the tune can be calculated independently from the machine because sometimes we have the resonance but maybe the resonances are less effective if you cross them in less time or more time.

Ingo Hofmann: Something about the half integer resonance problem - self consistent codes can model coherent effects; on the other hand frozen codes assume that there is an incoherent interaction with resonance. A quadrupolar pickup should allow to measure coherent response of the beam to the half integer resonance.

Chris: this could be tried in ISIS

Kazuhito Ohmi: one could also think of a feedback using a quadrupolar kicker

Elias Metral: Could also be tried in PSB (which has a quadrupolar pickup installed, but not operational at the moment)

Elias Metral: Prepared question 3) Which instrumentation we need to measure space charge effects?

- what can we think of in terms of instrumentation to see and check many simulation results?
- what about transverse tomography?
- can also use the collimator to reconstruct the transverse profile …
- do a fit of the transverse profile core, and the tails, for this the dynamic range is important
- beam loss is very important for high intensity labs
- absolut measurements are also important, especially for benchmarking

Fritz Casper: BBQ signal may also show quadrupole signals?

Simone Gilardoni: We tried but the problem is that the BBQ in the PS doesn't fit the part of the signal that seems to be interesting

Elias Metral: Prepared question 4) Which difference between noise of the PIC codes is related to artificial "intra beam scattering"?

Ingo Hofmann: I remember from using Michel Martinis code that dispersion complicates the intrabeam scattering.

Vincenzo Forte: In this respect, labeling of particles in the codes would be useful

Elias Metral: Prepared question 5) large part of the beam below integer resonance?

Gianluigi Arduini: where is the emittance measured? in the transfer lines or in the ring?

Giuliano Frankchetti: this also depends on how we cross the resonance!

Alexey Burov: not sufficient modeling of moderate space charge regime in connection with coherent effects (TMCI)! Also, circular modes as possibility for future …

Summary and conclusions:

- List of codes with specific features as generated in the past
  - Maybe not so useful to be updated
  - More interesting to combine modules of different codes
- Aspects to be considered for benchmarking of simulation codes
  - Physics behind emittance blow-up and losses
  - Numerical noise due to limited number of macro particles (2 strategies: more and more macro particles, or less particles but applying some filtering);
  - Statistics obtained from different seeds – to be sufficient to distinguish from noise
- Code benchmarking strategies
  - Linear lattice for benchmarking space charge (should concentrate on benchmarking the physics of space charge, and not machine specific non-linearities)
  - Study physics case which could be assessed easily in measurements, i.e. with a machine that is well equipped in terms of beam diagnostics
  - Separate benchmarking for nonlinearities
- Possible physics cases for code benchmarking
  - Bunched beams
  - Coasting beams
- Interesting aspects to be studied:
  - single particle effects in space charge dominated regime (crossing of different resonances, resonances excited by space charge, …)
  - micro-scale instability in PIC codes: impact on macroscopic observables, origin, …
  - interplay between incoherent and coherent effects, especially in the moderate space charge regime (sometimes space charge can be beneficial for mitigating coherent instabilities)
  - new definition of beam halo complementary to the standard definition- could help to interpret simulation results; can it be measured also?
  - Interaction with half integer resonance – could the coherent beam response be measured with a quadrupolar pick-up?
  - Artificial kind of "intrabeam scattering" due to numerical noise in PIC codes
- Nonlinear machine description
  - Importance of good nonlinear model depends on time spent in space charge dominated beam conditions
  - Methods to determine machine non-linearities
    - linear and nonlinear chromaticity
    - resonance driving terms
    - local orbit bumps
    - direct magnetic modeling of main magnets (as for the PS)

    - new machines should profit from measurements of the magnets prior to installation – good experience with database as generated for the LHC (FIDEL)
- Diagnostics for space charge
    - Quadrupolar pick-ups
    - Scrapers
    - Beam profile measurement with large dynamic range for halo measurements
- Computational resources and future developments
    - GPU clusters are very powerful for performing the same calculation in parallel, but slow communication between GPUs
    - GPUs still require quite low-level programming – this will become better in the future
    - GPUs are maybe not the best choice for space charge calculations yet – but this might change soon