Summary of Group A: Beam Dynamics in High-Intensity circular machines

Rick Baartman, TRIUMF
Giuliano Franchetti, GSI
Elias Métral, CERN

Abstract

32 papers were presented. Rather than summarizing each one individually, we give a few highlights, conditioned by the items in the working group charge, namely:

- Summarize the state of the art in simulation capabilities. What developments are needed?
- Summarize the state of the art in theory. What developments are needed?
- Summarize recent developments in benchmarking experimental data with simulations. What critical experiments and diagnostic developments are needed to further refine the theory and simulations?
- Summarize the state of the art in instability mitigation techniques. What further technology developments are needed?
- Summarize the primary limitations to beam intensity in existing circular machines.
- Summarize the key beam dynamics questions for high-intensity circular machines
- Summarize opportunities for advancing the field.

SIMULATION DEVELOPMENTS

There is a general understanding that simulations are important not only for the design, but also for optimizing the machine. An example is brought by V. Lebedev, who reports that 7 years of optimization were needed to bring the Tevatron to its current luminosity. Each optimization is obtained in steps where the machine performances are increased via consistent studies and simulations.

Elias Métral points out that there is still a need to accelerate calculations. There are slow losses that occur on long time scales in e.g. the CERN PS that are not understood.

Code Compendium: A proposal arising from the discussion is to convert the existing but obsolete Code compendium/web-page to a wiki and leave it up to the authors to keep the description and "CV" of each code up to date. That way, someone with a particular kind of problem can more easily find the best code to simulate it.

State of the art of high intensity simulation codes: Andreas Adelmann pointed out that parallelization of tracking codes has so far not yielded gains in computation speed proportional to number of processors. The reason is that there has been a concentration on the physics aspects without a concomitant parallelization of the other aspects such as data handling.

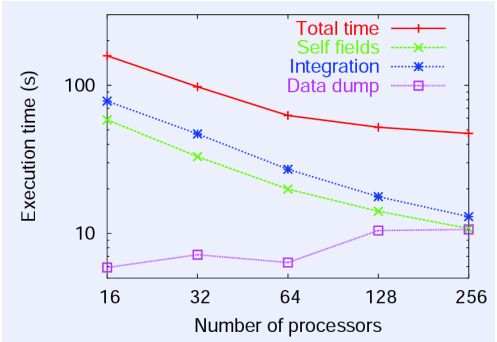

Figure 1: Parallelization.

He also reviewed the technique of transforming the calculation of multi-species physics (electron cloud, beam-beam, etc.) into an optimal reference frame. He showed an example where the simulation of a beam interacting with an electron cloud is 3 orders of magnitude faster in the appropriate Lorentz-boosted reference frame.[1]

Both of these aspects (changing reference frame and parallelization) are areas of future developments for improving code speed.

E-Cloud: Miguel Furman reported that simulations of electron cloud buildup look very consistent with observations except for one aspect: the dependence on beam energy. Simulations are hardly dependent on energy, in disagreement with CERN SPS observations and data for the FNAL MI.

Note that the single bunch E-Cloud instability (ECI) is shown in a recent paper[2] to be strongly affected by the transverse beam size. Transversely, smaller beams going through an electron cloud generate higher electron peak densities and lower the intensity threshold to make the beam unstable. In particular, since higher energy beams have smaller transverse sizes (for equal normalized transverse emittances), the scaling of the ECI threshold with the beam energy turns out to be surprisingly unfavorable.

Cyclotron/FFAG simulation with space charge: The PSI space charge code `OPAL-CYCL` (see Yang, whose talk was given by Adelmann) is now developed to the point that it can model a bunch surrounded by 4 (radially) neighbouring bunches. The new result is that the effect of the space charge from the neighbours is to sharpen the bunches further, making for better turn separation. This is a surprise.

It would be easy to modify `OPAL-CYCL` to also handle

FFAGs, since in principle the only difference is that the magnet system is not isochronous.

BENCHMARKING

The need to establish a set of standard benchmarking/validating simulations has been proposed, but not discussed in detail. A difficulty is that benchmarking for the international community is often not seen by any particular lab as a priority.

Measurements have been performed in the CERN PSB (M. Martini) to try to understand the space charge mechanisms in view of the future operation with LINAC4 (at 160 MeV, replacing the 50 MeV LINAC2).

These measurements have been bench-marked against `ACCSIM` and `ORBIT`. The agreement is rather good between measurements and ORBIT. However there are significant discrepancies between `ACCSIM` and `ORBIT`, which were not present in the benchmarking of the Montague resonance in the PS. It is worth noting as well that as reported by Igarashi et al. at HB2006, `ACCSIM` successfully reproduced the measured profiles at high intensity in the KEK PS at injection. So these discrepancies are a puzzle.

Resistive-wall instability is damped on the long injection flat-bottom of the CERN PS by linear coupling. `HEADTAIL` simulations recently confirmed that linear coupling can be used to damp a transverse coherent instability, as observed and theoretically predicted in the past. This method is used since 10 years.

V. Lebedev and A. Burov published a new theory on the effect of coupling on the beam dynamics, and these results should be compared to the previous ones and PS observations.

THEORY DEVELOPMENTS

Resistive-wall impedance (F. Roncarolo): Numerical simulations and laboratory measurements have been performed in the low-frequency (kHz) regime of interest for the transverse resistive-wall impedance of an LHC graphite collimator. The agreement with new theories published in the last years (Henry-Napoly, Burov-Lebedev, Zotter, and Al-Khateeb et al.) is impressive.

Transverse Mode-Coupling Instability (B. Salvant): For several years now, a fast vertical instability is being studied at SPS injection with an LHC-type bunch of low longitudinal emittance (in view of future intensity upgrades). It is becoming more and more clear that this is a TMCI.

A double instability threshold (stable, unstable, stable again, unstable again as intensity increased), and a tune step were observed on both simulations of the 20 kickers' impedance and on SPS experiments performed in 2007. These two typical features of TMC instabilities are yet again other indications that the fast instability observed in the SPS could be explained by a coupling between modes $m = -2$ and -3.

Furthermore, it is worth mentioning that simulation studies were performed with a flat chamber compared to a round one, and without and with space charge. In both cases the effect is rather small ($\sim 20\%$); this is believed to be due to the fact that the mode coupling does not occur between modes $m = 0$ and -1 (as usual in electron machines) but between higher order modes. Note also that it was checked with HEADTAIL simulation that in the case of a flat chamber, linear coupling can raise the intensity threshold by $\sim 30\%$ as foreseen in some theories.

Space charge effects, Landau damping: Ingo Hofmann gave an interesting talk regarding a way to summarize the effect of crossing a space charge resonance. Define the parameter

$$S = \frac{(\Delta Q_x)^2}{dQ_x/dn};$$

the square of the tune shift divided by the tune change per turn. When $S \gg 1$, crossing is slow and adiabatic; when $S \ll 1$, it is sudden.

In simulations, it is found that emittance growth on crossing various resonances is proportional to S to some power; the higher the order of the resonance, the higher the power. This scaling law is very useful for quick evaluation of dangerous regimes.

V. Kornilov, V. Lebedev and B. Ng talked about this subject and previous work by D. Möhl, Métral-Ruggiero, Mike Blaskiewicz. It seems that there is a relatively good agreement for coasting beams. For bunched beams and Q_s not small, the situation is much more involved and some work is still needed to get a good understanding of the effect of space charge and longitudinal nonlinearities on Landau damping.

The point was made that for sufficiently fast synchrotron motion as in the FNAL Booster (see below), it is not correct to think of the transverse tunes as sweeping over betatron resonances as a result of synchrotron motion. Nor is it correct to think of the spread of tunes due to the dependence of transverse tune on position within the bunch, as contributing to Landau damping. This picture is an approximation that is only valid in the slow (adiabatic) limit[3]. Rigorously, there are 3 coupled harmonic oscillators.

Another way to say the same thing is that the adiabatic picture is only valid if there are many synchrotron sidebands within one space charge tune spread, such as in the GSI SIS18 (see Franchetti's talk). In this picture, $dQ_x/dn \sim \Delta Q_x Q_s$, so Ingo's $S \sim \Delta Q_x/Q_s \sim$ the number of sidebands within the space charge tune spread. So again the adiabatic condition becomes $S \gg 1$. Thus whether resonance crossing is due to sweeping the bare tune or to synchrotron motion, S can be understood as an adiabaticity parameter: if it is large, it means the beam will act like a coasting beam, and the picture of particles in frequency space crossing betatron lines is the correct one. If it is small, this picture is not correct.

The width of the Montague resonance crossing in the CERN PS does not agree experimentally with the codes.

This might be due to insufficiently slow synchrotron motion.

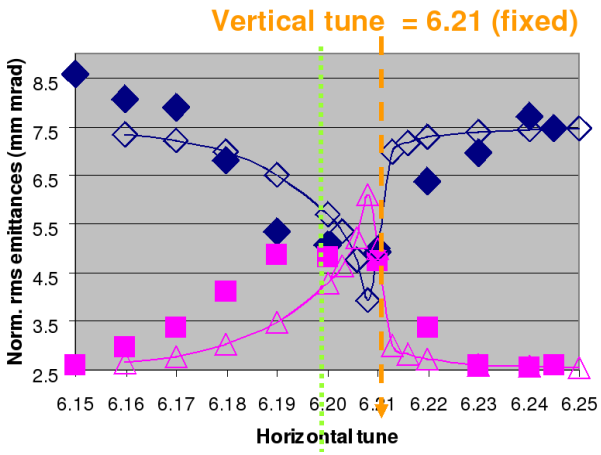

Figure 2: CERN PS: Montague resonance crossing. Open symbols are simulations, closed symbols are measurements.

During discussion, Oliver Boine-Frankenheim showed results for simulated transverse Schottky signals which could help understanding the effect of space charge on head-tail modes. The signals show the incoherent betatron band splitting into synchrotron sidebands when synchrotron motion is modeled. Landau damping originates from the synchrotron frequency spread; not from the betatron frequency spread resulting from the synchrotron motion.

An interesting aspect of these simulations is that they come for free from the (usually thought to be a nuisance) numerical graininess inherent in multi-particle simulations.

Space Charge Effect in Isochronous Machines: Edouard Pozdeyev gave an interesting talk on a kind of beam breakup effect that occurs in isochronous rings. This effect will cause a long bunch to break into "droplets", since the stationary distribution is a circular cylinder (as first shown by Kleeven[4]). The final bunches have the same length as their original width. This may have consequences for rings that stay a long time near transition.

It is also observed in the PSI cyclotron, and hints of it have been seen in the TRIUMF cyclotron. In the case of PSI, this effect could be related to the talk by Andreas Adelmann (standing in for Jianjun Yang) where he described simulations of their ring cyclotron: the incoming beam is prepared so that there is only one of these "droplets", and so counter-intuitively, even though space charge force is not small, it serves to help, not hinder the maintenance of very short bunches.

INSTABILITY MITIGATION

FNAL Booster Instability: This instability, mentioned in a talk in HB2006 as an unsolved mystery, has been solved. Burov and Lebedev presented a convincing case that it is the third synchrotron sideband of the integer. $Q_{x,\mathrm{coh}} = 6.85 = n - 3Q_s$, since $Q_s = 0.05$. The driving force is dispersion at the rf gaps.

A confusing aspect is that the clearest signature appears in the vertical instead of the horizontal plane. This is due to the strong coupling and unsplit tunes. Currently, instability is minimized by going to very high chromaticity. This does not solve it; it simply makes it somewhat weaker. A better solution would be to arrange the cavities in a symmetric pattern so the driving kicks are canceled.

To cross or not to cross transition: In the CERN PS, in the n-ToF mode, the bunch has to be blown up longitudinally before crossing transition otherwise all of it is lost due to a fast vertical instability.

V. Ptitsyn told us that at RHIC, a transverse instability presently limits the ion beam intensity. The current explanation of these effects is that the electron cloud, accumulated in the beam with large number of bunches, lowers the instability threshold and introduces a dependence of instability strength on bunch train position.

Elena Shaposhnikova raised the following question: For future machines, should we cross transition or not, if this can be avoided using a lattice with an imaginary γ_t? Experts at our discussion unanimously said one should try and avoid it; even though many tricks have been developed over the years there are always some losses near transition. However, such lattices have their own unique characteristics, for example, longitudinal motion at top energy can be quite slow. The implications should be carefully examined.

SNS Ring: Cousineau reported an interesting observation. The e-p instability seems to depend primarily on turn number (= accumulation time), rather than on bunch charge. In any case, however, just is with the PSR, the instability is killed with sufficient rf voltage, and there is plenty of voltage available.

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