BENCHMARKING OF SIMULATION CODES BASED ON THE MONTAGUE RESONANCE IN THE CERN PROTON SYNCHROTRON

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Abstract

Experimental data on emittance exchange by the space charge driven "Montague resonance" have been obtained at the CERN Proton Synchrotron in 2002-04 as a function of the working point. These data are used to advance the benchmarking of major simulation codes (ACCSIM, IMPACT, MICROMAP, ORBIT, SIMBAD, SIMPSONS, SYNERGIA) currently employed world-wide in the design or performance improvement of high intensity circular accelerators. In this paper we summarize the experimental findings and compare them with the first three steps of simulation results of the still progressing work.

INTRODUCTION

Benchmarking of simulation codes for high-intensity synchrotrons and storage rings is necessary in order to raise confidence in predictions on beam loss and quality for new projects (like SNS, J-PARC, the new FAIR-project [1] and others); or to explain observations and possibly improve the performance of running high intensity machines in different laboratories. Efforts of code validation in this field are relatively new (for an overview see Cousineau [2]) and are a result of both the development towards higher intensities and the steadily increasing performance of computers.

Are we using experiments to test and improve codes, or vice versa? The situation is more complex - opportunities lie on both sides:

1. Predictions by theory and simulation - before experiments are carried out - are an important element in the advancement of all science - also of beam physics.

2. Codes cannot cope with the full complexity of the real world and need to be compared with observation.

3. Experimental measurements are imperfect and incomplete; codes open a larger space of parameters and interpretable quantities.

The next question is: what is a meaningful comparison between measurement and simulation? Are we just comparing data of both? In the present study we realize that proper code benchmarking is a complex interaction process, where improvements in experiments and critical tests of our beam physics models have to go in parallel with the desired advancement in code validation.

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In the circular accelerators under discussion beams need to be tracked for a number of turns in the range from 10^3 up to 10^6 with new challenges coming into play if both, space charge and the nonlinear lattice matter. The data obtained in the CERN Proton Synchrotron (PS) in 2002-04 are suitable for such a benchmarking. We are particularly focusing here on the "Montague resonance" measurements in the range of several 10^4 turns [3], which can be easily accessed by a number of self-consistent simulation codes; another set of measurements taken during the same campaign by using an external octupole with data up to 5×10^5 turns is currently only accessible to codes employing "frozen-in" space charge calculations [4].

We note here that since Montague's [5] original single-particle analysis of the space charge driven resonance $2Q_x - 2Q_y = 0$, the topic was not given much further theoretical attention. It was, however, realized more recently that it merits more detailed study as a *collective* process in synchrotrons with high intensity, which has been explored in some detail in Ref. [6].

MEASUREMENTS AND SIMULATION CHALLENGES

The number of protons in the single-bunch (180 ns long at 4σ) was 1×10^{12} at 1.4 GeV kinetic energy, where a flat-bottom was provided for carrying out the measurements. The vertical bare machine tune was fixed at $Q_{0,y} = 6.21$; the horizontal one was also fixed during the injection magnetic flat-bottom, but varied in the interval $Q_{0,x} = 6.15 - 6.25$ from shot to shot. Beams were injected, and their emittances measured with a flying wire 30 ms (13.000 turns) after injection, which was more than two orders of magnitude longer than the theoretical exchange time of the Montague resonance, which is typically 20-50 turns for our parameters. If we infer the injection emittances from measurements near $Q_{0,x} = 6.245$ - off the Montague resonance - we find for the initial normalized rms emittances $\epsilon_x \approx 7.5$ and $\epsilon_y \approx 2.5$ πmm-mrad, which we adopt for the simulations. In order to improve statistics we have averaged emittance data from five subsequent shots under identical conditions. These values lead to calculated maximum initial space charge tune shifts (in the bunch center) of $\Delta Q_y \approx -0.1$ and $\Delta Q_x \approx -0.06$.

Two types of measurements have been carried out: 1) "static" measurements with fixed tunes as described above; 2) "dynamical crossing" measurements, where the stopband was slowly crossed in the time-span of 100 ms [3]. Results from these "static" measurements of the final emittances are shown in Fig. 1.

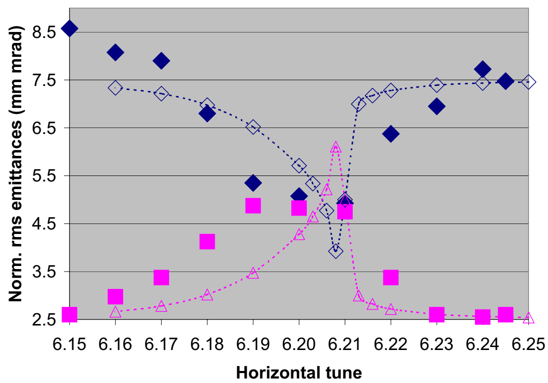

Figure 1: Final measured (full markers) and simulated (open markers) emittances as function of $Q_{0,x}$.

For a first orientation we have compared these measurement with the simulation results obtained with the fully 3D particle-in-cell code IMPACT employing a grid of $65 \times 65 \times 257$ in x, y, z and 10^6 simulation particles, but using the constant focusing lattice over 2000 turns. Since emittances were practically stationary after the first few hundred turns, there was no need to run them over more turns. The synchrotron period was set to 600 turns, which appears to be relatively unimportant, since 2D coasting beam simulations in constant focusing show a nearly identical emittance exchange as shown below.

Our code comparison is based on the observation that measurements and 3D constant focusing simulations agree reasonably well as far as width and asymmetry of the stopband are concerned, although a visible discrepancy lies in the band between tune 6.19 and 6.21. There the final measured emittances are equal suggesting the presence of stronger coupling, which may be due to the real nonlinear (combined function) lattice. Resolving these issues with self-consistent simulations modelling the real accelerator is part of the task. For this purpose increasing levels of complexity have been planned with simulations, first in 2D approximation and up to 2000 turns:

- step (1) in constant focusing approximation;
- step (2) using a linearized version of the AG lattice;
- step (3) using the fully nonlinear lattice of the PS [7]);
- step (4) the $2\frac{1}{2}$D or 3D bunched beam simulations including all lattice effects;
- step (5) extension up to the full 13.000 turns of the measurements provided that necessary CPU times – presumably of the order of months – are not prohibitive.

At a later point, after suitable code optimization, the even more ambitious dynamical crossing may be addressed, preferably after new measurements are carried out over less than the demanding 44.000 turns of the 2003 experiment. In this paper results of different codes are presented for steps 1-3. Note that some of the steps are omitted by codes that are not set up to handle them. Progress is reported on our web page [8].

CODE COMPARISON RESULTS

Codes participating in this project are listed in Table 1, where N is the number of simulation particles used in the examples below. Codes with $2\frac{1}{2}$D are employing 2D FFT-Poisson solvers assuming local (in z) transverse slices folded with the line density. Most codes have used identical Gaussian input distributions truncated at 3.5σ; IMPACT, MICROMAP and SIMPSONS so far have employed untruncated Gaussian distributions, which may account for minor differences. The vertical bare machine tune is set to 6.21 and the diameter of the conducting boundary to 14 cm (note that the actual pipe is elliptical) with a transverse grid of 128×128. The number of particles is relatively uncritical due to the 2D approximation, and 10^5 is sufficiently large. The lower particle numbers employed in the MICROMAP and SIMPSONS simulations - to speed up calculations - cause a weak emittance growth visible beyond 10^3 turns.

Table 1: Participating codes

Code	Lab	Dim	N
ACCSIM (ACC)	TRIUMF	$2\frac{1}{2}$ D	10^6
IMPACT (IMP)	LBNL	3D	10^6
MICROMAP (MIC)	GSI	2D	5×10^4
ORBIT (ORB)	ORNL	$2\frac{1}{2}$ D	10^6
SIMBAD (SIMB)	BNL	$2\frac{1}{2}D$	10^5
SIMPSONS (SIMP)	KEK	$2\frac{1}{2}$ D	10^4
SYNERGIA (SYN)	FNAL	3D	10^6

For the comparison we chose $Q_{0,x} = 6.19$, where the discrepancy between measurement and simulation in Fig. 1 is largest. In Fig. 2 we show the emittance evolution for

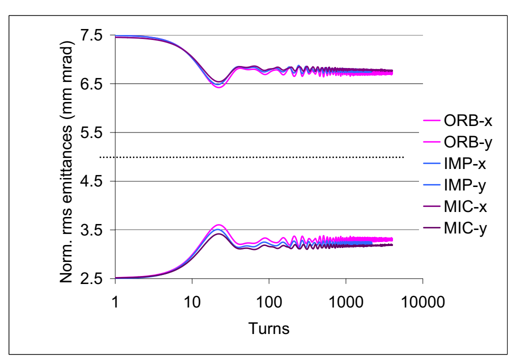

Figure 2: $\epsilon_{x,y}$ for constant focusing lattice, $Q_{0,x} = 6.19$.

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constant focusing (step 1). It indicates a fast initial exchange of emittances and the presence of weakly damped emittance oscillations. The agreement in emittance exchange is quite good, with maximum deviations of ± 0.05 mm-mrad between codes. The codes differ, however, in the strength of damping of the emittance oscillations, which may be of relevance for the long-term simulation aspects and needs further study.

Since the sum of emittances of each run is found constant (within $\approx 0.1\%$) we only plot the vertical emittances in the following graphs, the horizontal ones are mirrored about 5 mm mrad. In step 2 we have found that the emittance evolution is almost identical with step 1 as shown in Fig. 3. This may be explained by the observation that the periodic

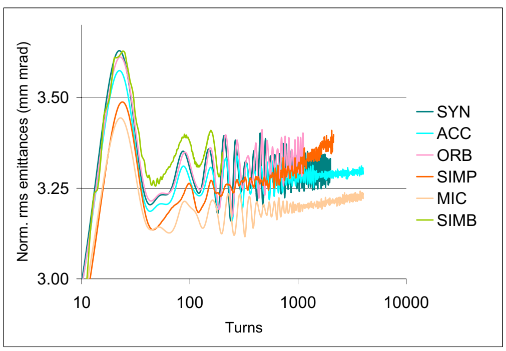

Figure 3: ϵ_y for linearized AG lattice, $Q_{0,x} = 6.19$.

flutter due to the AG focusing is too fast to have an effect on the emittance coupling. The relatively long-wavelength emittance oscillations – with about 70 turns period – increase significantly in amplitude if $Q_{0,x}$ is approaching $Q_{0,y}$. We have therefore chosen the tune $Q_{0,x} = 6.207$ as additional test to explore the response of different codes on this persisting coherent structure, which is shown in Fig. 4. The emittances show a significant overshoot, and the oscillations continue to damp at different rates. For step 3

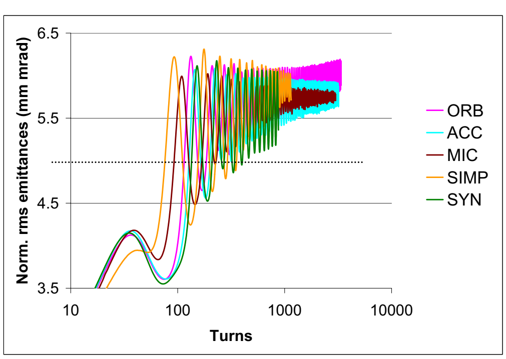

Figure 4: ϵ_y for linearized AG lattice, $Q_{0,x} = 6.207$.

we have employed the fully nonlinear lattice and obtained the results shown in Fig. 5. The effect of the full lattice

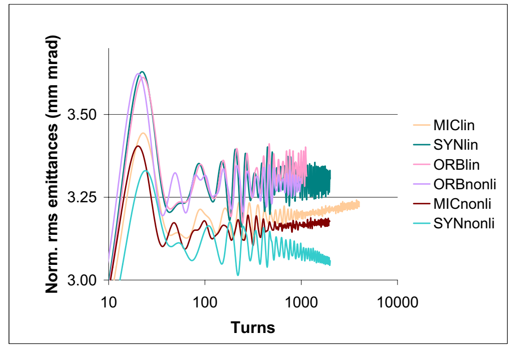

Figure 5: ϵ_y for fully nonlinear lattice, $Q_{0,x} = 6.19$ (compared with linearized AG).

is seen to be a minor one at the level of these 2D simulations. The emittance exchange is nearly identical with that of the linear lattice. We have also explored the nonlinearities by computing single-particle phase space portraits in the vicinity of $Q_{0,x} \approx Q_{0,y} \approx 6.21$ and found no lattice resonances for amplitudes within the physical aperture. Whether or not these weak nonlinearities in connection with synchrotron oscillations will help in step 4 to explain the much stronger emittance exchange of the measurements in Fig. 1 needs to be seen.

SUMMARY AND OUTLOOK

The agreement between codes is found to be very good on the coasting beam level. This gives confidence that all involved Poisson solvers are sufficiently accurate in modelling the nonlinear space charge features of the Montague resonances. Calculations confirm that the process of space charge induced emittance transfer is quite insensitive to the type of lattice - whether constant, alternating gradient or even the fully nonlinear lattice. Differences in damping of rms emittance oscillations exist and need to be explored further before progressing to the bunched beam effects.

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