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haroon.rafique@cern.ch

PTC-PyORBIT SIS18 Benchmark

Haroon Rafique / BE-ABP

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Summary

The effects of space charge on particle beams in accelerators are many and complex. Interplay exists between space charge and other effects such as amplitude detuning. Space charge is dependent on the beam distribution longitudinally and transversely, the structure and layout of the particle accelerator in which the beam is maintained, and the complex dynamics that may include other coherent and incoherent effects.

As such, comparing a space charge simulation with experiment or other simulation tools is difficult. Giuliano Franchetti, together with Ingo Hofmann and Shinji Machida compared the space charge simulation tools MICROMAP and SIMPSONS using the SIS18 accelerator in GSI Darmstadt.

Giuliano Franchetti's SIS18 benchmark has been performed with the PTC-PyORBIT code, the steps taken to achieve this, and the results, are detailed in this report.

1 Introduction

Details of the SIS18 benchmark can be found at: https://web-docs.gsi.de/ giuliano/research_activity/trapping_benchmarking/main.html

These instructions are repeated and expanded upon here.

Parameter	Symbol	Value	Unit
Sextupole Strength	K_2	0.2	m^{-2}
Maximum Tuneshift	ΔQ_x	0.1	$-$
Horizontal Transverse Size (rms)	X_{rms}	5	mm
Vertical Transverse Size (rms)	Y_{rms}	5	mm
Longitudinal Size (rms)	Z_{rms}	40.35	m
Horizontal Geometric Emittance (2 σ)	ϵ_x	12.57	$mm\ mrad$
Vertical Geometric Emittance (2 σ)	ϵ_y	9.30	$mm\ mrad$
One Synchrotron Oscillation	N_{synch}	15000	$turns$
Bunch Length (4 σ_z)	τ	3472.7	ns
Kinetic Energy	E_k	11.4	MeV/u
Transition Gamma	γ_t	5	$-$
Momentum Spread (3 σ)	$\frac{\Delta p}{p}$	$2.5{\cdot}10^{-4}$	$-$
Sextupole Strength	K_2	0.2	m^{-2}

Table 1: Parameters used for the SIS18 benchmark steps 1 - 6.

Parameter	Symbol	Value	Unit
Longitudinal Size (rms)	Z_{rms}	2.69	m
One Synchrotron Oscillation	N_{synch}	1000	$turns$
Bunch Length (4 σ_z)	τ	231.51	ns

Table 2: Parameter changes used for the SIS18 benchmark steps 7 - 9.

2 Simulation Setup

2.1 SIS18 Parameters

The parameters in table 1 are used in steps 1 - 6, and the changes in table 2 are used in steps 7 - 9.

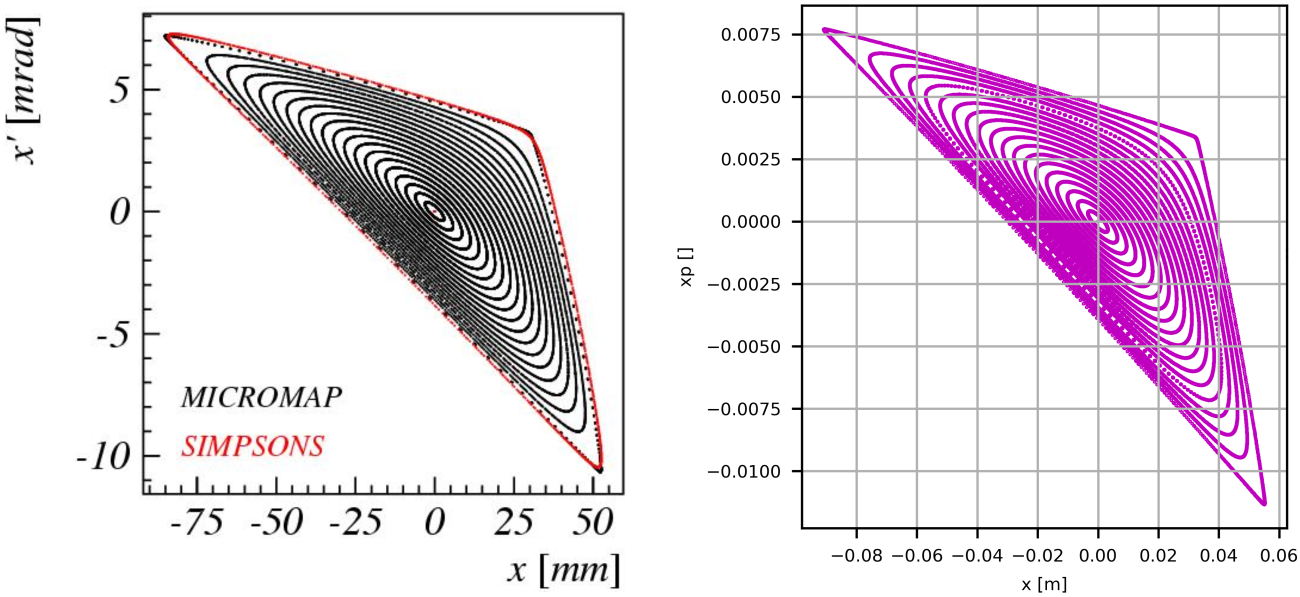
2.2 PTC-PyORBIT Setup

The PyORBIT version used was pulled from Hannes Bartosik's GitHub repository in March 2018. It can be found at: https://github.com/hannes-bartosik/py-orbit.gitThe PTC version used was pulled from Jean-Baptiste Lagrange's GitHub repository in March 2018. It can be found at: https://github.com/hannes-bartosik/py-orbit.git

It is important to note that in order to ensure that PTC uses the correct units, the time.ptc file must be included in the PTC-PyORBIT simulation. The file contents are shown in Fig. 1.

```
select layout
1
+time
set orbit state
return
```

Figure 1: time.ptc file required to use correct units in PTC.



(a) MICROMAP and SIMPSONS.

(b) PTC-PyORBIT.

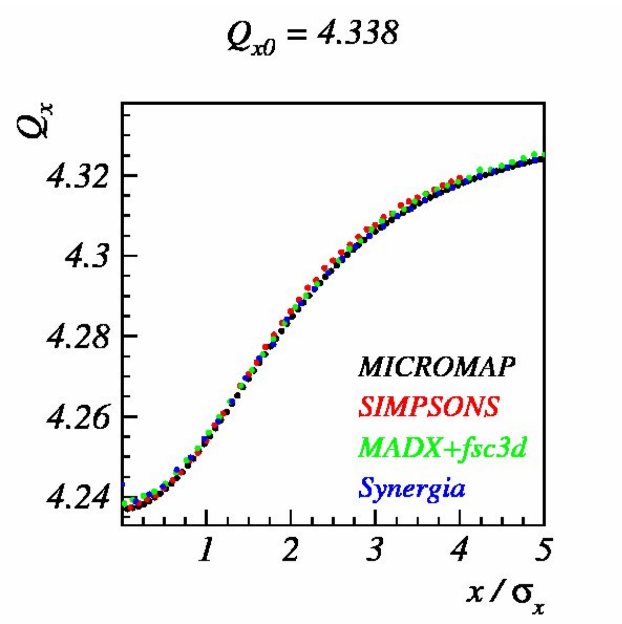
Figure 2: Step1: Phase space with sextupole on and no space charge.

3 Step 1: Benchmarking of the phase space

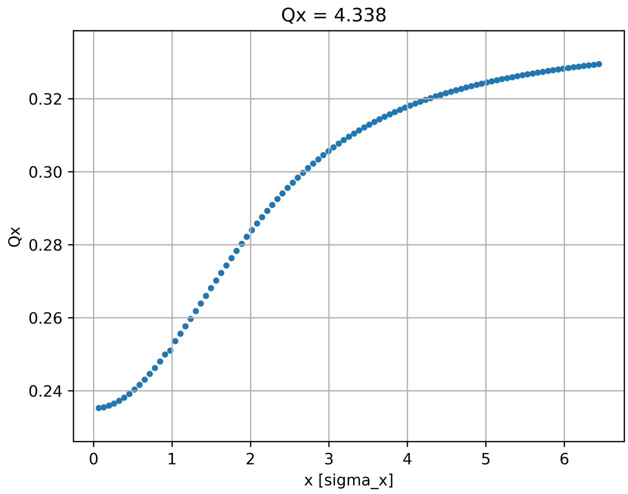
The first step is to confirm that the phase space near the 3rd order resonance has the same topology for all codes. We check the orbits up to the border of stability (dynamic aperture). For this test the tunes are $Q_x = 4.338$, $Q_y = 3.2$, the Poincaré section is plot at the beginning of the SIS18 lattice.

4 Step 2: Tunes with sextupole off

The second step is to benchmark the dependence of a test particle tune from its amplitude. The amplitude of the particle is here meant as the effective maximum amplitude that the particle can have in one betatron oscillation. The particle coordinates of the test particles are: $x_0 = 0, ..., 4\ \sigma_x$, $p_{x0} = y_0 = p_{y0} = 0$. The particle amplitude is therefore $x = \sqrt{\beta_x \gamma_x} x_0$. The same definition applies to the y amplitude. The lattice sextupole is off. As the bunch space charge is maximum at the center of the bunch, the test is performed keeping the



(a) MICROMAP and SIMPSONS.



(b) PTC-PyORBIT.

Figure 3: Step2: Horizontal tune with space charge.

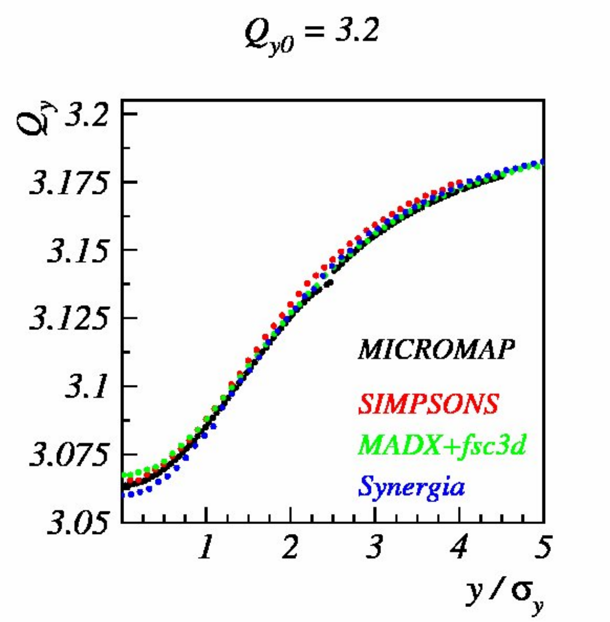
particle at z = 0. The bare tunes are are $Q_x = 4.338$, $Q_y = 3.2$. The tunes are computed with a fourier transform of the motion of a test particle over 1024 turns. The factor $\sqrt{\beta_x \gamma_x}$ is that required to transform the initial particle (with co-ordinate $(x, xp) =$ (0 - 4 σ_x, 0)) to it's maximum amplitude in x, as $x_0 = \sqrt{\frac{\epsilon_x}{\gamma_x}}$, and the maximum amplitude is $\sqrt{\beta_x \epsilon_x}$.

5 Step 3: Tunes with sextupole on at $Q_x = 4.338$

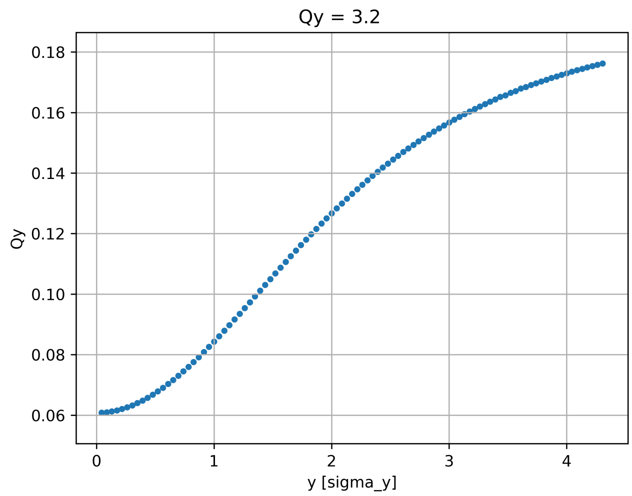
The third step is to benchmark the dependence of a test particle tune from its amplitude when the sextupole is on. The calculation of the tune is performed as described in step 2. In order to visualize the island not too far from the bunch center we take the tunes: Q_x = 4.338, Q_y = 3.2. Note that the island is not visible because we are too far with respect to the range explored: in order to see the island we need to take a tune further from the resonance, this is done in the next step. The particle amplitudes are as defined in Step 2.

6 Step 4: Tunes with sextupole on at $Q_x = 4.3504$

The fourth step is to benchmark the dependence of a test particle tune from its amplitude when the sextupole is on. The calculation of the tune is performed as described in step. In order to visualize the island far from the bunch center we now take the tunes closer to the 3rd order resonance i.e.: $Q_x = 4.3504$, $Q_y = 3.2$.

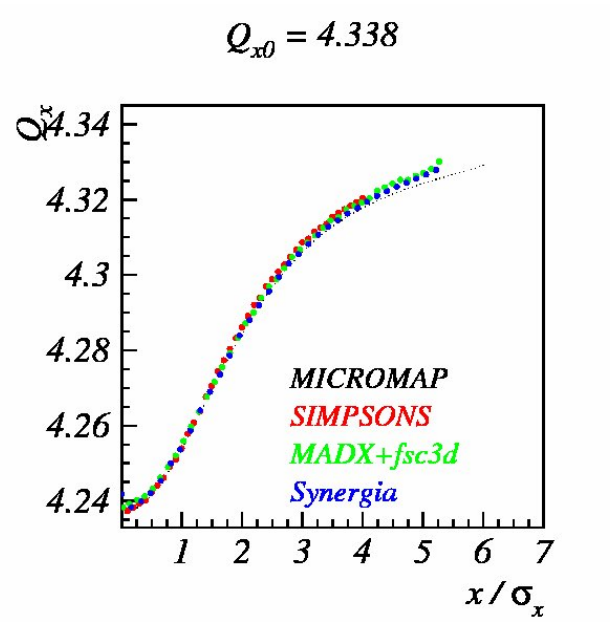


(a) MICROMAP and SIMPSONS.

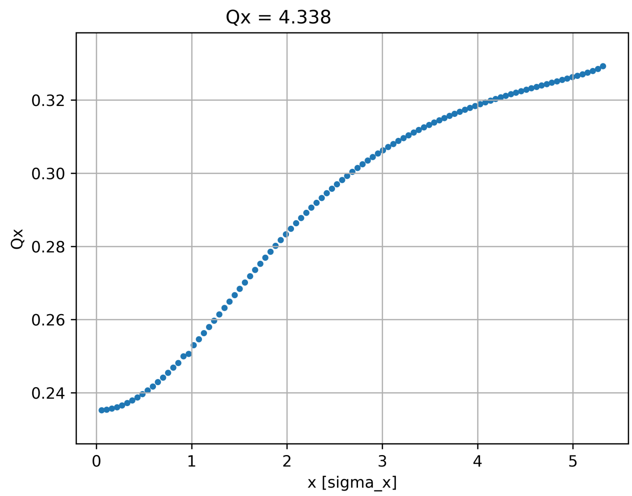


(b) PTC-PyORBIT.

Figure 4: Step2: Vertical tune with space charge.

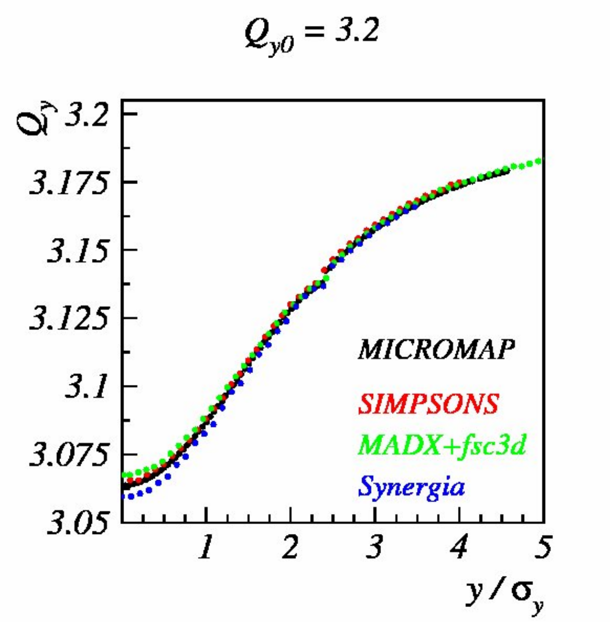


(a) MICROMAP and SIMPSONS.

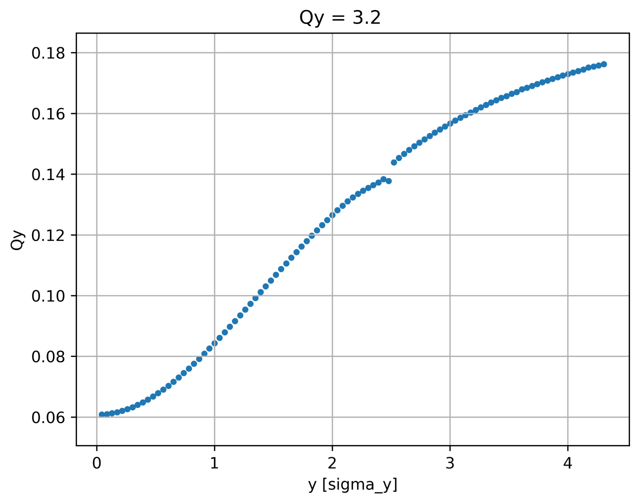


(b) PTC-PyORBIT.

Figure 5: Step3: Horizontal tune with space charge and Sextupole.

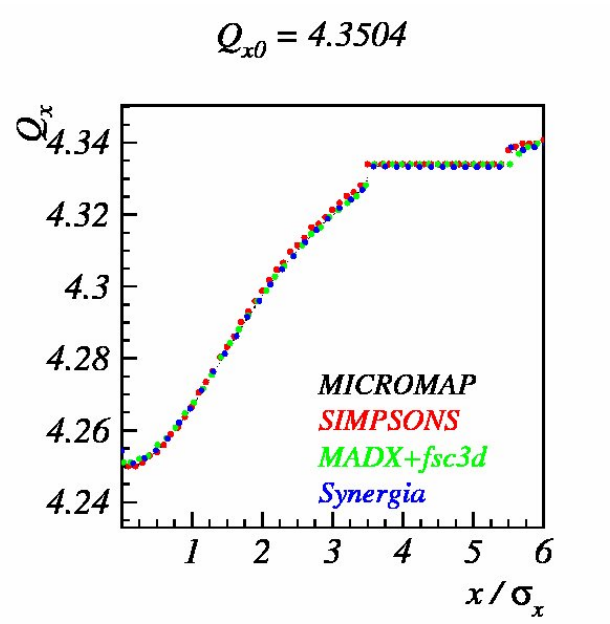


(a) MICROMAP and SIMPSONS.

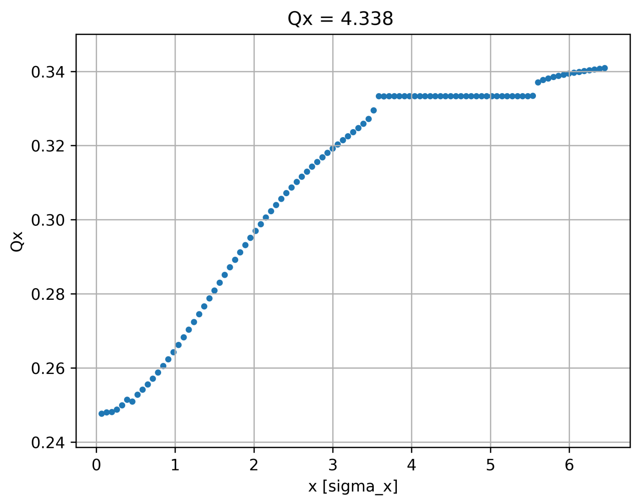


(b) PTC-PyORBIT.

Figure 6: Step3: Vertical tune with space charge and Sextupole.

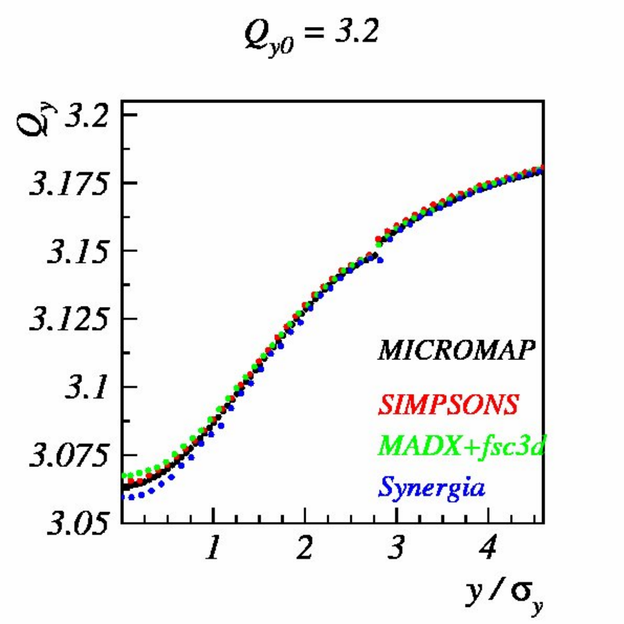


(a) MICROMAP and SIMPSONS.

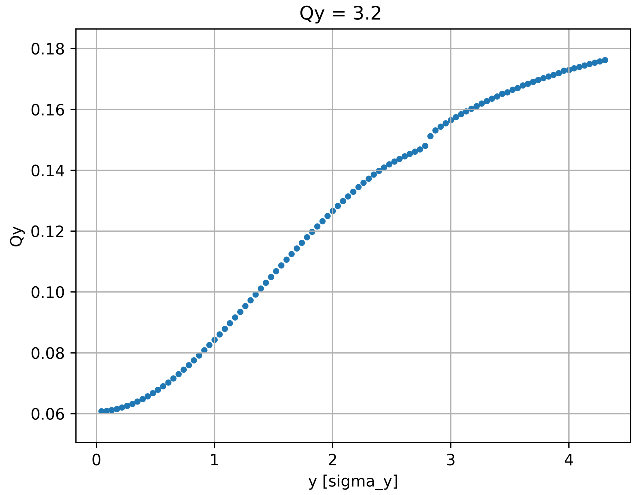


(b) PTC-PyORBIT.

Figure 7: Step4: Horizontal tune with space charge and Sextupole at $Q_x = 4.3504$.



(a) MICROMAP and SIMPSONS.



(b) PTC-PyORBIT.

Figure 8: Step4: Vertical tune with space charge and Sextupole.

7 Step 5: Phase space with space charge and sextupole on at $Q_x = 4.3504$

The fifth step is to benchmark the phase space with test particles when the sextupole is on and in the presence of space charge. Here the orbits are already subjected to trapping as the synchrotron motion is not frozen.

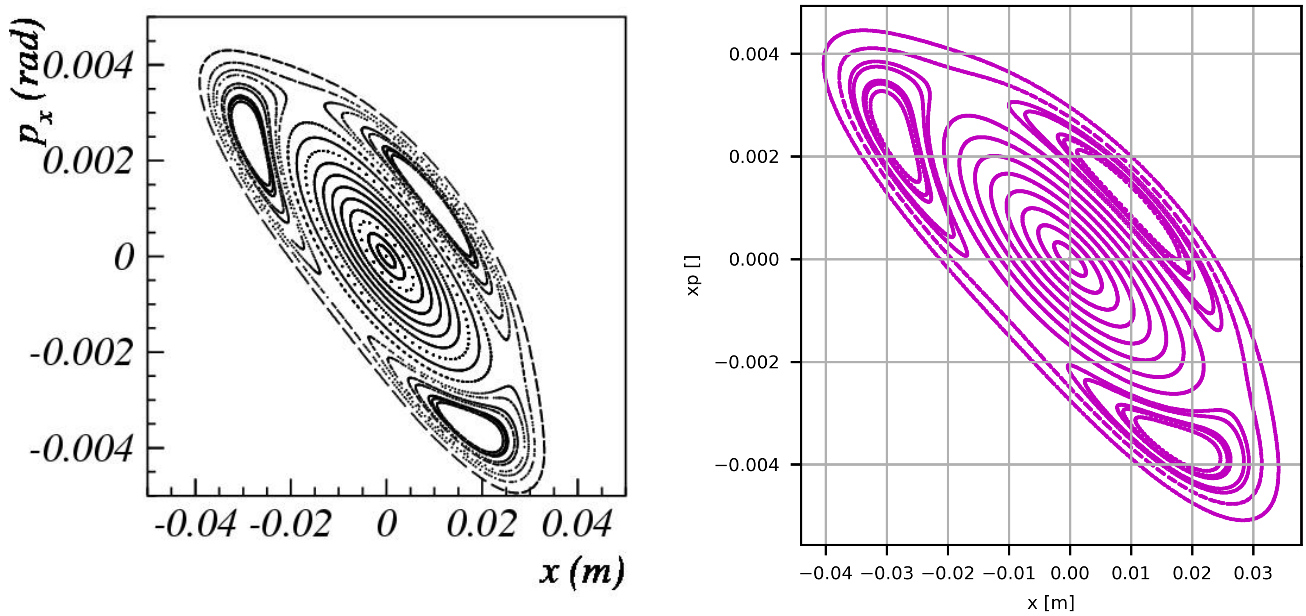
8 Step 6: Benchmarking of trapping in 1 synchrotron oscillation for $Q_s = 1/15000$

The sixth step is to benchmark the trapping of 1 test particle during 1 synchrotron oscillation. The parameters used are those of the steps 4 and 5. In order to visualize the increase of the single particle invariant we take the tunes: $Q_x = 4.3504$, $Q_y = 3.2$.

The test particle has the following initial coordinates:$x = 5$ mm, $px = y = py = 0$ and $z = 2.5\sigma_z$, $pz = 0$.

Note that the probability of trapping is very sensitive to initial conditions. Therefore it may happen that "scattering" is seen in place of trapping. A slight variation of the particle initial coordinates should allow the trapping phenomena as in Fig 10.

One synchrotron oscillation takes 15000 turns. We compare the trapping by plotting the evolution of the single particle emittance $\epsilon_x = \beta_x px^2 + 2\alpha_x xpx + \gamma_x x^2$ of the test particle



(a) MICROMAP and SIMPSONS.

(b) PTC-PyORBIT.

Figure 9: Step5: Phase space with sextupole and space charge at $Q_x = 4.3504$.

(normalised with the initial value) vs. number of turns. Note that the maximum amplitude of the center island is roughly 30 mm (see step 5), and a particle with initial coordinates x = 5 mm $px = 0$ has maximum amplitude of 8.125 mm. Therefore one expects a maximum emittance growth of $\frac{\epsilon_x}{\epsilon_{x0}} \approx \left(\frac{30}{8.125}\right)^2 = 13.6$.

The synchrotron motion in PTC-PyORBIT is performed as an energy kick $dE = dE_0 + zF$ where F is the restoring force required to maintain a synchrotron period of 15000 turns, performed once per turn.

9 Step 7: Benchmarking of trapping in 1 synchrotron oscillation for $Q_s = 1/1000$

First we find the linear restoring force required to maintain a synchrotron tune of $Q_s = \frac{1}{1000}$ without the sextupole, and without space charge. Using an iterative approach, with the suggested reference particle ($x = 5$ mm, $px = y = py = 0$ and $z = 2.5\sigma_z$, $pz = 0$) the force required was found to be $F = -4.4038 \cdot 10^{-9}$. The poincaré section is shown in Fig.

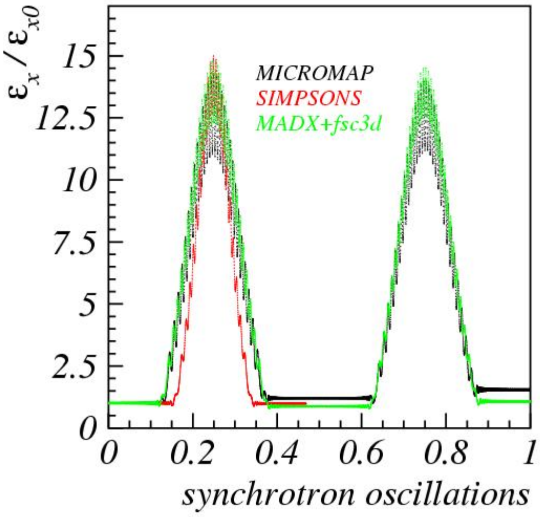


Figure 10: Step6.

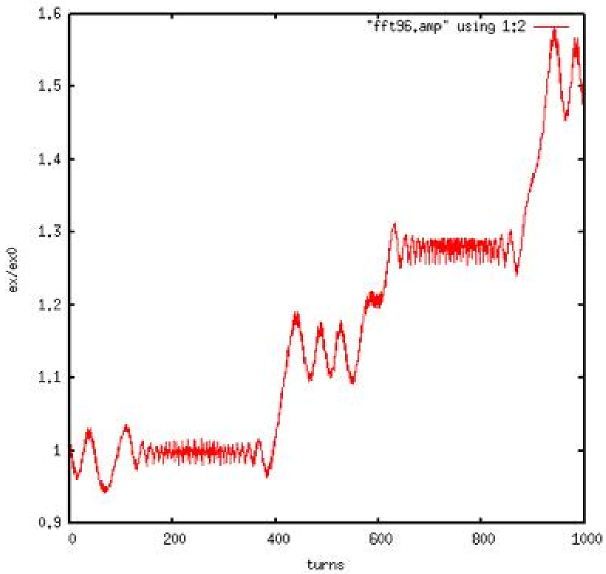


Figure 11: Step7.

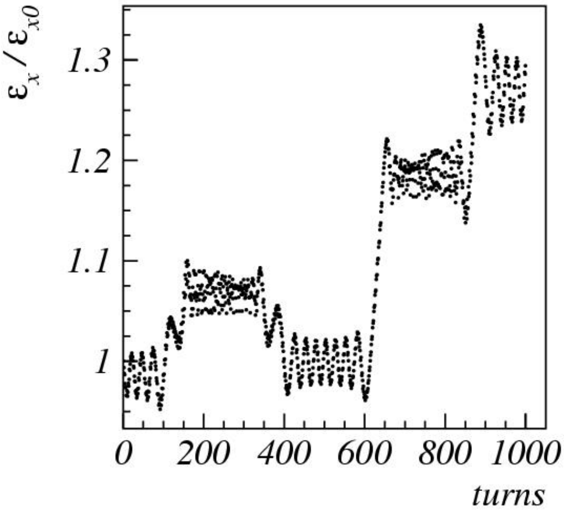


Figure 12: Step7.

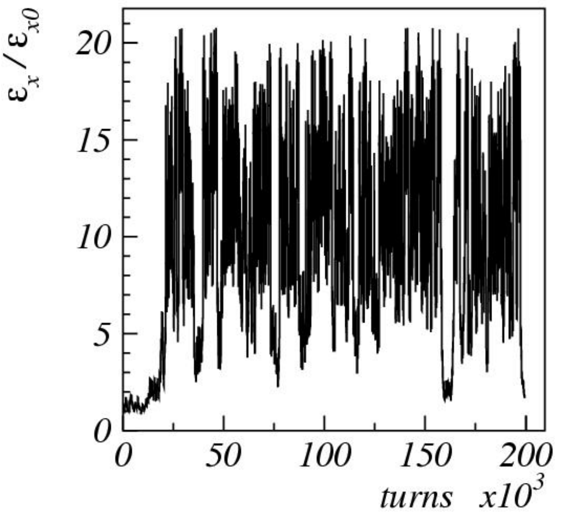


Figure 13: Step8.

10 Step 8: Benchmarking of trapping in $5 \cdot 10^5$ turns for $Q_s = 1/1000$

11 Step 9: Benchmarking of RMS ϵ_x evolution in $5 \cdot 10^5$ $Q_s = 1/1000$ for $Q_x = 4.3604$

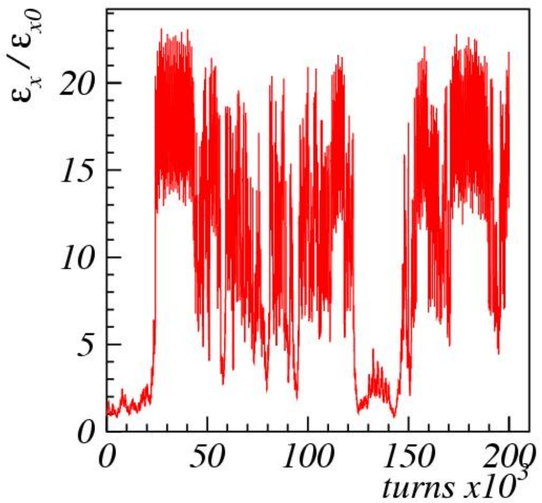


Figure 14: Step8.

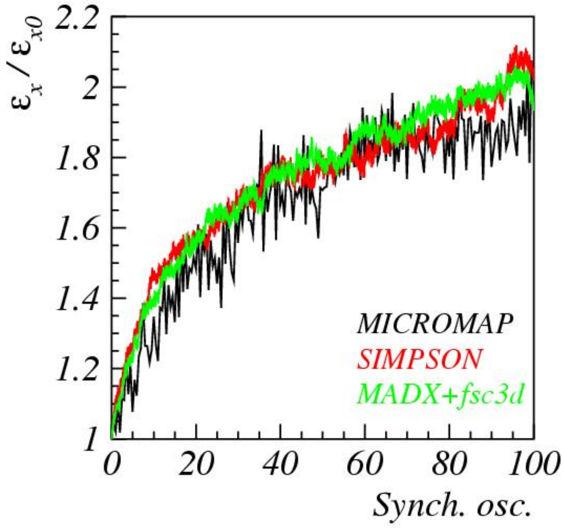


Figure 15: Step9.