Progress of KURRI FFAG simulation - update on 16 December 2015 -

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16 December 2015

KURRI FFAG Simulation Plan

KURRI FFAG Simulation Plan – second draft

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Benchmark step1

After benchmarking of step 0, that is a test of single particle trajectory, track multi-particles to see the followings,

- whether emittance is preserved and no coherent oscillations are excited when initial particle distribution matches
  - the lattice function in transverse and
  - rf bucket in longitudinal.

- whether normalised emittance stays constant and physical emittance decreases with inversely proportional to (\beta)*(\gamma) when accelerated.
  - adiabatic damping.

Without space charge, impedance or foil effects, nothing should happen!

Benchmark step2

Several effects will be included and see how the beam deteriorates.

- Space charge
  - Beam quantities as a function of beam intensity.
  - Space charge effects saturate when the beam energy increases.
- Impedance
- Foil

Longitudinal matching

small amplitude approximation without space charge

Starting from Hamiltonian in (ϕ, δ) coordinates space

$$H = \frac{1}{2}h\omega_0\eta_0\delta^2 + \frac{\omega_0 eV}{2\pi\beta^2 E}\left(\cos\phi - \cos\phi_s + (\phi - \phi_s)\sin\phi_s\right)$$

Small amplitude trajectory has the ratio on ϕ, δ axis

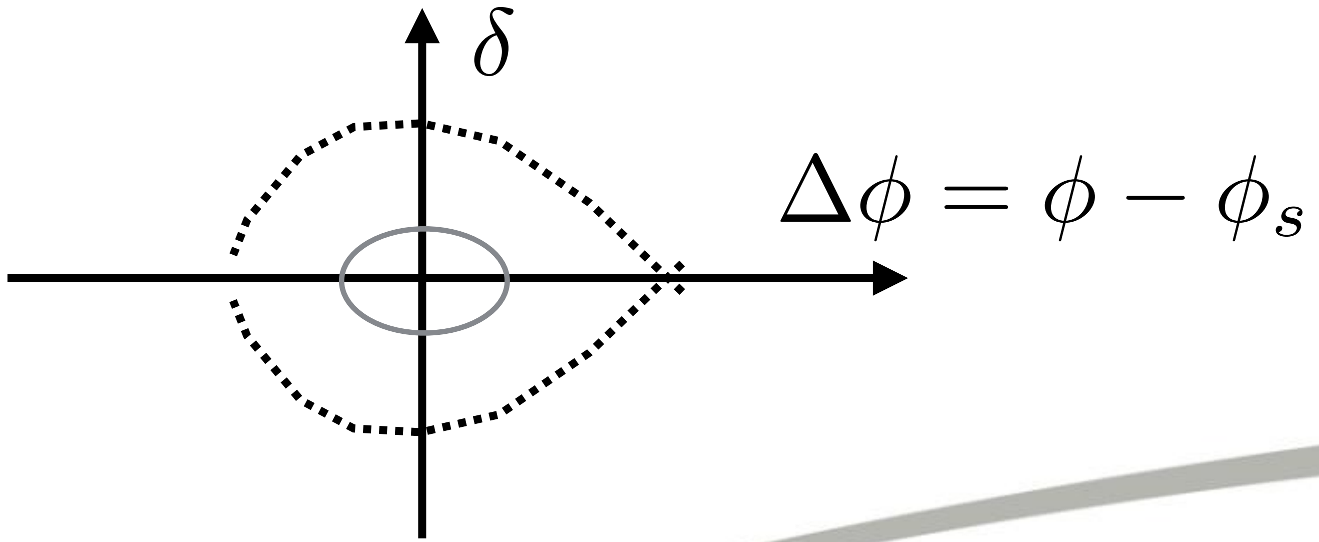
$$\delta/\Delta\phi = \sqrt{\frac{eV\cos\phi_s}{2\pi h\eta_0\beta^2 E}}$$

where $\Delta\phi = \phi - \phi_s$

Set rms of phase and momentum spread with that ratio.

c.f. Synchrotron tune is

$$Q_s = \sqrt{\frac{heV\eta_0\cos\phi_s}{2\pi\beta^2 E}}$$



Longitudinal matching

small amplitude approximation without space charge

with KURRI parameters

V:	4 kV
\phi_s:	30 degree
\eta at 11 MeV:	0.8520
E:	949.272 MeV
h:	1
C:	28.751 m
T_rev:	0.6318 us
f_rev:	1.5828 MHz

$$\delta/\Delta\phi = \sqrt{\frac{eV\cos\phi_s}{2\pi h\eta_0\beta^2 E}}$$ = 5.439 x 10^{-3}

$$Q_s = \sqrt{\frac{heV\eta_0\cos\phi_s}{2\pi\beta^2 E}}$$ = 4.634 x 10^{-3} (or 216 turns)

Transverse matching
without space charge

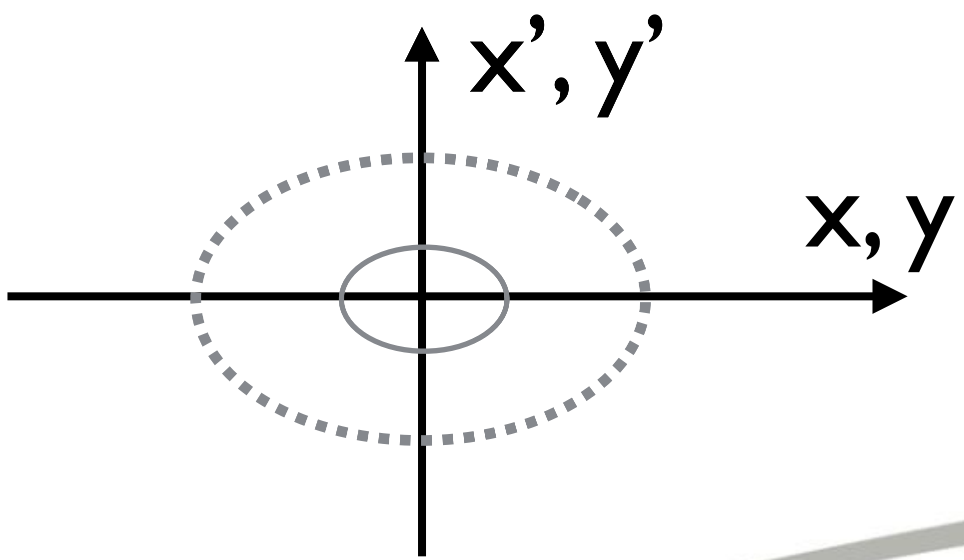
Use lattice \beta and \alpha functions to match an input beam.

At the injection point in the model lattice,

\beta_y (horizontal) = 0.7398 m, \alpha_y = 0

\beta_z (vertical) = 4.1012 m, \alpha_z = 0

\dispersion_y (horizontal) = 0.5408 m, \dispersion_y’ = 0



Remarks on matching

1. On the level of space charge in a ring, space charge effects change the matching condition only slightly

- It turns out it is not true for a short bunch, come back later.
- If necessary, solution of the envelope equations gives more accurate matching condition (in the rms sense).

2. Emittance (rms) is calculated based on coordinates from the tracking.

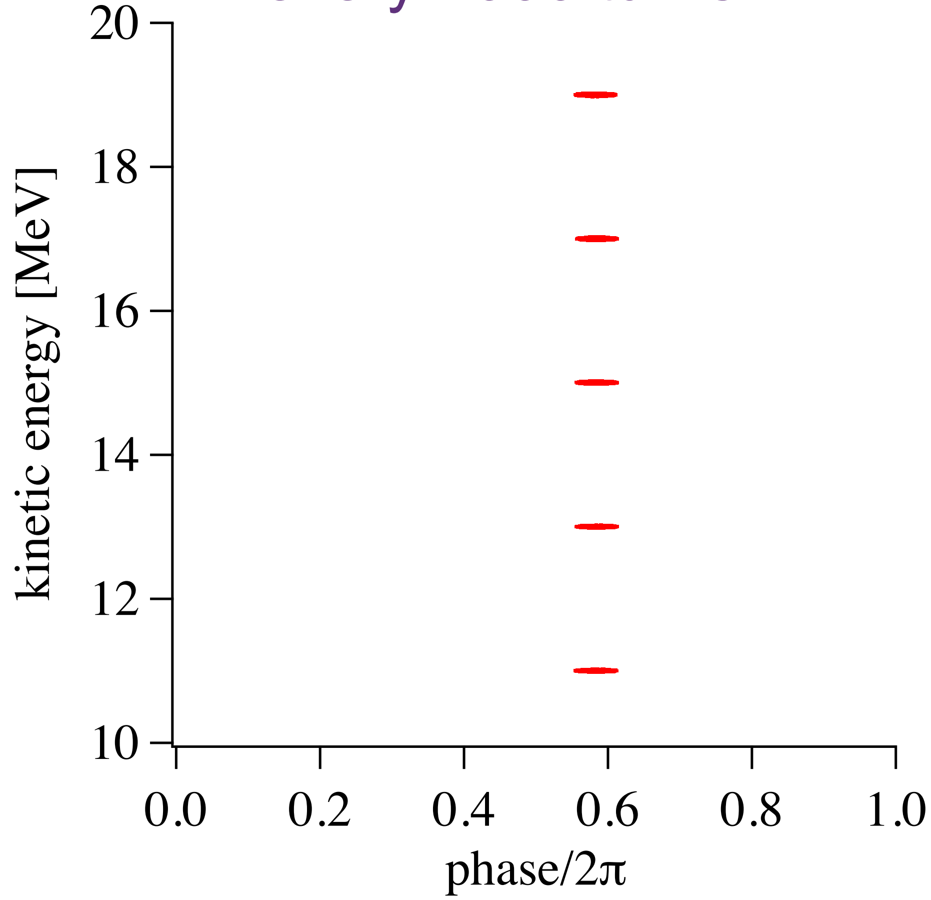
- Dispersion with momentum spread makes the beam size larger in horizontal so that the emittance value is larger than the one specified at the beginning.

Benchmark step1 results

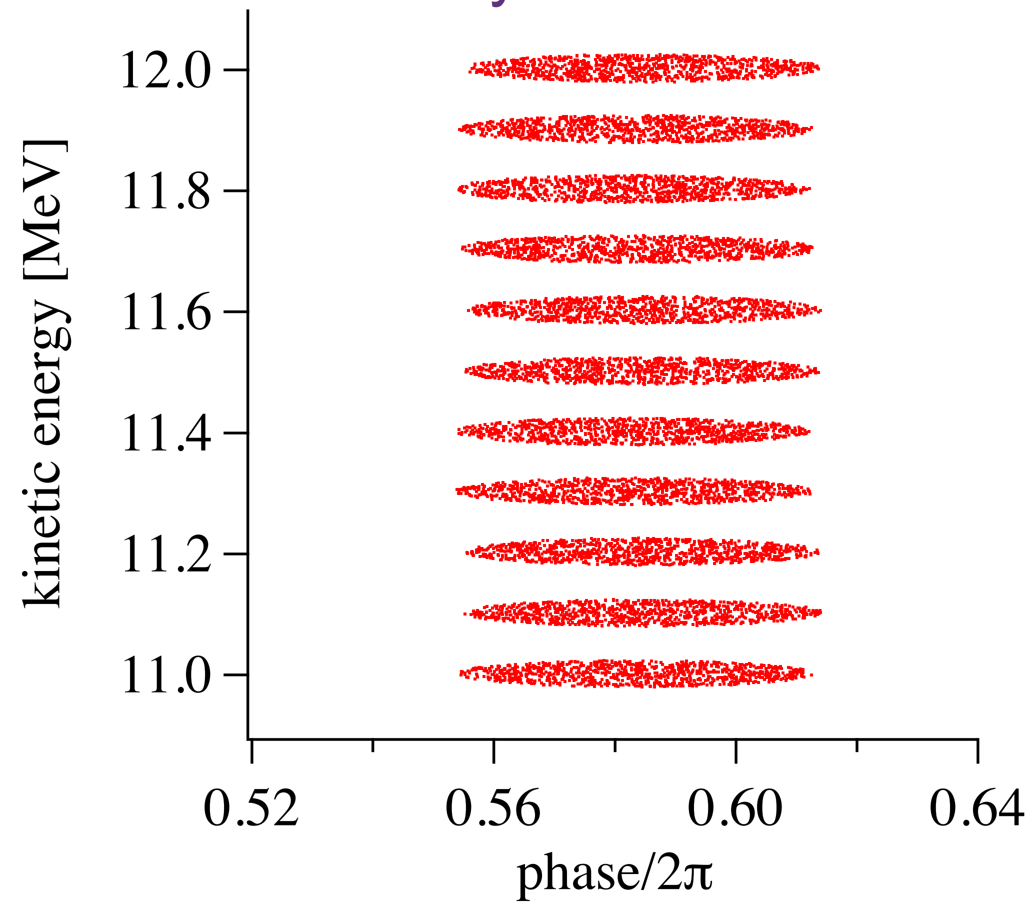
without space charge

Acceleration with constant voltage of 4 kV and phi_s of 30 deg.

every 1000 turns



every 50 turns



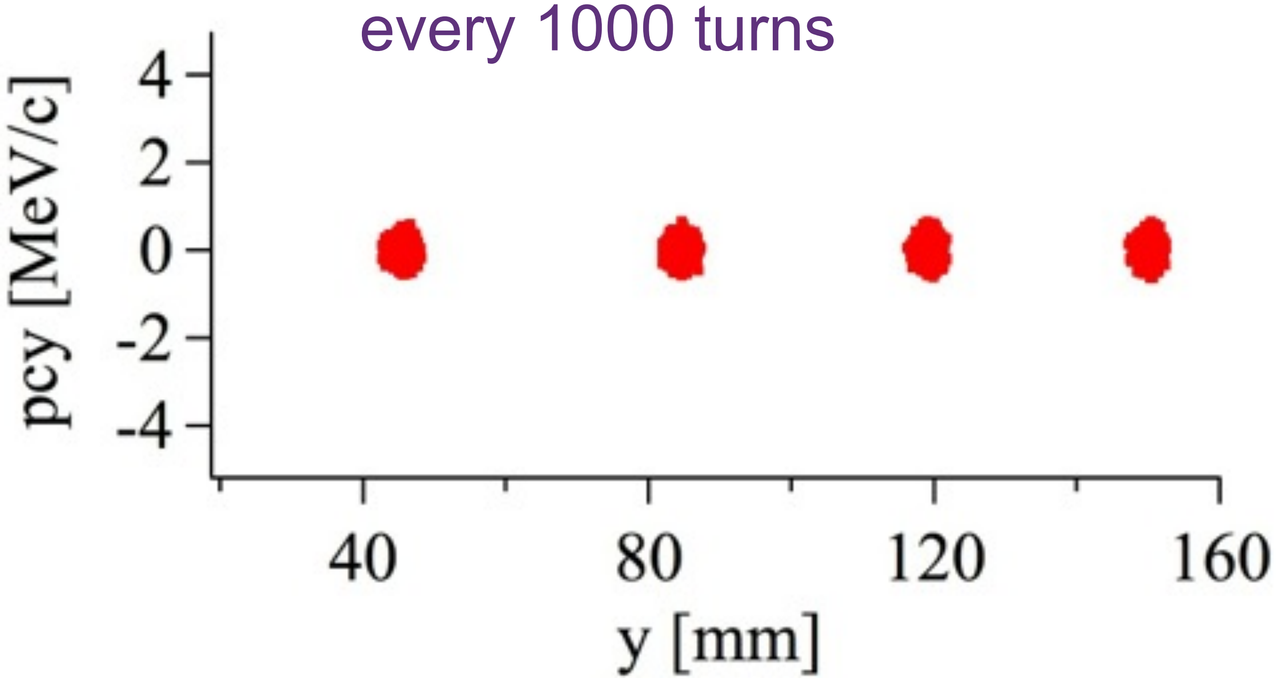
Right figure shows small dipole oscillations due to mismatch.
(synchrotron oscillation is 216 turns.)

Benchmark step1 results

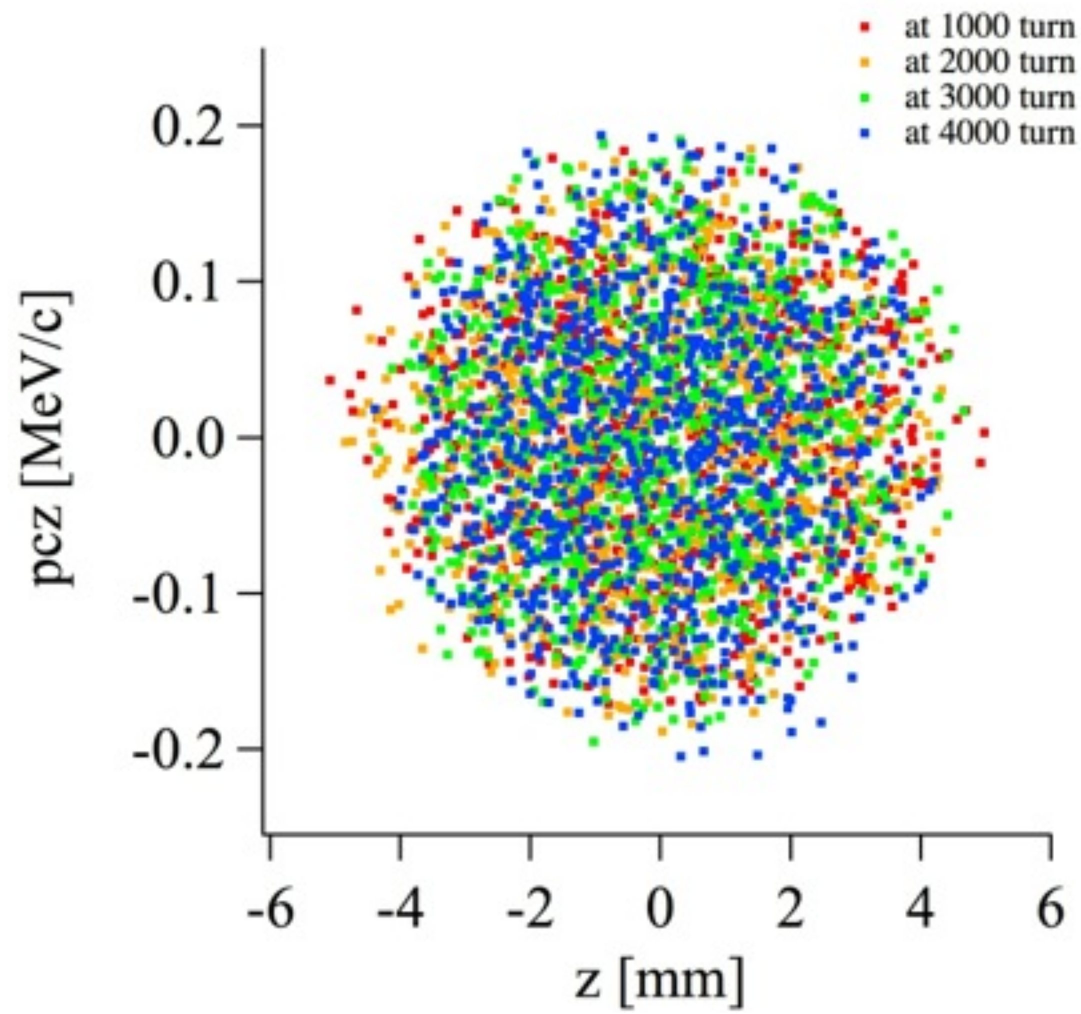
without space charge

In transverse direction, no coherent oscillations are noticeable.

every 1000 turns



horizontal phase space

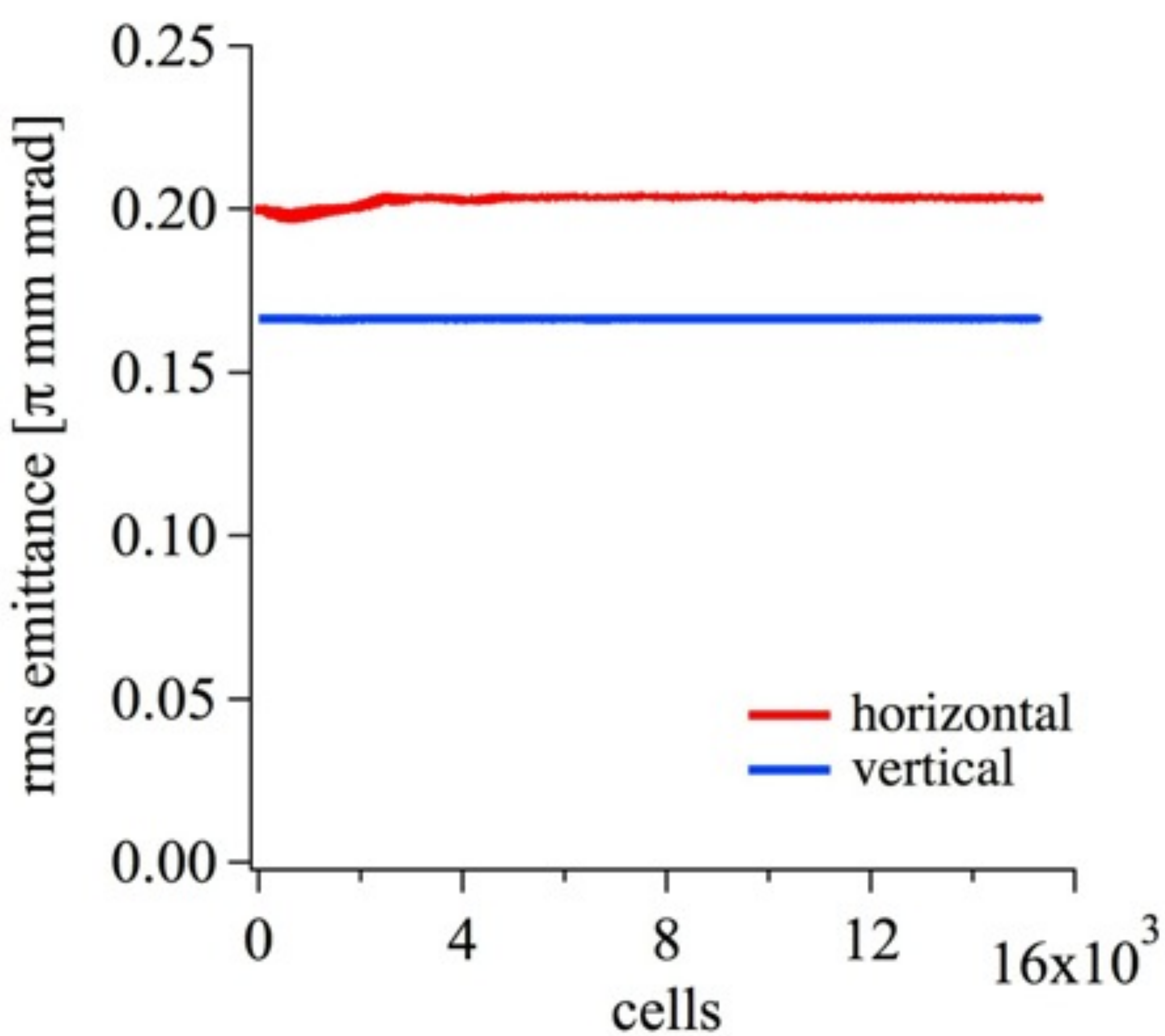


vertical phase space

Benchmark step1 results

without space charge

RMS emittance is almost constant except initial slight growth in horizontal direction.



particle distribution	6 D waterbag
transverse emittance	1 pi mm mad (total) 0.17 pi mm mrad (rms)
dp/p (rms)	0.1%
ds (rms)	0.842 m

Benchmark step2 results

with space charge

With space charge, there is tune shift/spread.

$$\Delta Q = -\frac{n_t r_p F}{2\pi \left(4\epsilon_{n,rms}\right) \beta\gamma^2 B_f}$$

Form factor *F* is
1 for KV
4/3 for Waterbag
2 for Gaussian

Bunching factor is *Bf* = 0.029
in order to match small dp/p=1.E-3.

n_t	Delta Q
0.1x10	-0.11
0.2x10	-0.21
0.5x10	-0.54

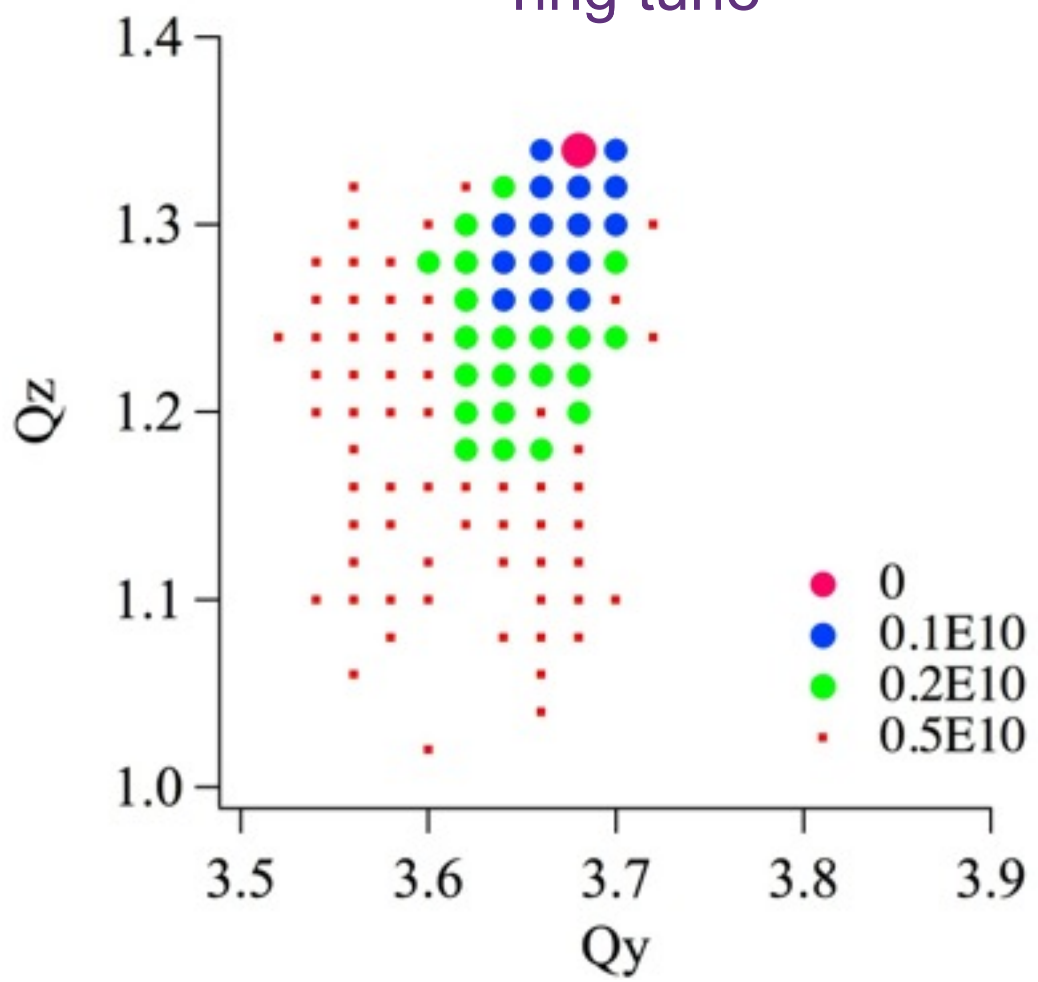
Because the lattice has a perfect 12 fold symmetry, there is only a few low order systematic resonances.

4Qy=12 (Qy=3): in horizontal
None: in vertical

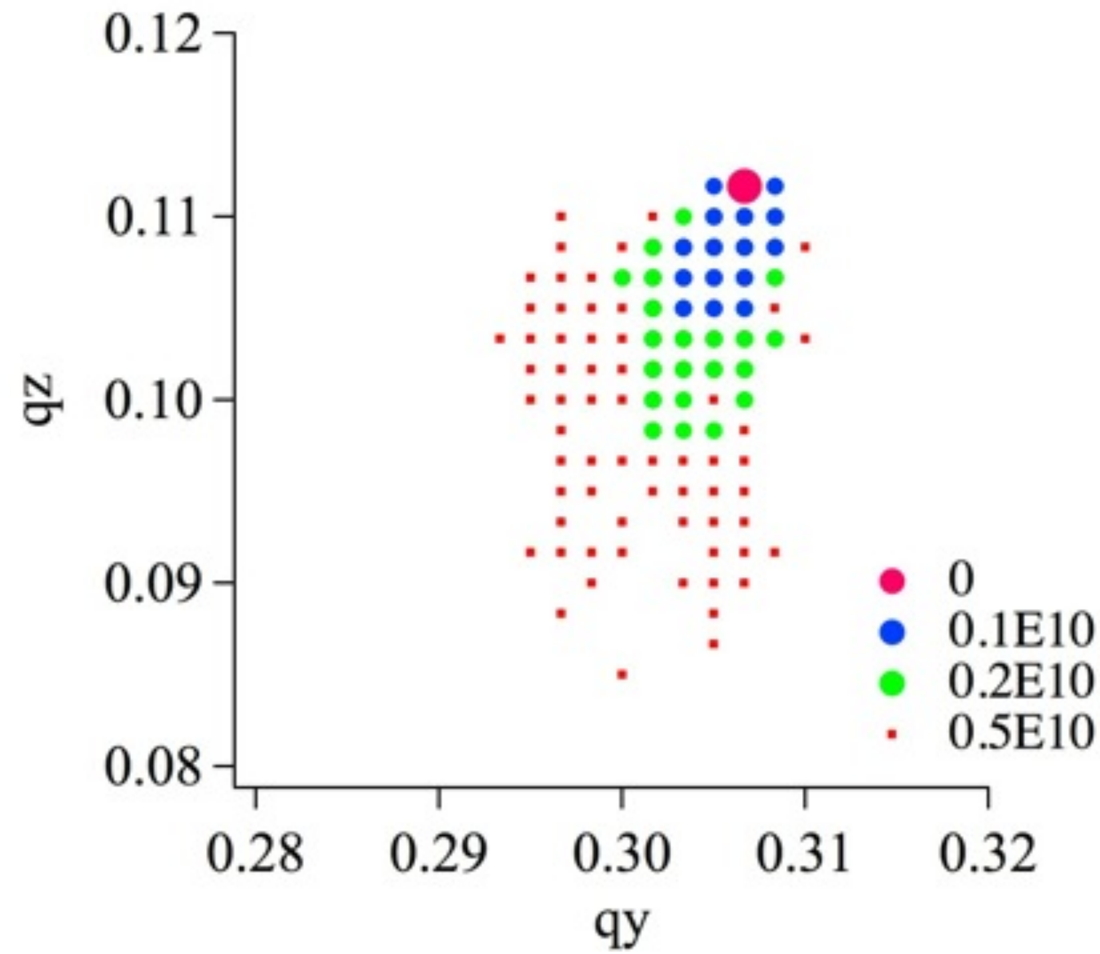
Benchmark step2 results
with space charge

Space charge tune spread for the first 50 turns

ring tune



cell tune



n_t	Delta Q
0.1x10	-0.11
0.2x10	-0.21
0.5x10	-0.54

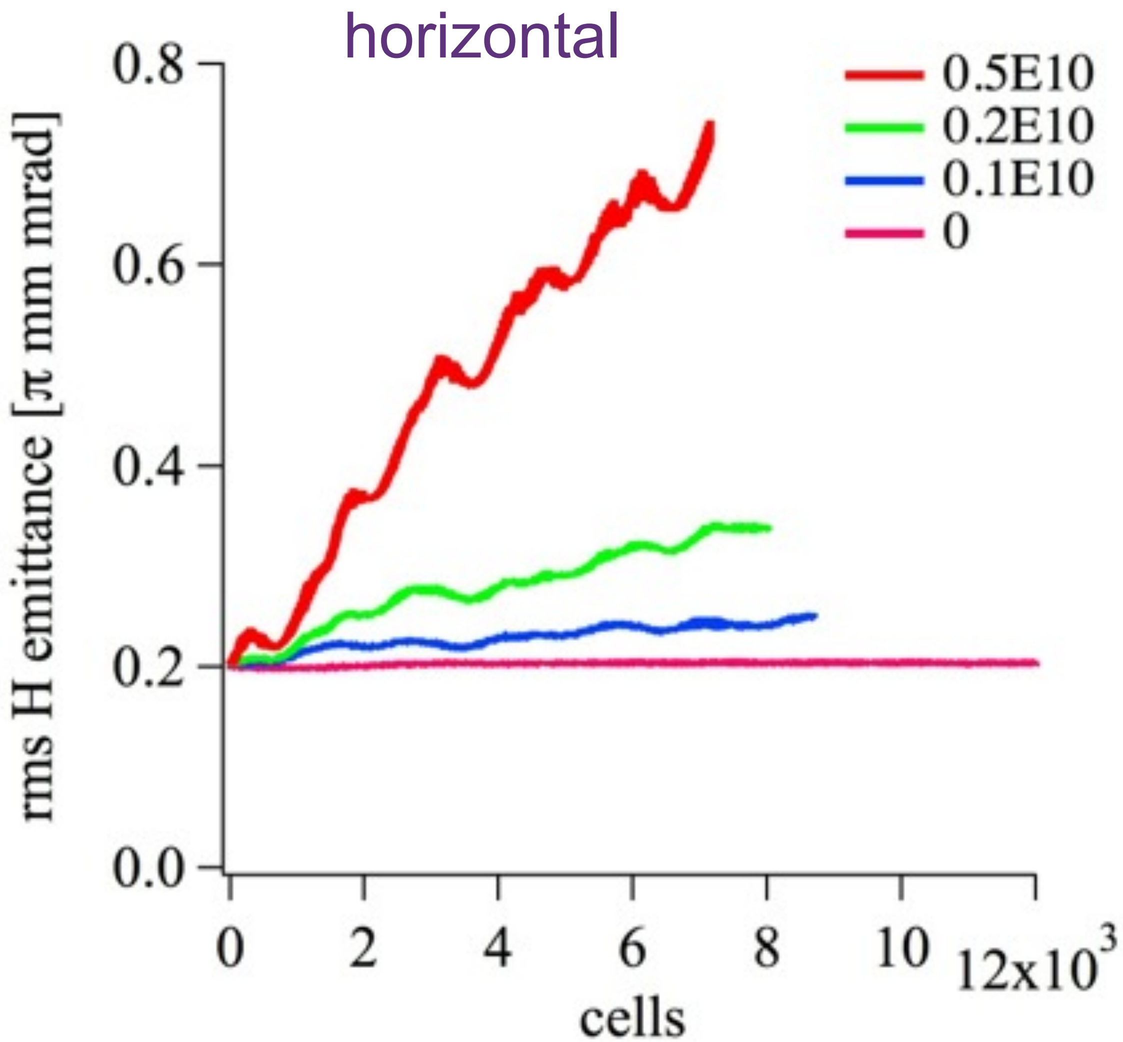
Agreed with the formula.

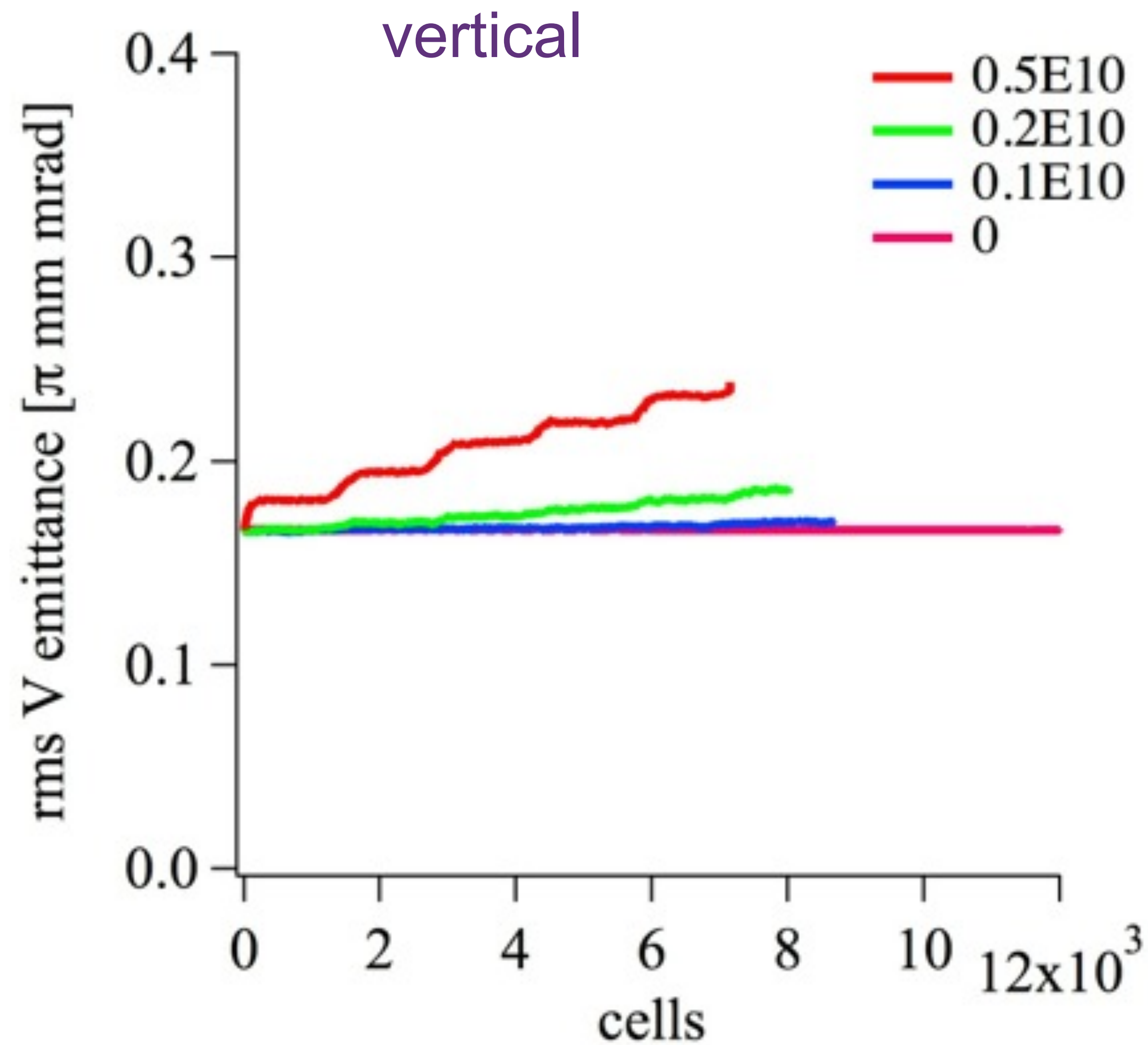
except for 0.5E10 when emittance changes significantly (next page).

Benchmark step2 results

with space charge

Emittance evolution of the first 1000 turns with acceleration.





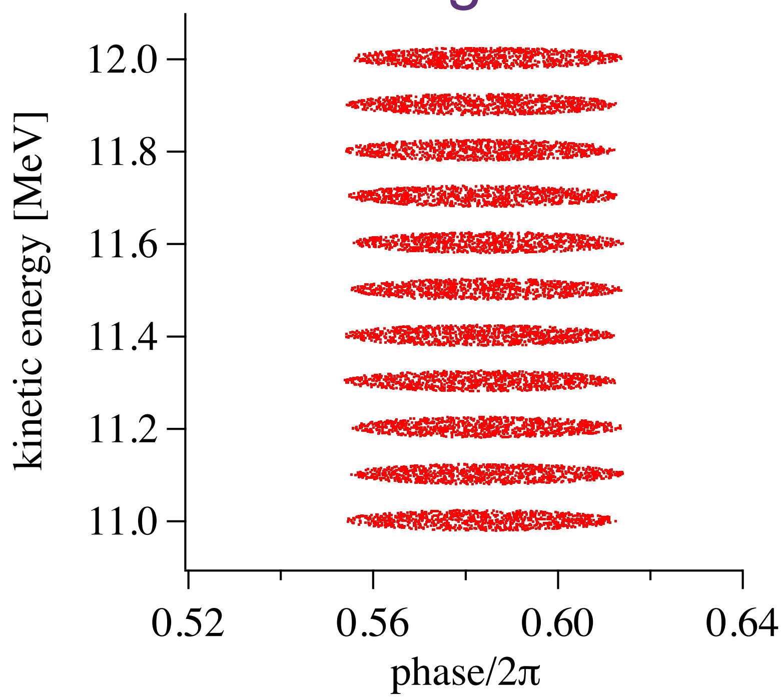
Increase by a step corresponds to a half synchrotron oscillation. (~1,300 cells)

Benchmark step2 results

with space charge

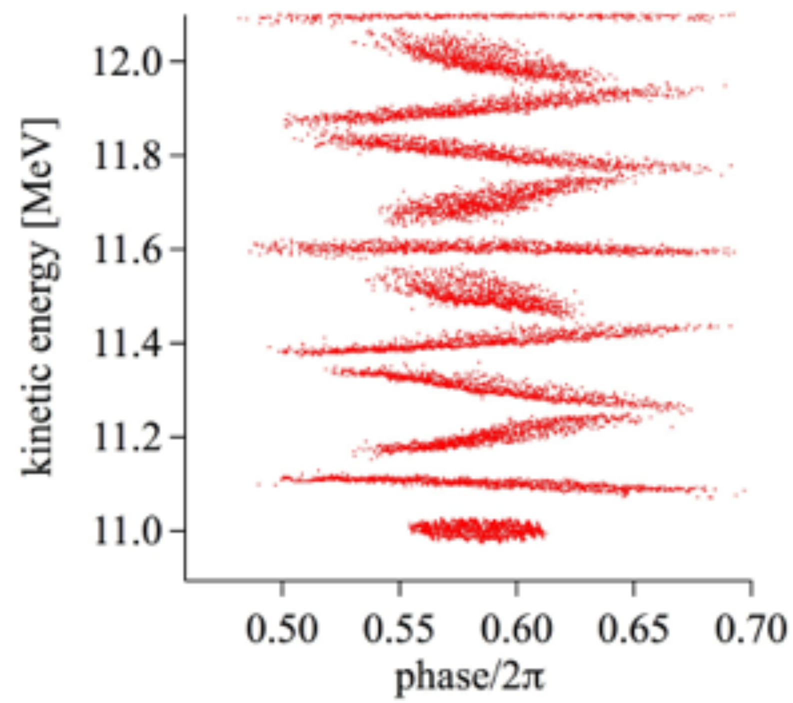
without space charge

longitudinal

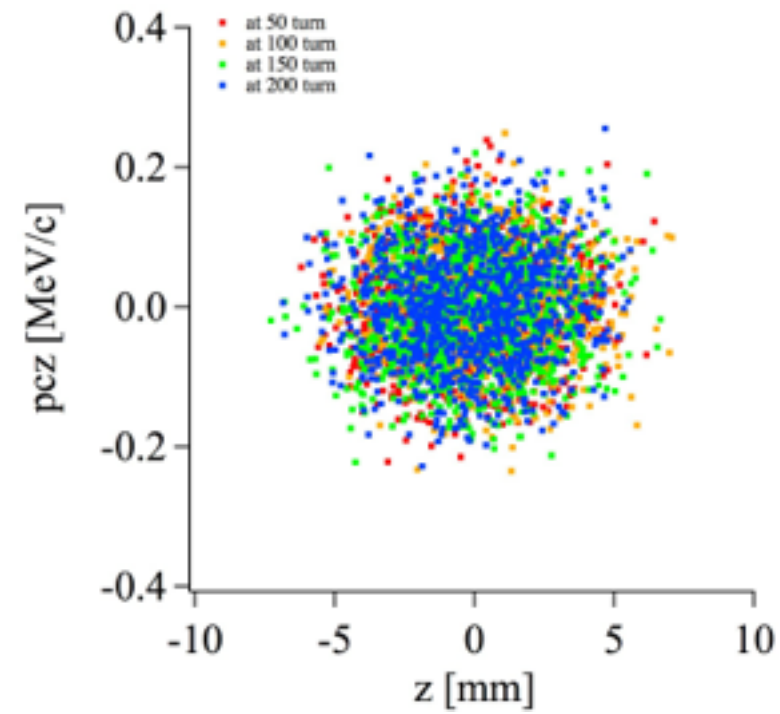


with 0.5E10

longitudinal



vertical



- Quadrupole oscillation in longitudinal phase space is the source of stepwise emittance growth in transverse.
- This can be eliminated with initial condition.
- No coherent oscillation in transverse phase space.

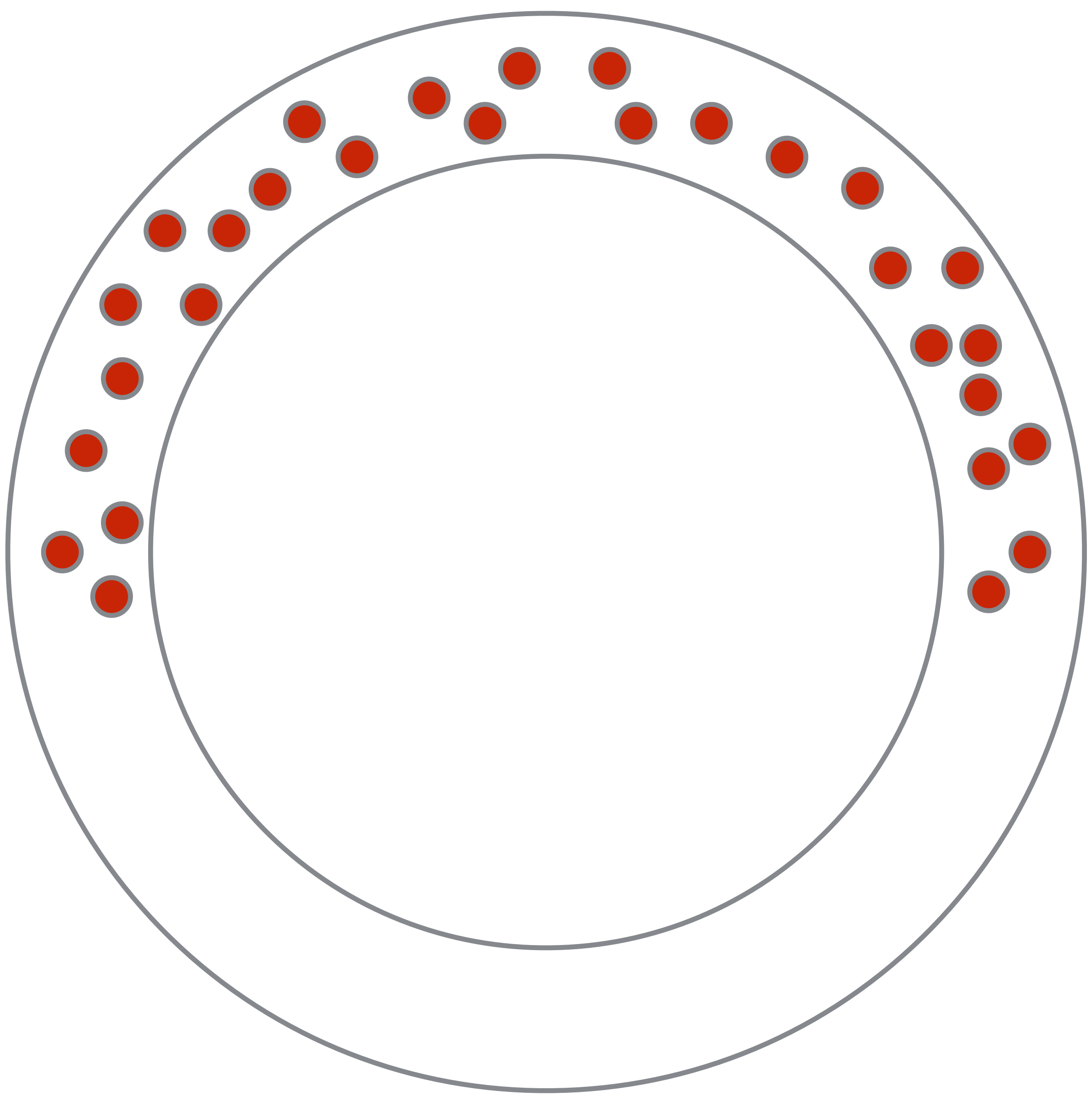
Final remarks

- This is the first iteration of space charge simulation using KURRI FFAG lattice.
- As usual, we have to optimise simulation parameters such as # of macro particles, # of grids, etc, that has not been done yet.
- It would be very interesting to see how each code (Zgoubi, OPAL, Scode, …) comes to convergence.
- More importantly, whether converged values (emittance, bunch length, etc) are the same.

Backups

Benchmark step2 results
with space charge

Difficultly to simulate a long bunch (when h=1).



- Make a slice in longitudinal direction and approximate each beam in cylindrical coordinates.
- Short bunch is preferable from simulation point!