Space charge simulation for 4th order resonance

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Observation at CERN-PS

At space charge workshop 2013, Simone and Raymond presented a problem of

4Qy=25

- Invisible by resonance scan with low brightness beams.
- Impose the upper bound in tune space for high brightness beams.

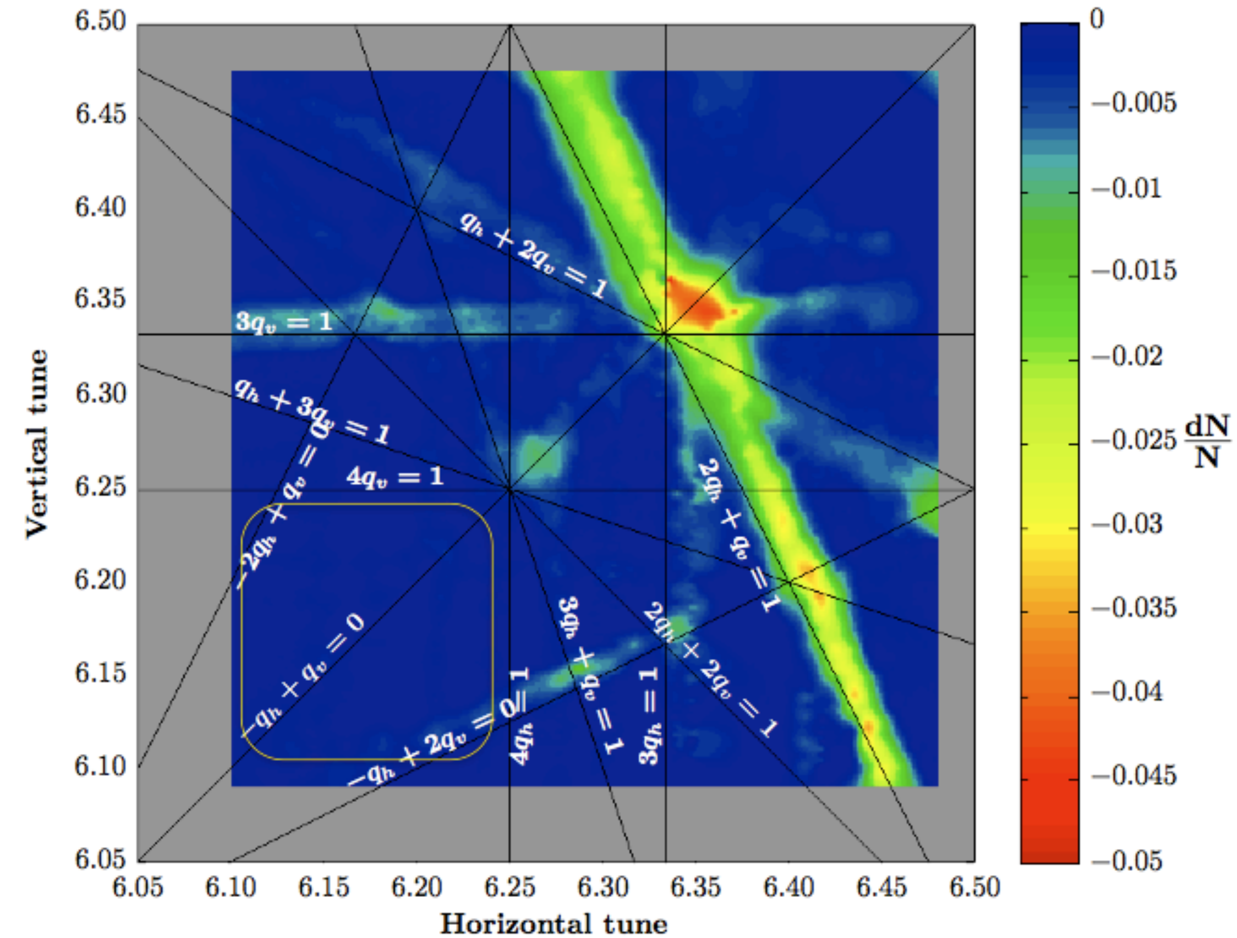

Figure 1: Tune loss map. The color code indicates losses. The operational working area is identified by the rectangle.

What is this and how can we cure?

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Summary

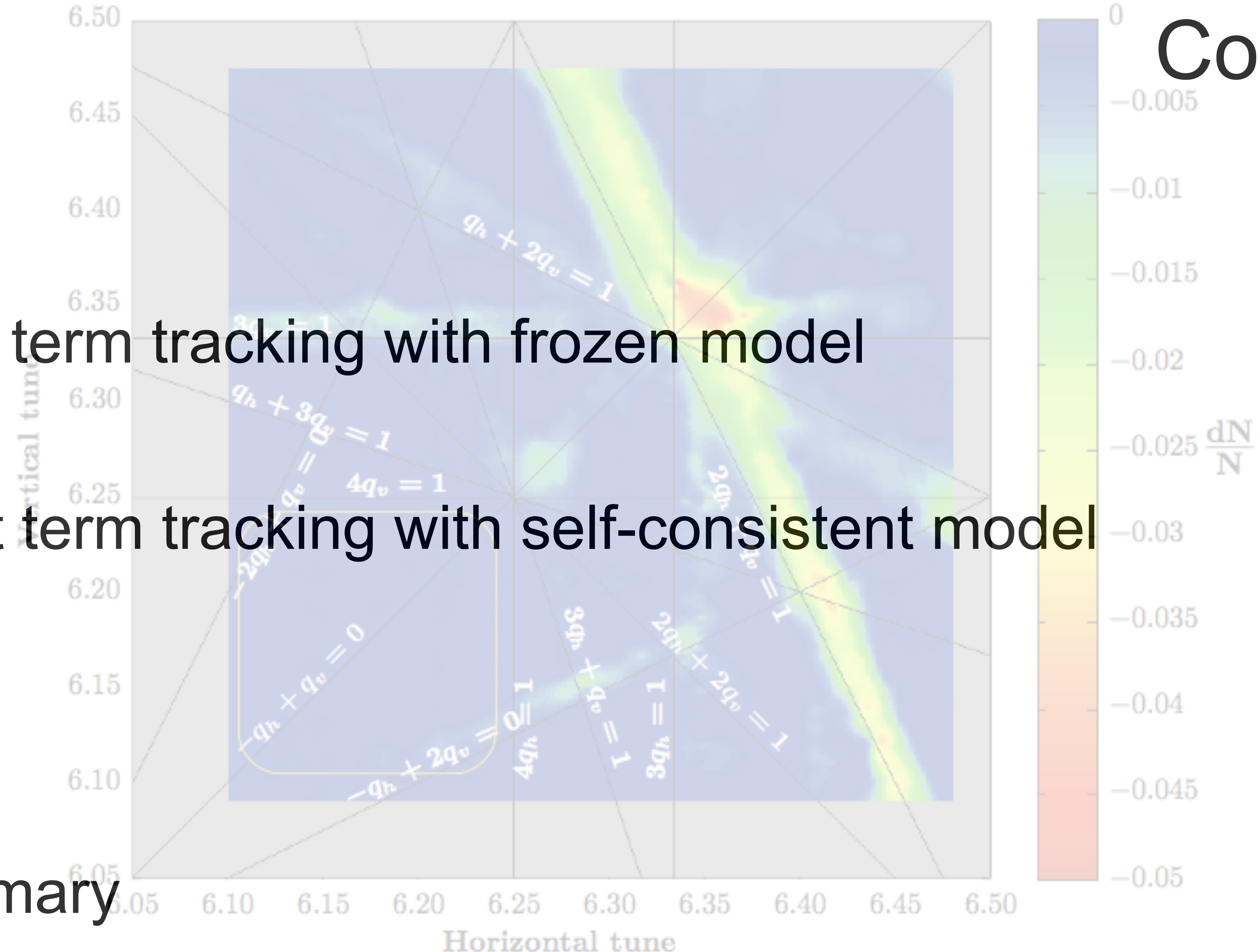

Figure 1: Tune loss map. The color code indicates losses. The operational working area is identified by the rectangle.

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Long term tracking with frozen model

Frozen model in *Simpsons*

Space Charge potential based on Gaussian in 6-D.

Use rewritten CWERF (CERN library) based on Bassetti and Erskine formula (CERN-ISR-TH/80-06).

Main modification: Symmetry is restored although it becomes slow.

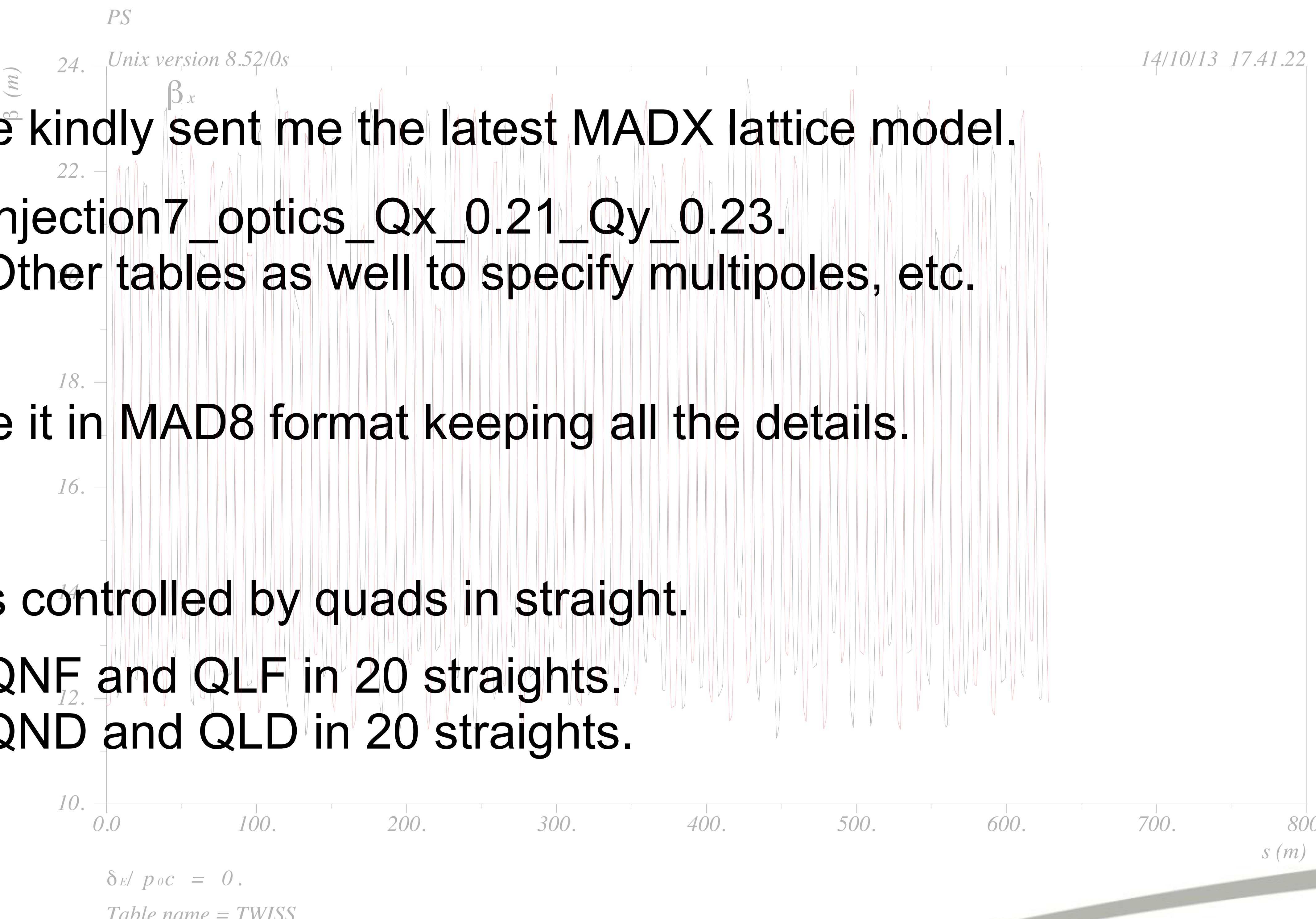
Aspect ratio (H/V) is updated each time step, not at fixed locations. *Simpsons* uses "time" as the independent variable.

No longitudinal space charge, but transverse space charge depends on longitudinal position.

$$\lambda(s) = \lambda_0 \exp(-\frac{s^2}{2\sigma_s^2})$$

Use 2000 particles with Gaussian distribution (up to 4 sigma) to see beam loss and emittance growth.

Lattice description



Simone kindly sent me the latest MADX lattice model.

- Injection7_optics_Qx_0.21_Qy_0.23.
- Other tables as well to specify multipoles, etc.

Rewrite it in MAD8 format keeping all the details.

Tune is controlled by quads in straight.

- QNF and QLF in 20 straights.
- QND and QLD in 20 straights.

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Beam and rf parameters

Raymond kindly sent me beam and rf parameters

"Beam1"

hori. emittance (rms, normalised)	1.3 pi mm mrad
vert. emittance (rms, normalised)	1.6 pi mm mrad
number of proton per bunch	1.15×10^{12}
hori. incoherent tune shift	-0.18
vert. incoherent tune shift	-0.33

I assume parabolic in longitudinal and gaussian in transverse

rf parameters

total rf voltage	200 kV
synchrotron oscillation period	about 240 turns
bunch length (rms, half)	6.2 m
momentum spread (rms, half)	0.0018
bunching factor	0.26

"Beam1" simulation result with circular aperture

Circular beam pipe aperture: H/2=V/2=73 mm.

Comparison with measurement for the first 100 ms.

Wasef et al, IPAC13

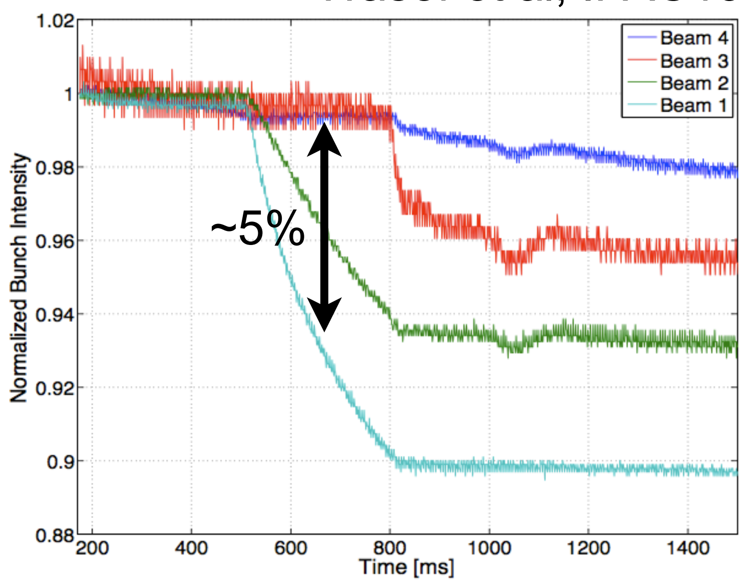
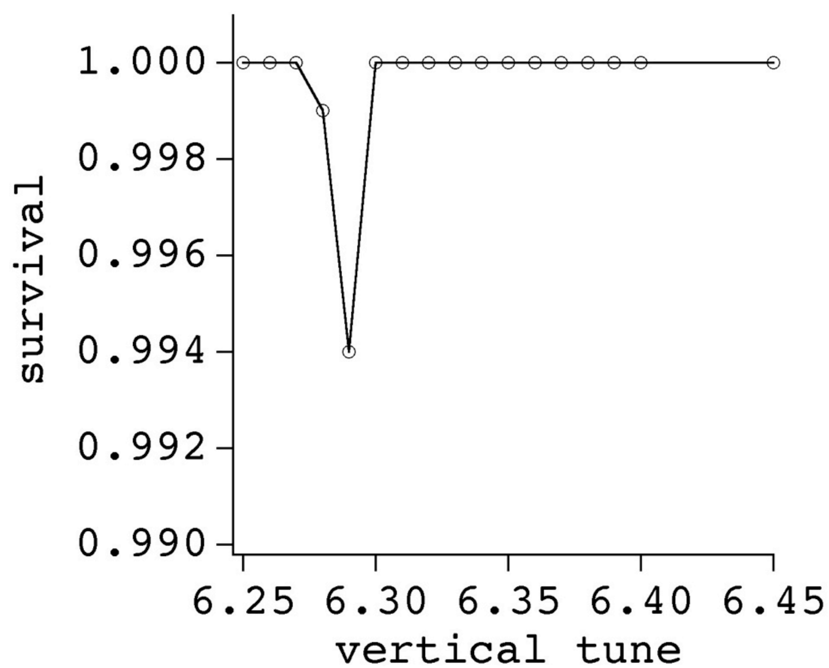
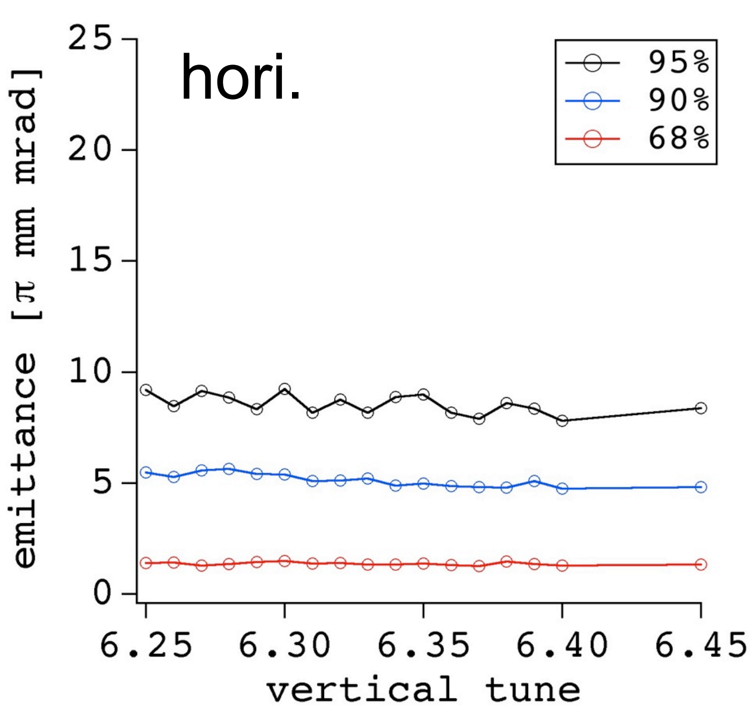
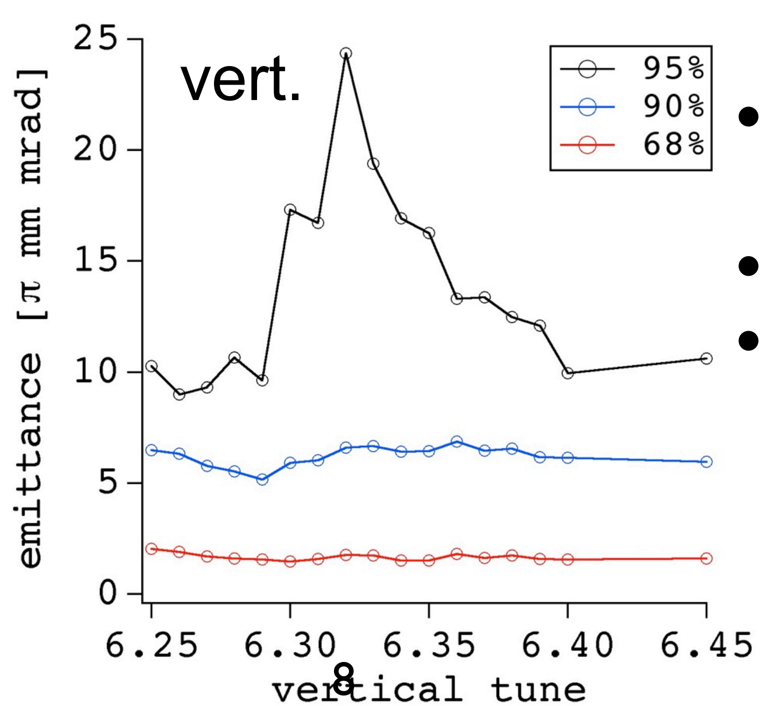


Figure 3: Losses during crossing $4Q_y = 25$ resonance.



- Experiment shows more than 5% in 100 ms.
- Simulation shows only less than 1%.





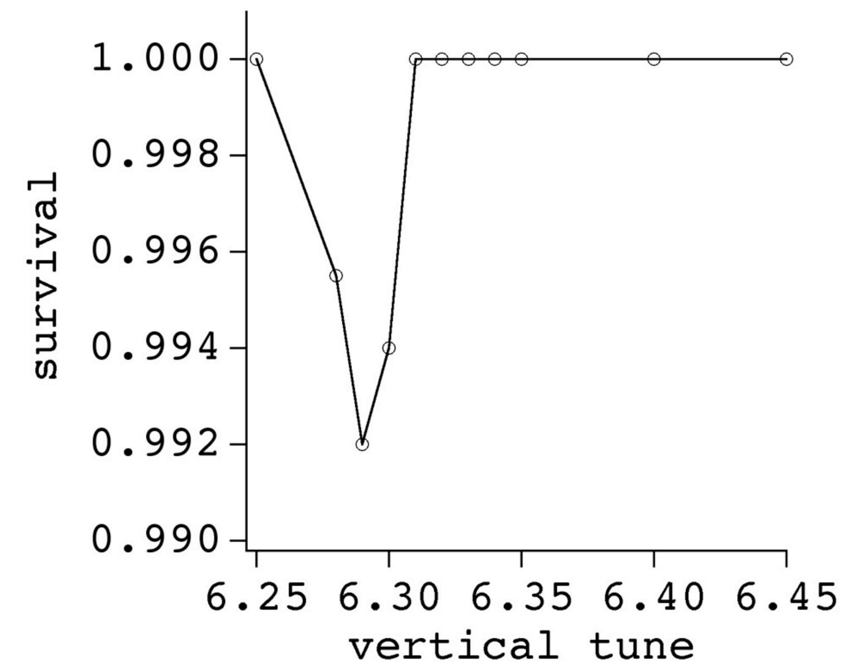
- Beam core up to 90% emit does not change much.
- Only 95% beam emit grows.
- Beam loss and 95% growth occurs at different tune.

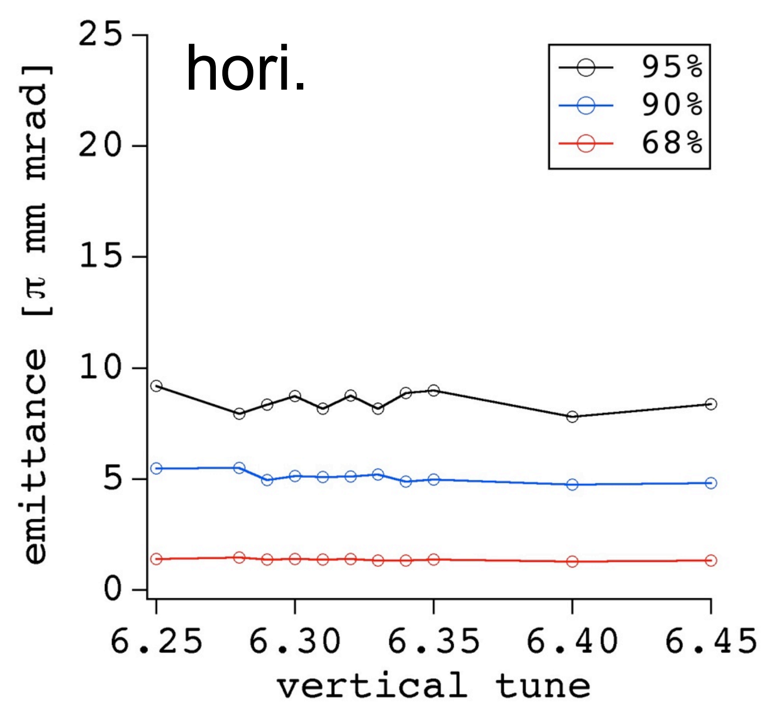
"Beam1" result with more realistic aperture

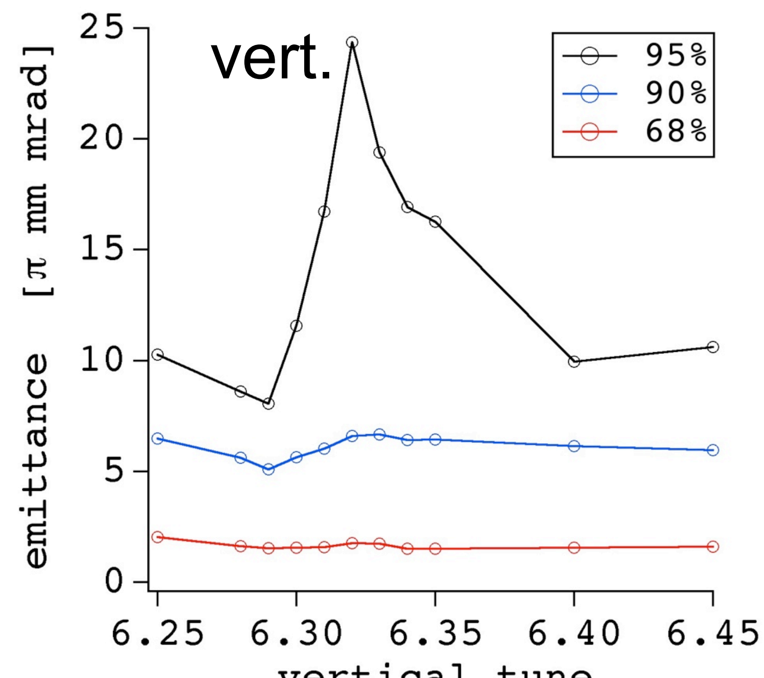
Elliptical beam pipe aperture: H/2=73 mm and V/2=35 mm.

- Not much difference from the one with circular aperture.

- 2000 macro particles are not enough to model a real beam, especially tail.
- Discrepancy of beam loss could come from poor statistics at tail.







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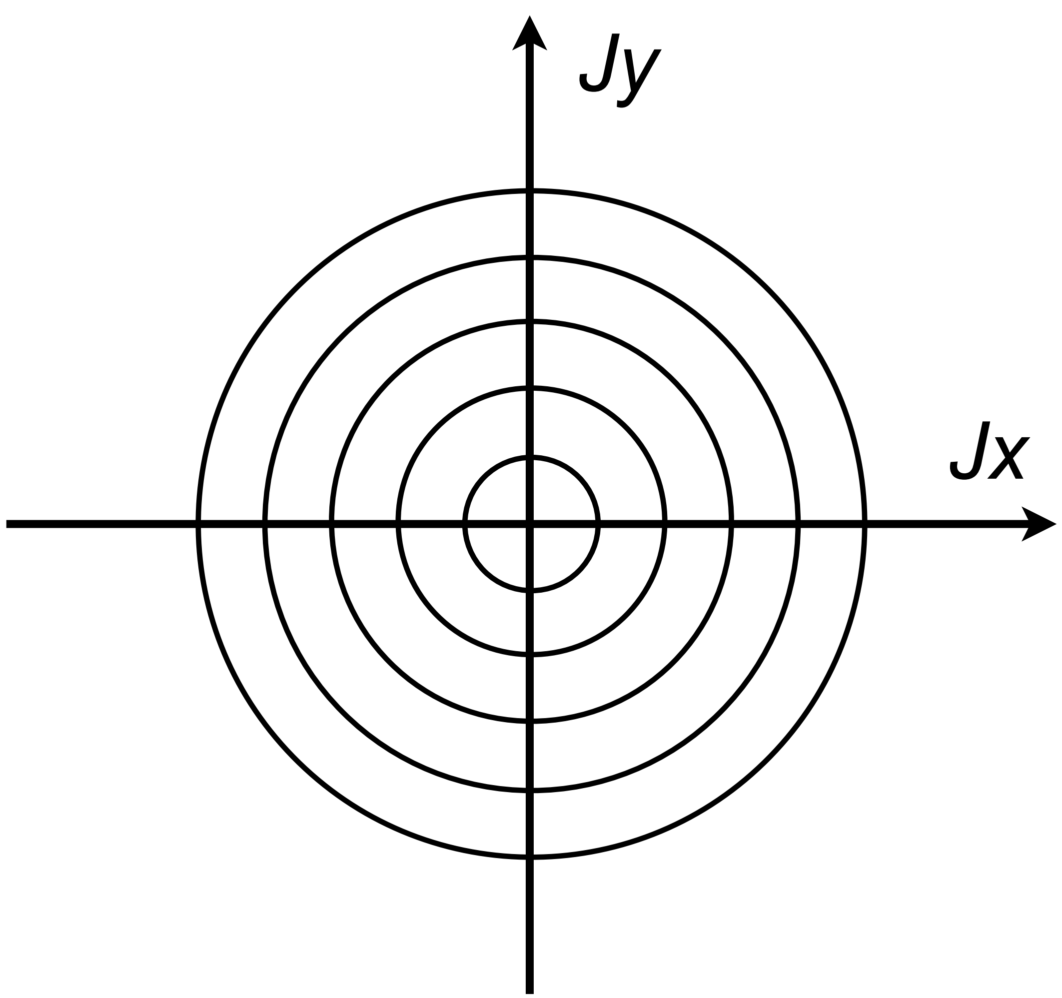
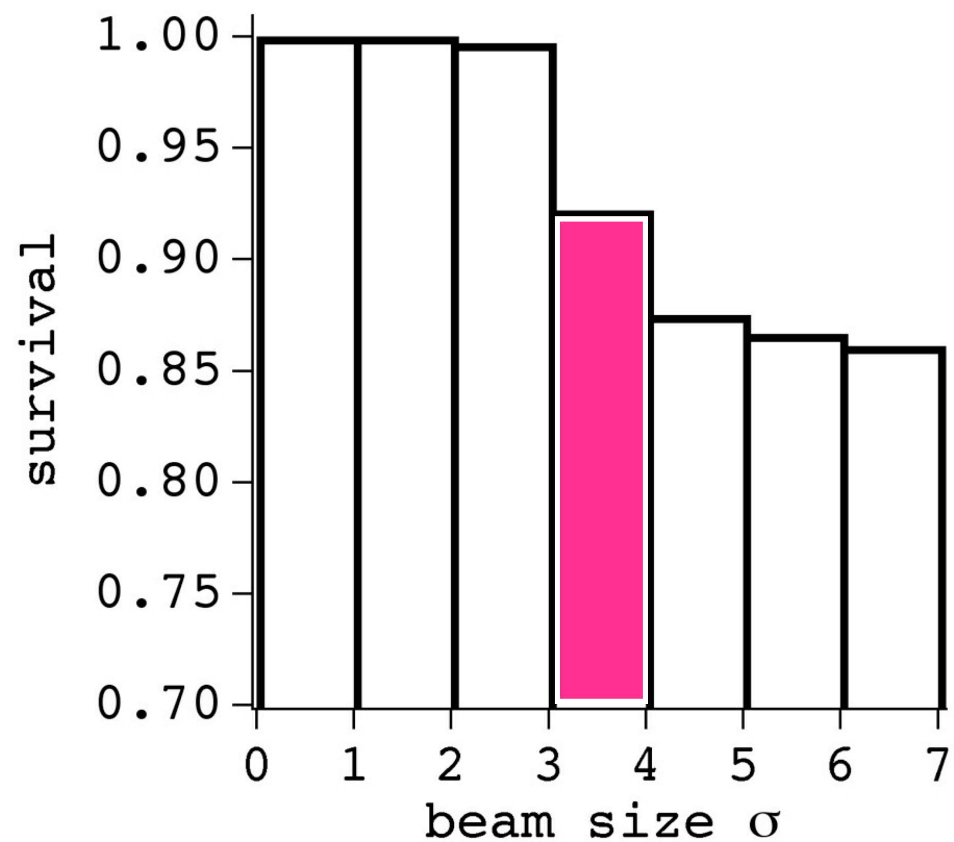
"Differential" beam loss (transverse)

Identify which part of a beam will be lost.

Define beam loss ratio for each initial transverse amplitude band.





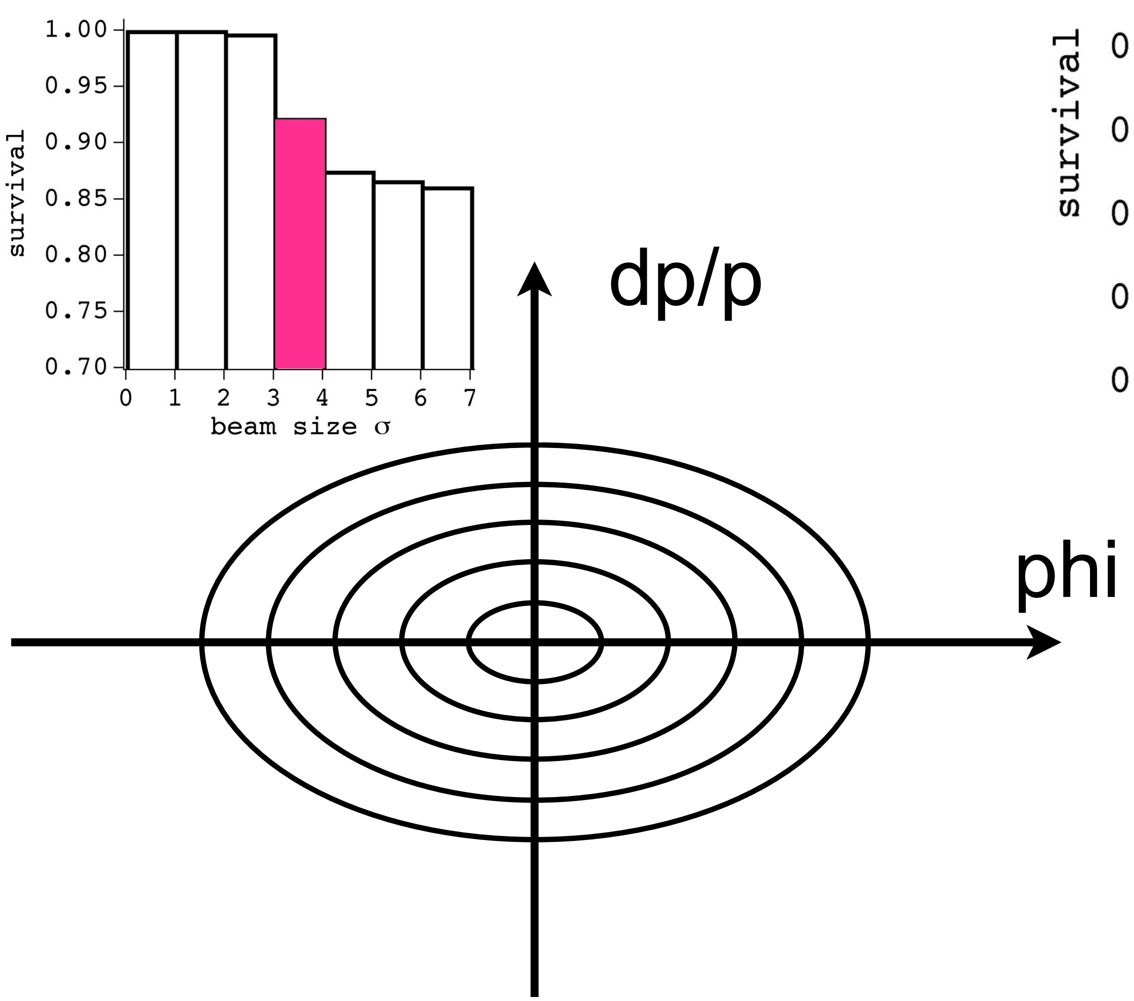
Only particles which are initially more than 3 sigma in transverse are lost.

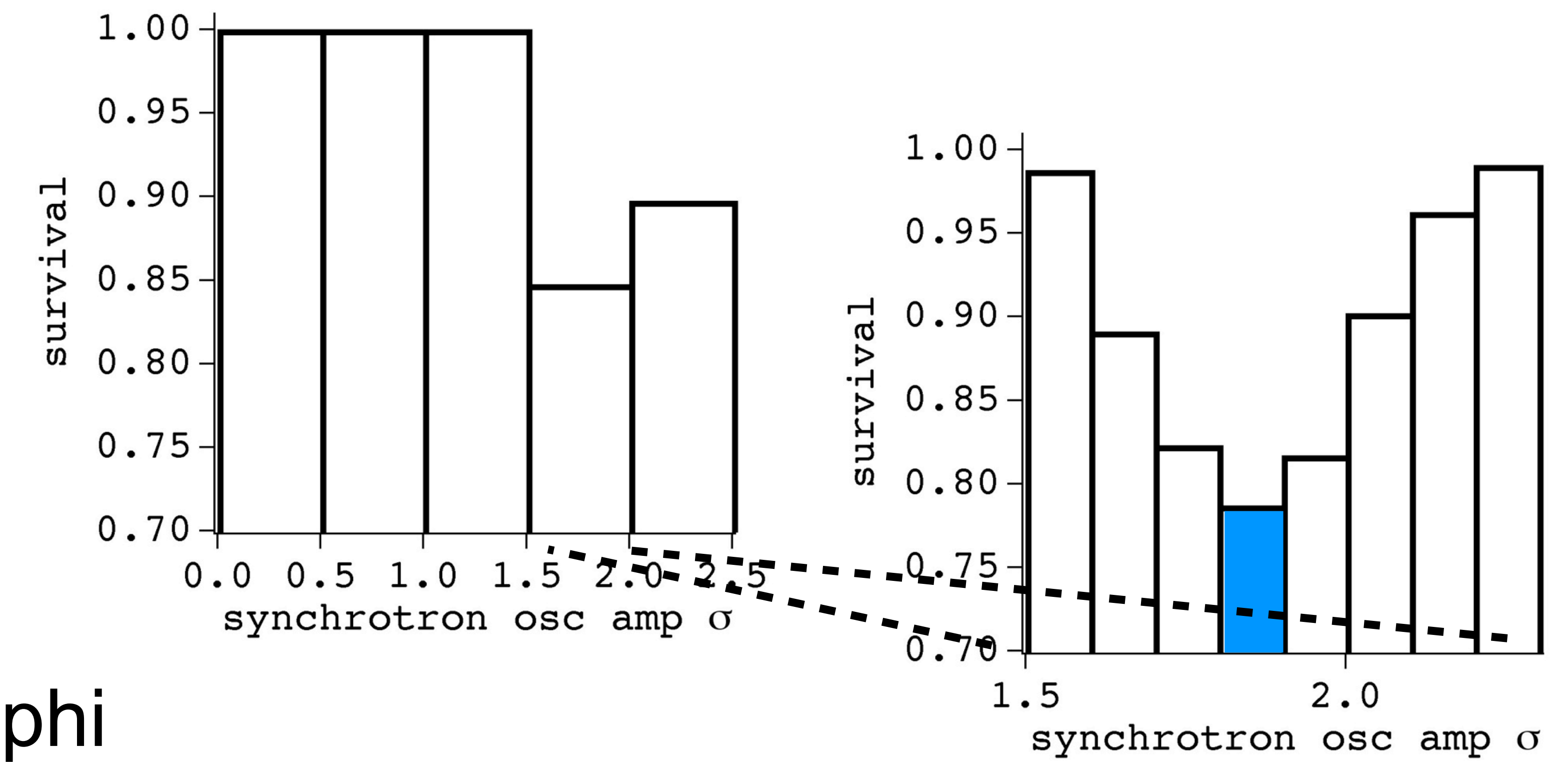
“Differential” beam loss (longitudinal)

Identify which part of a beam will be lost.

Define beam loss ratio for each initial longitudinal amplitude band.

With 3 to 4 sigma in transverse.



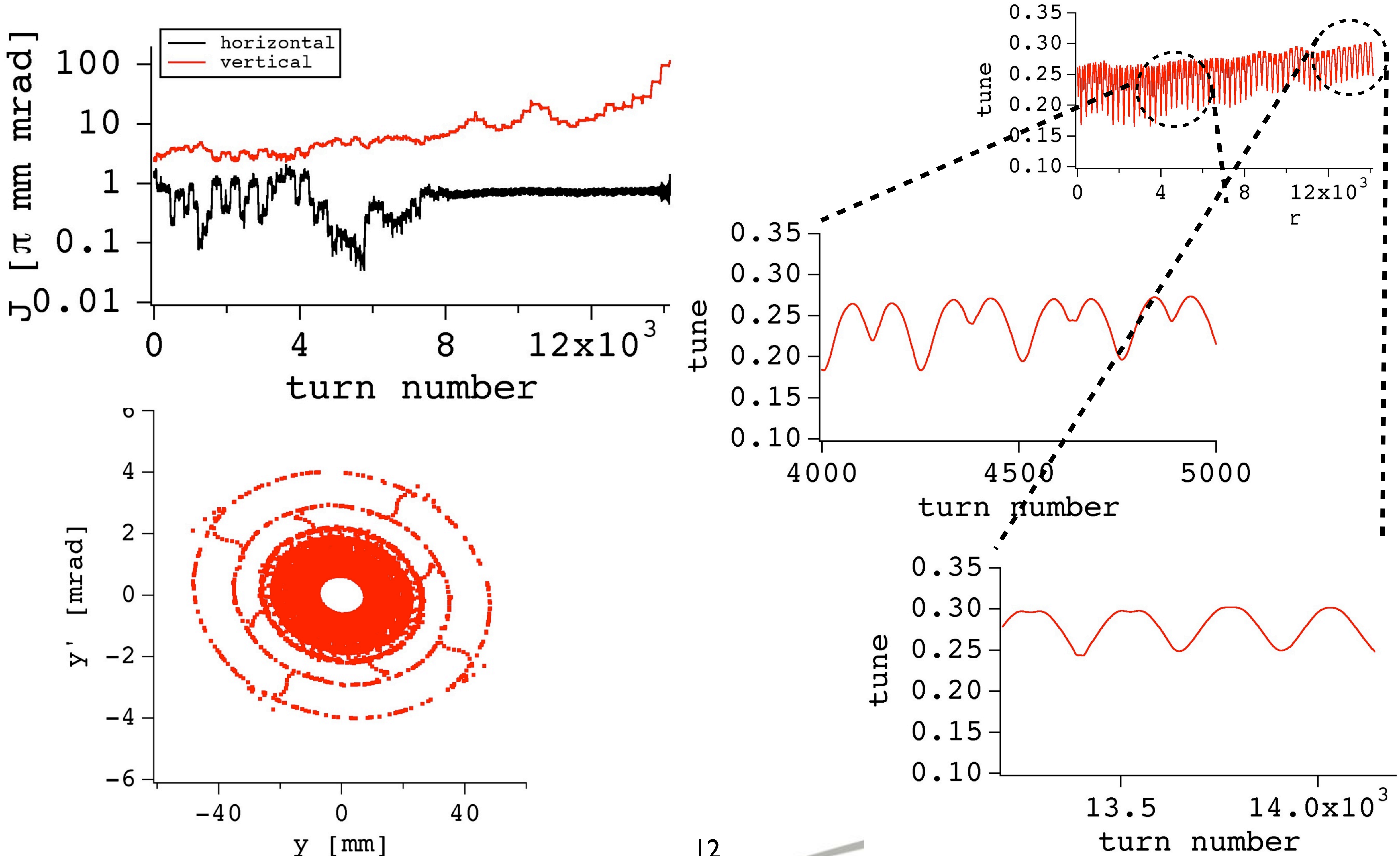


transverse (red)	3 - 4 sigma
longitudinal (blue)	1.8 - 1.9 sigma

has the highest prob. to become loss.

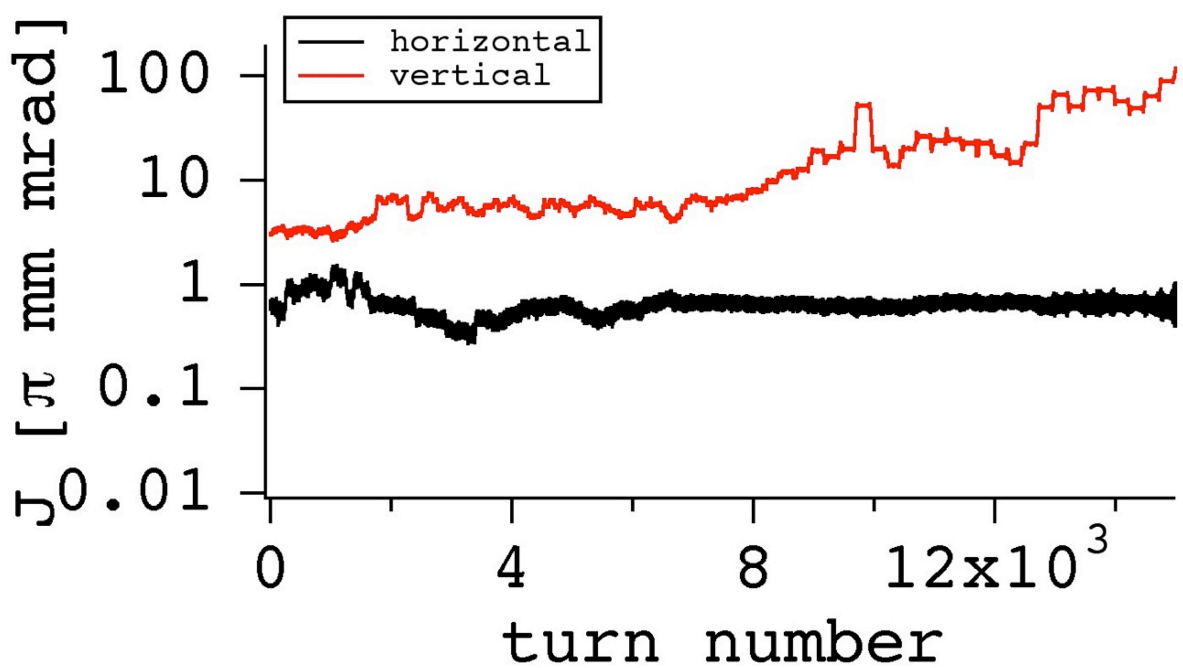
Single particle analysis

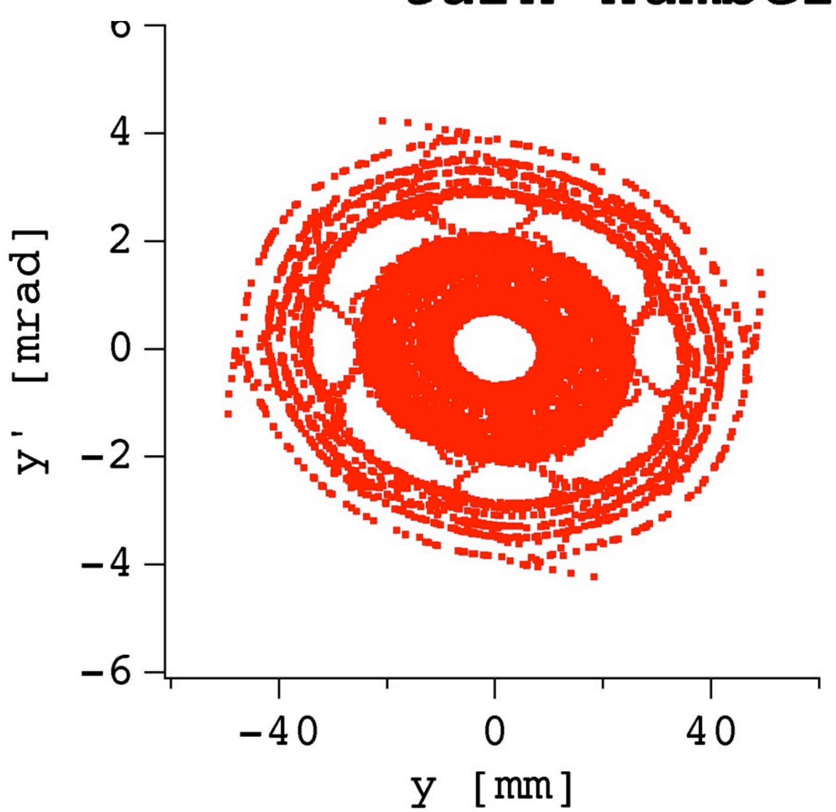
Take a close look at lost particle motion in that band.



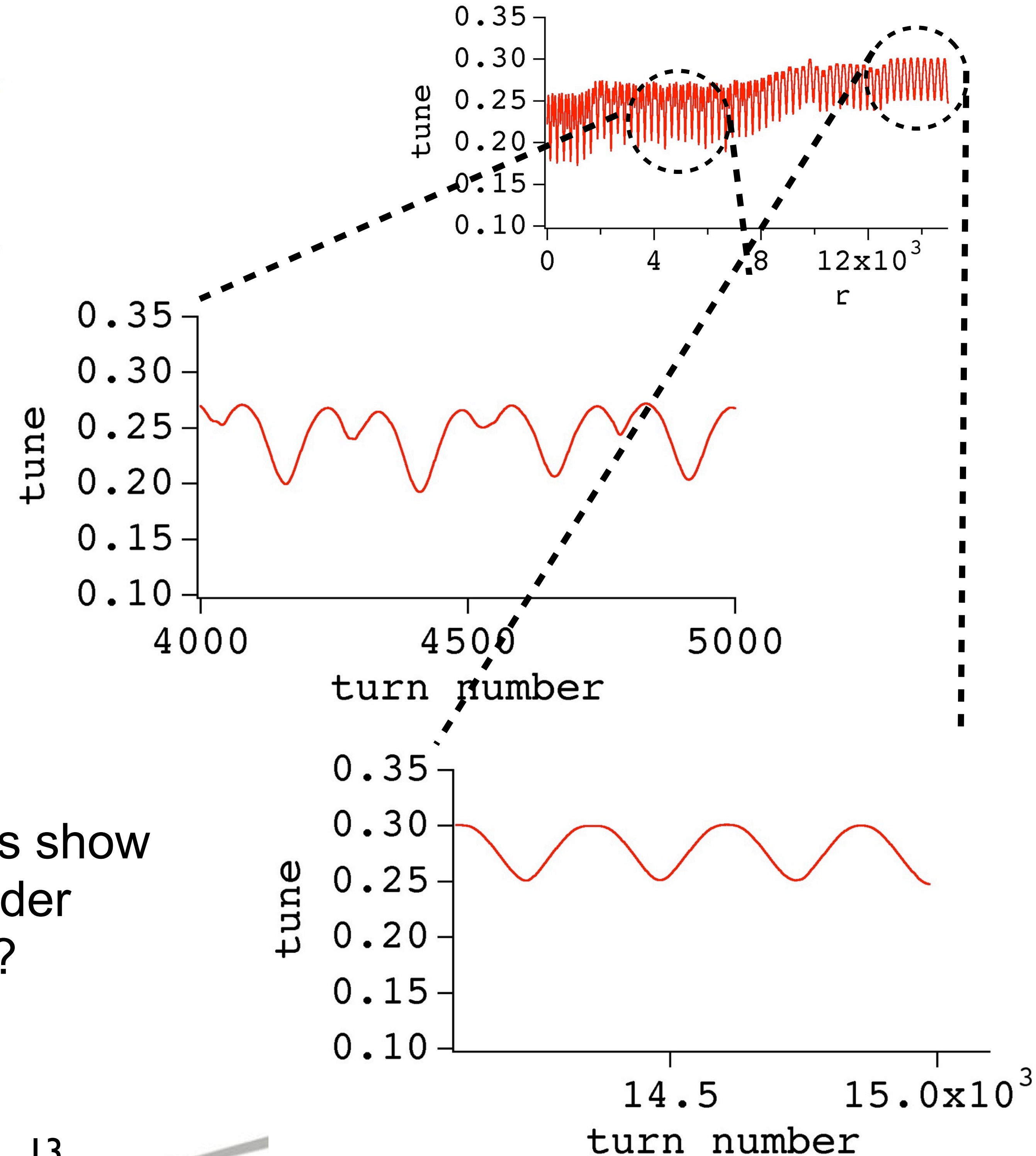
Single particle analysis (another example)

Take a close look at lost particle motion in that band.



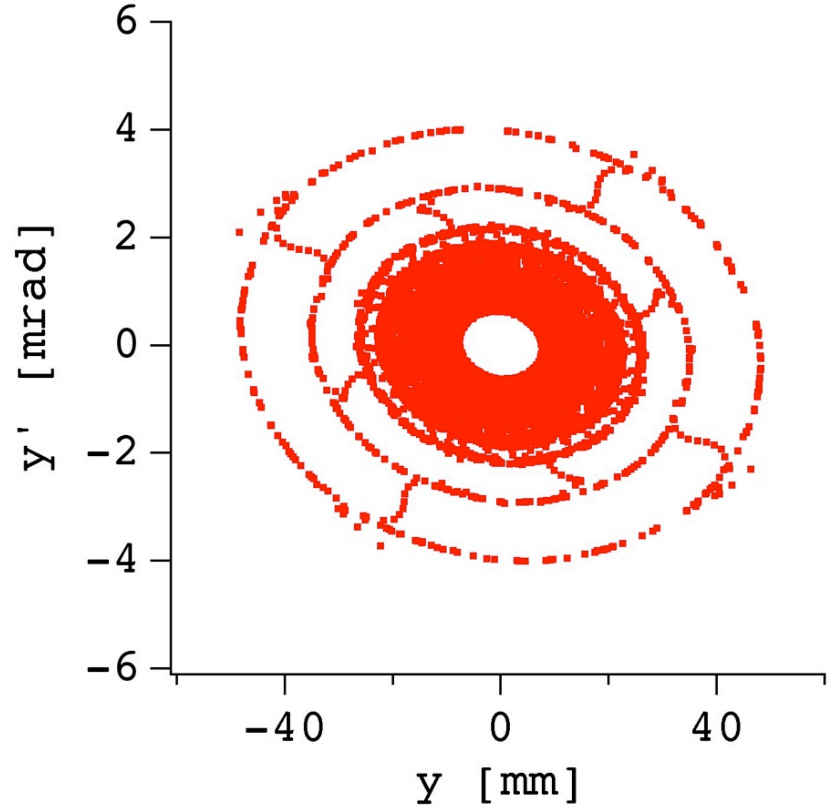


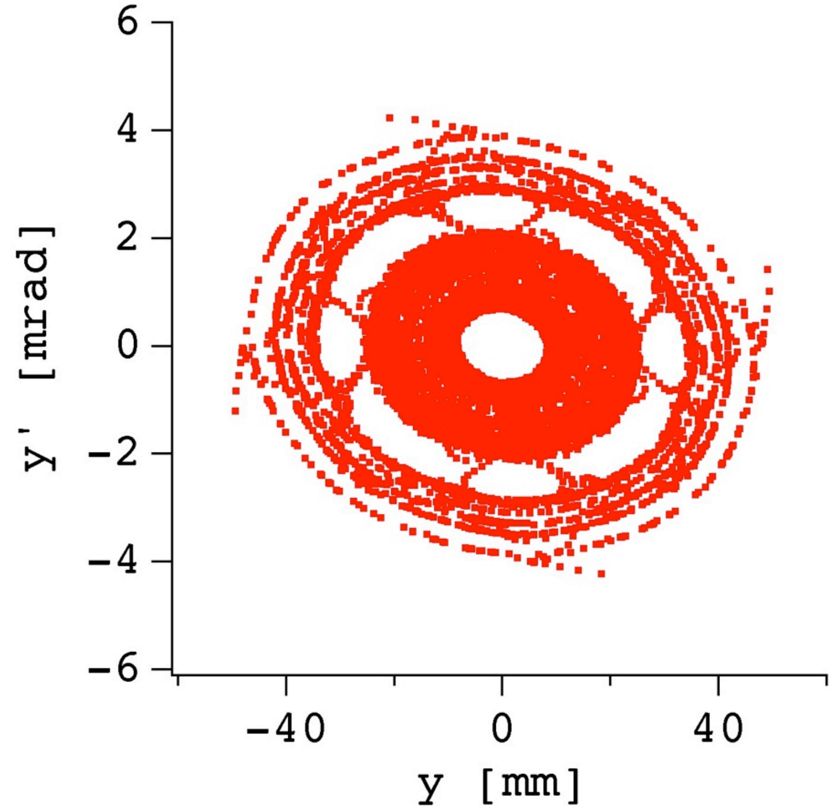
Does this show fourth order 4Qy=25?



Loss mechanism

Plausible explanation is trapping/scattering as a result of resonance crossing (Giuliano Franchetti).





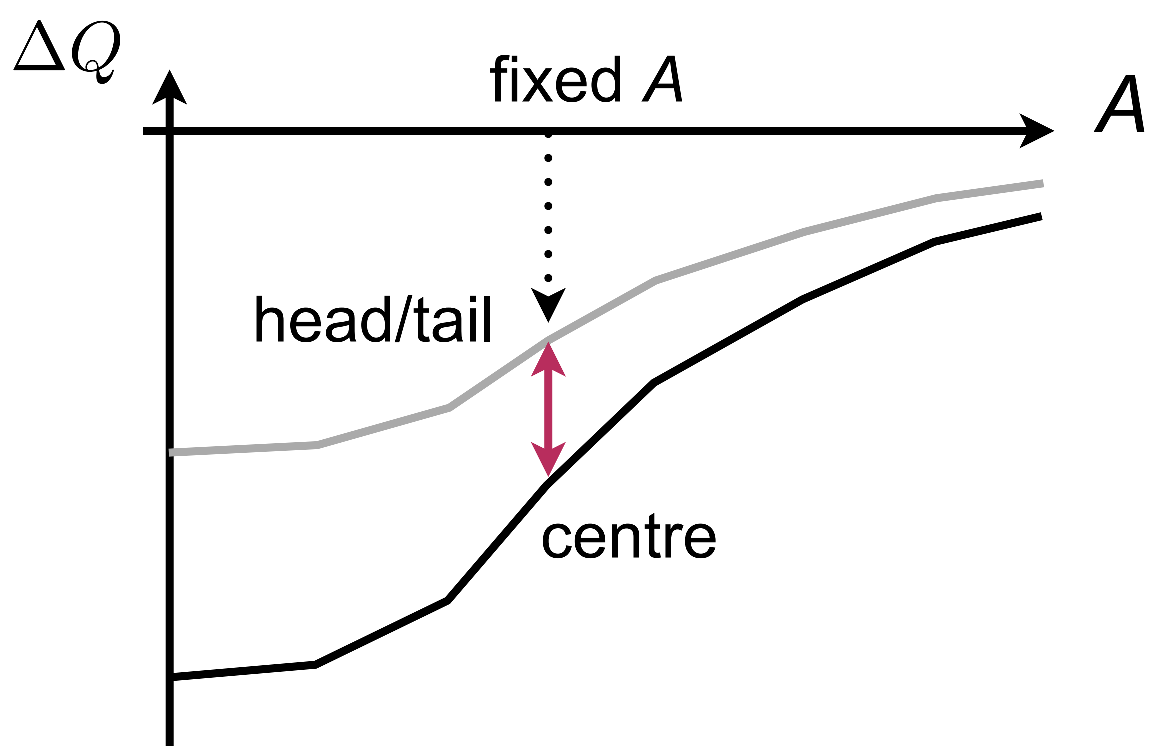
Two ingredients are needed.

- Tune modulation to cause resonance crossing.
- Resonance driving source.

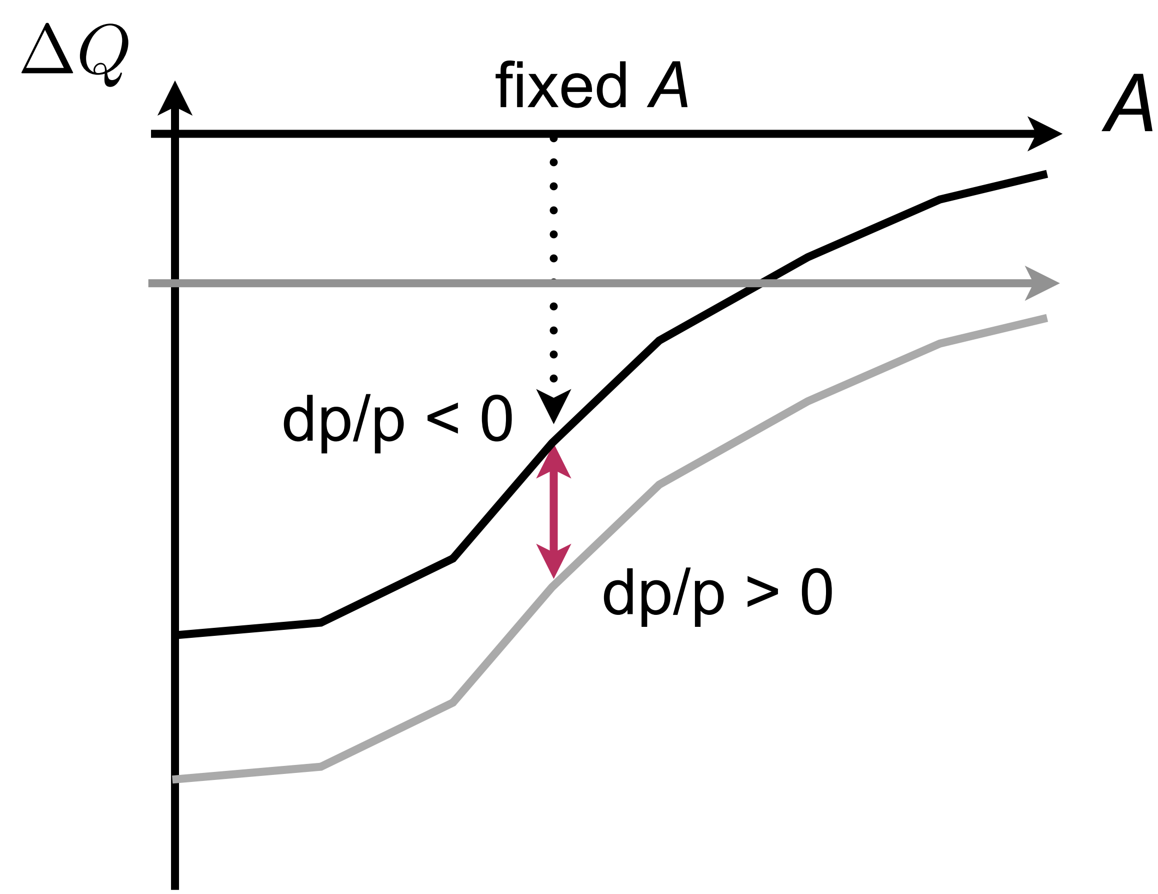
Loss mechanism
tune modulation

Two sources of tune modulation.

Space charge depends on longitudinal position.

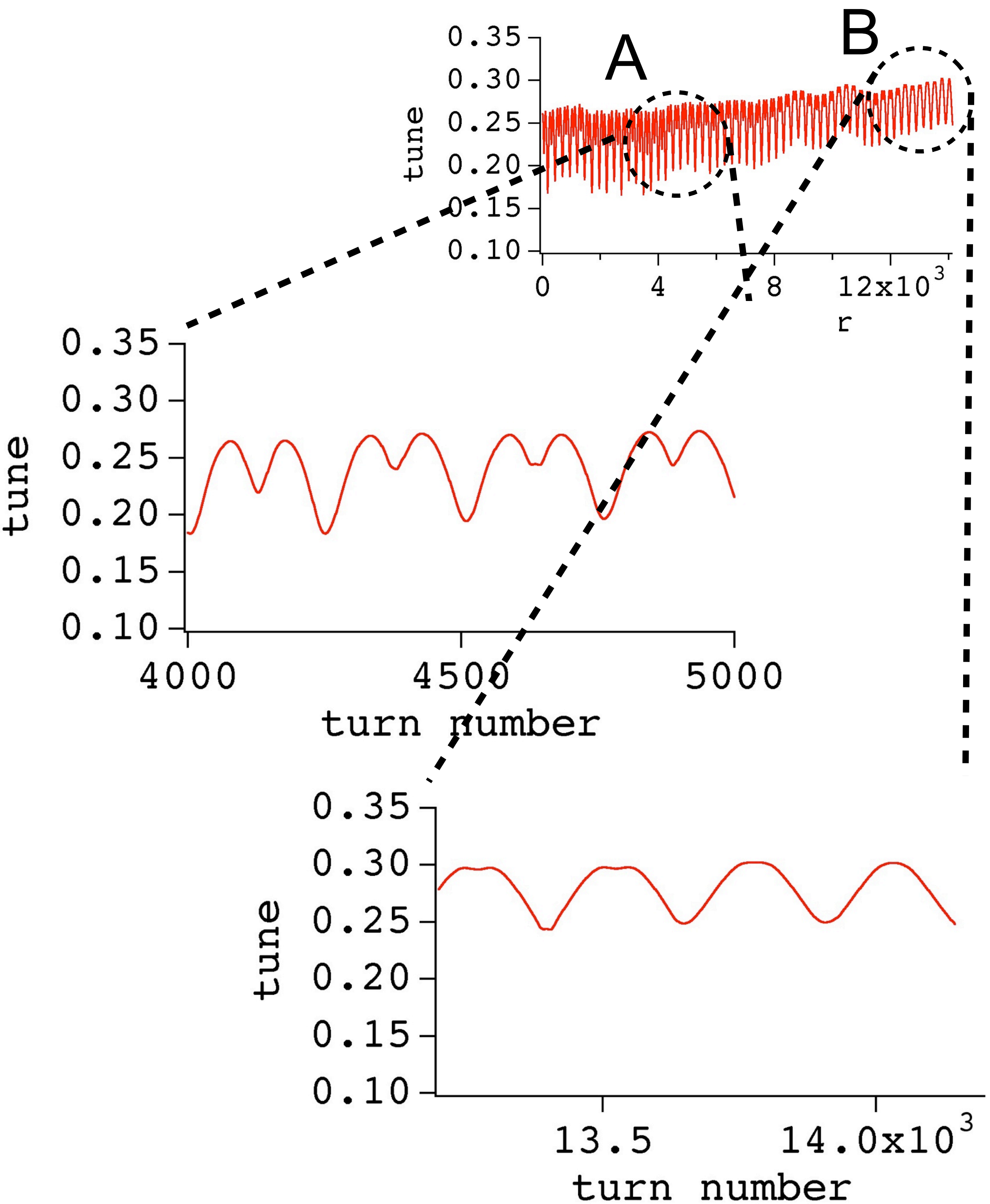


Finite chromaticity and momentum oscillation.

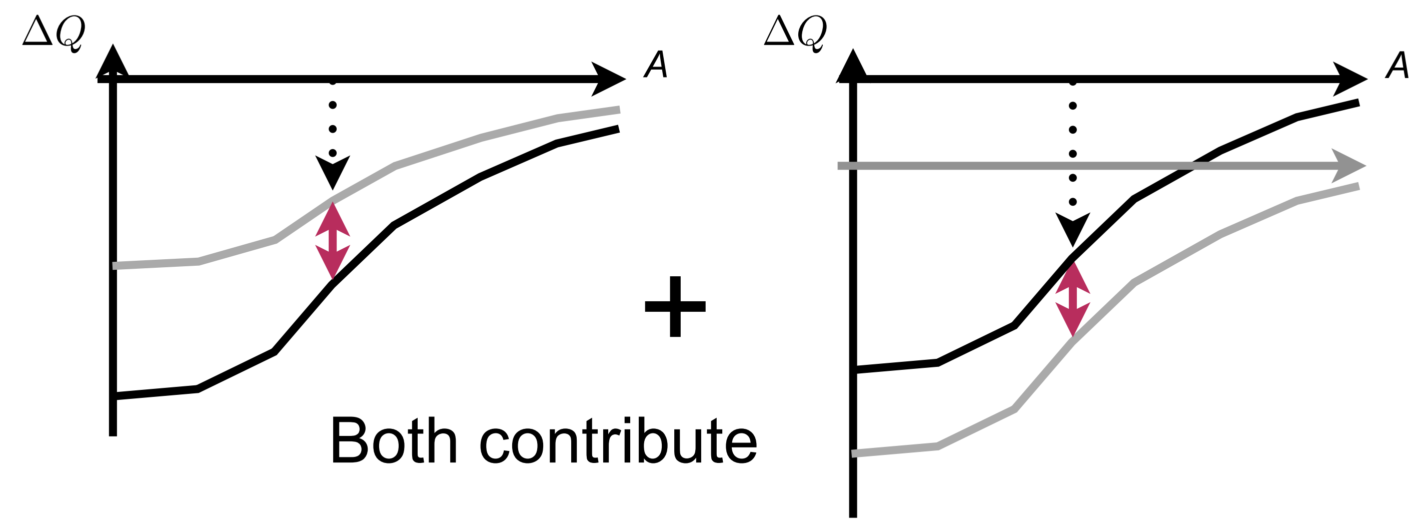


Loss mechanism

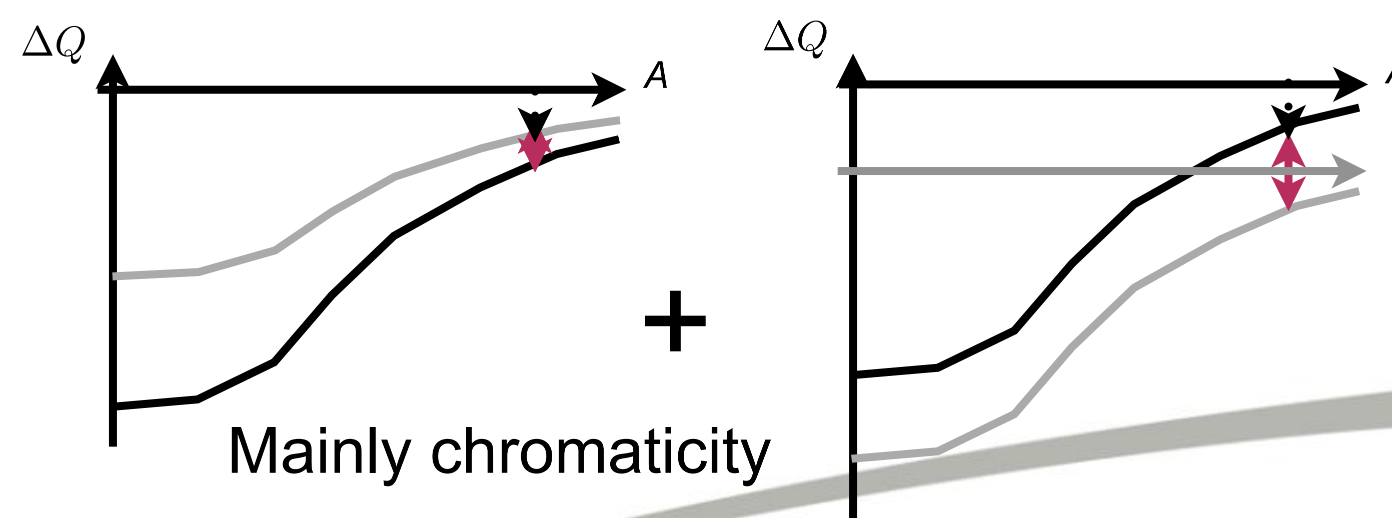
amplitude dependence of tune modulation



Small amplitude at A

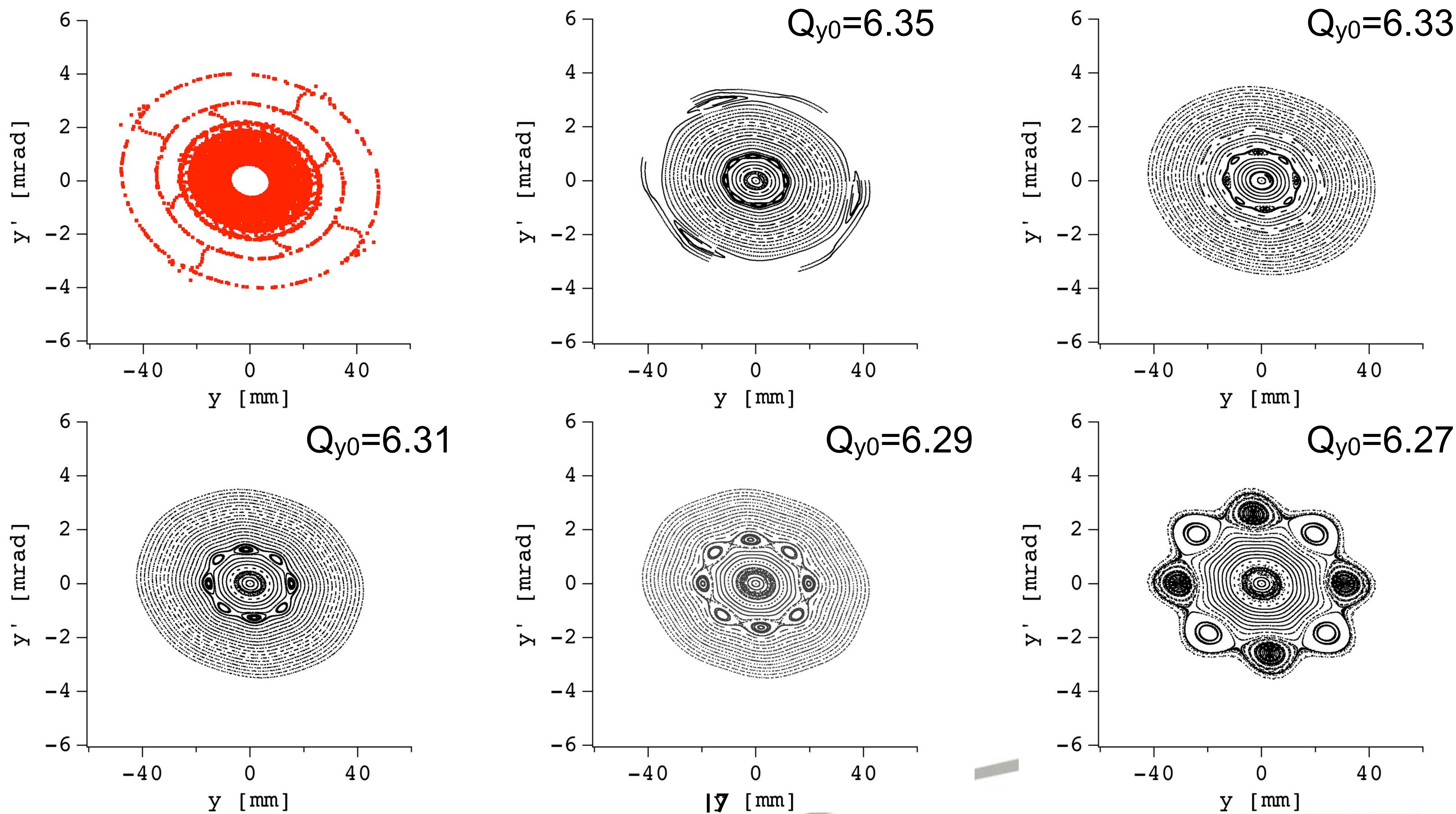


Large amplitude at B



Loss mechanism
phase space geometry

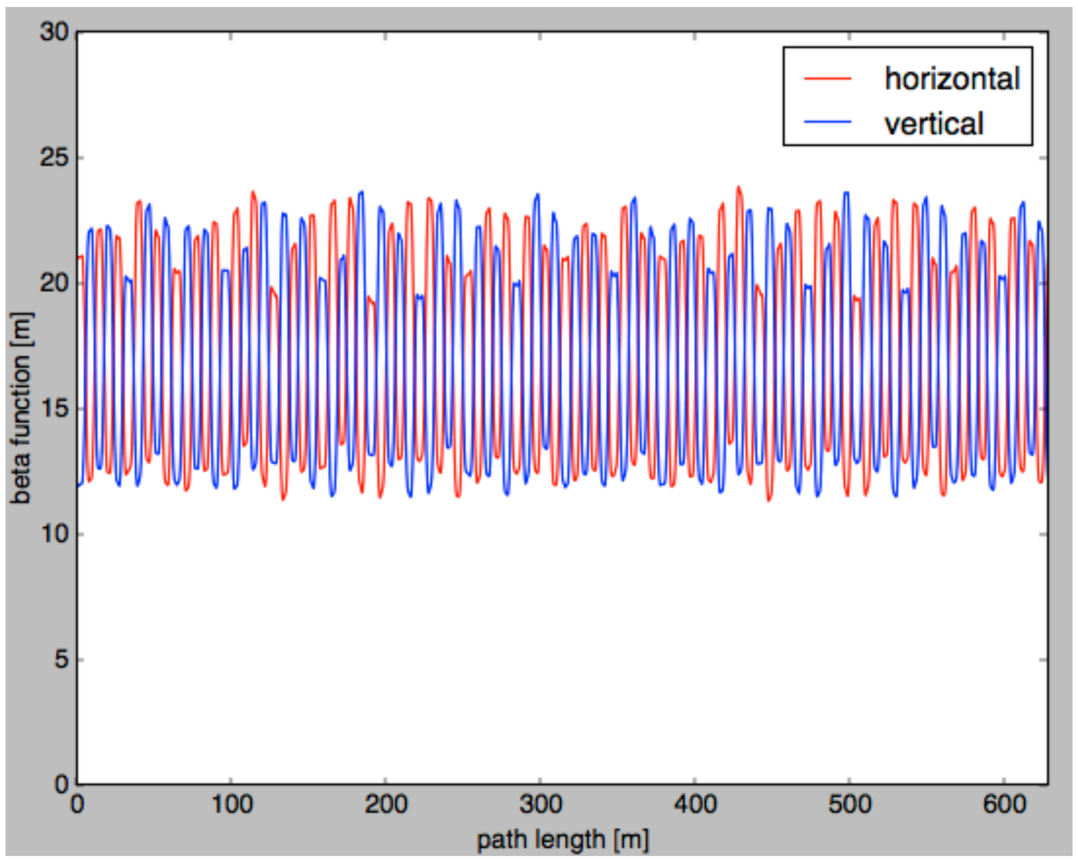
8 islands at Qy=6.25, not 4 islands, presumably excited by space charge.

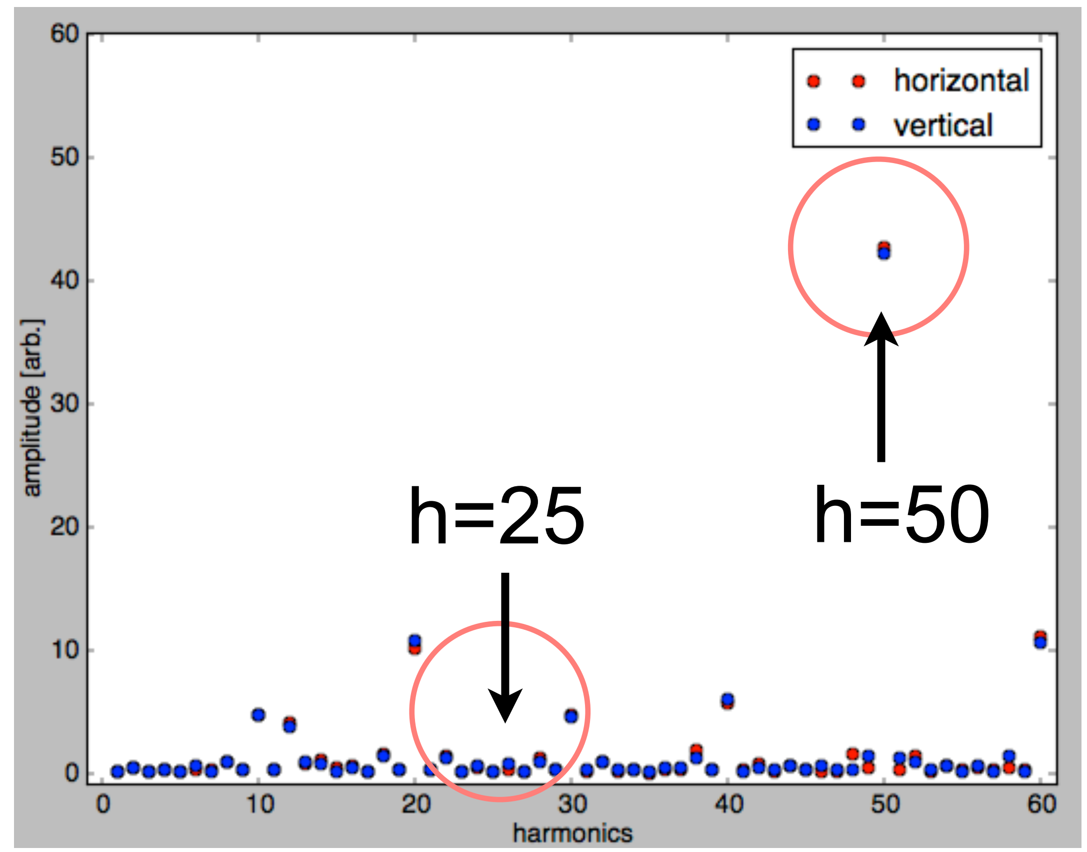


Loss mechanism

harmonics of driving term

Beta function and its harmonic contents at (6.211, 6.231) with tune control quadrupoles.





- h=25 is not strong in PS lattice because excited only by errors.
- h=50 is systematic harmonics due to 50 FDDF structure.
- h=10n (n: integer) appears due to 10 superperiod.

8Q=50, not 4Q=25, is the driving term.

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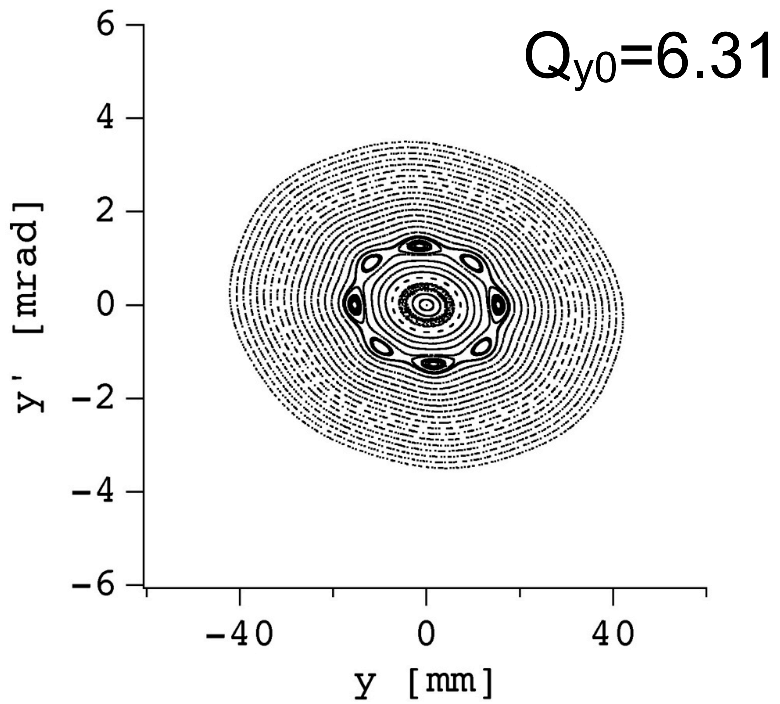
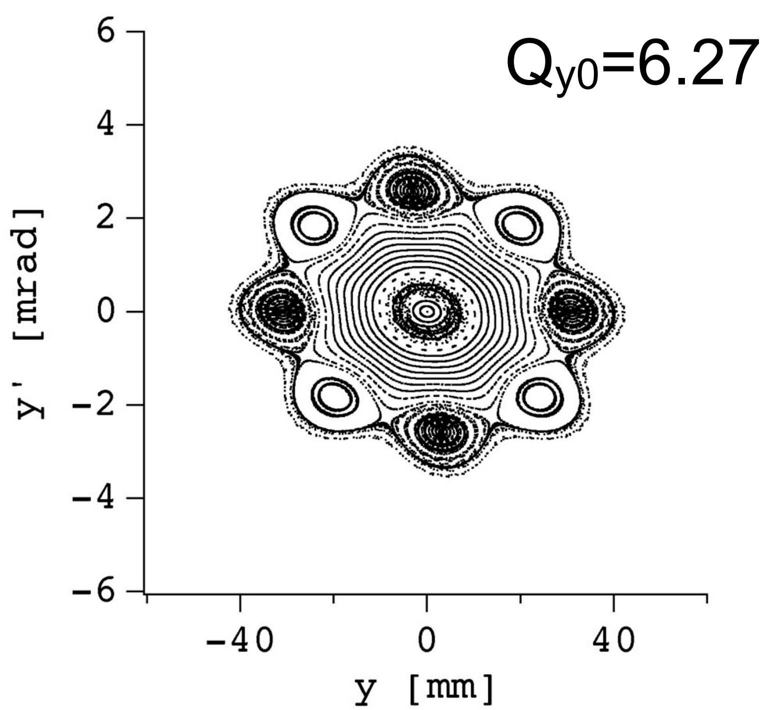
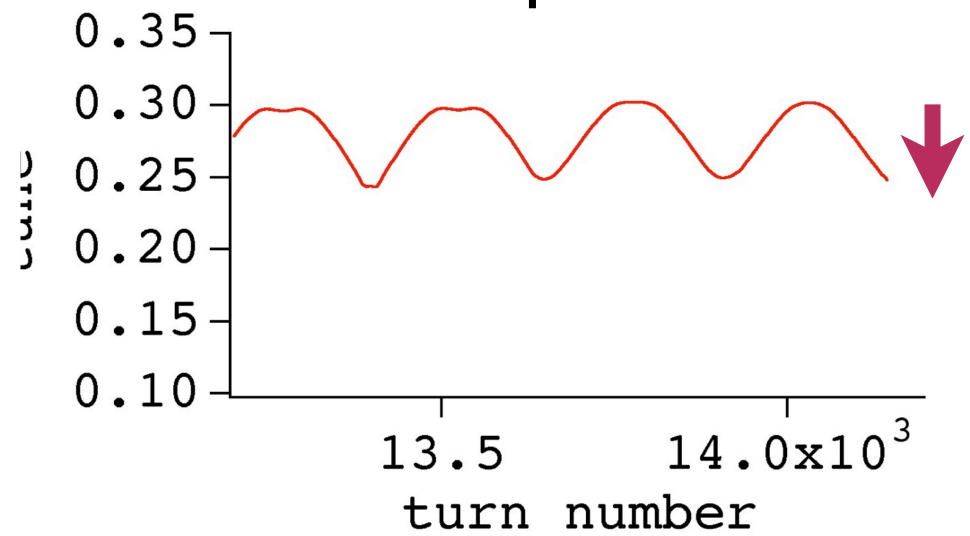
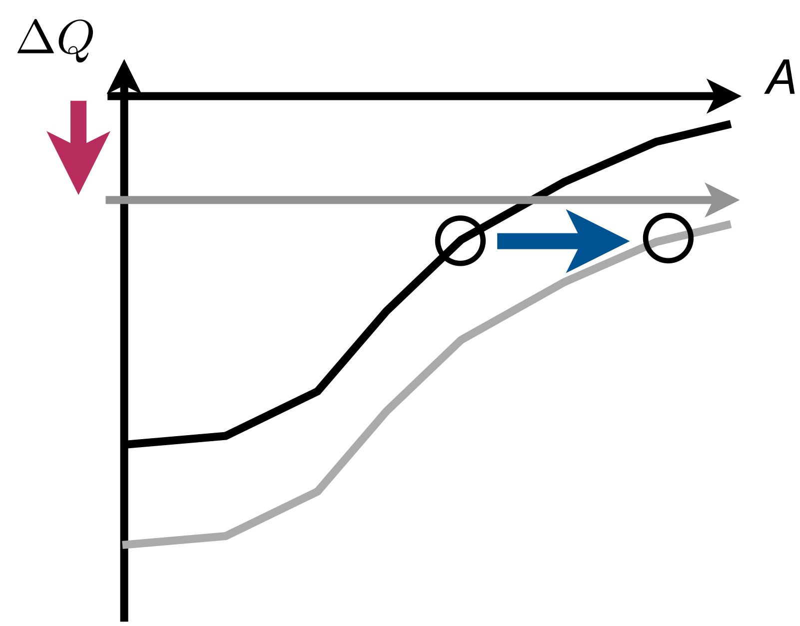
Loss mechanism
all together

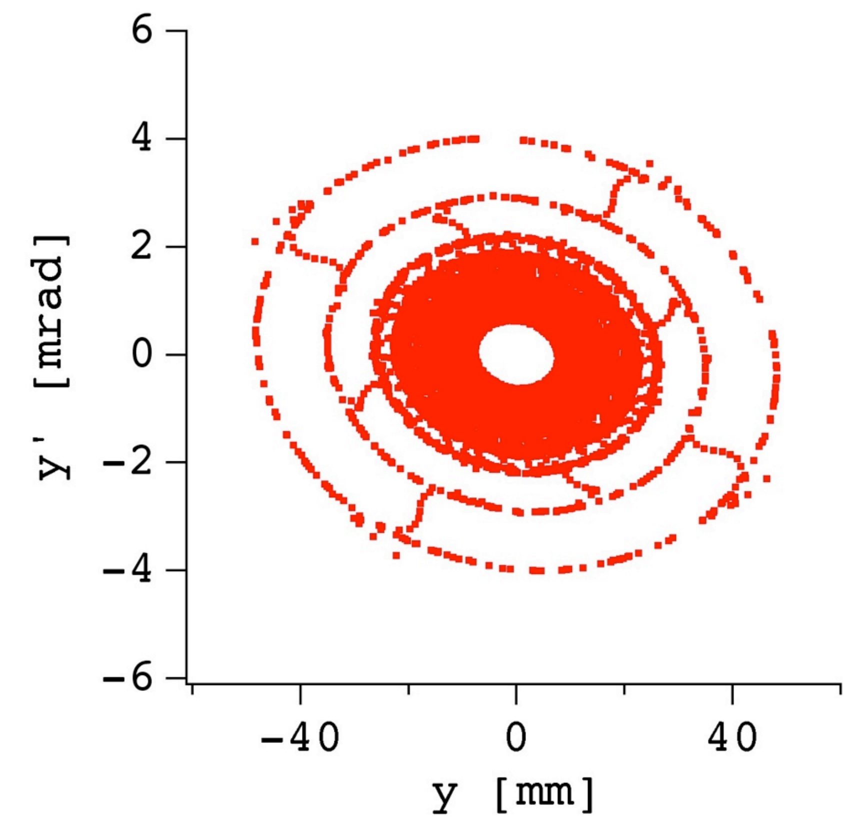




Decrease of tune push island with particle outward.

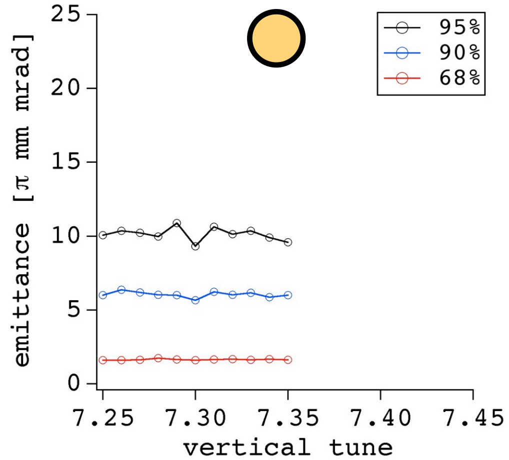


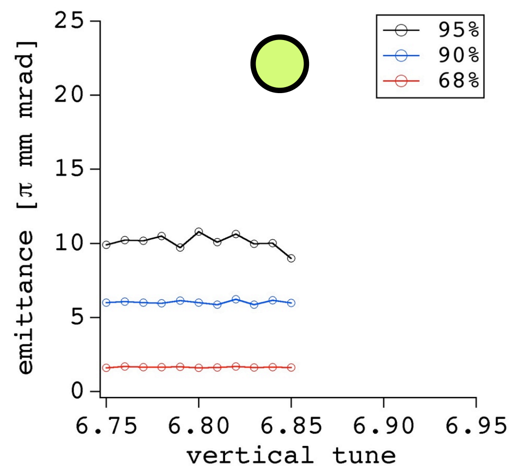




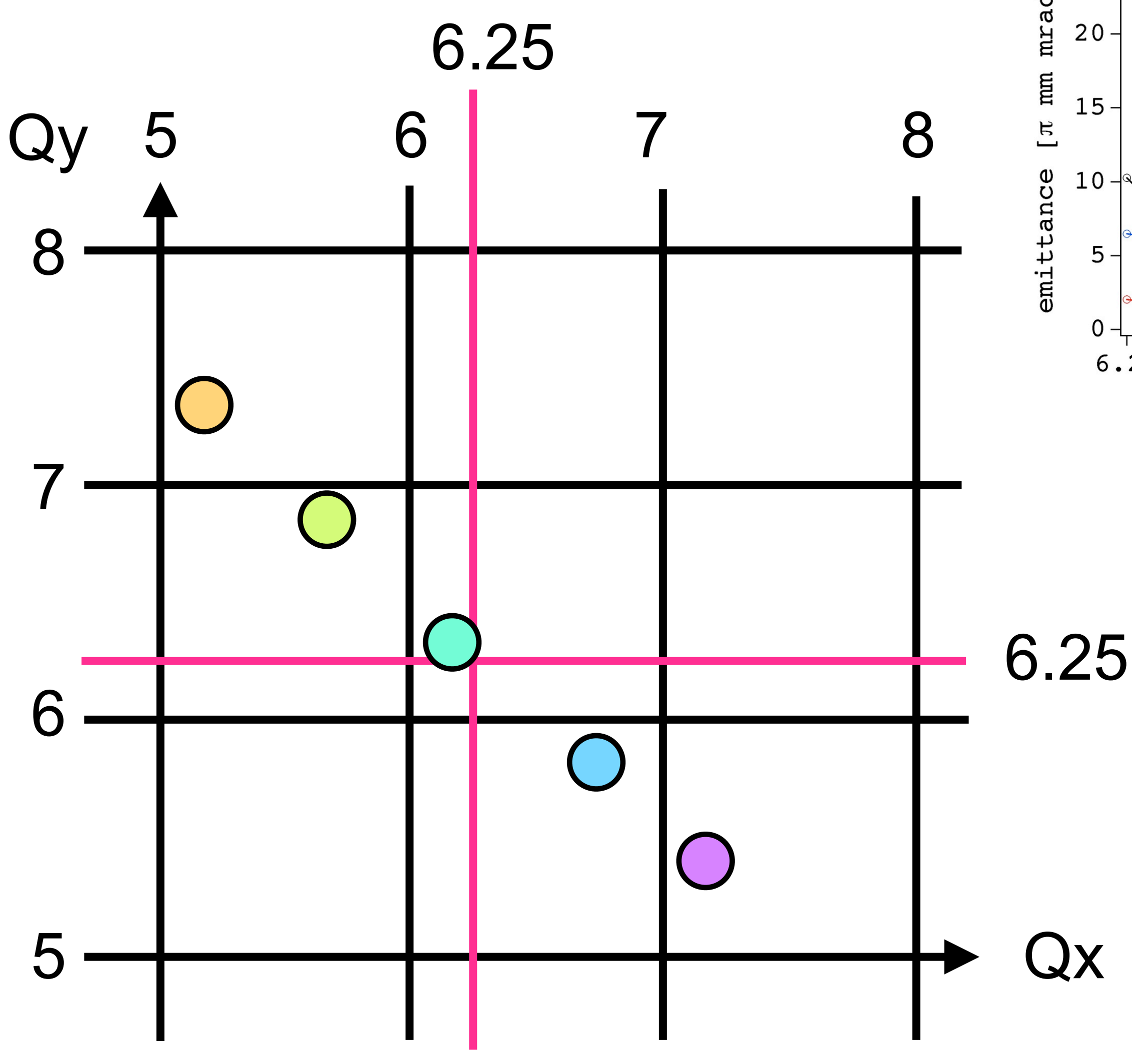
Emittance growth at different tune

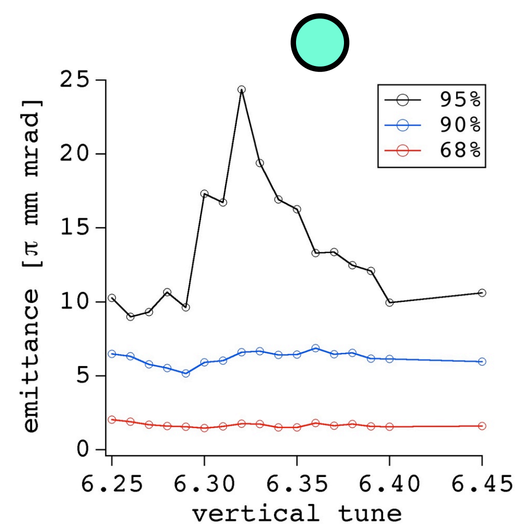
vertical

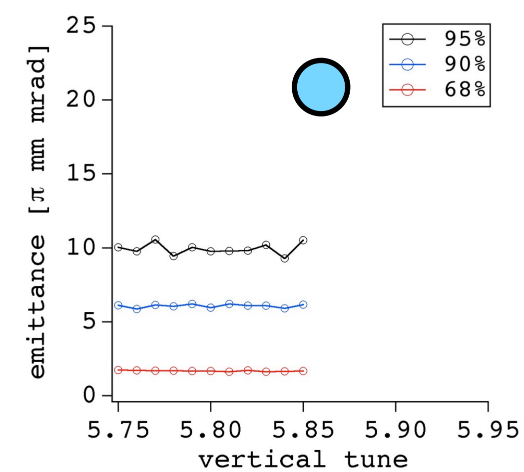


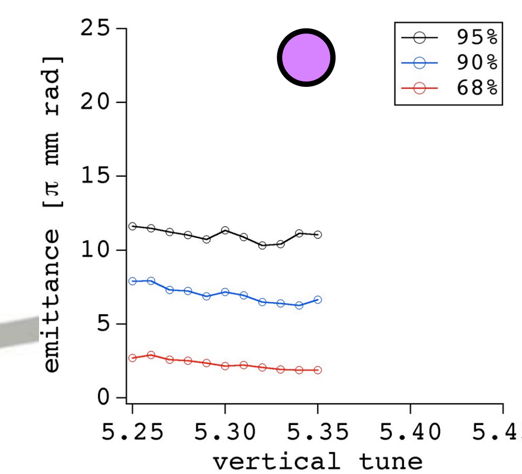


- All other tune (5.23,7.30), (5.73,6.80), (6.73, 5.80), (7.23,5.30) does not show emittance growth.
- Only (6.23,6.30) is no good!



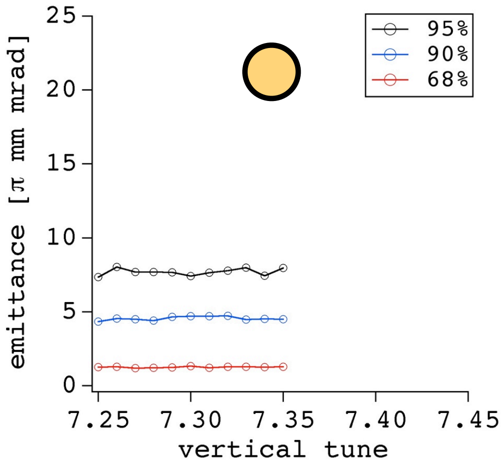


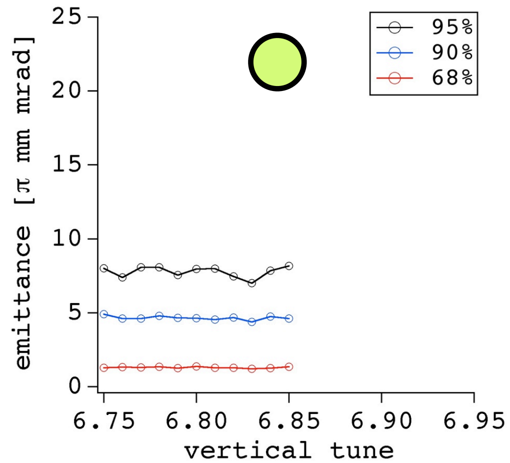




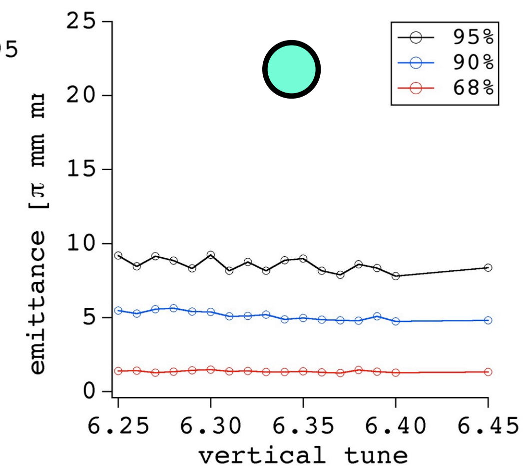
Emittance growth at different tune

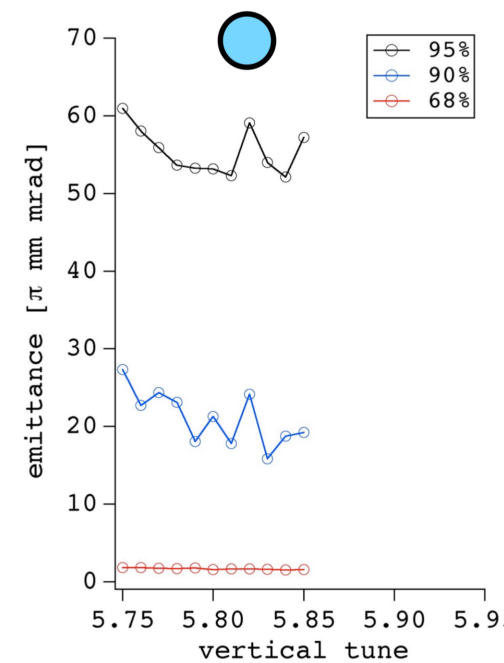
horizontal

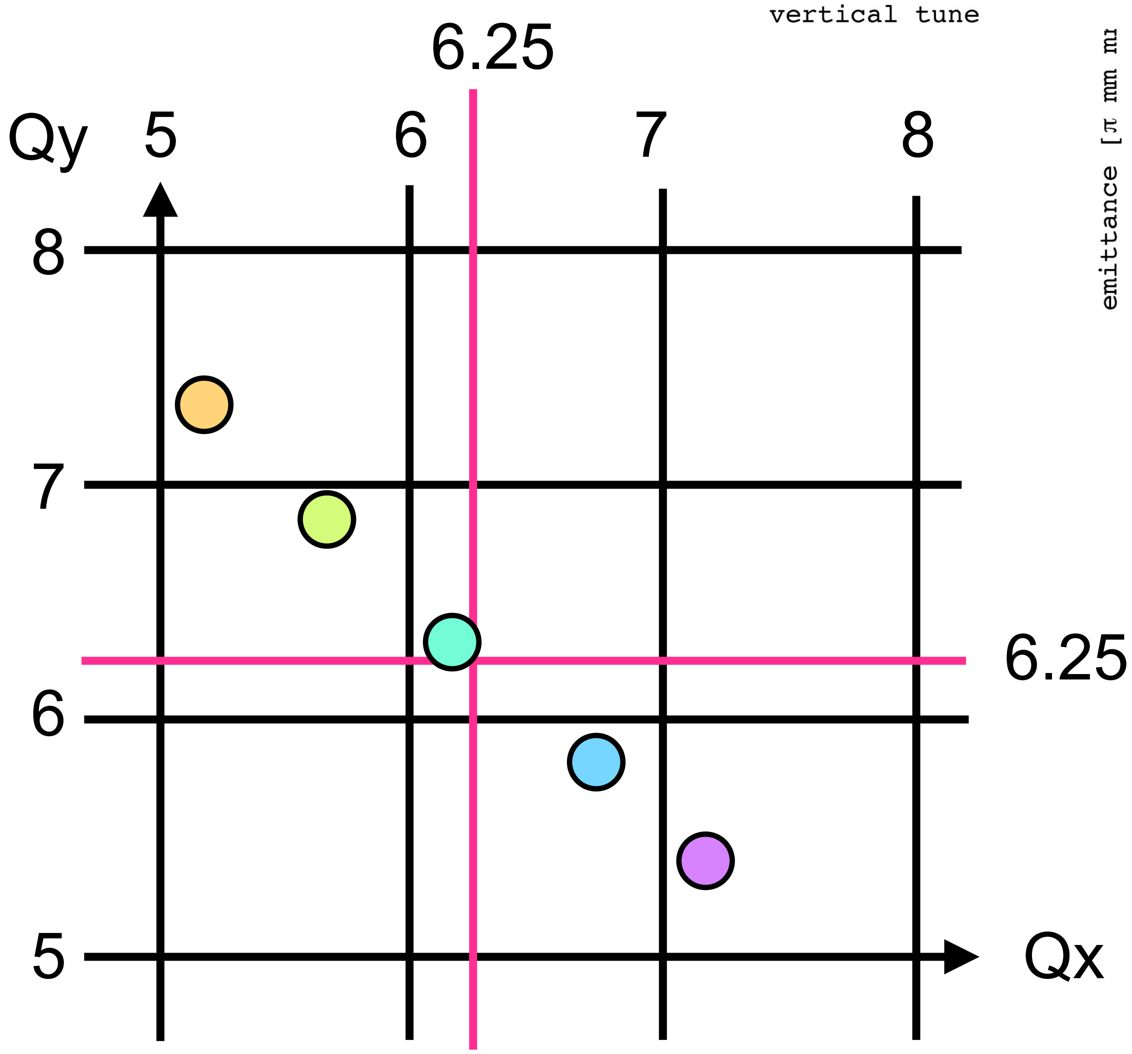


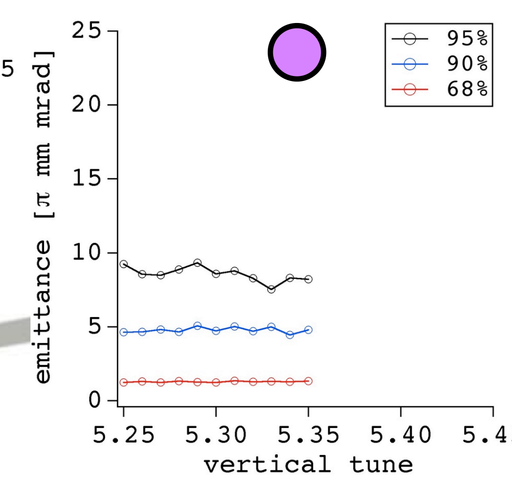


- All tune (5.23,7.30), (5.73,6.80), (6.23, 6.30), (7.23,5.30) does not show emittance growth.
- (6.73,5.80) shows large growth of 90 and 95% emittance.







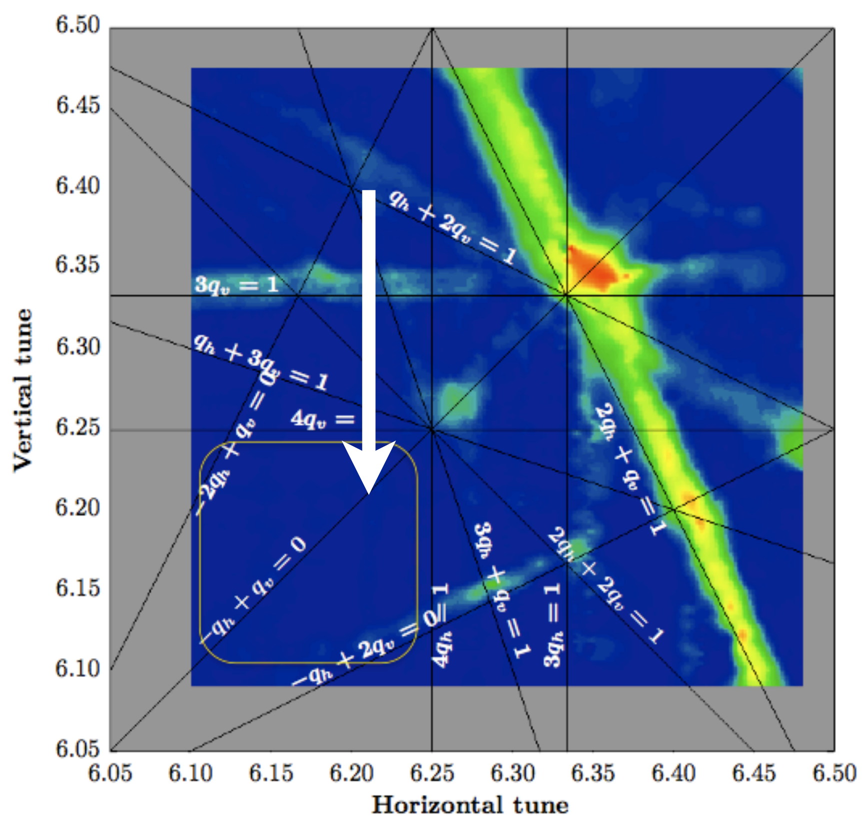


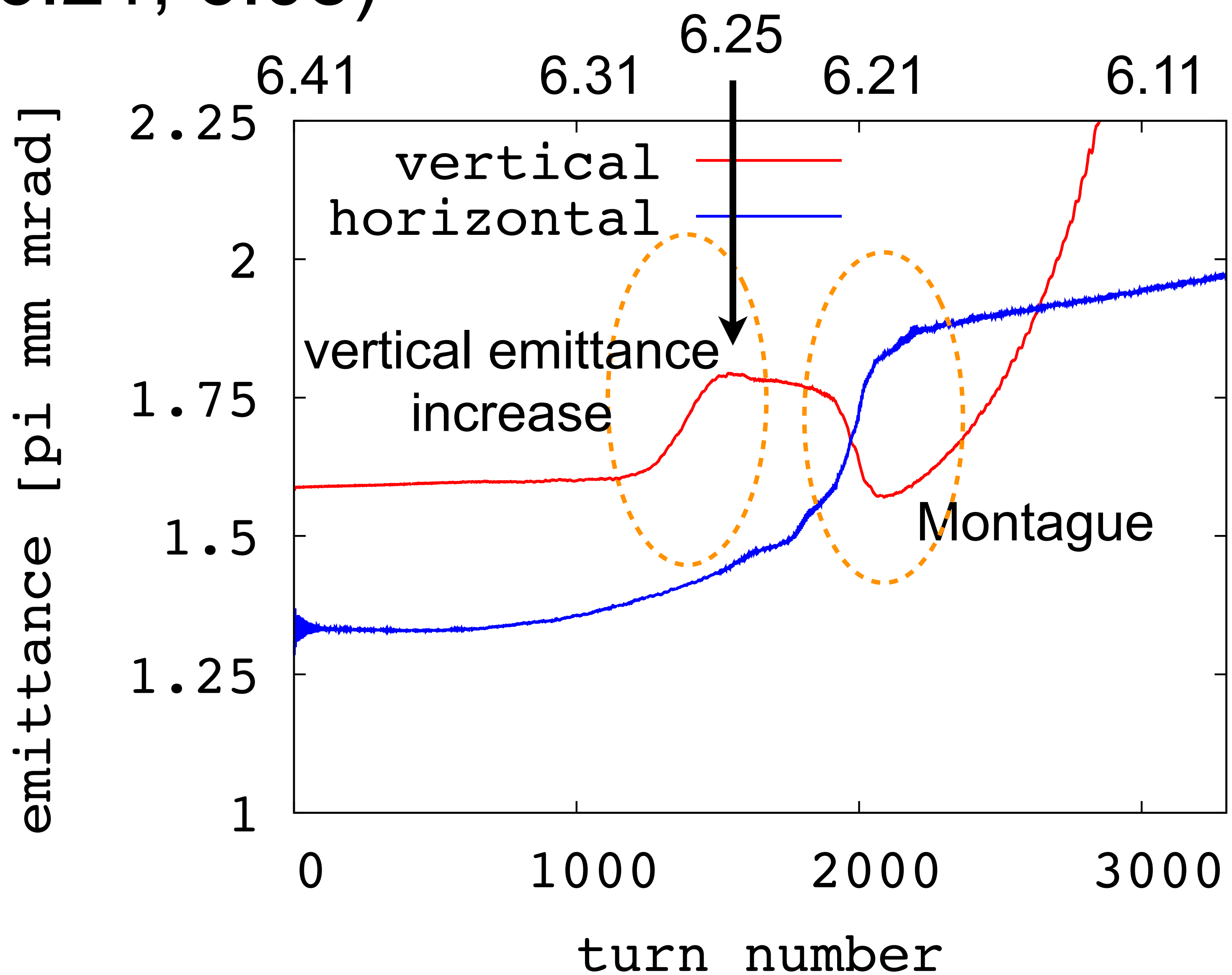
Short term self-consistent tracking

- to identify resonance source -

Tune scan results (1)

- from (6.21, 6.41) to (6.21, 6.08)





- Increase of vertical emittance when the tune approaches Qy=6.25.
- Montague resonance (2Qx-2Qy=0) is also clear.
- Vertical sharp increase below Qy=6.15 is due to resonance at Qy=6.00.

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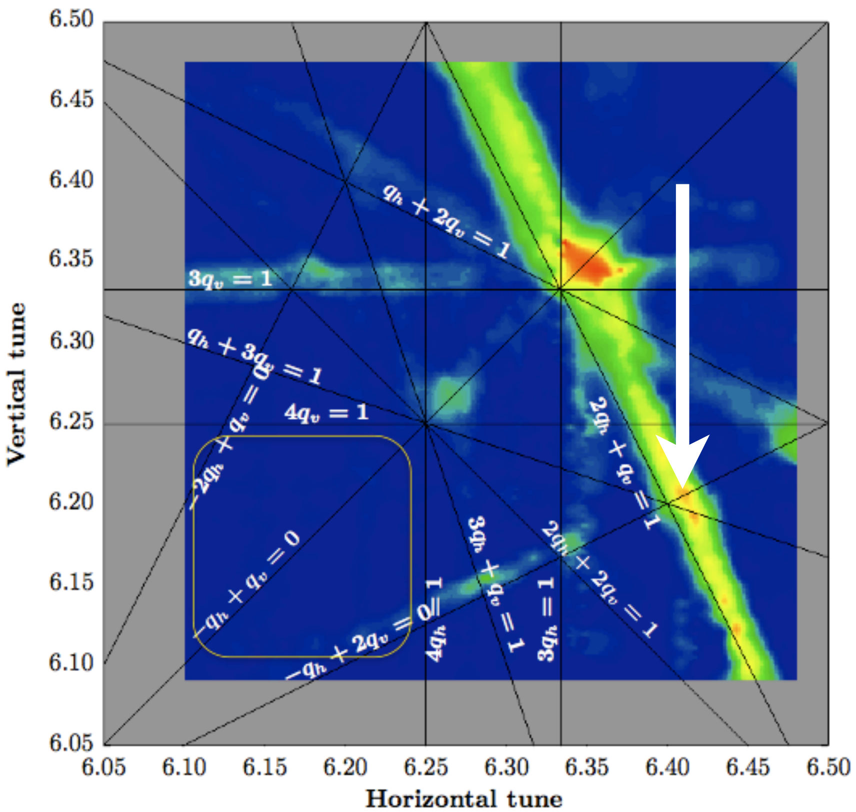
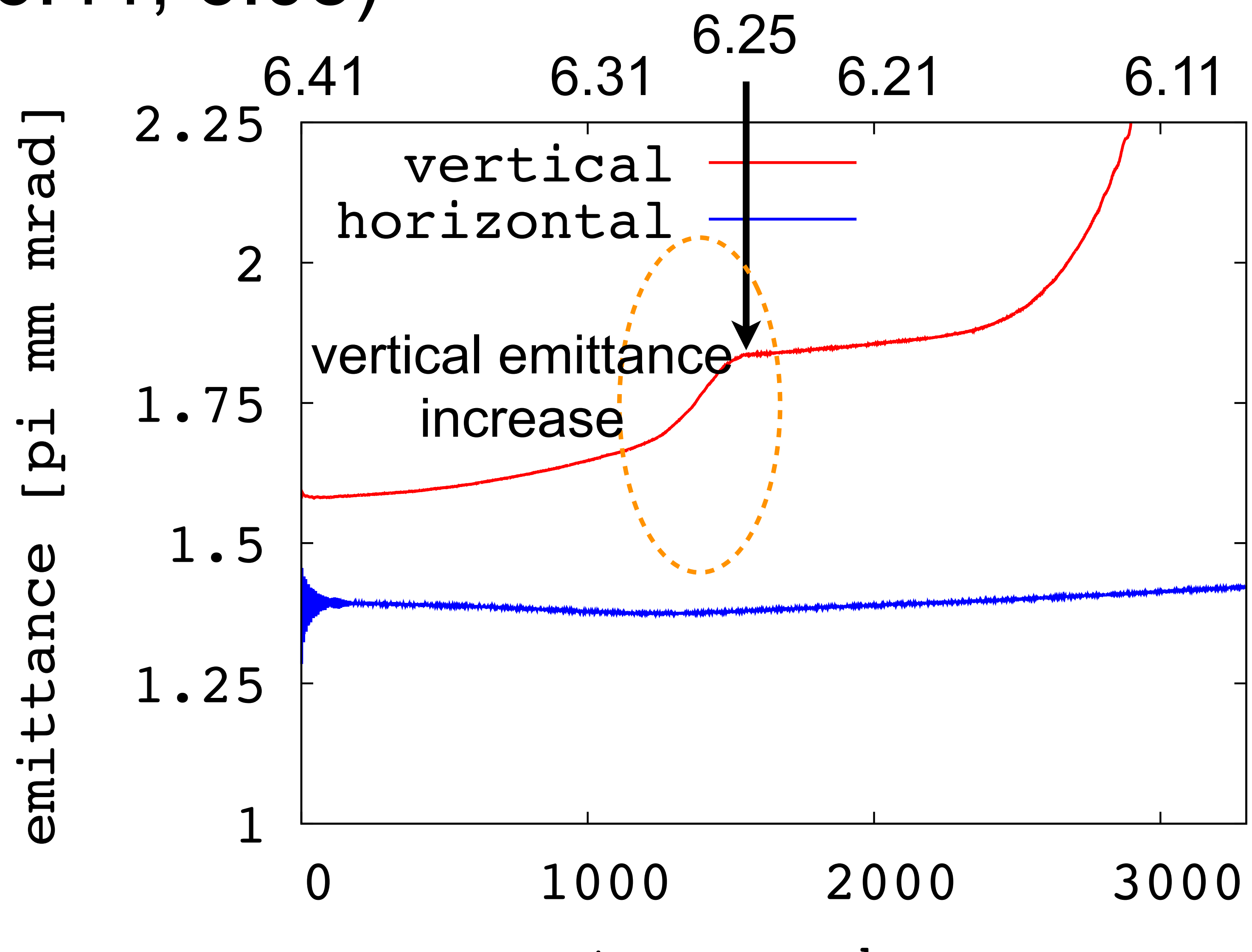
Tune scan results (2)

- from (6.41, 6.41) to (6.41, 6.08)





- Montague resonance (2Qx-2Qy=0) disappears.
- Similar increase of vertical emittance when the tune approaches Qy=6.25 as before.
- Vertical sharp increase below Qy=6.15 is due to resonance at Qy=6.00.
- No skew sextupole is included.

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PS alike lattice with different periodicity

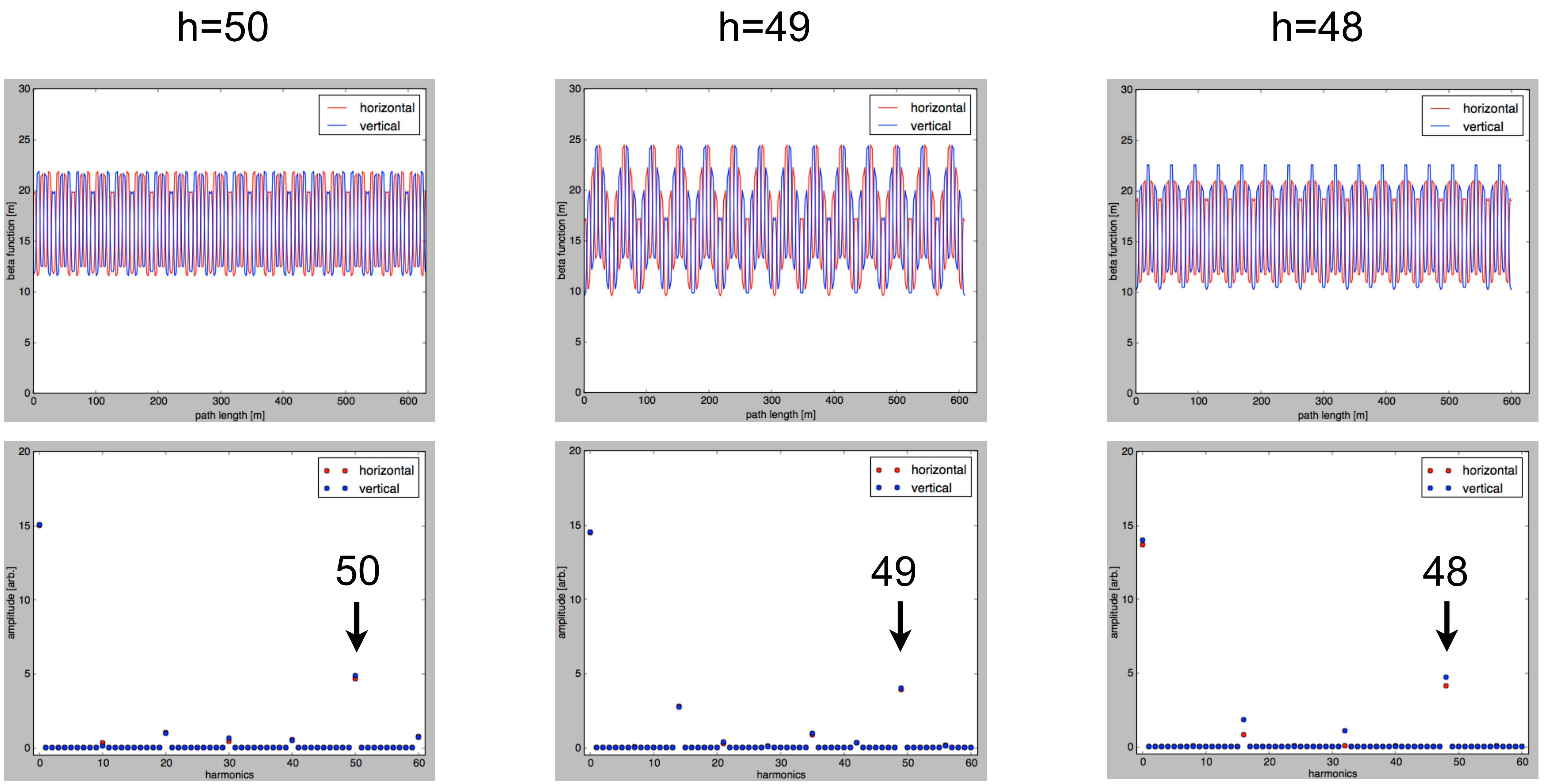
- In the previous two cases, vertical emittance increase at Qy=6.25 is clear.
- This could be 8Qy=50 since h=50 coming from 50 FDDF in CERN-PS is strong.

Set up similar lattices as CERN-PS with slightly different structure with different harmonic contents.

h=50 lattice (original): 10 x (FD-DF-FD-DF-FD----DF-FD-DF-FD-DF----)
h=49 lattice: 7 x (FD-DF-FD-DF-FD-DF-FD----DF-FD-DF-FD-DF-FD-DF----)
h=48 lattice: 8 x (FD-DF-FD-DF-FD-DF----FD-DF-FD-DF-FD-DF----)

Harmonics contents

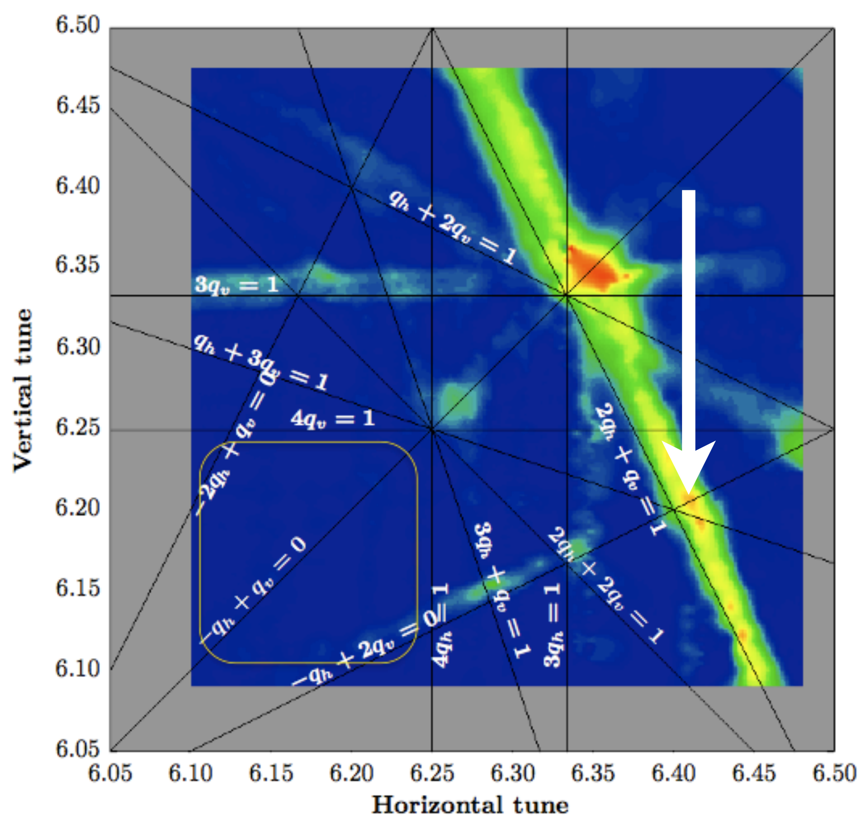
beta function and its harmonic contents of 3 lattices.

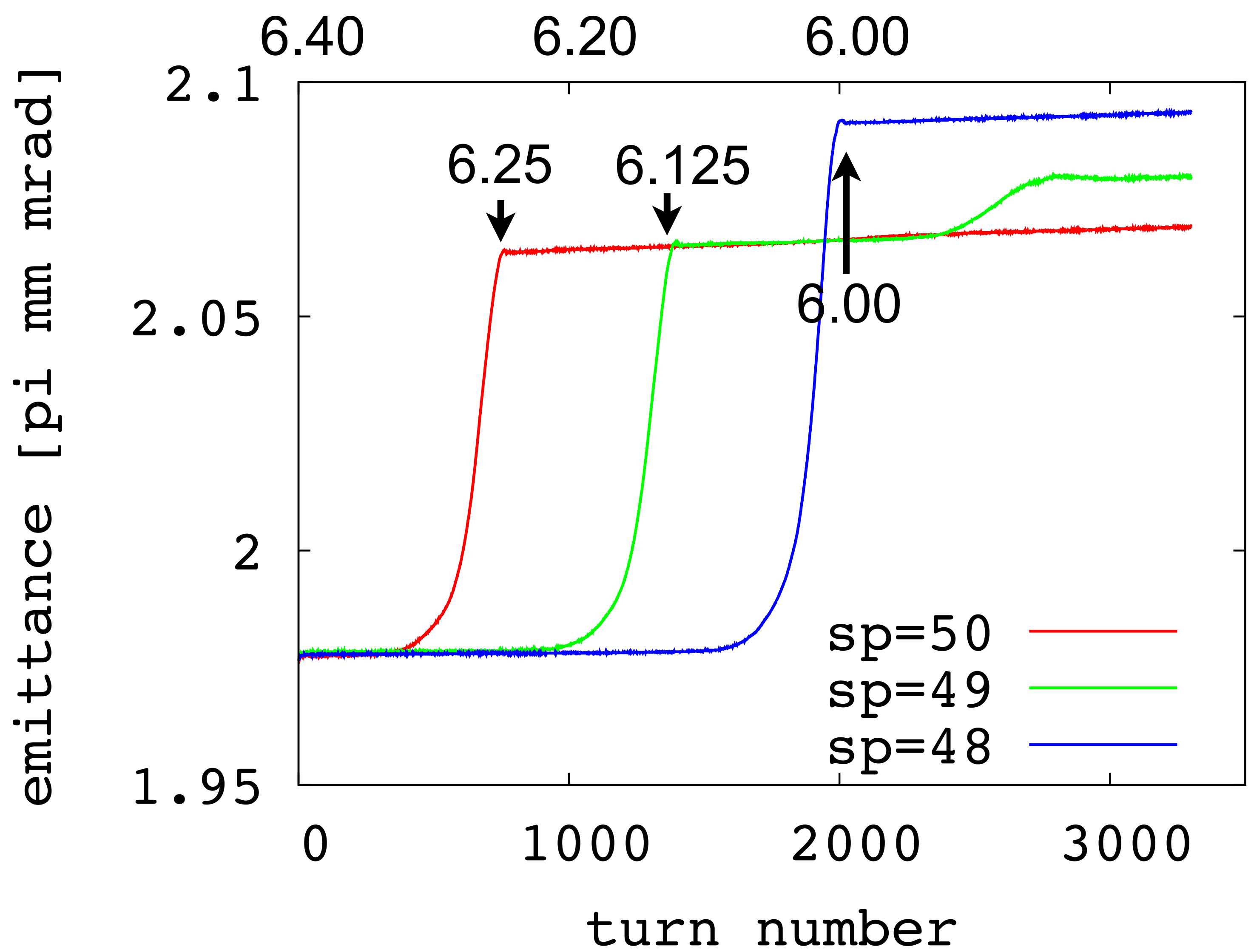


Strong harmonic component moves according to lattice periodicity.

Tune scan results (3)

- from (6.41, 6.40) to (6.41, 6.20)





Vertical emittance increase occurs at different tune.

8Qy=50, 49, 48 seem to be the source of emittance growth.

Summary

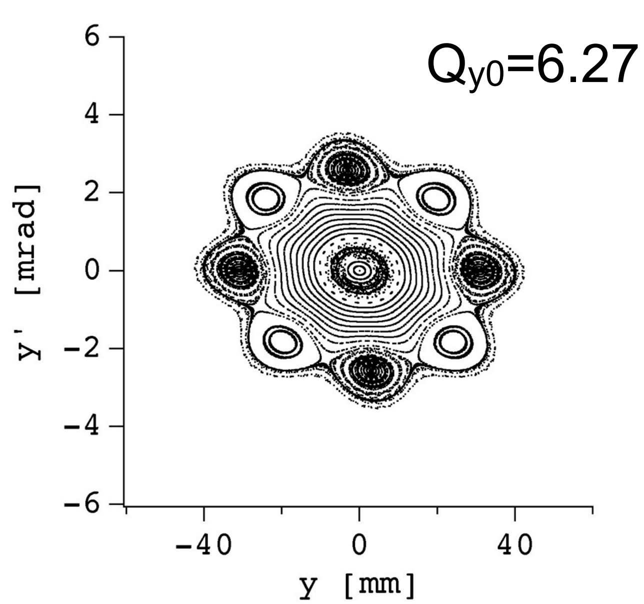
Findings

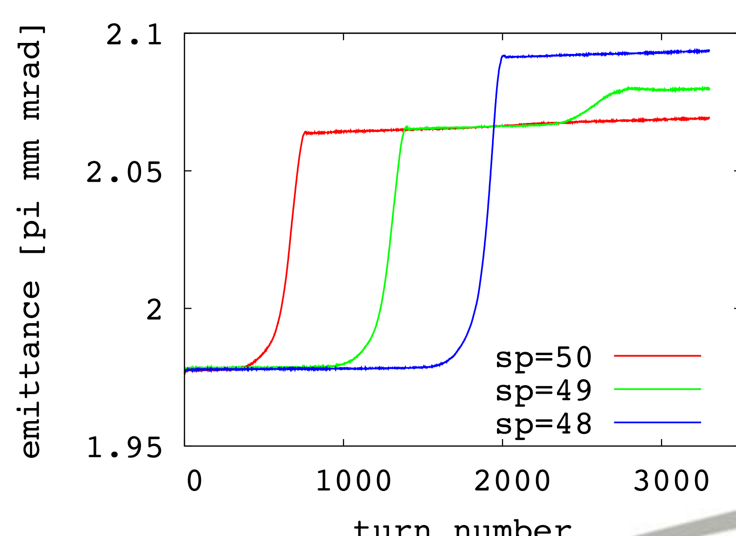
Single particle motion with frozen space charge model shows amplitude growth due to trapping/scattering caused by tune modulation.

Envelope modulation of h=50 is **intrinsic** in CERN-PS and likely the source of a resonance driving term of 8Q=50 (at Q=6.25).

This can be seen in phase space as 8 islands (fixed points) equally distanced from the centre.

Self-consistent tracking also shows 8Q=h resonance.





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Comments on quantitative comparison of beam loss

Need to know particle population larger than 3 sigma in transverse.

- The beam from PSB may have more particles in tail than predicted by Gaussian model.
- Injection orbit mismatch creates tails.

Longitudinal motion may not be as stable as simulation.

- RF noise for example keeps changing longitudinal amplitude and feeding particles to dangerous band.

Strategy

If the source of beam loss is 8Q=50, not 4Q=25, the strategy of loss mitigation would be different.

- Compensation by octupole magnets does not work.
- Eliminating error harmonics (h=25) by smoothing beam envelope does not work.

- The most effective way is to keep distance from Q=6.25 (below Q=6.25 is always no problem).
- Chromaticity correction (even partially) may help to suppress resonance crossing.

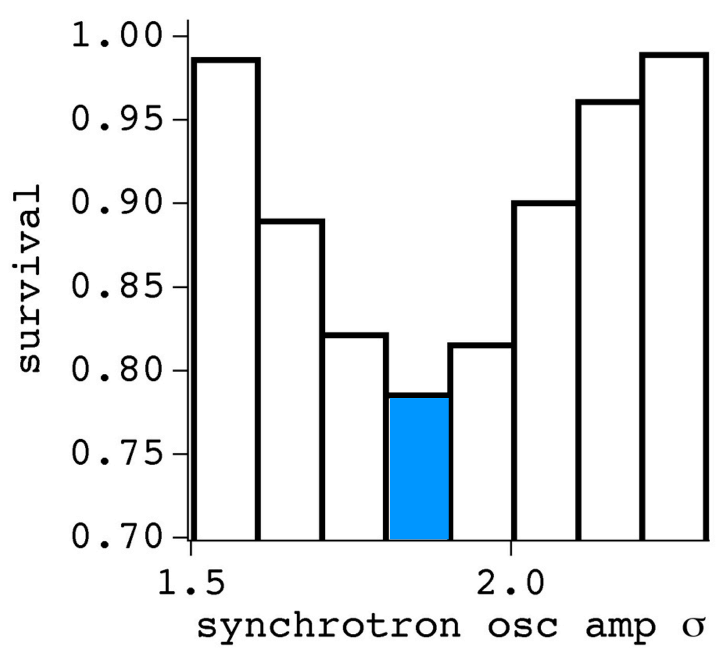
More physics

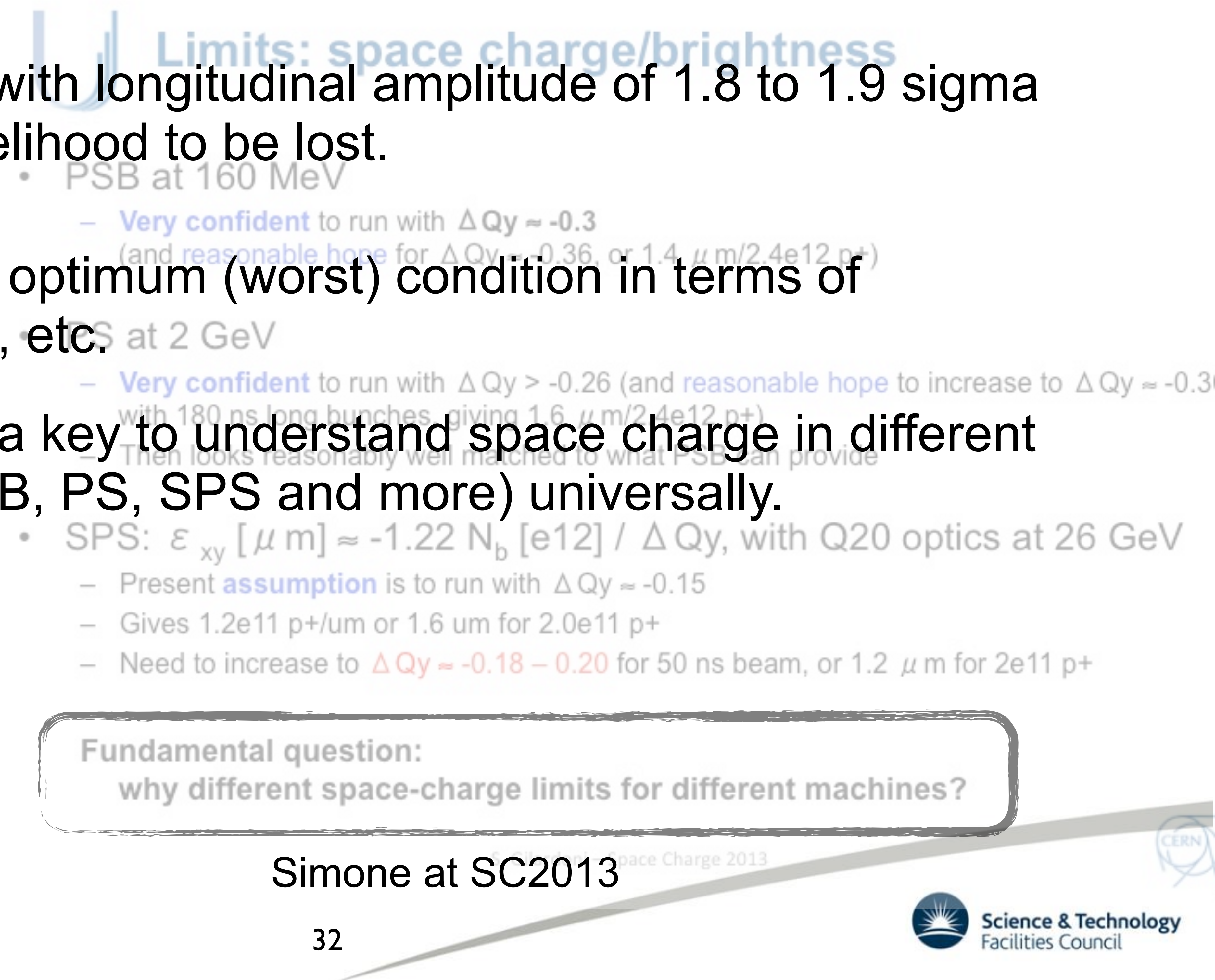
Probability of becoming a lost particle depends on initial position in the beam.

e.g. Particles with longitudinal amplitude of 1.8 to 1.9 sigma have more likelihood to be lost.

There must be some optimum (worst) condition in terms of crossing speed, dp/p, etc.

This could be a key to understand space charge in different machines (PSB, PS, SPS and more) universally.





Simone at SC2013

Science & Technology Facilities Council

but, according to Okamoto & Yokoya paper

NIMA 482, pp.51-64, 2002.

this could be called "4th order".

8th order?

Space charge simulation for ~~4th order~~ resonance

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Thank you for your attention