# Slow Integer Tune Crossing in EMMA

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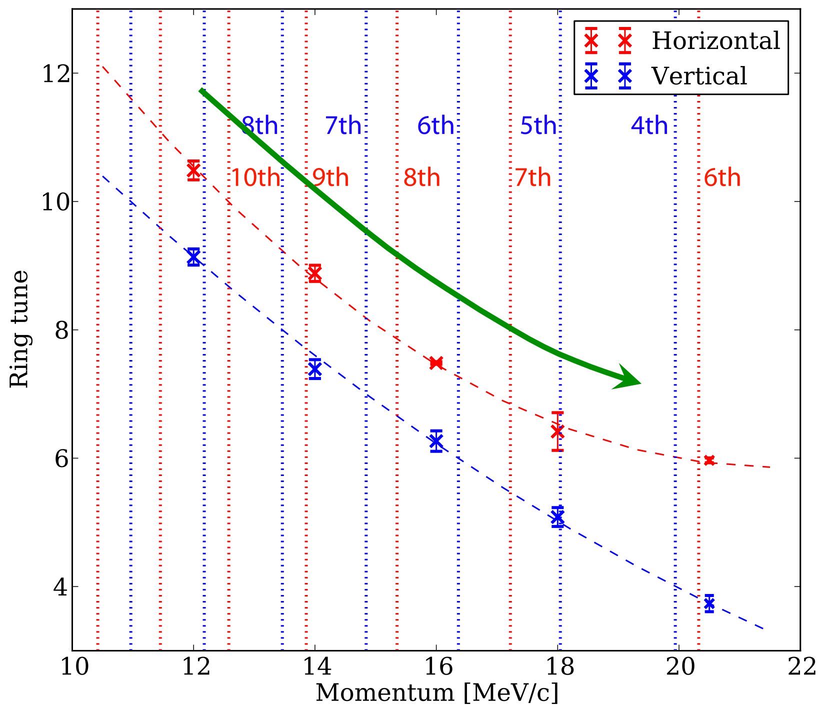
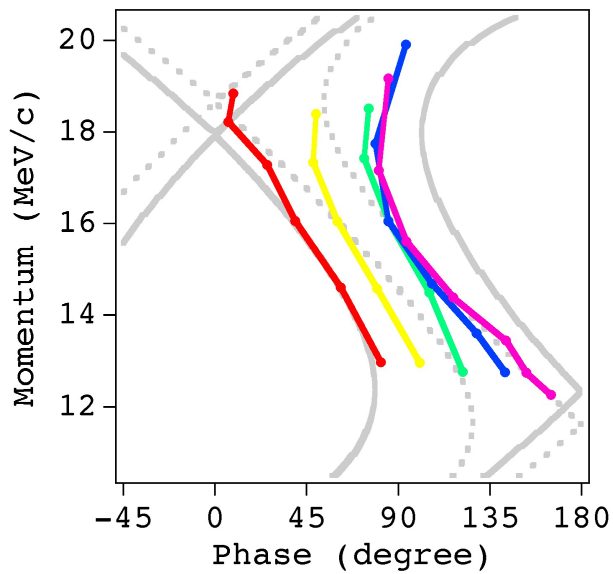
# Serpentine Acceleration

The Cockcroft Institute of Accelerator Science and Technology

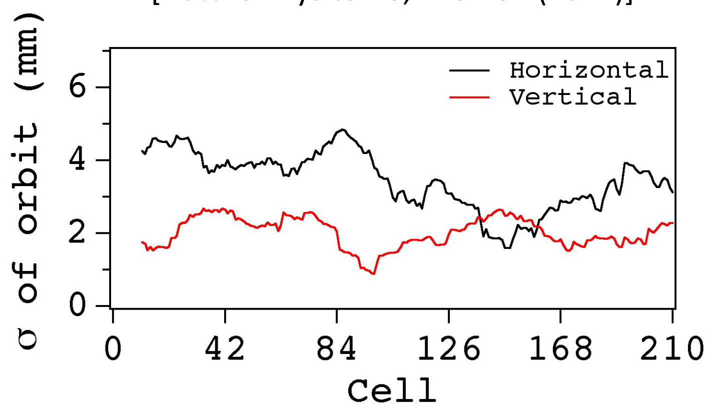
- Serpentine channel acceleration was demonstrated in EMMA from ~12 -> 19 MeV in around 5-6 turns. ~12 -> ~19 MeV/c.

At least four integers are crossed with no evidence of significant amplitude change



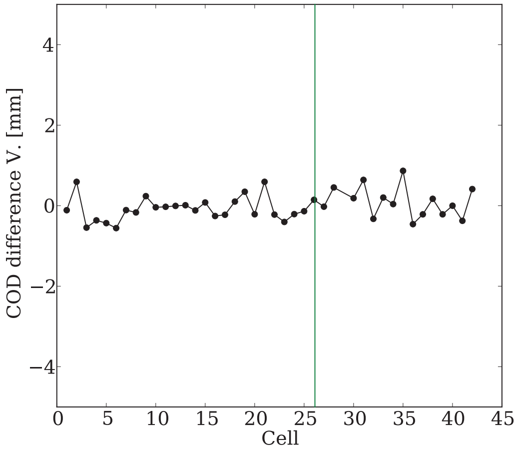




[Nature Physics N8, 243-257 (2012)]

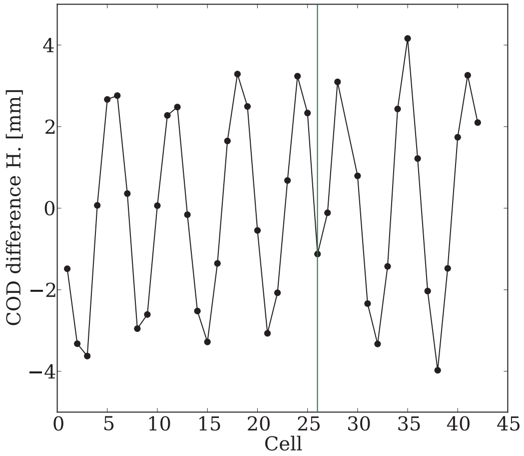


# What about slower acceleration? -> Lattice Error in EMMA

- Largest source of error in EMMA was determined to be the septum stray field which acts in the horizontal direction.

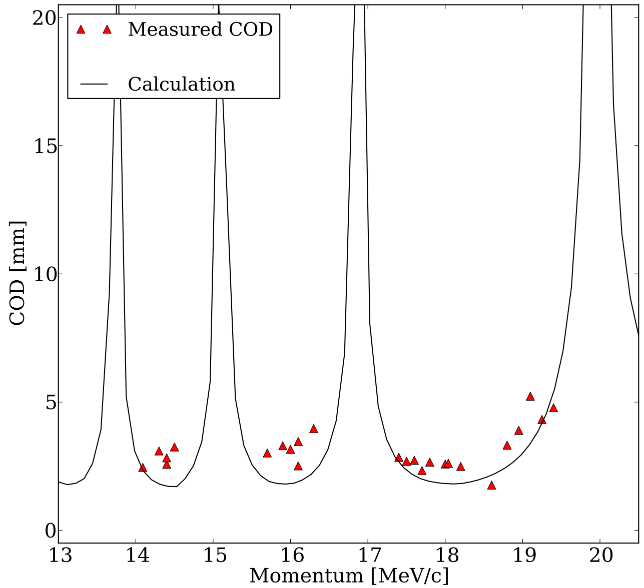



Vertical COD from extraction septum




Horizontal COD from extraction septum

Injection is analogous to extraction and the stray field is the same.

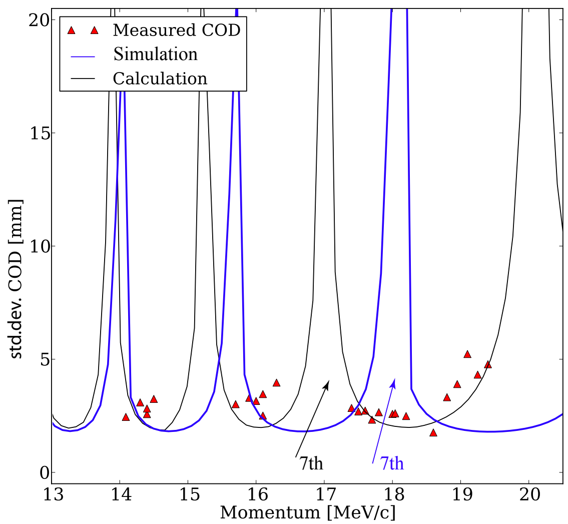


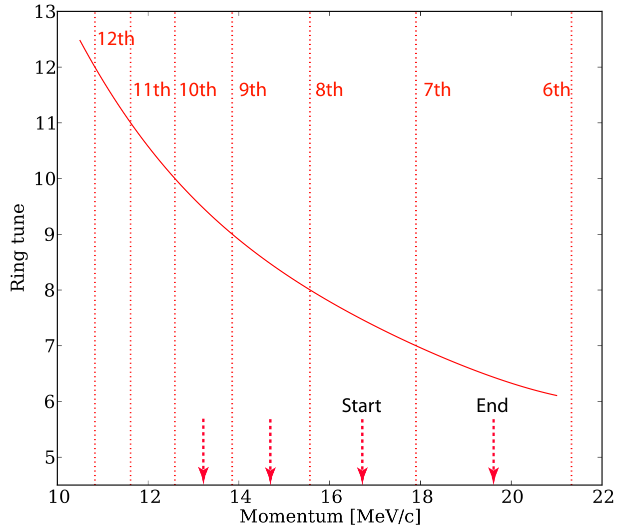

Measured and calculated horizontal COD. Calculation uses 0.5 mTm integrated dipole field error.

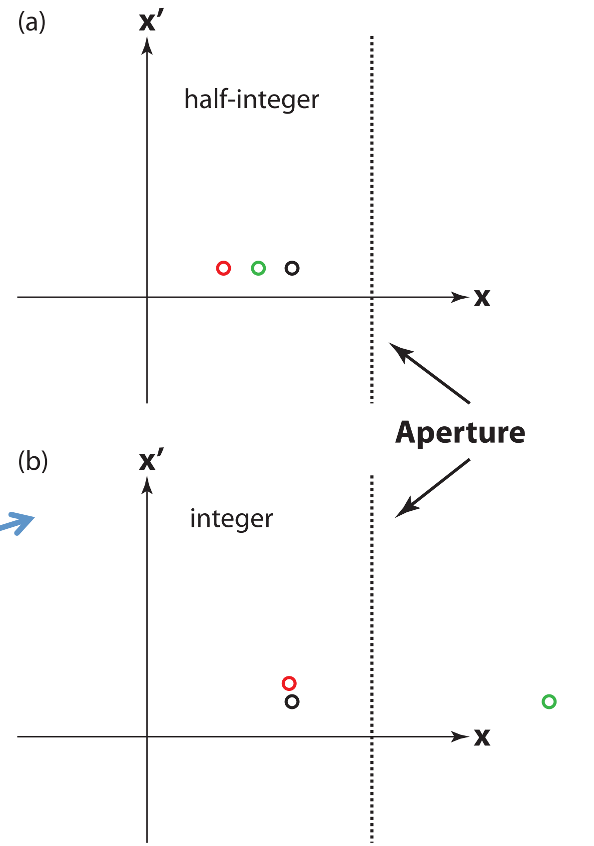
- Dipole field error is ~0.5 mTm from the septum.

# Simulation in Zgoubi
# Single Particle

- Uniform acceleration across single integer horizontal tunes. Start on closed orbit.
- COD same at beginning and end.
- 0.5 mTm single dipole error kick at end of first cell.




- Measuring the charge centre of the bunch. May encounter this situation.
- Cannot calculate closed orbit during acceleration and therefore cannot calculate amplitude *A*.
- Measure coherent oscillation amplitude. For single particle this was taken as std. dev. of horizontal coordinate *(x)*. Also averaged over a 21 cell window.

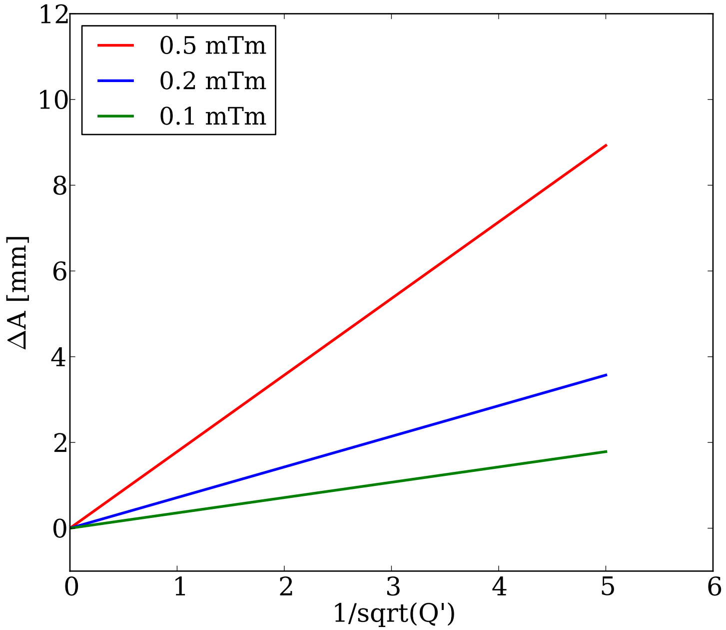
Green = CO pos, black = turn 1, red = turn 2

# Single Integer Crossing Theory (R. Baartman)

- R. Baartman et. al. developed a theory of single resonance crossing. For a single dipole field error the amplitude change *ΔA* when accelerating with a tune crossing speed *Q'* is given by:

$$\Delta A = \frac{\pi}{\sqrt{Q'}} \frac{\overline{R}}{\overline{B}} \frac{\Delta B \Delta s / C}{\upsilon}$$

| | |
|---|---|
| $\overline{R}$ | Average radius |
| $\overline{B}$ | Average bending field |
| $C$ | Average circumference |
| $\Delta B \Delta s$ | Integrated field error |




$$A = \sqrt{2J\beta}$$

$$2J\beta = x^2 + \left(\alpha_x x + \beta_x x'\right)^2$$

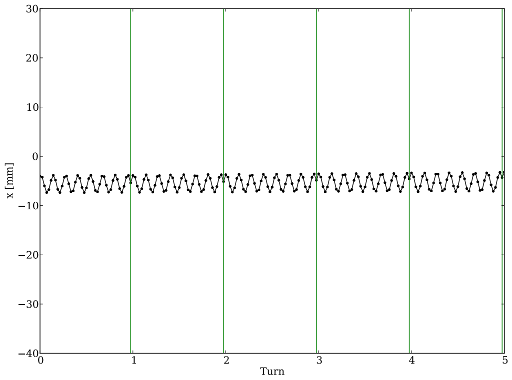
| dE/dT [MV/turn] | 1/√Q' |
|---|---|
| 0.2 | 3.2 |
| 0.5 | 2.3 |
| 1.0 | 1.4 |
| 2.0 | 1.0 |

EMMA acceleration rate and crossing speed

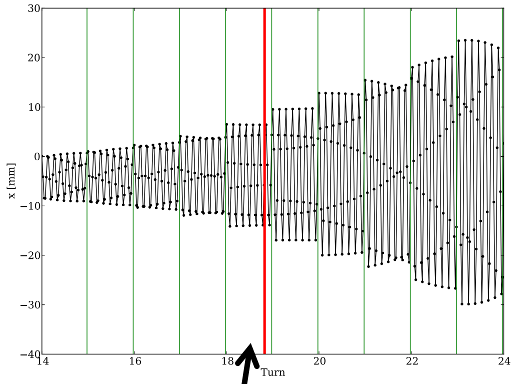
# Simulation in Zgoubi
# Single Particle

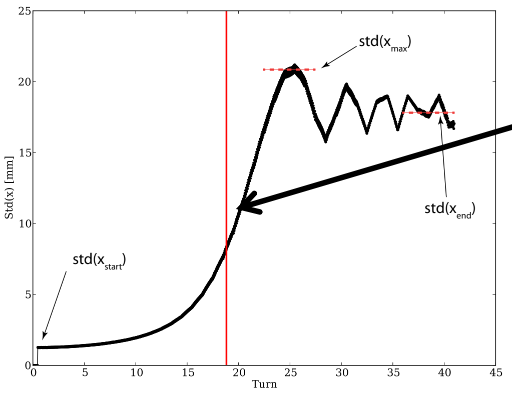
- $\Delta A_{max}$ may show betatron amplitude growth on top of some COD.
- $\Delta A$ shows the amplitude growth without COD as the COD is the same at the beginning and end of the simulation.

Start

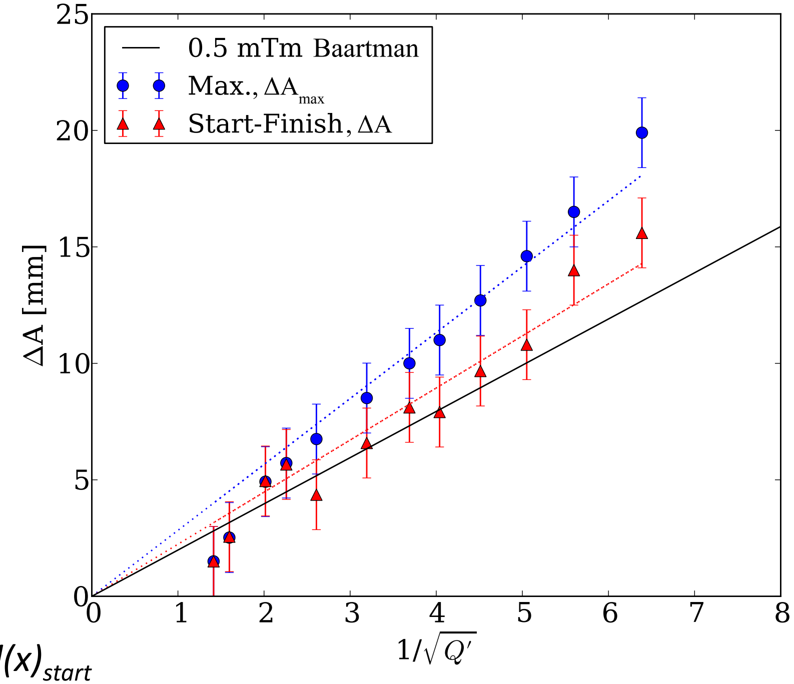



Res. Cross




$\nu_x = 7$



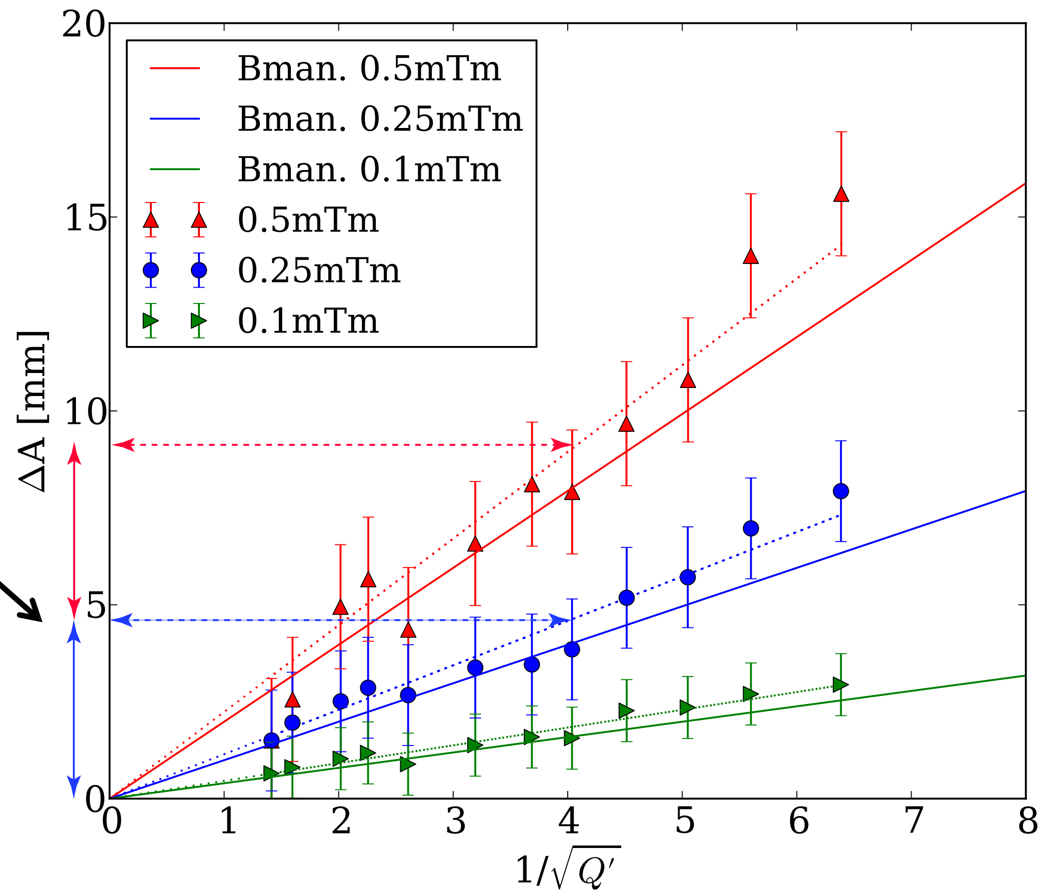

$\Delta A_{max} = std(x)_{max} - std(x)_{start}$

$\Delta A = std(x)_{end} - std(x)_{start}$

# Simulation in Zgoubi
# Single Particle

- Comparing simulated amplitude increase due to single resonance crossing when modeled with a single dipole field error agrees reasonably with Baartman.

Double error strength means double the amplitude growth

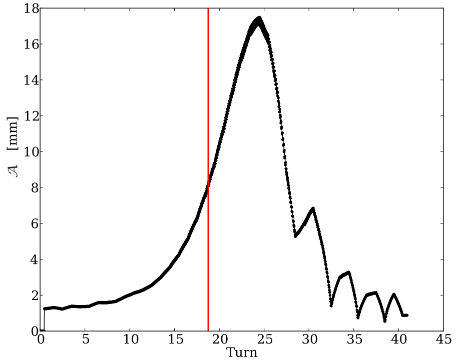


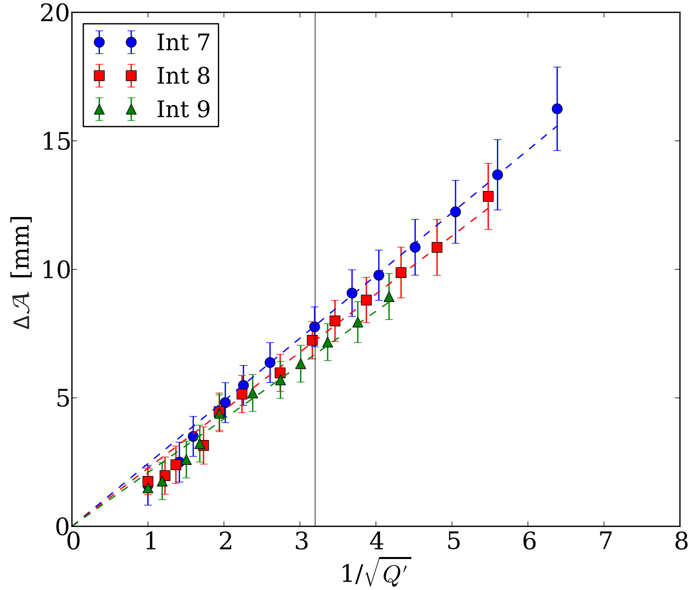

Also shown by Machida:

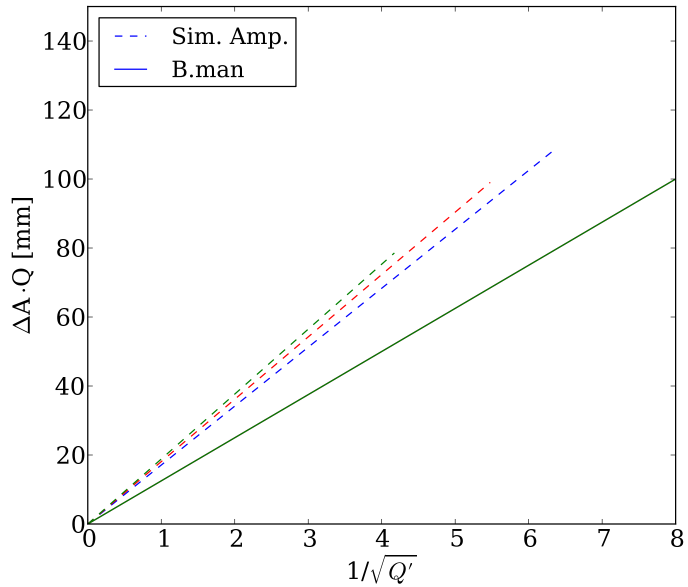
Phys. Rev. ST Accel. Beams 11, 094003 (2008)

# Simulation in Zgoubi Multi-Particle

- Multi-particle simulations: 1000 particles, started on closed orbit. Transverse and longitudinal emittance similar to real machine. $\nu_x$=7,8,9 studied.
- Measure coherent oscillation. Mean of horizontal particle coordinates. Only max value taken as *A* drops off (decoherence discussed in a minute).



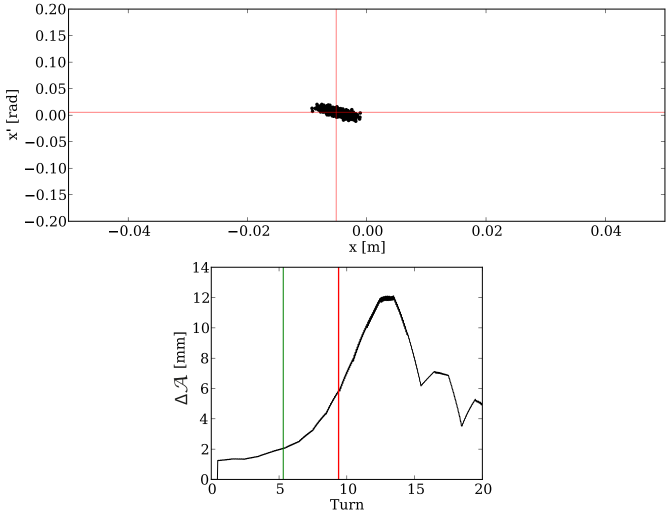

$$\Delta A = \frac{\pi}{\sqrt{Q'}} \frac{\overline{R}}{\overline{B}} \frac{\Delta B \Delta s / C}{\upsilon}$$

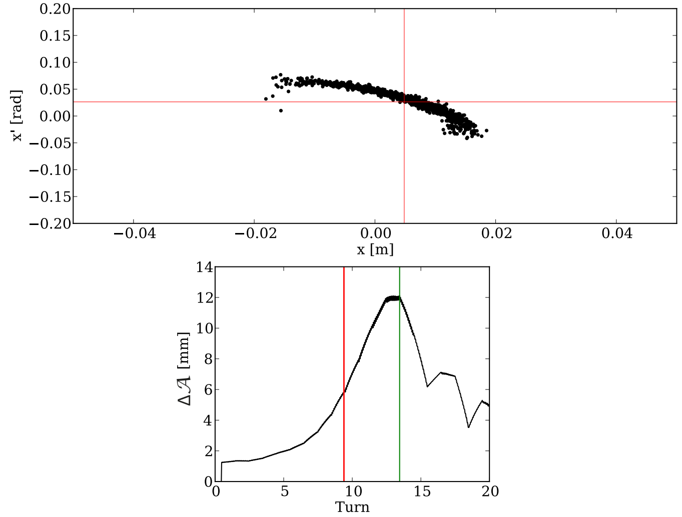
*ΔA* shows linear relationship again with fit through the origin.

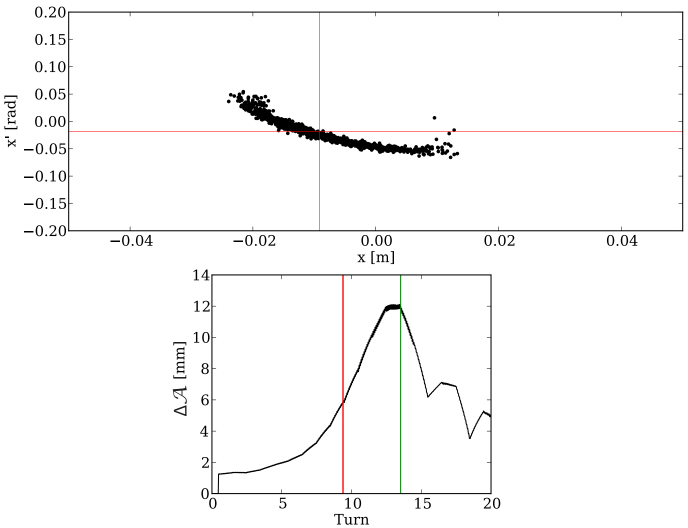
*ΔA•ν* is different to prediction from Baartman due to combination of COD and betatron amplitude growth measured by the max. std. dev. of *x*.

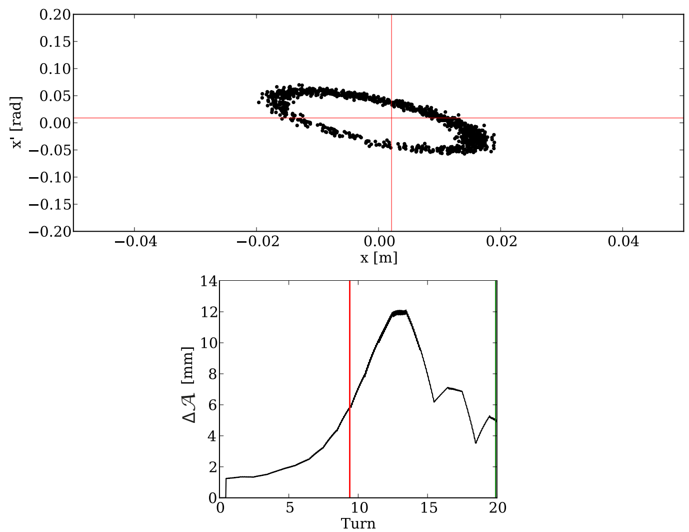
# Simulation in Zgoubi Multi-Particle

- Momentum spread and natural chromaticity lead to transverse decoherence.



# Simulation in Zgoubi Comments

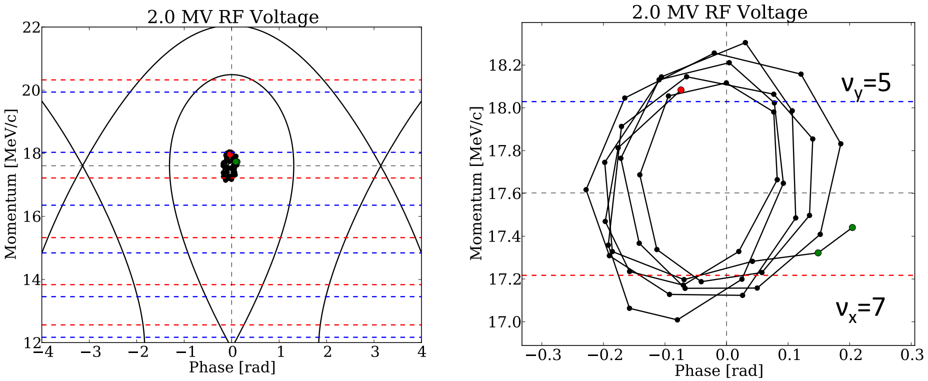
- Single particle simulations agree with Baartman relation. Multi-particle relationship is linear but decoherence (plus other effects?) means the exact relation differs.
- ΔA ~ 1/√Q' and ΔA ~ ΔBΔs.
- Multi-particle simulations show that decoherence makes it more difficult to calculate amplitude. Max value of std(x) has component of COD and decoherence.
- However linear relationship remains, even though amplitude growth from simulations cannot be calculated as in the literature in this case.
- No initial amplitude so decoherence comes after amplitude growth from resonance crossing.

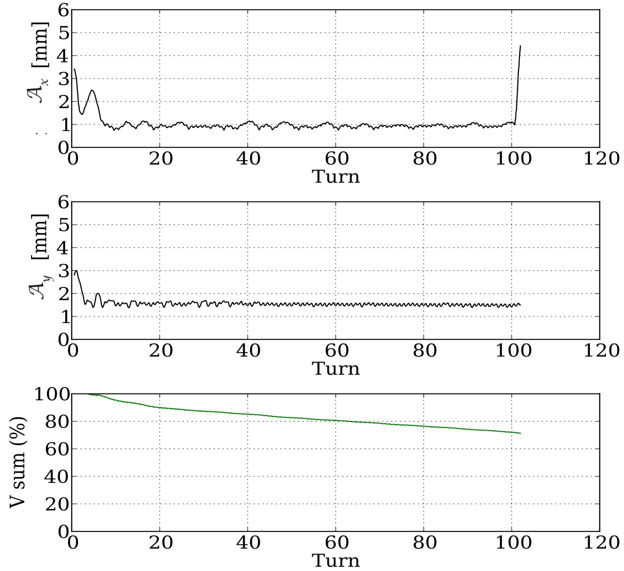
$$A = \sqrt{2J\beta}$$

$$2J\beta = x^2 + \left(\alpha_x x + \beta_x x'\right)^2$$

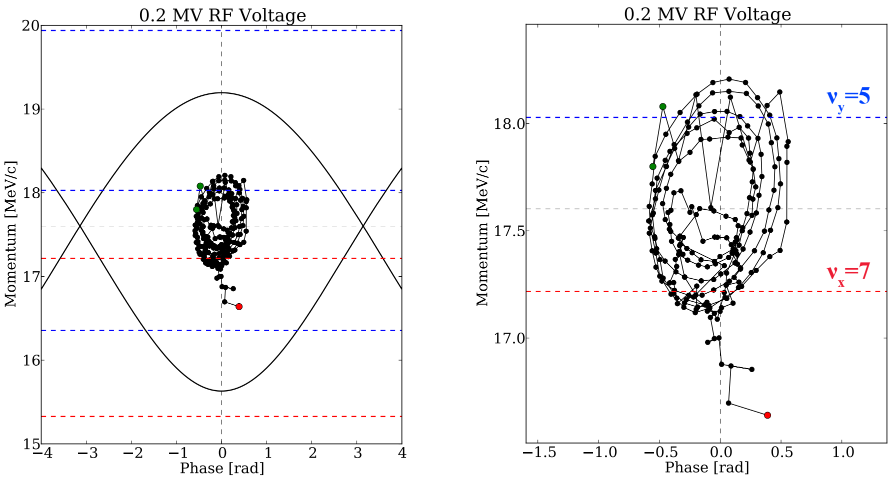
# Experiments in EMMA

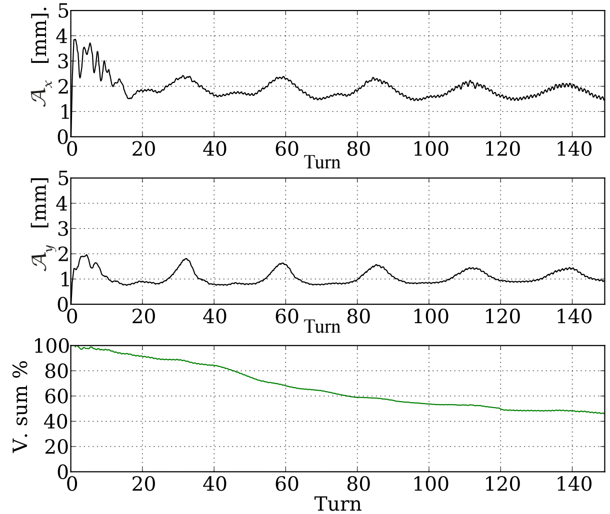
- Can't measure amplitude in EMMA.
- Measure coherent oscillation amplitude of bunch using BPMs (charge centre). Also measure longitudinal phase space.




2.0 MV/turn

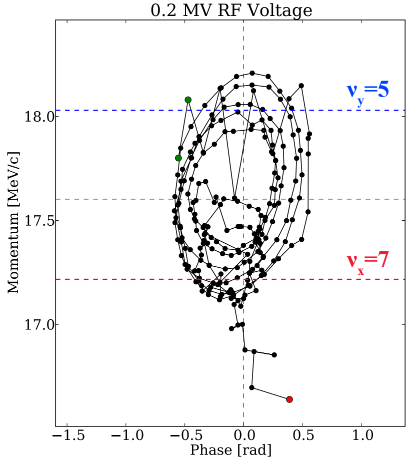


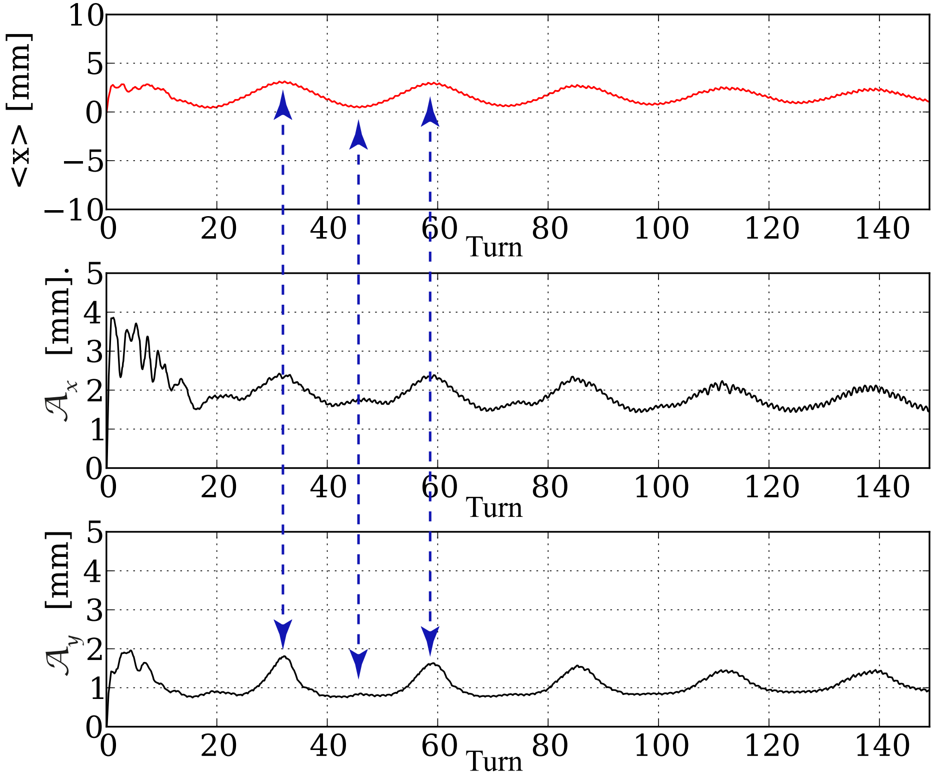

0.2 MV/turn

# Experiments in EMMA

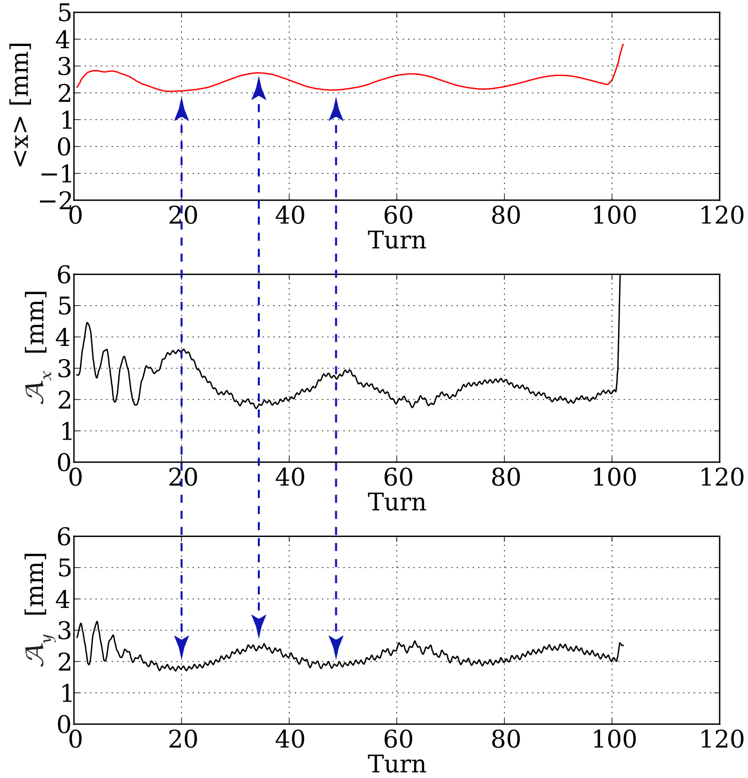
- Two sets of data taken with two different lattice corrections schemes applied.
- Increase in $A_x$ and $A_y$ is 'out of phase' in the left and 'in phase' on the right.
- Two different correction schemes applied to the two sets of data…




2011 data




2012 data



# Experiments in EMMA

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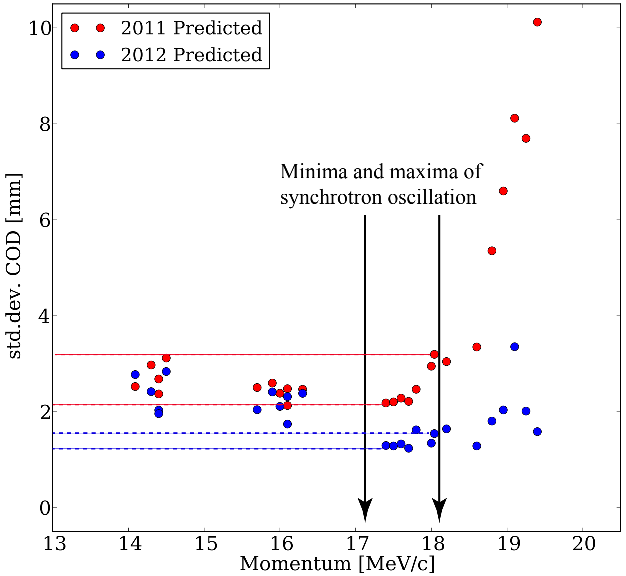
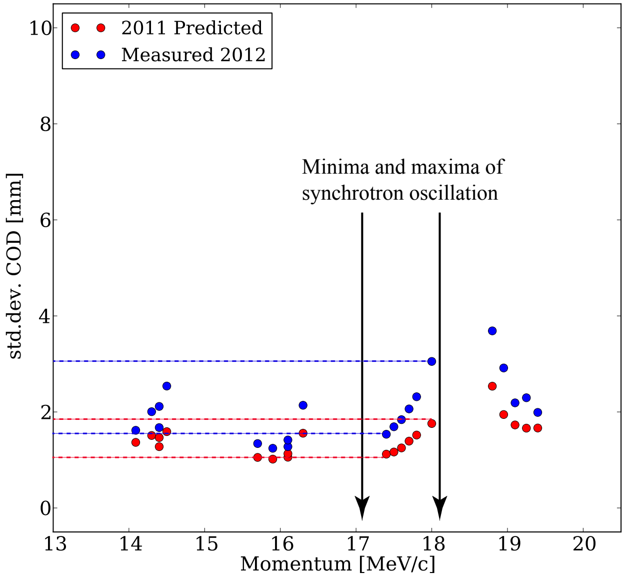
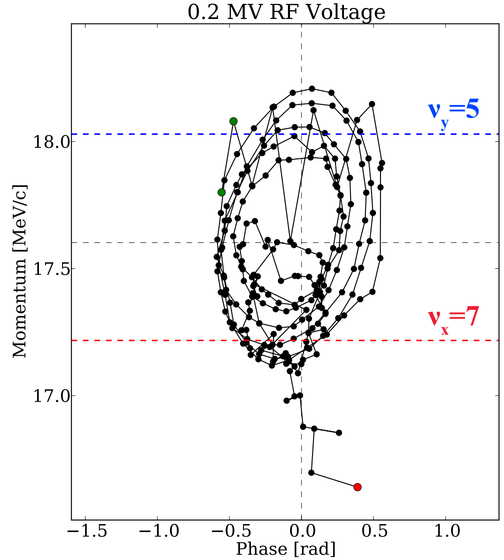
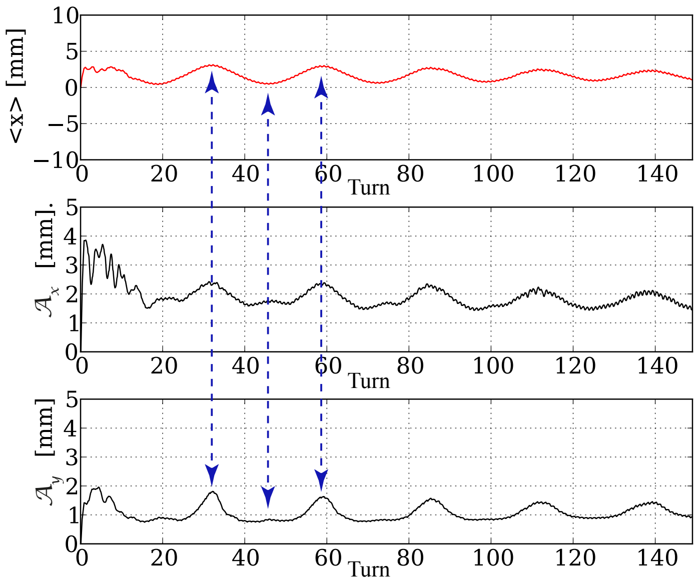
## Horizontal COD



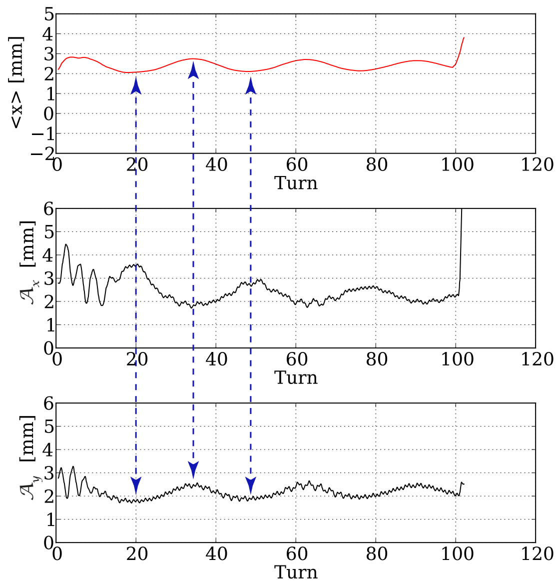

## Vertical COD



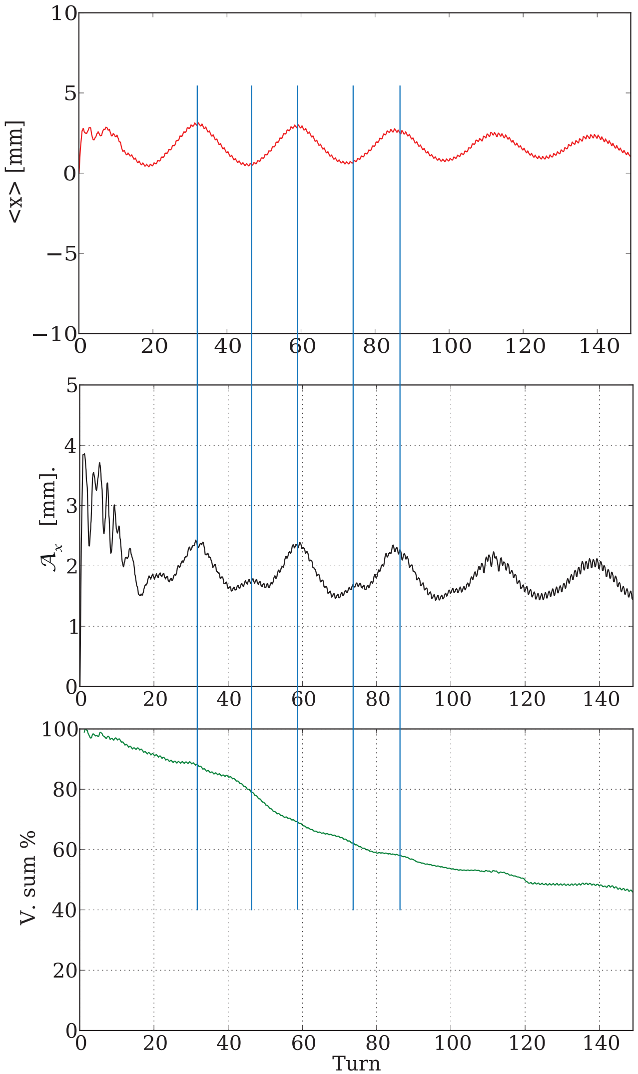

*ΔA* agrees with COD prediction in both planes.

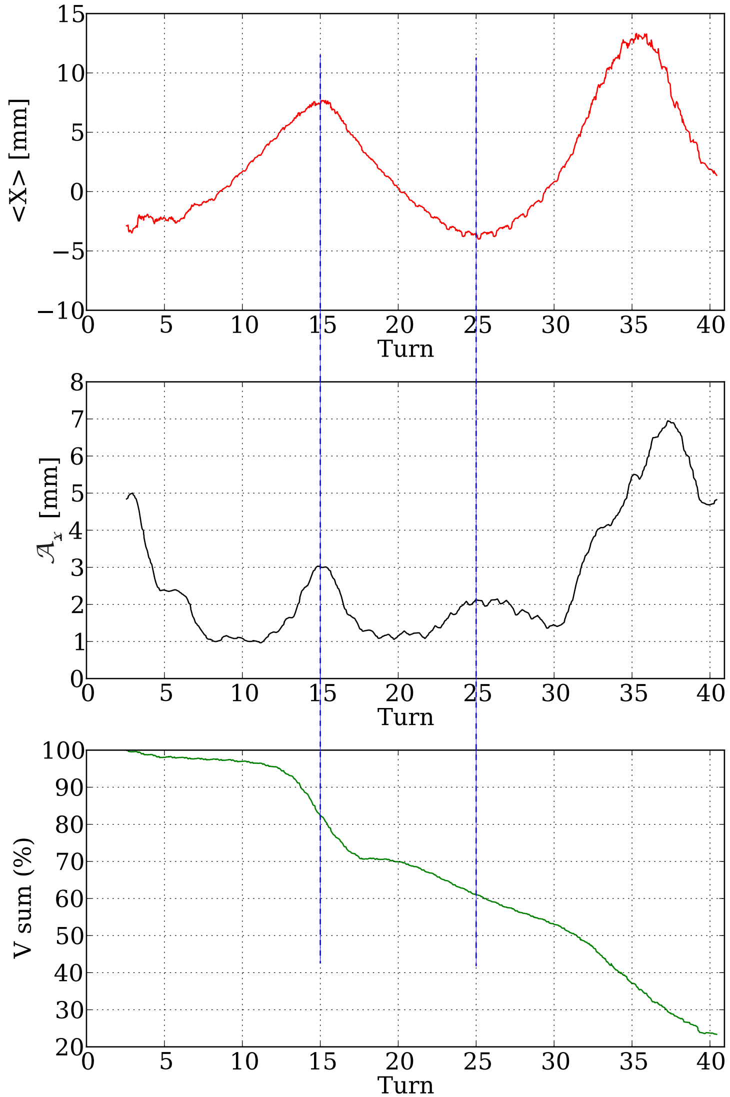



***ΔA* disagrees with COD predicted in horizontal plane. Agrees in vertical. $A_h$ rises when the $\nu_h$=7 integer tune is crossed and when the predicted COD falls.**

# Experiments in EMMA

- Charge loss can be observed at tune crossing and min/max of momentum oscillation.



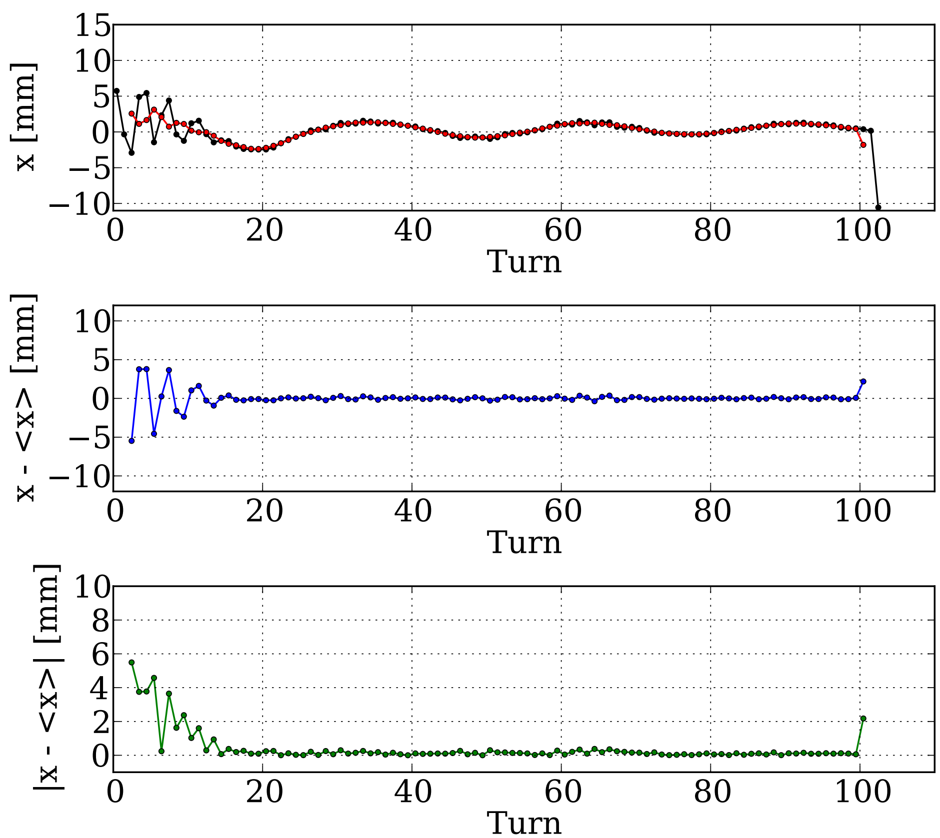
# Decoherence Calculation

- Decoherence calculation with 0.05 MeV momentum spread and linear part of the chromaticity as -10

$$\xi_x = \frac{\Delta \nu_x}{\delta}$$

$$\Delta \nu_x = 0.03$$

Fully decohered in ~30 turns.
But momentum spread increases rapidly.




Single BPM per turn.
Decoherence of betatron oscillation and then appears to follow closed orbit.

# Experiments in EMMA

- In the lattice used to take the 2011 data, the correction scheme is applied (by D. kelliher using response matrix technique) to correct COD in the momentum range ~17 – 18 MeV/c. In this case the observed increase in $\Delta A_{x,y}$ agrees with the predicted/measured COD.
- In the lattice used to take the 2012 data the correction was more "global" => for larger momentum range and reduces COD. While $\Delta A_y$ agrees with the measured COD, $\Delta A_x$ disagrees. The increase in $\Delta A_x$ occurs when $\nu_x=7$ is crossed.
- This shows that at slower crossing speeds, there is an increase in the standard deviation of the orbit which is not explained by the COD.
- Charge loss occurs at the min and max of the orbit, near the integer tunes but it is not clear what the mechanism is…
- We cannot analyse the transverse phase space in the experimental results so we used a simulation in Zgoubi.

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# Synchrotron Oscillation Simulations in Zgoubi (0.5 MV/turn)

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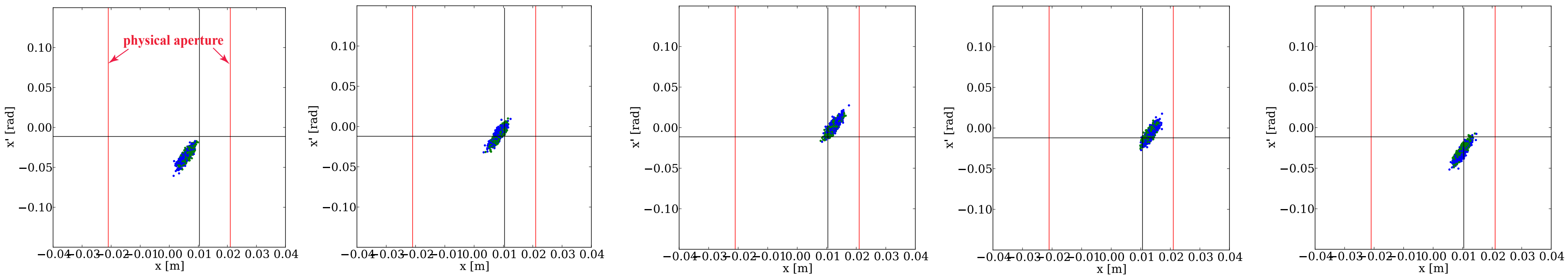
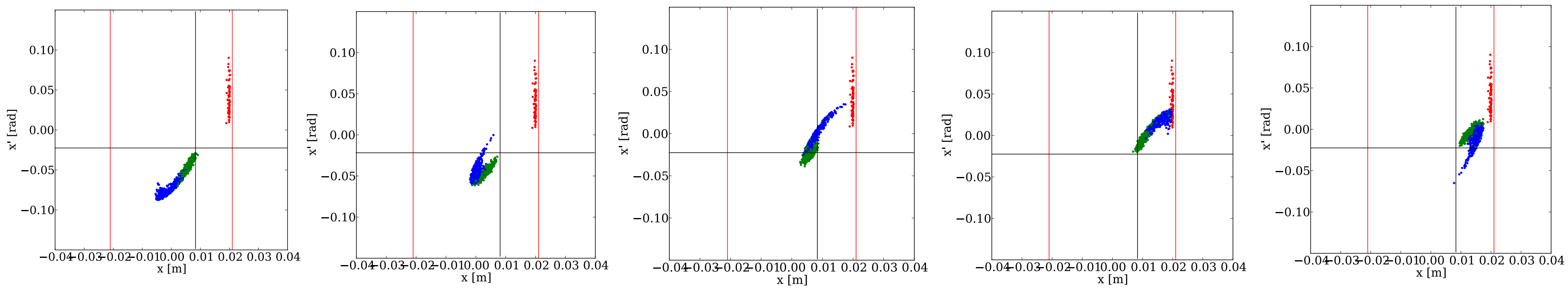
- Zgoubi was used with the same bunch parameters as mentioned previously, except some finite initial amplitude of the bunch.
- The aim was to simulate the synchrotron oscillations in the EMMA experiment.

Before integer crossing

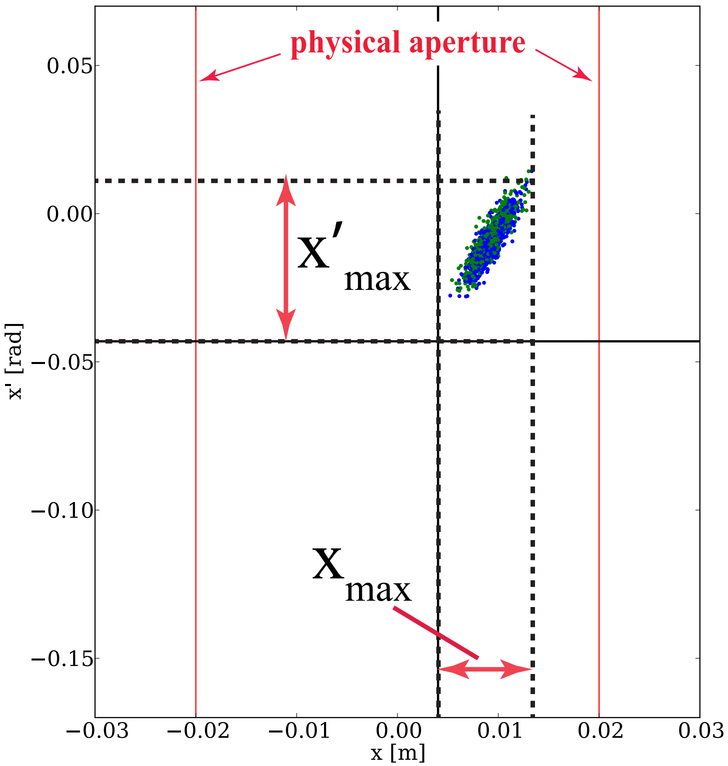



During integer crossing

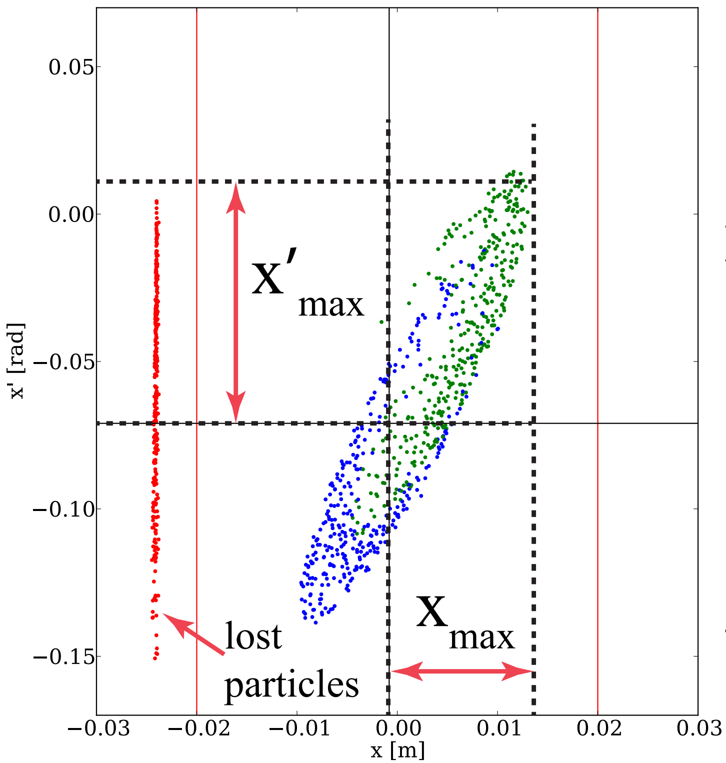


# Synchrotron Oscillation Simulations in Zgoubi

Before integer crossing




After integer crossing




Assuming black cross-hair is closed orbit away from integer tune, estimate amplitude growth using

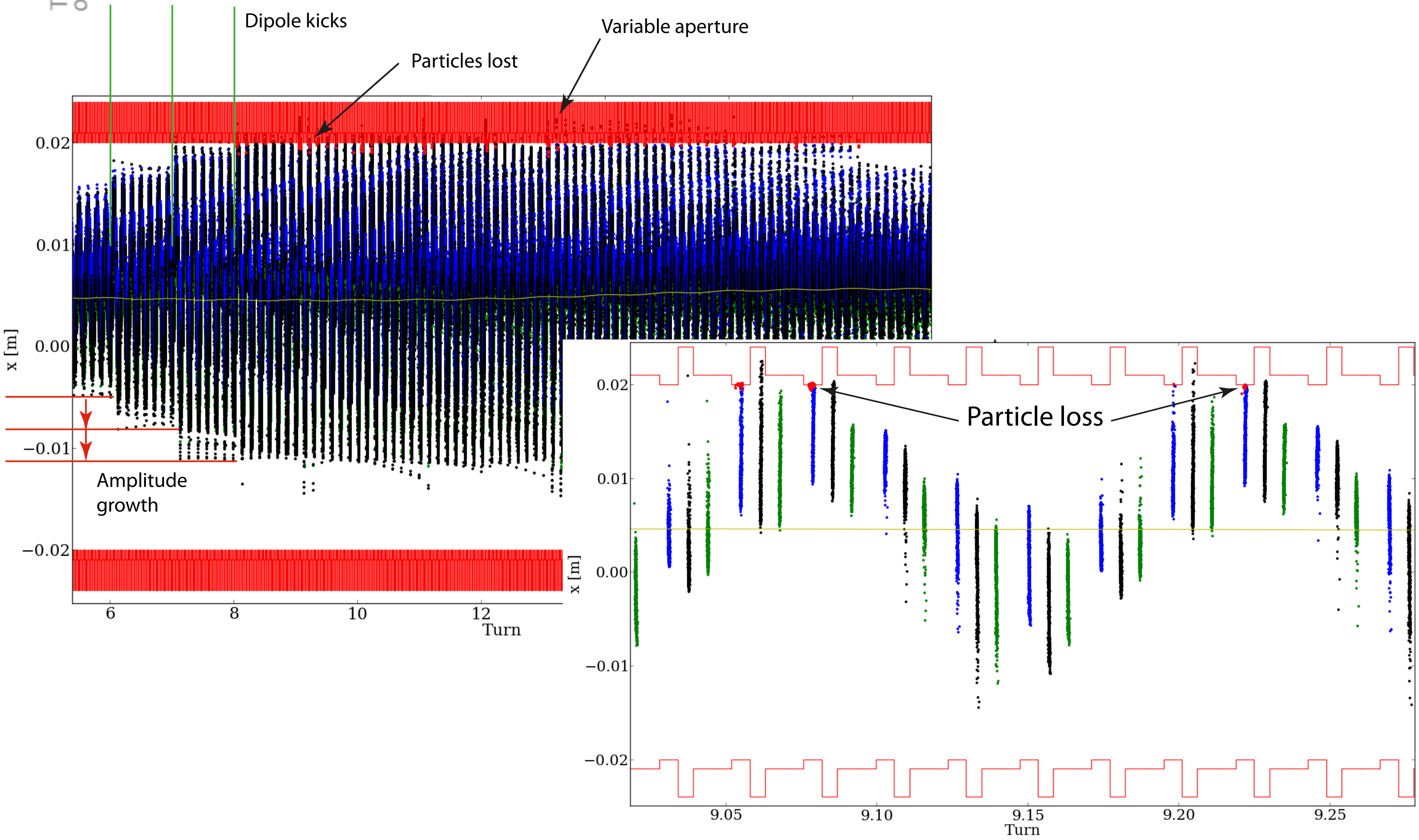
$$A = \sqrt{2J\beta}$$

$$2J\beta = x^2 + \left(\alpha_x x + \beta_x x'\right)^2$$

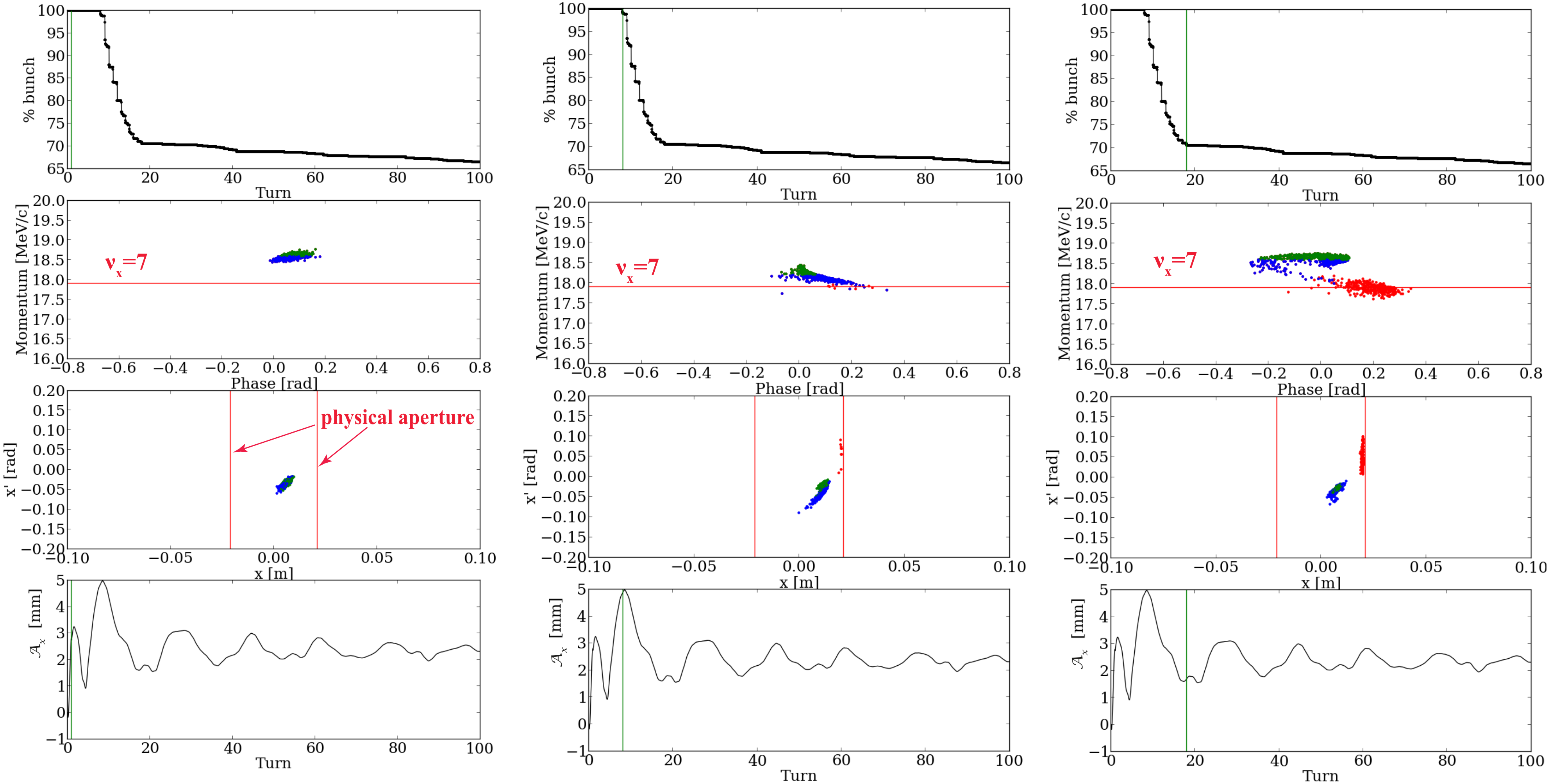
Amplitude growth estimate yields *A* = 5 mm.

By examining the Baartman relation and previous simulations at a crossing speed of 1/√Q'=2 (0.5 MV/turn) we find that the amplitude growth A=5 mm.

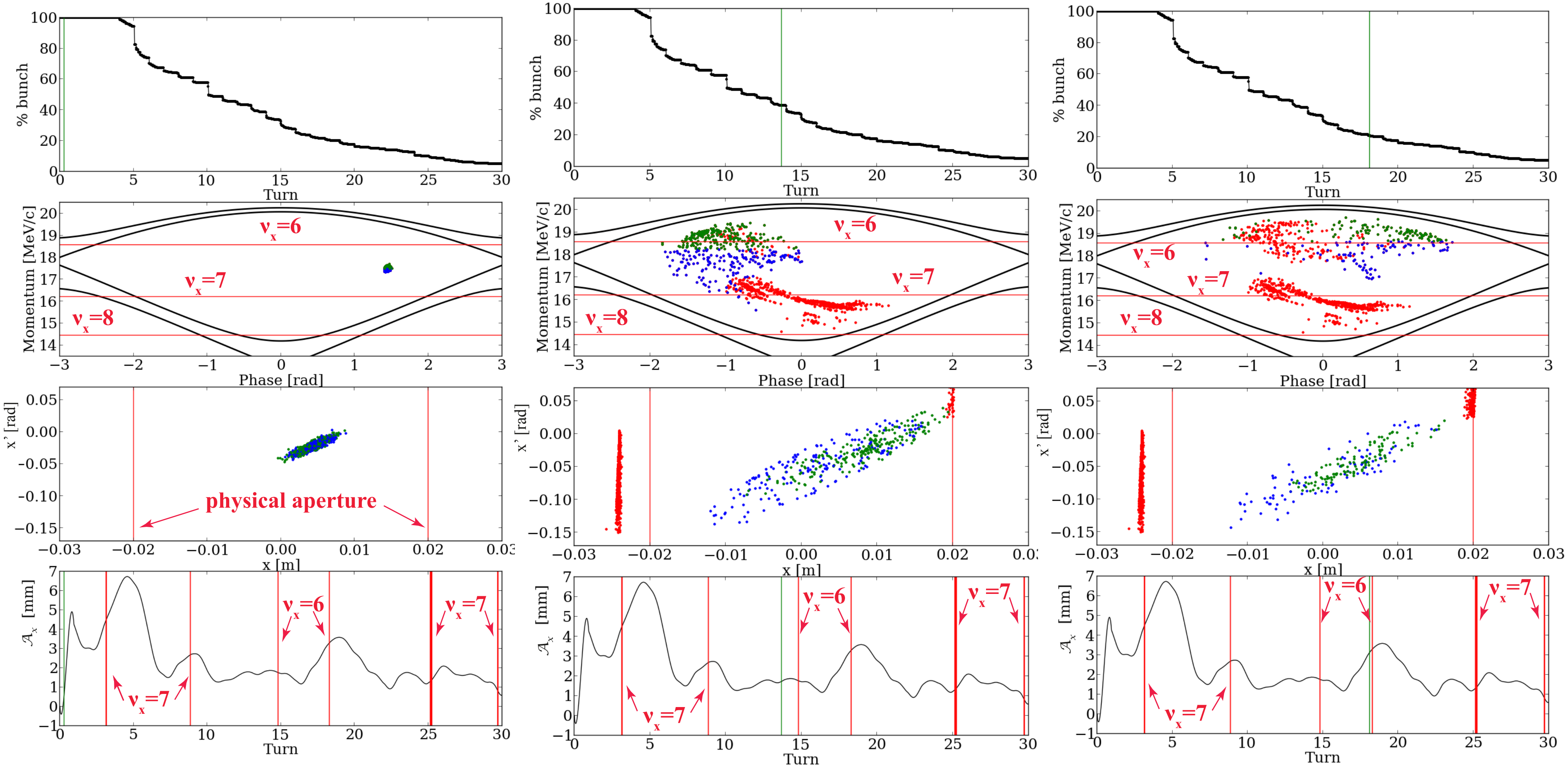
# Synchrotron Oscillation Simulations in Zgoubi



# Synchrotron Oscillation Simulations in Zgoubi



# Synchrotron Oscillation Simulations in Zgoubi

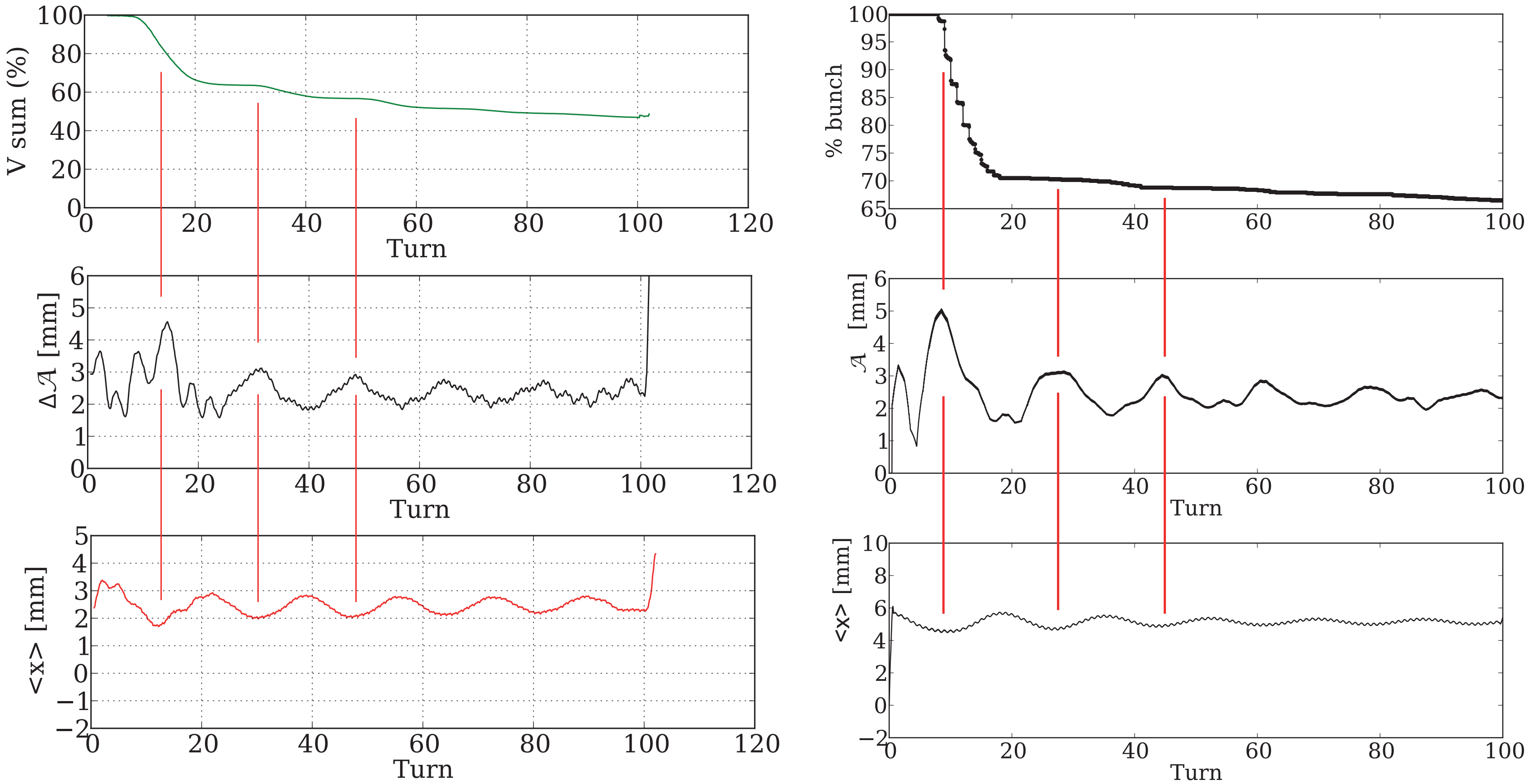


# Synchrotron Oscillation Simulations in Zgoubi

- Spread of finite transverse amplitude particles and finite initial momentum spread means longitudinal decoherence.
- Longitudinal decoherence => momentum spread increases => transverse decoherence rate increases rapidly.
- Difficult to measure amplitude on top of COD as cannot measure COD dynamically.
- Particles are lost in the the aperture when they cross integer tunes due to the coherent addition of amplitude to some particles from the kick delivered by the dipole field error once per turn.

# Comparison of Simulation and Experiment

0.5 MV/turn    1/√Q’ ~ 2.3



# Comments

- Good agreement between simulation and experiment.
- Shows that the simulation is a good approximation and explains the behavior and mechanism of slow resonance crossing in EMMA.
- Simulations show linear relationship between crossing speed and amplitude growth and show dependence on error strength.
- In EMMA, amplitude growth during many turns becomes a problem with acceleration below 2.0 MV/turn.
- In a linear non-scaling FFAG the amplitude growth should be considered for a given requirement with attention to the linear-type Baartman relation. Should attempt to correct magnet errors in order to bring amplitude increase for a resonance crossing inside the requirement for a given crossing speed in the machine.