LHC Injectors Upgrade

Studies on tune ripple

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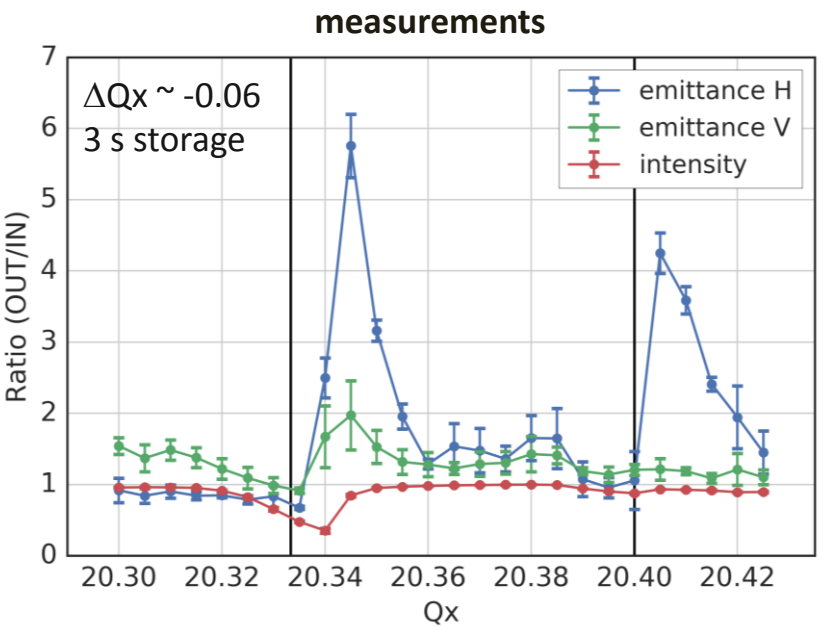
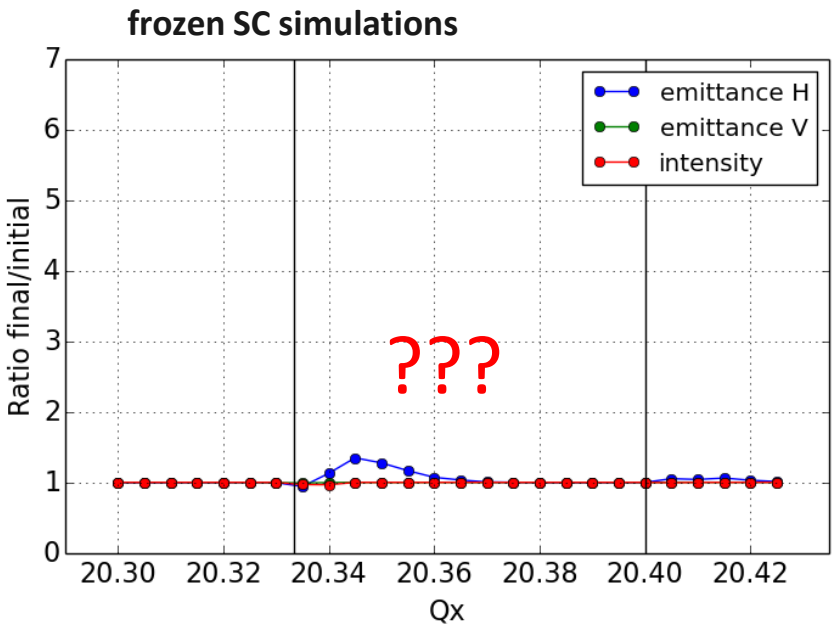
Acknowledgements:
R. De Maria, G. Franchetti, G. Iadarola, S. Kostoglou, A. Oeftiger, Y. Papaphilippou, K. Paraschou, M. Schwinzerl

4th ICFA Mini-Workshop on Space Charge 2019 (4-6 November)

Observations from CERN SPS experiment

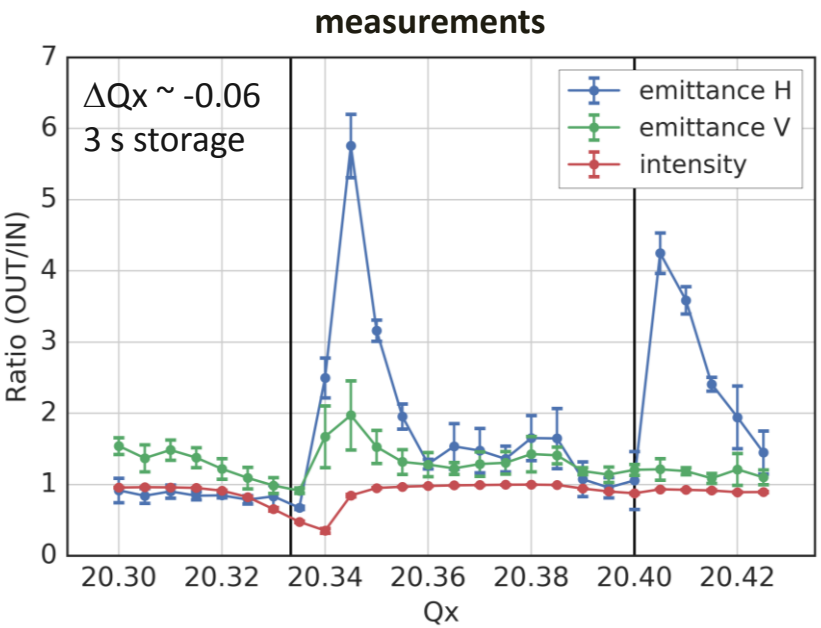
- **Benchmark experiment**
  - Horizontal 3rd order resonance at Qx = 20.33 deliberately excited
  - Additional resonance observed at Qx = 20.40 (space charge driven)

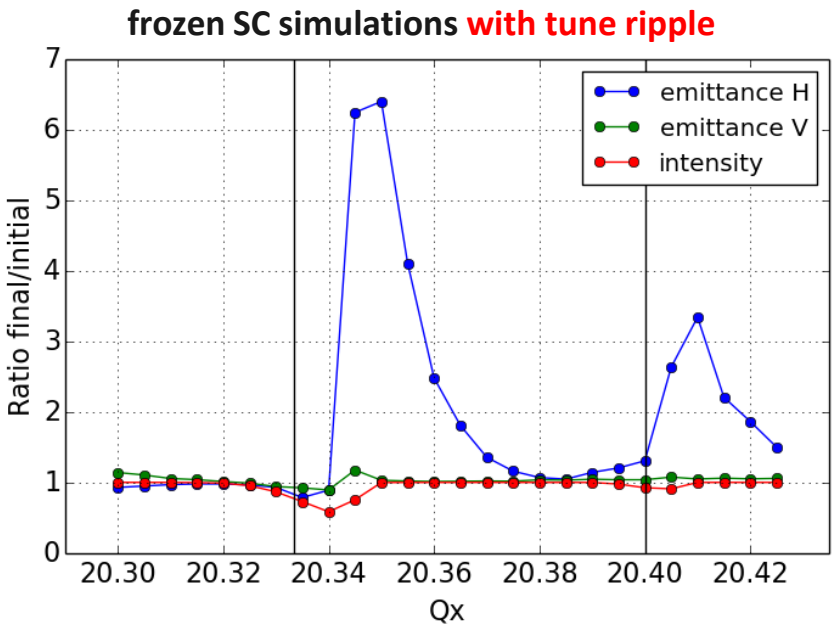




Observations from CERN SPS experiment

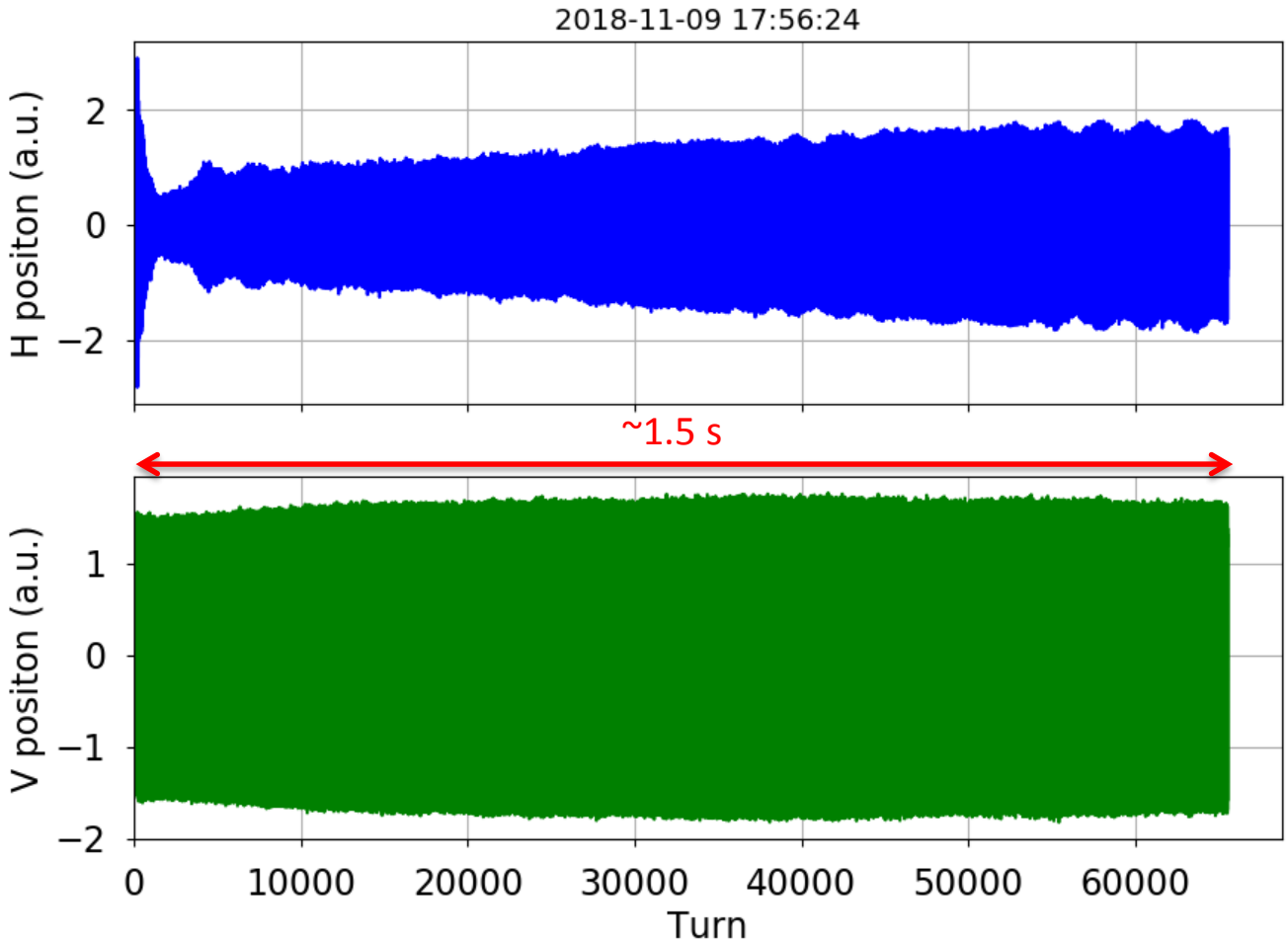
- **Benchmark experiment**
  - Horizontal 3rd order resonance at Qx = 20.33 deliberately excited
  - Additional resonance observed at Qx = 20.40 (space charge driven)
  - Simulations with **frozen potential** far from experiment unless SPS **tune ripple** from quadrupole power converters is taken into account



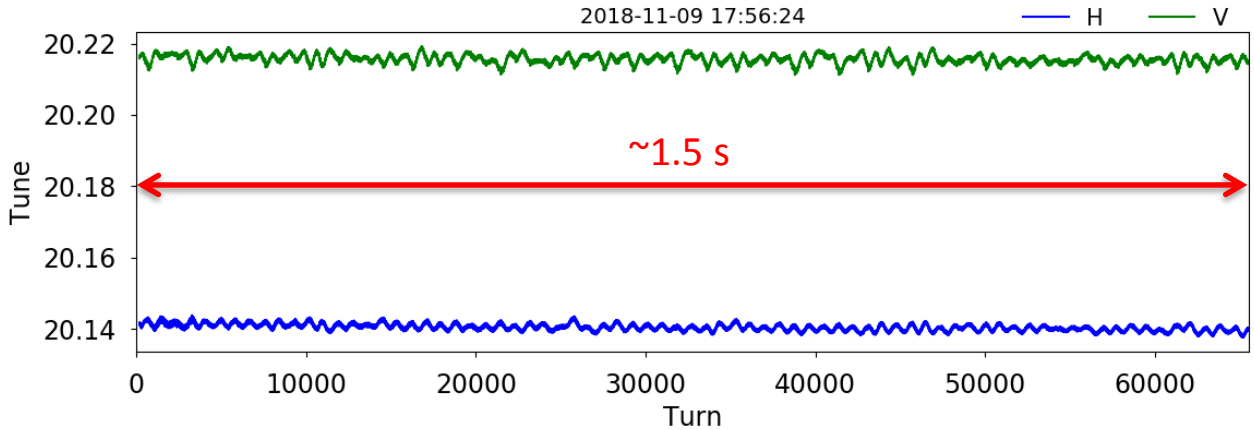


Measurement of natural SPS tune ripple

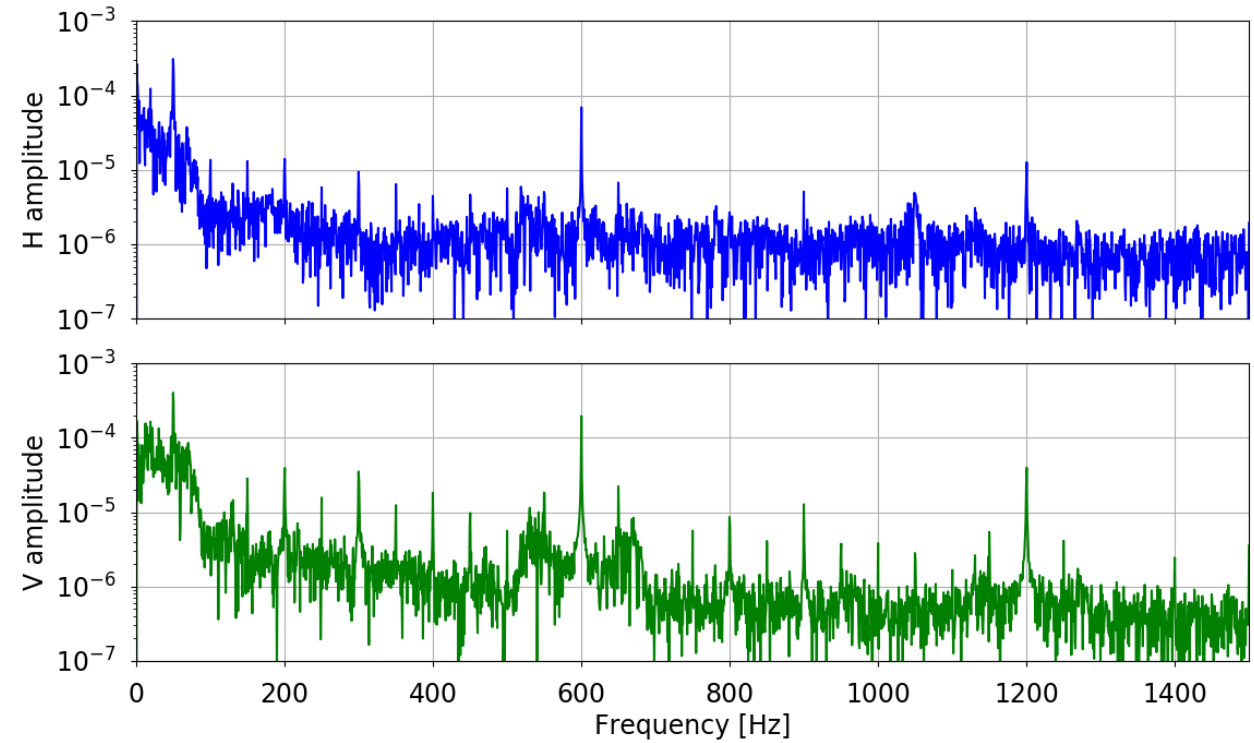
- Machine non-linearities corrected as much as possible
- Single kick induced betatron oscillation lasting for more than 70k turns
- FFT analysis of data in moving slices of 40 turns



Measurement of natural SPS tune ripple



resulting tune evolution

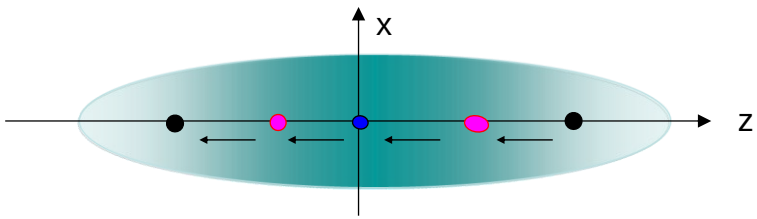


FFTs of tune evolution show clear harmonics of 50 Hz and 600 Hz (12 pole rectifier of quadrupole power supplies)

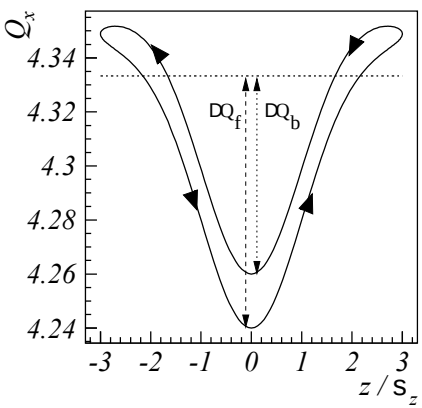
Questions addressed in this talk

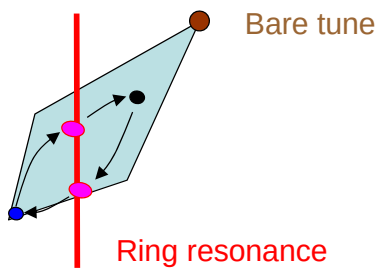
1. **Why is the beam response in simulations with a frozen model so weak for SPS when tune ripple is not included?**

Periodic resonance crossing

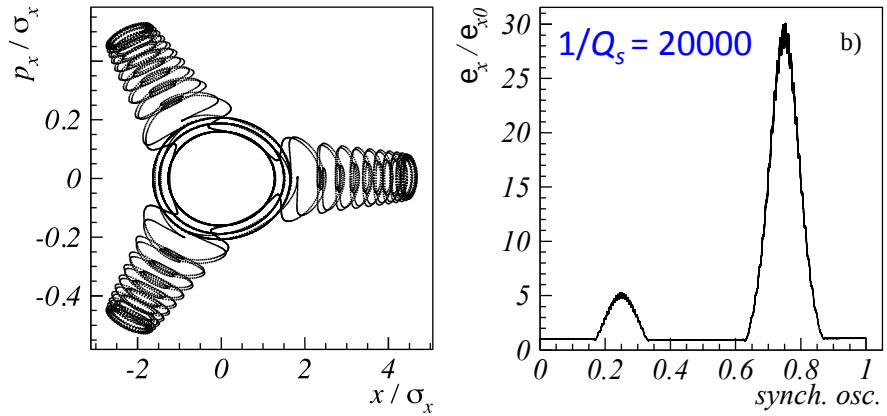


- space charge detuning varies along bunch
- synchrotron motion results in periodic tune modulation of individual particles
- chromaticity enhances tune excursion in one half synchrotron period and reduces it in other half

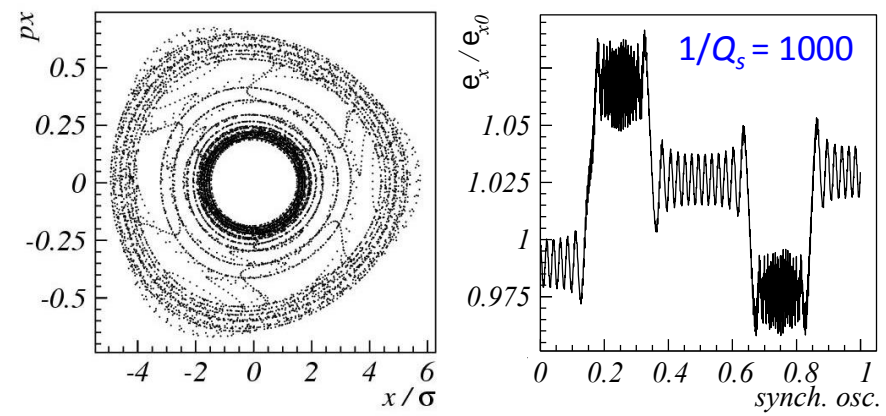




adiabatic limit of resonance crossing:
particle trapping in resonance islands



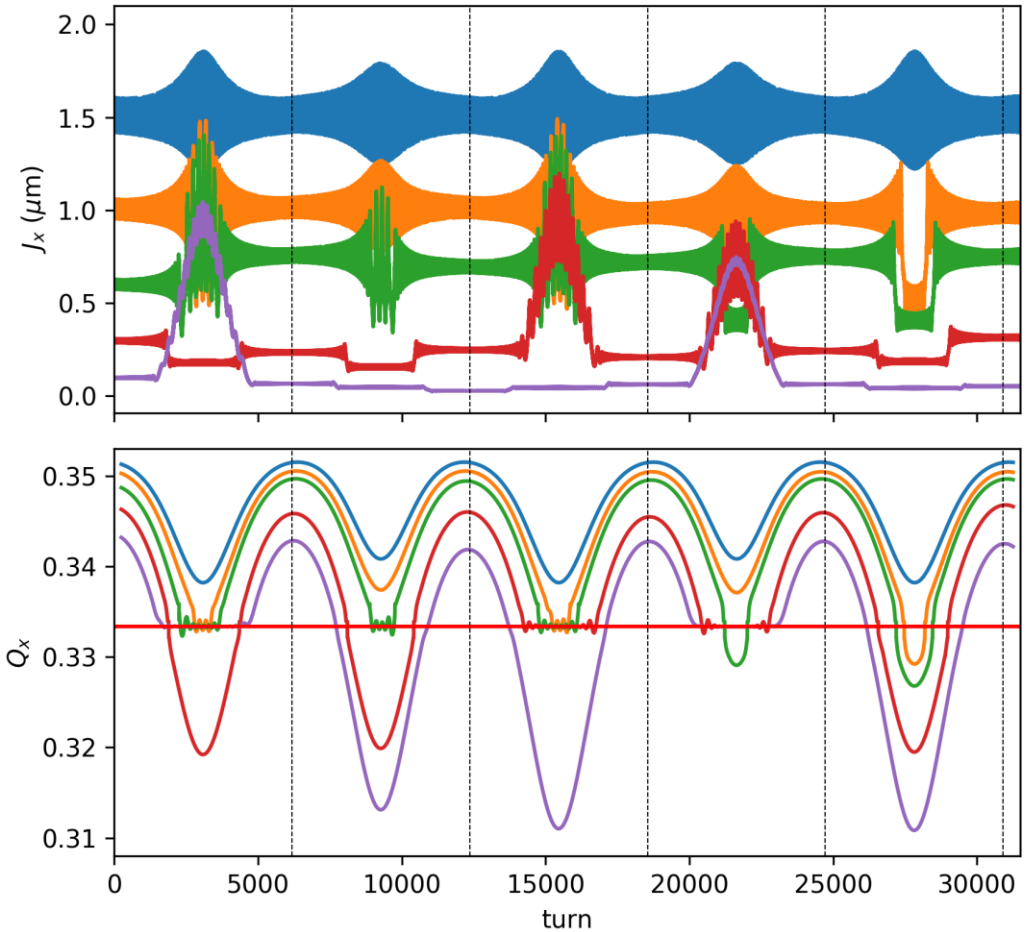
non-adiabatic resonance crossing:
scattering of particle trajectory



G. Franchetti et. al (2005)

Illustration of regimes

- **SPS model with 1/3 resonance and low synchrotron tune ($1/Q_s$ ~ 12500 turns)**
  - adiabatic limit of resonance crossing → particle trapping in resonance islands



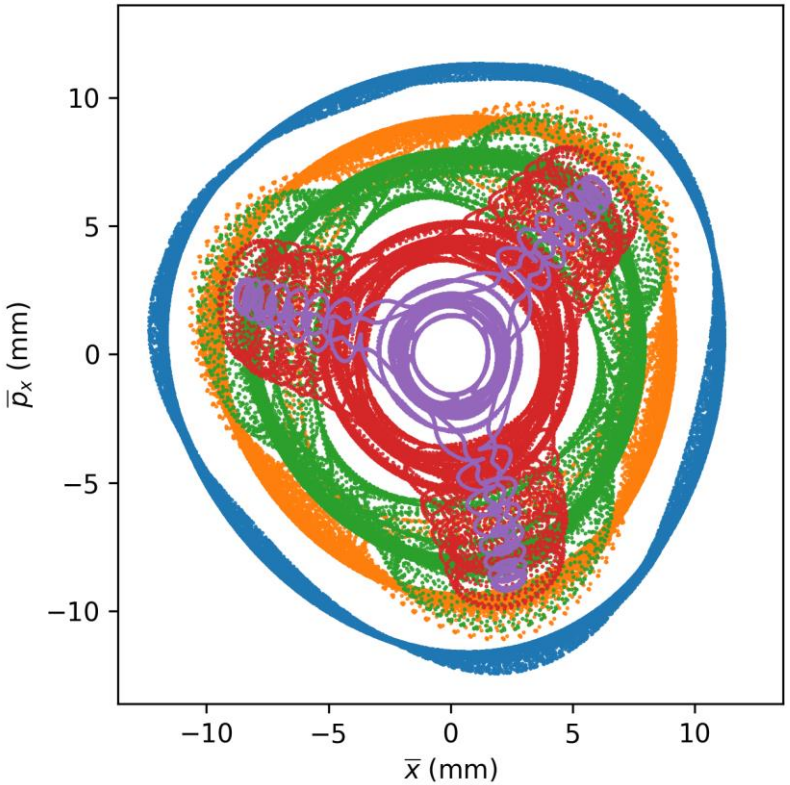
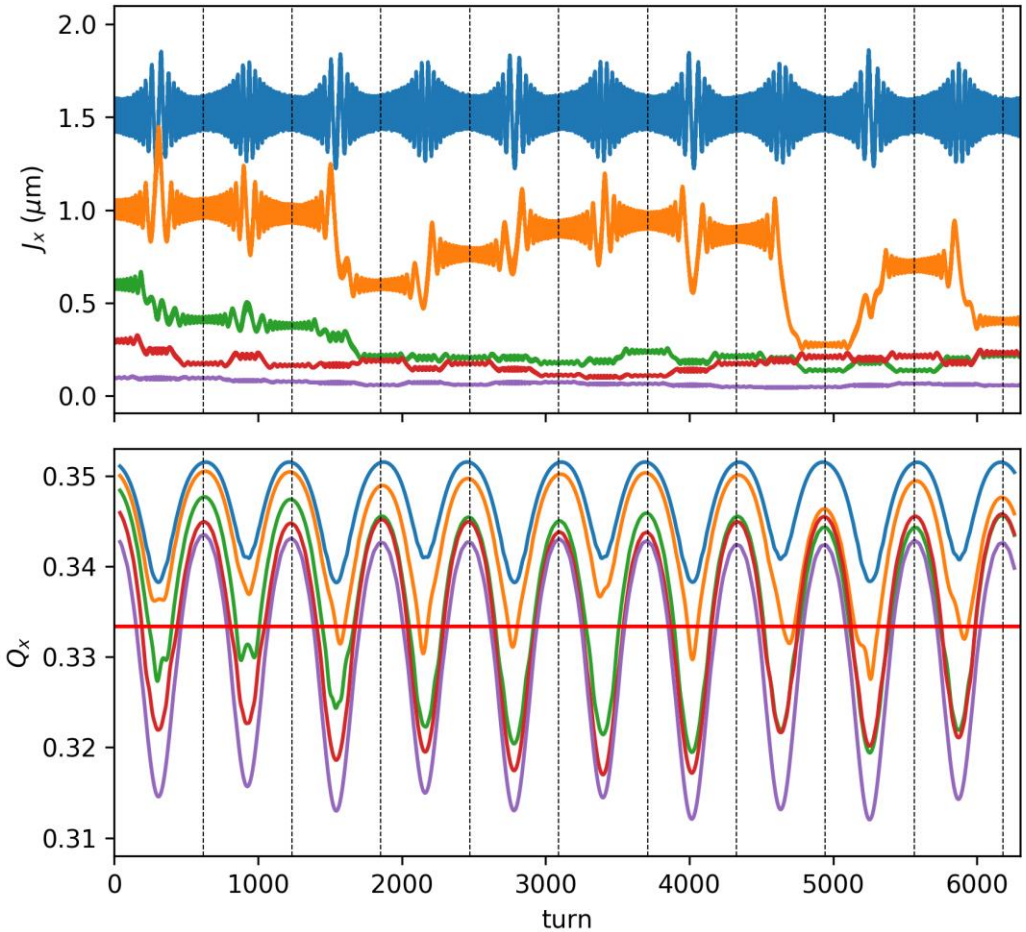


Illustration of regimes

- **SPS model with 1/3 resonance and "typical" synchrotron tune ($1/Q_s$ ~ 1200 turns)**
  - non-adiabatic resonance crossing → scattering of particle trajectories resulting in diffusion



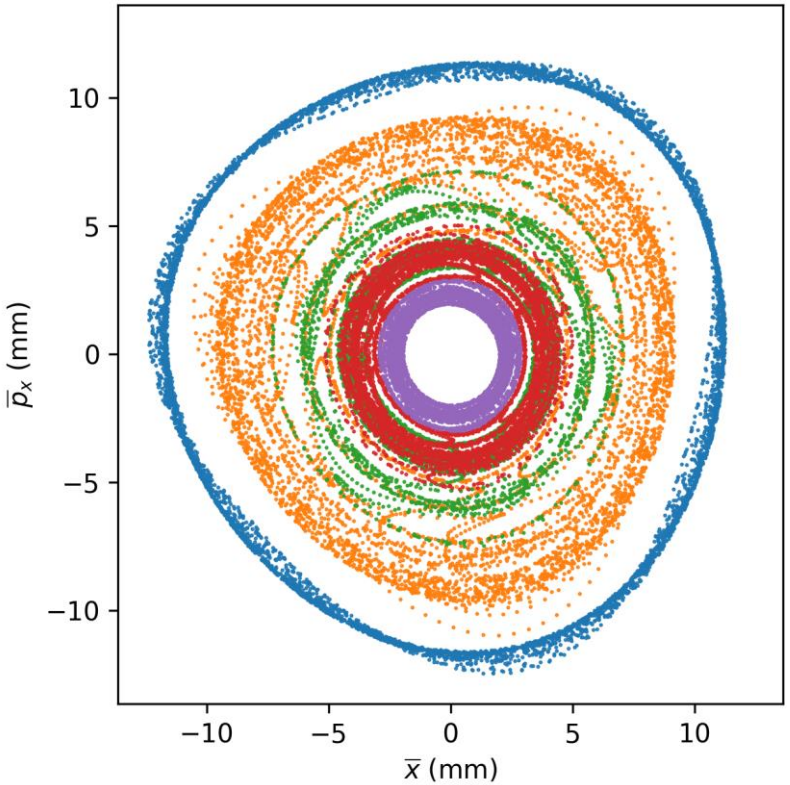
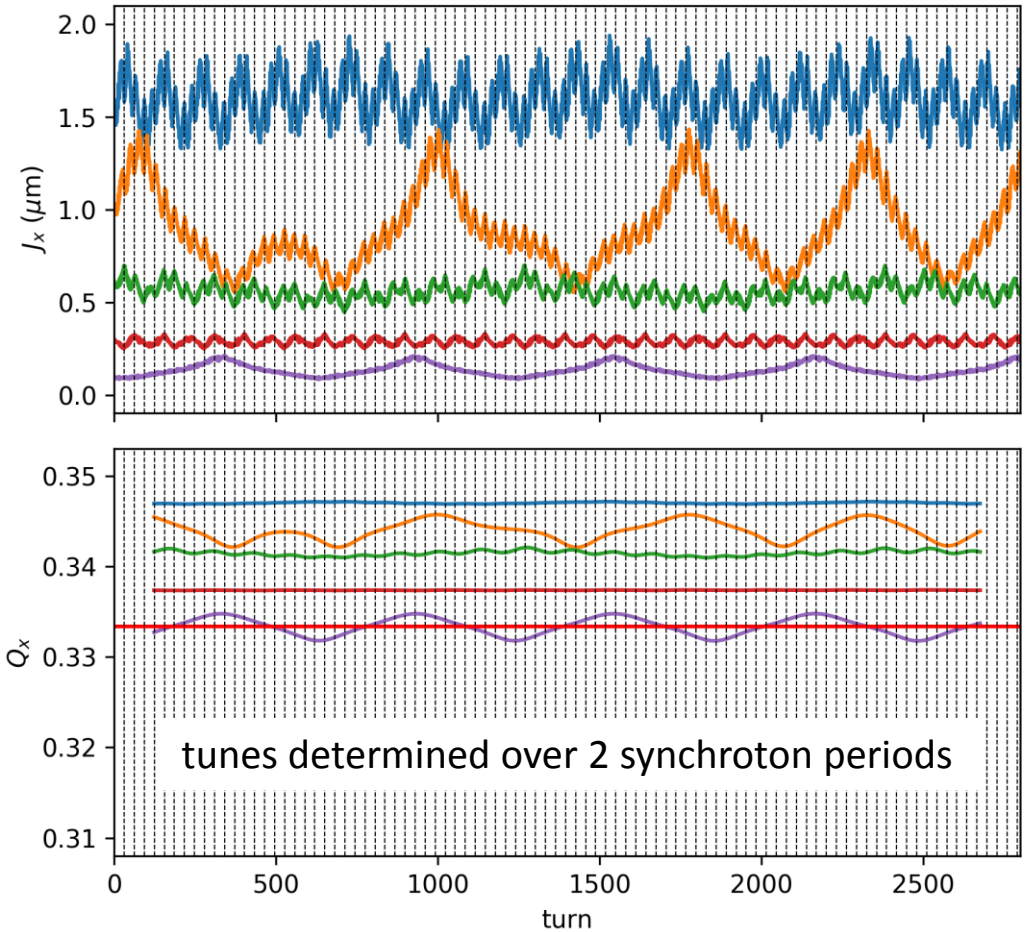


Illustration of regimes

- **SPS model with 1/3 resonance and high synchrotron tune ($1/Q_s$ ~ 66 turns)**



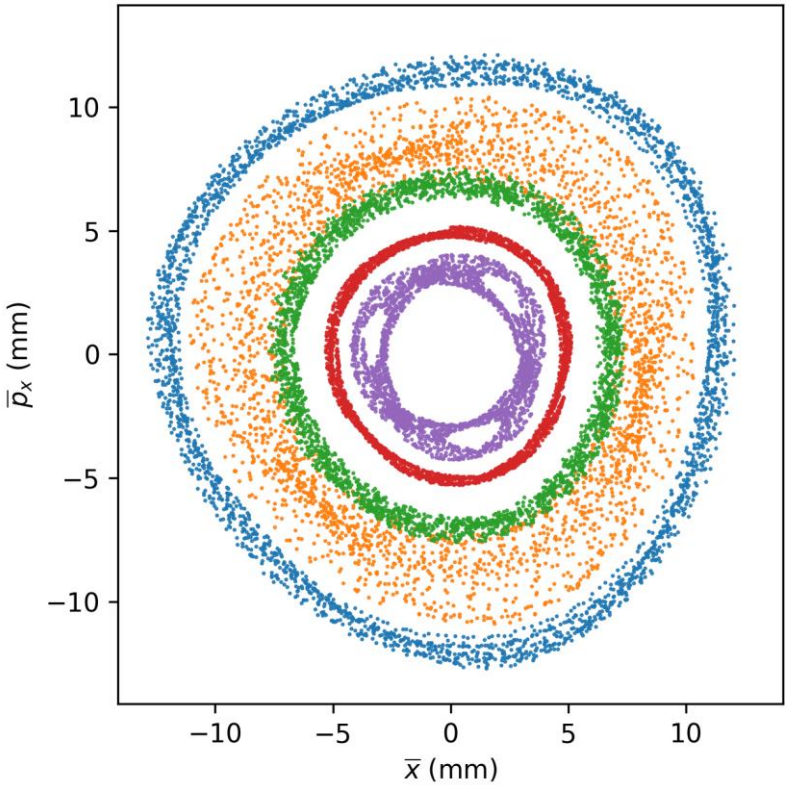
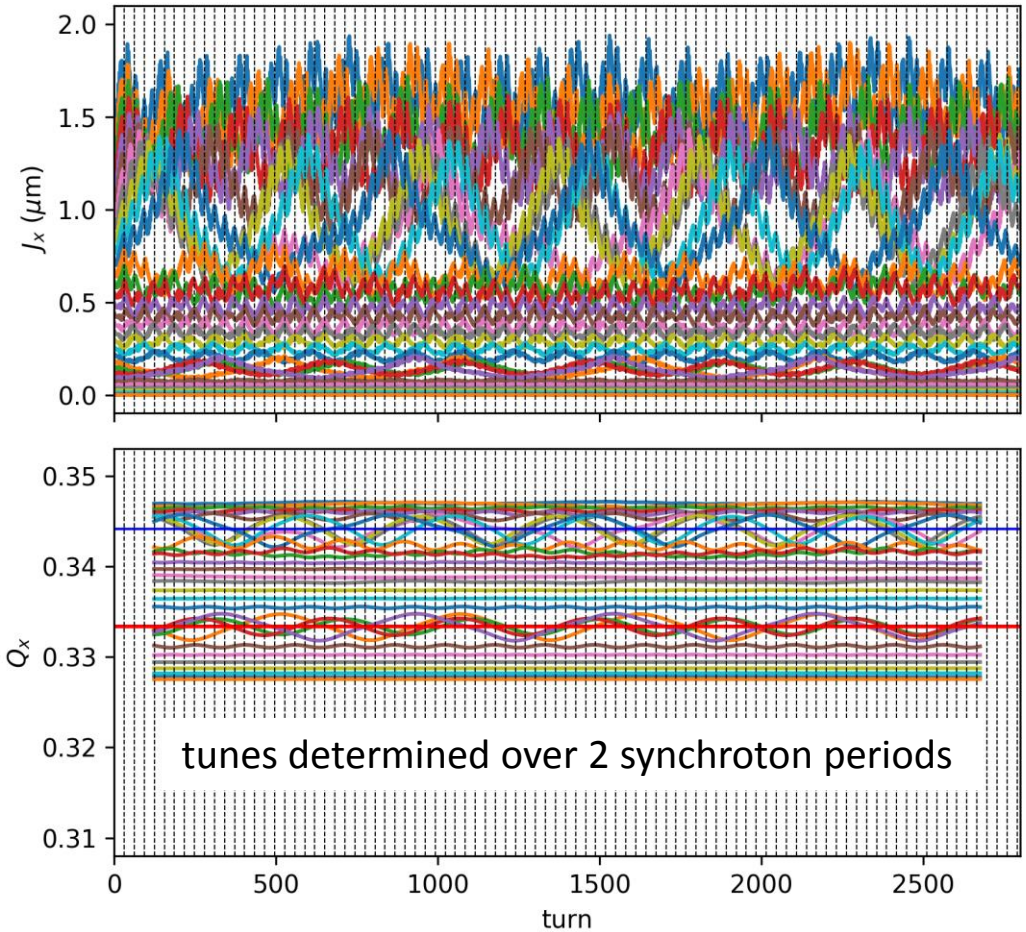


Illustration of regimes

- **SPS model with 1/3 resonance and high synchrotron tune ($1/Q_s$ ~ 66 turns)**
  - Fast tune modulation creates resonance sidebands



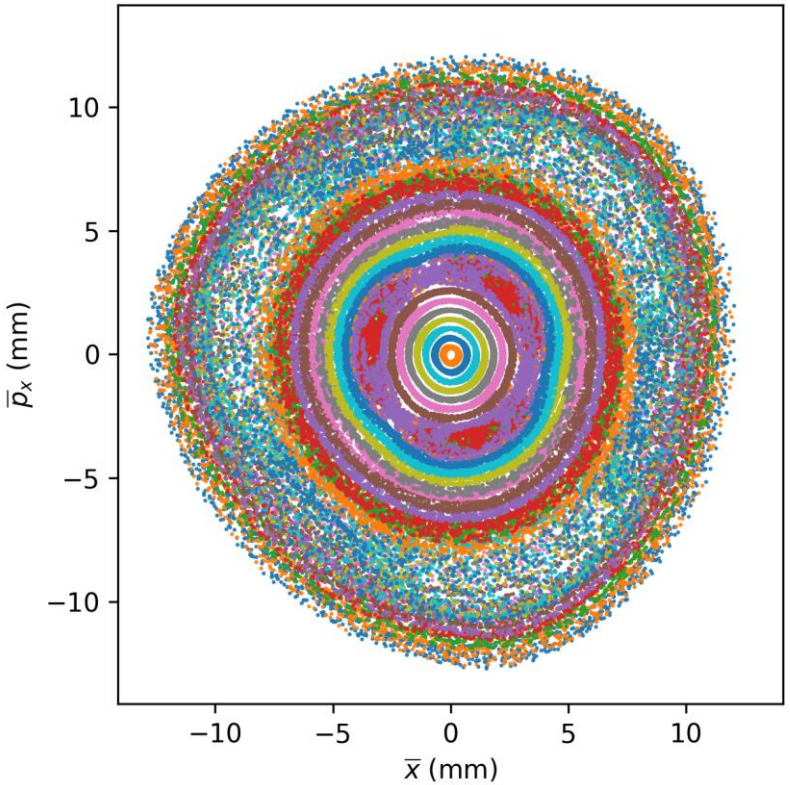
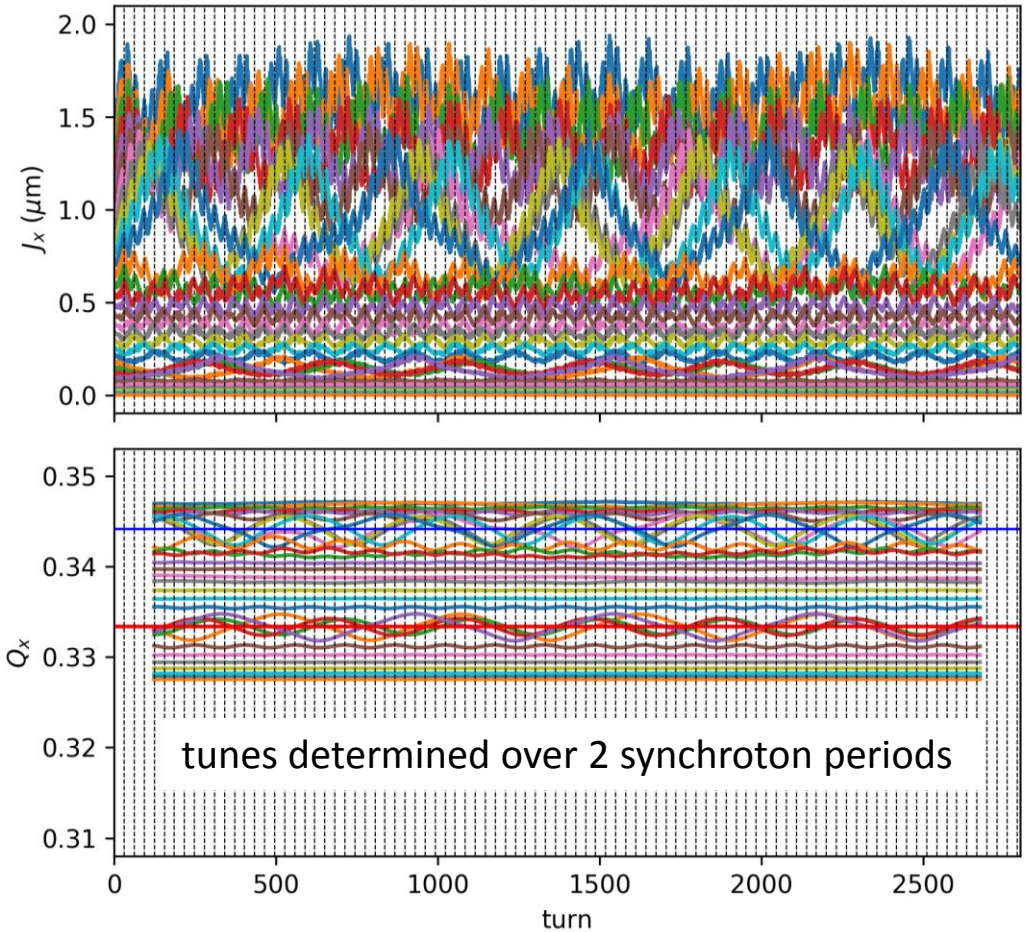
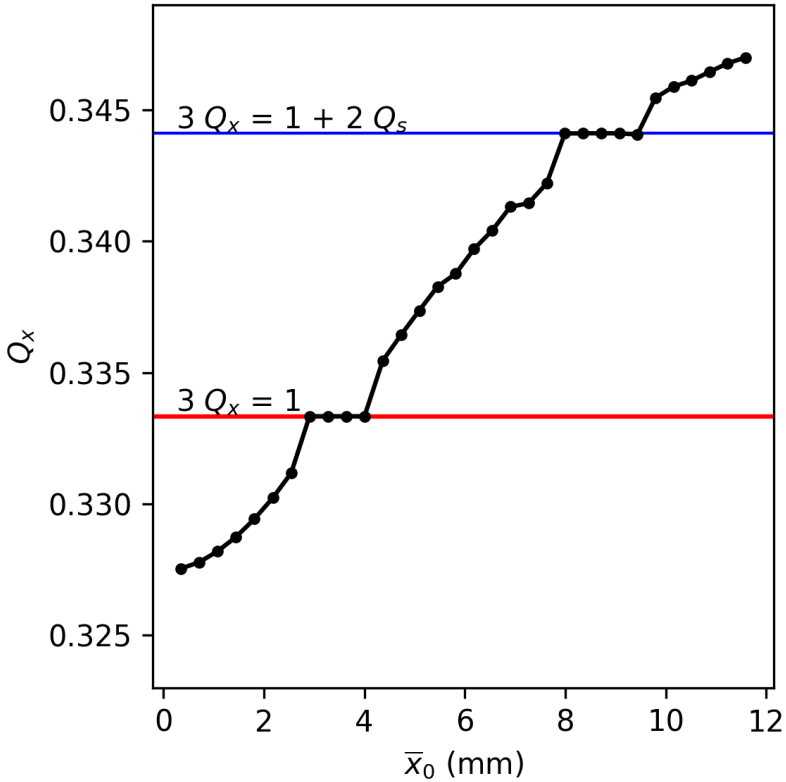


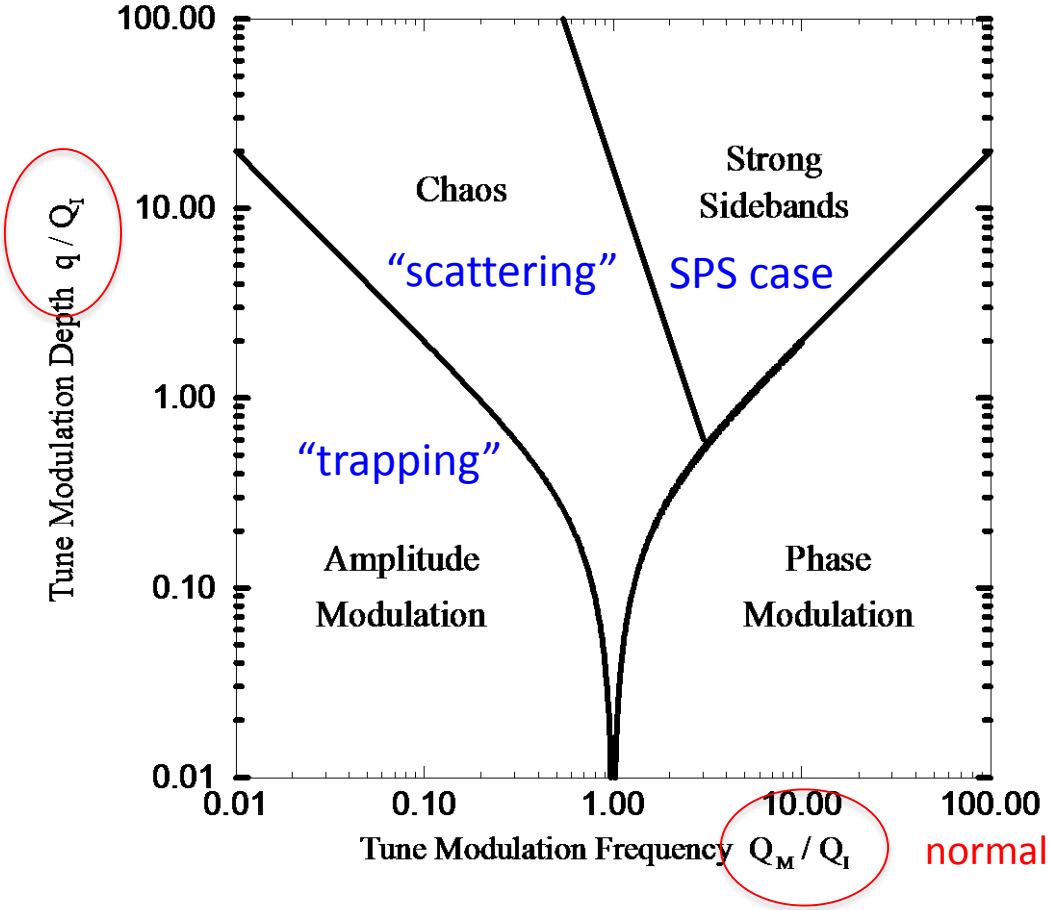
Illustration of regimes

- **SPS model with 1/3 resonance and high synchrotron tune ($1/Q_s$ ~ 66 turns)**
  - Fast tune modulation creates resonance sidebands (at multiples of 2 Q_s since space charge force is modulated by 2 Q_s)
  - **This is the regime of the SPS: not much diffusion since there is no resonance "crossing"!**





Regimes of tune modulation effects



normalized to island tune Q_I

Analysis for 1D
5th order resonance

S. Peggs et al. 1989

Figure 4.1: The (q, Q_M) parameter plane for $N = 5$, showing four distinct phases of motion. Local motion near the fixed point of the $5Q_x$ resonance is stable (i.e. phase-locked, or resonant) for all regions except "Chaos".

Figure from T. Satogata, PhD thesis (1993)

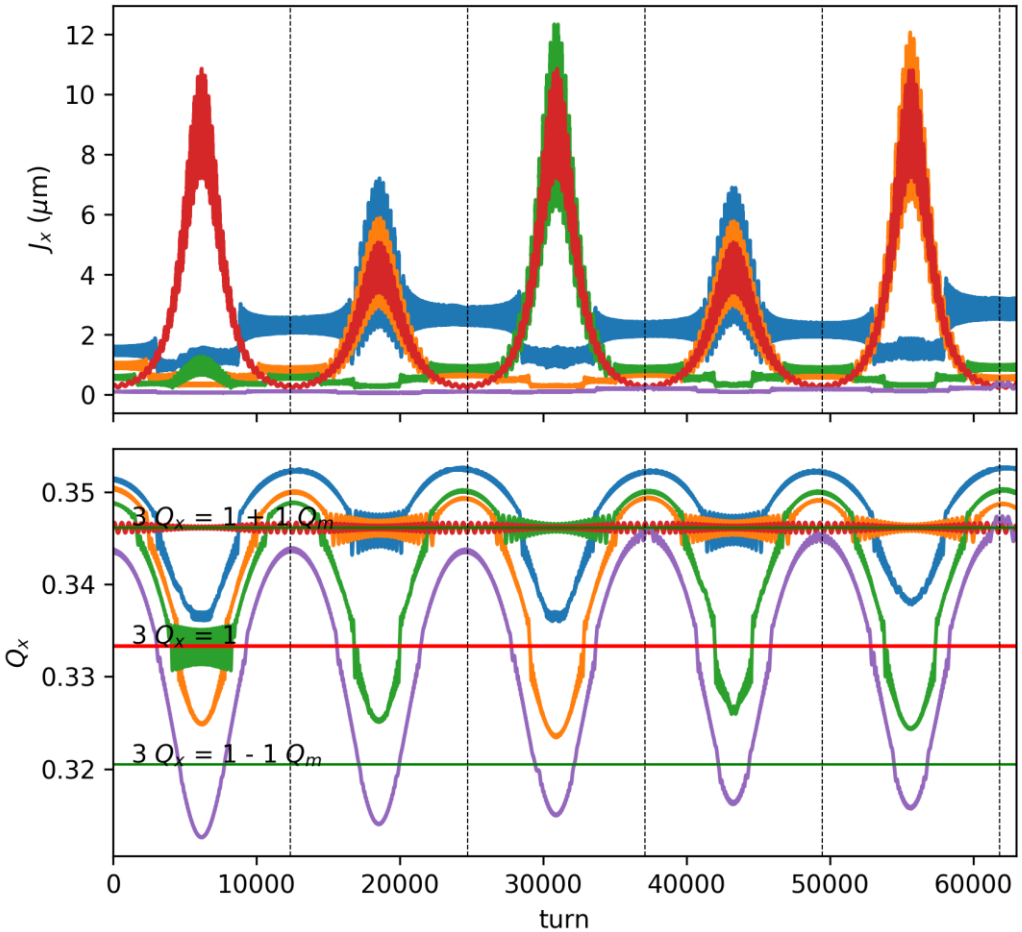
Questions addressed in this talk

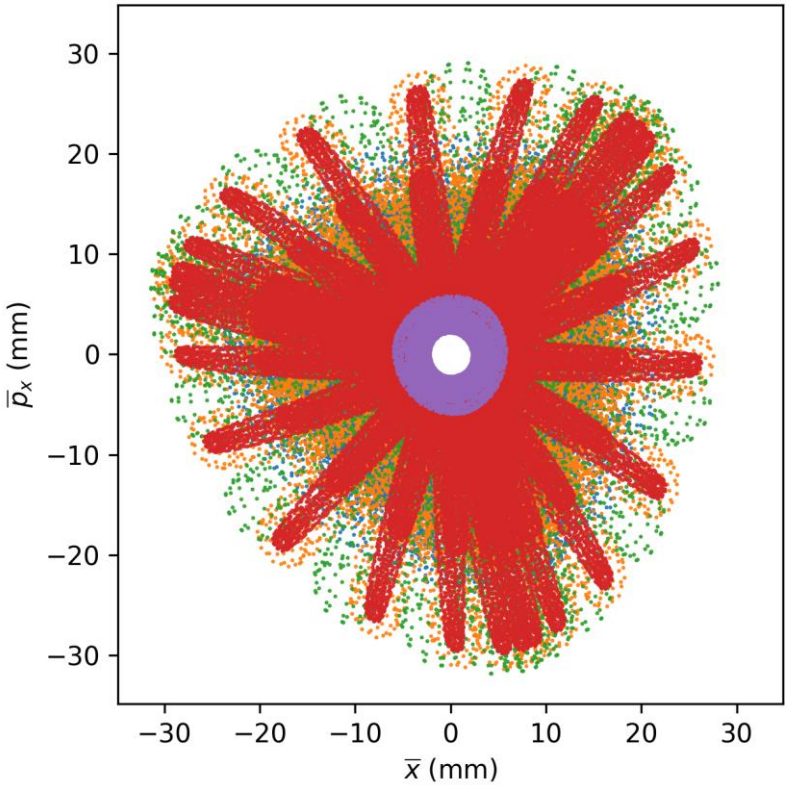
1. **Why is the beam response in simulations with a frozen model so weak for SPS when tune ripple is not included?**
   - SPS falls in “strong sideband” regime due to fast synchrotron motion ($1/Q_s$ ~ 70 turns)
   - There is not much diffusion since there is no real “resonance crossing”, but rather additional stable islands are created due to resonance sidebands

2. **What happens when combining space charge in a bunched beam with external tune modulation?**

Slow synchrotron tune + fast modulation

- **SPS model with $1/Q_s$ ~ 12500 + external tune modulation with $1/Q_m$ = 26**
- **Trapping can occur on resonance sidebands (at multiples of Q_m)**





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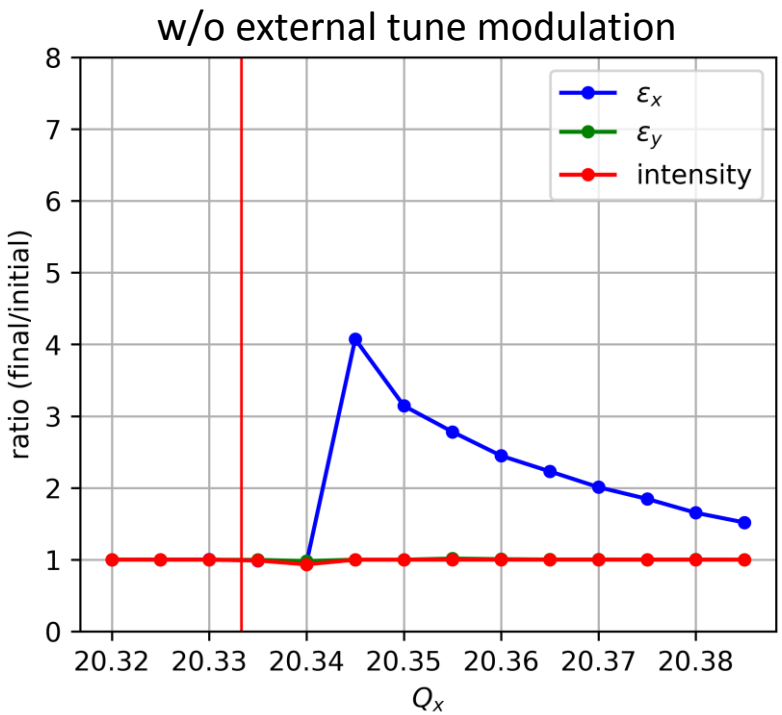
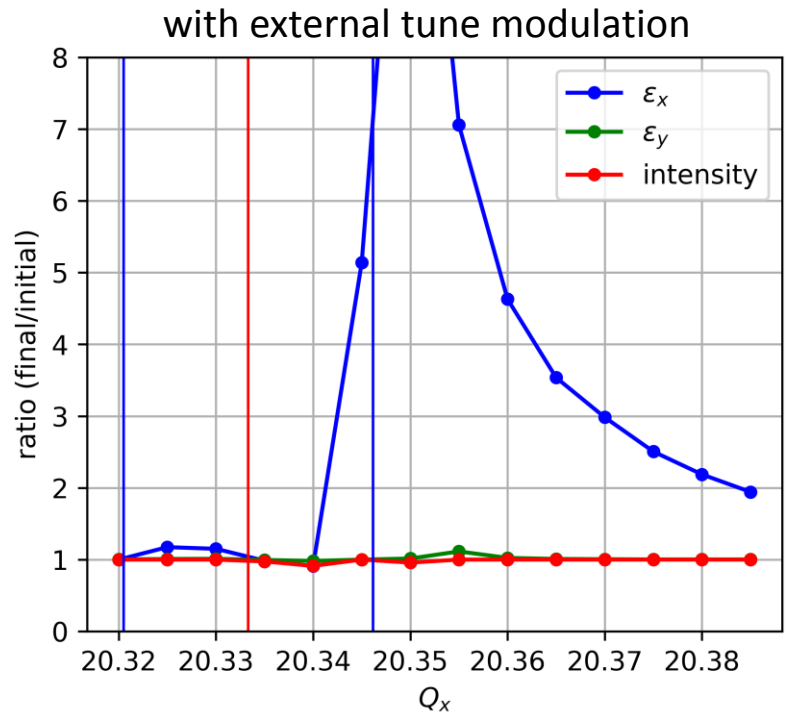
  - Resonance sidebands can enhance emittance growth (also for tunes below main resonance)





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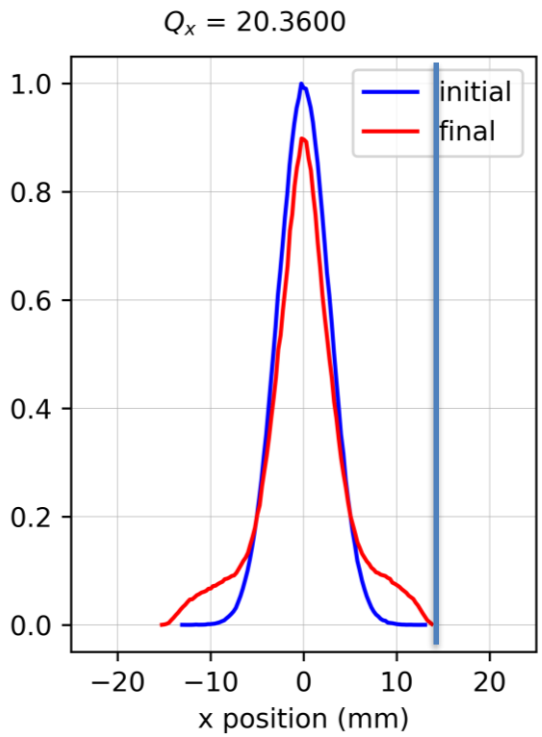
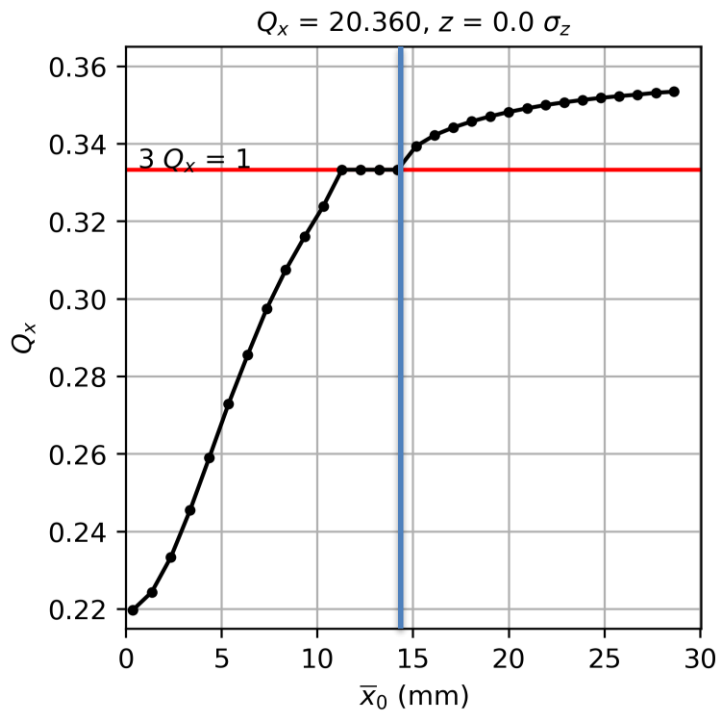
  - Resonance sidebands can enhance emittance growth (also for tunes below main resonance)

w/o external tune modulation





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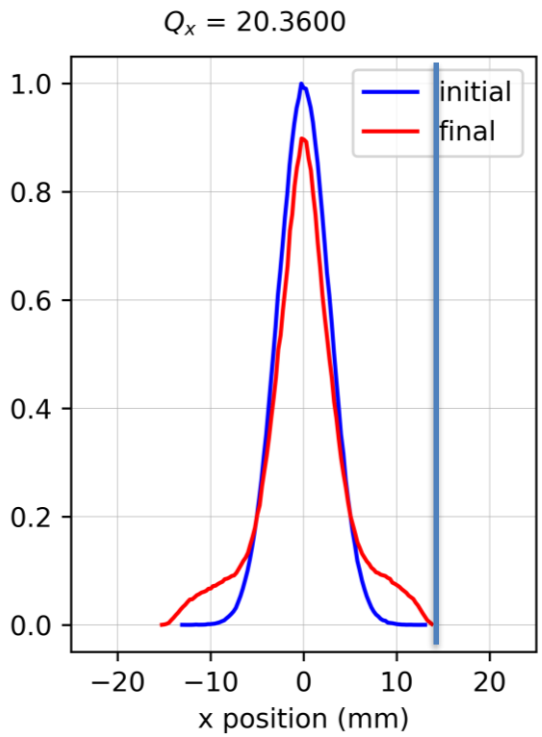
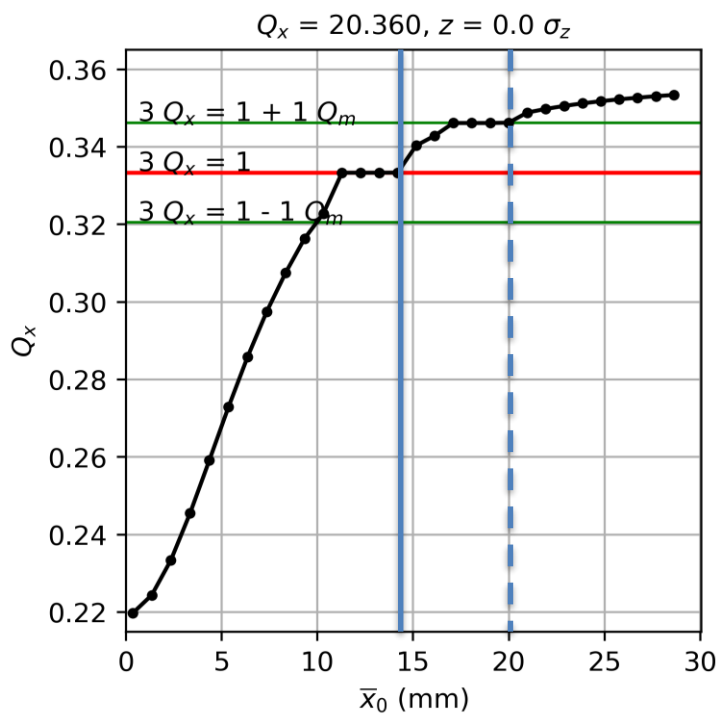
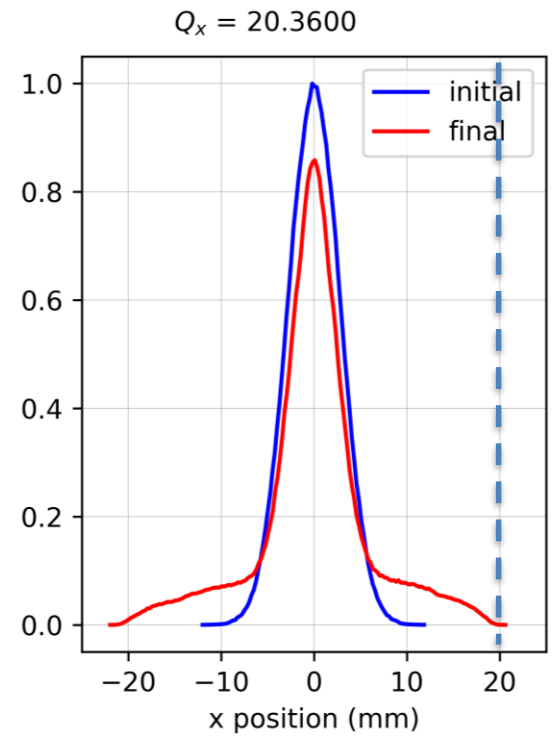
  - Resonance sidebands can enhance emittance growth (also for tunes below main resonance)
  - Resonance sidebands can increase halo size

w/o external tune modulation



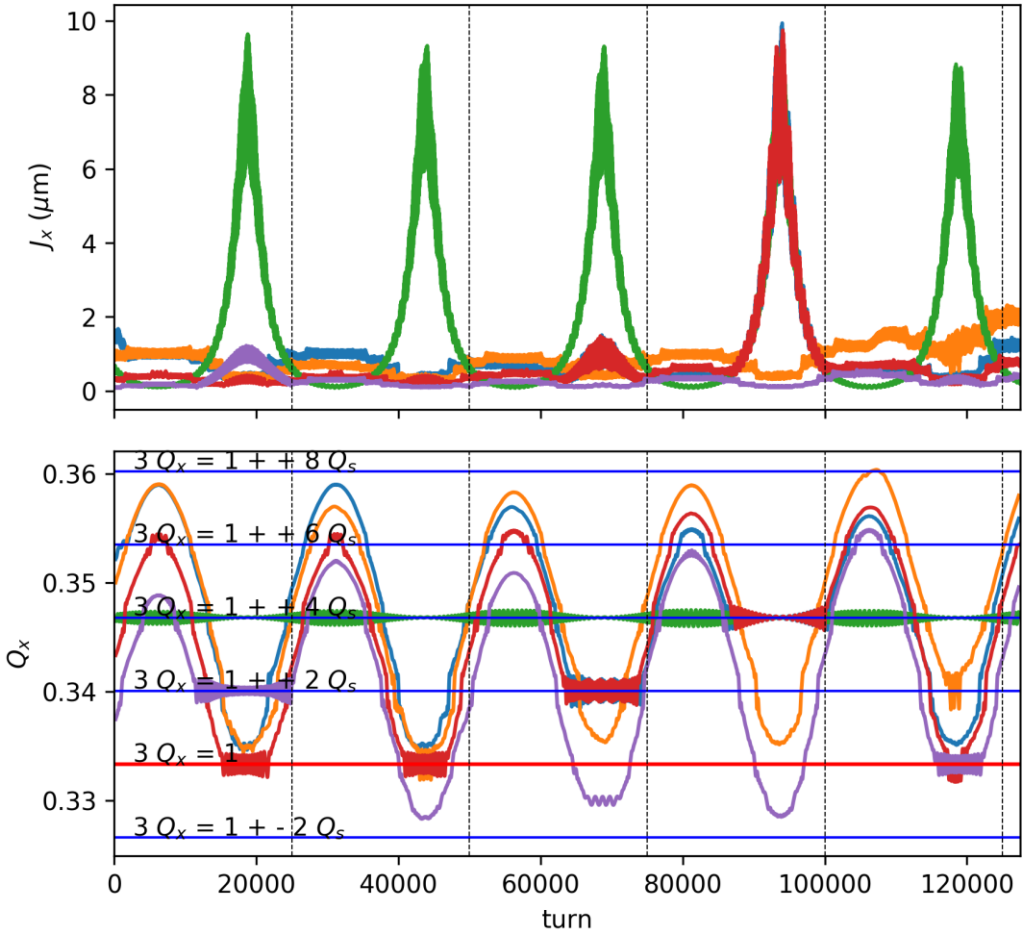


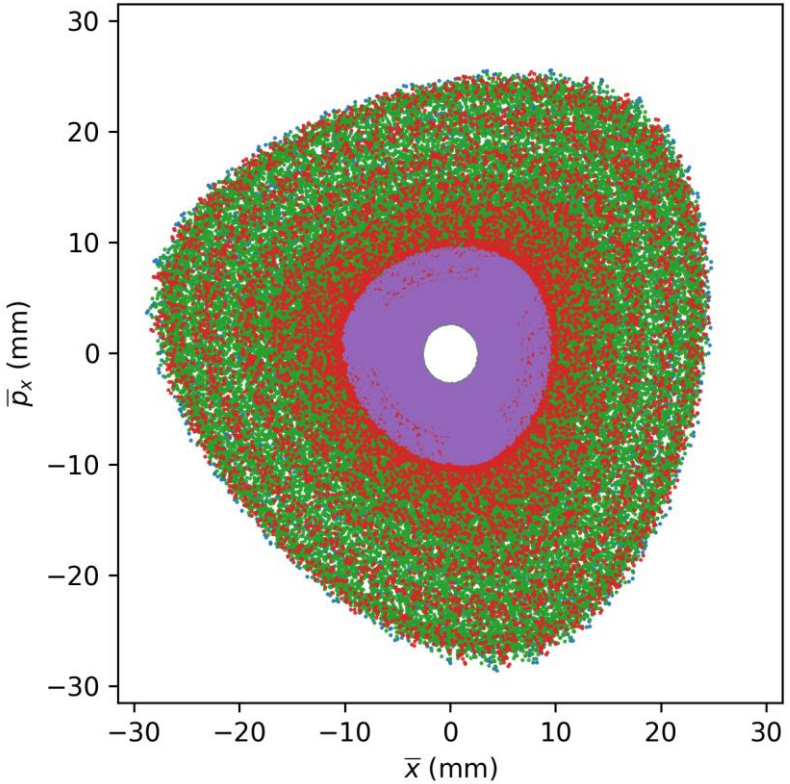
with external tune modulation



Fast synchrotron tune + slow modulation

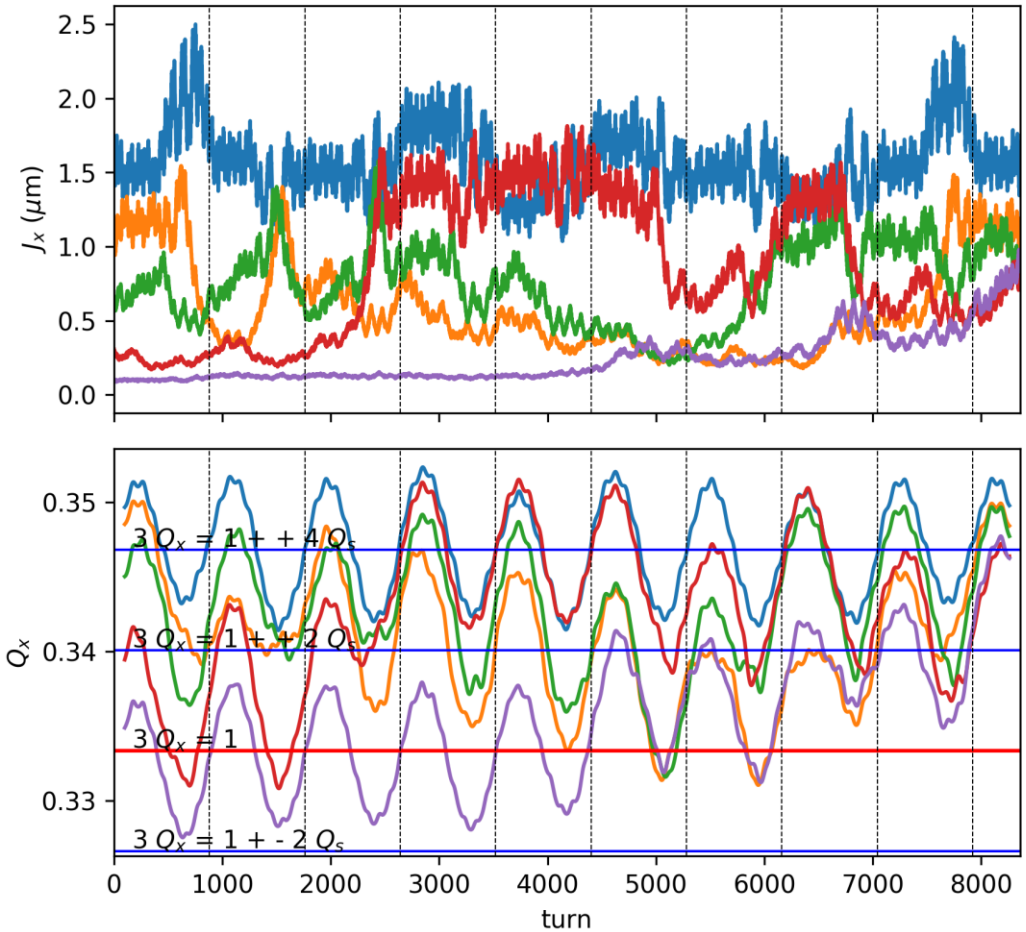
- **SPS model with $1/Q_s$ ~ 99 + external tune modulation with $1/Q_m$ = 25000**
- **Trapping can occur on resonance sidebands (from SC → at multiples of 2 Q_s)**
  - Particle excursions determined by amplitude of external tune modulation

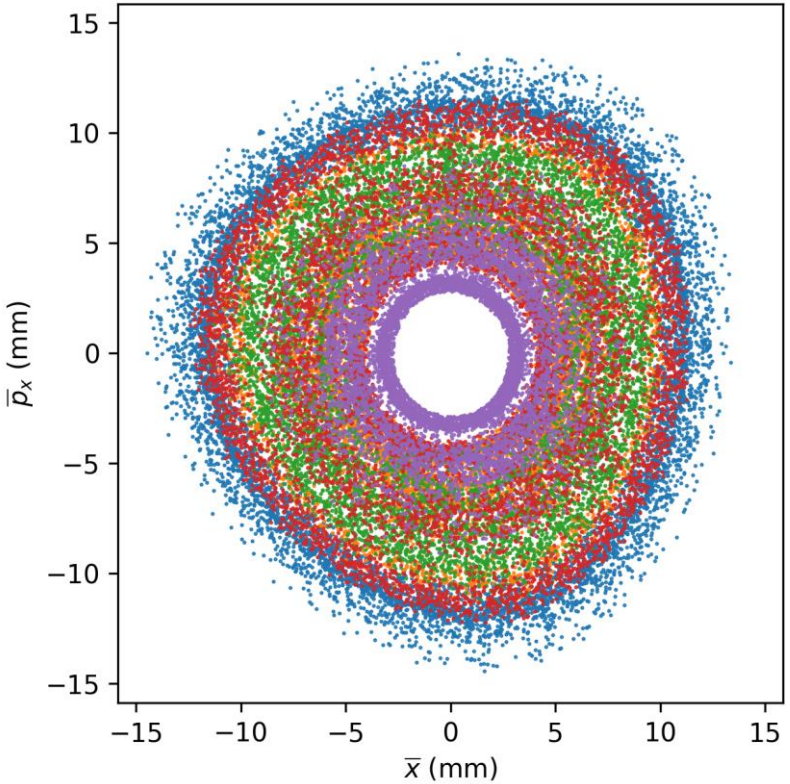




Fast synchrotron tune + moderate modulation

- **SPS model with $1/Q_s$ ~ 99 + external tune modulation with $1/Q_m$ = 880**
- **Scattering can occur on resonance sidebands (from SC → at multiples of 2 Q_s)**
  - Chaotic motion dominates, particles diffuse between sidebands if modulation depth large enough





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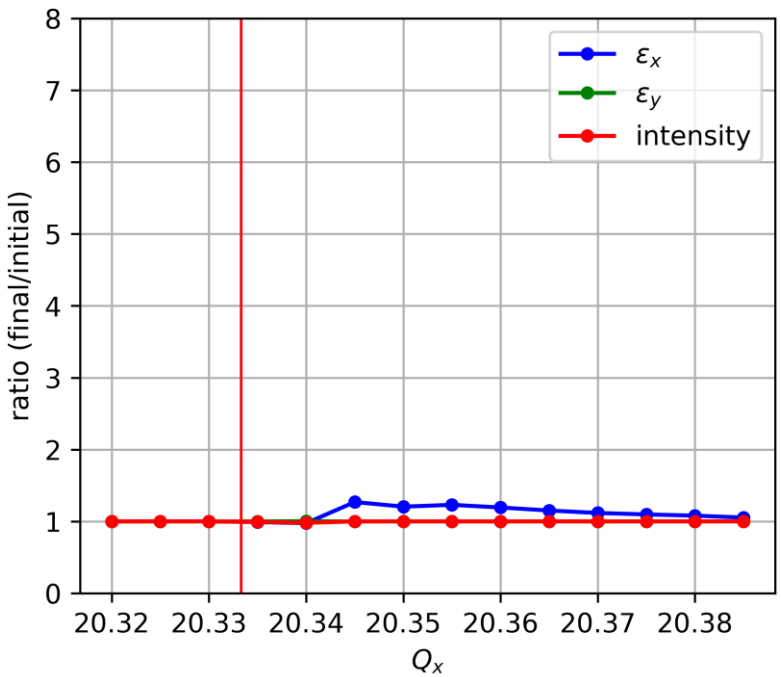
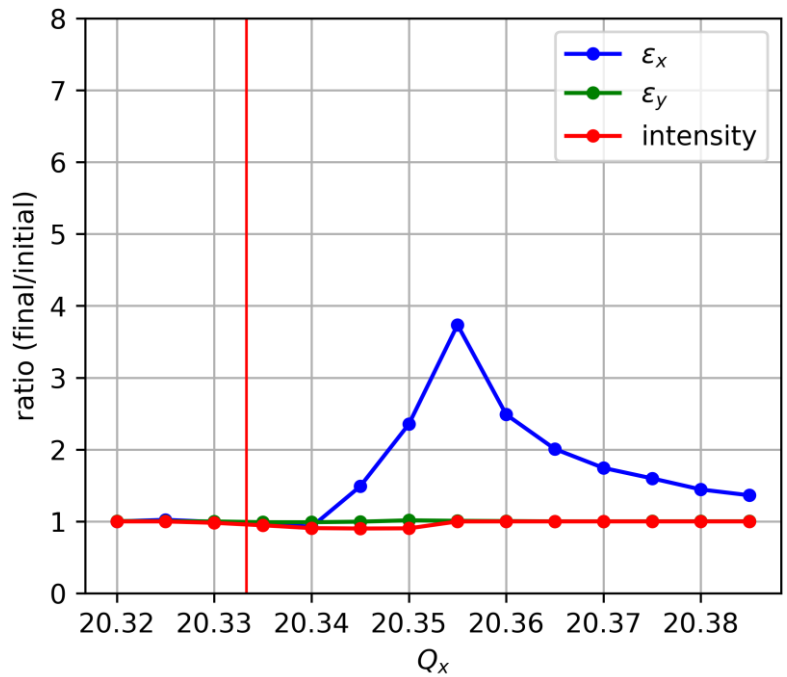
w/o external tune modulation



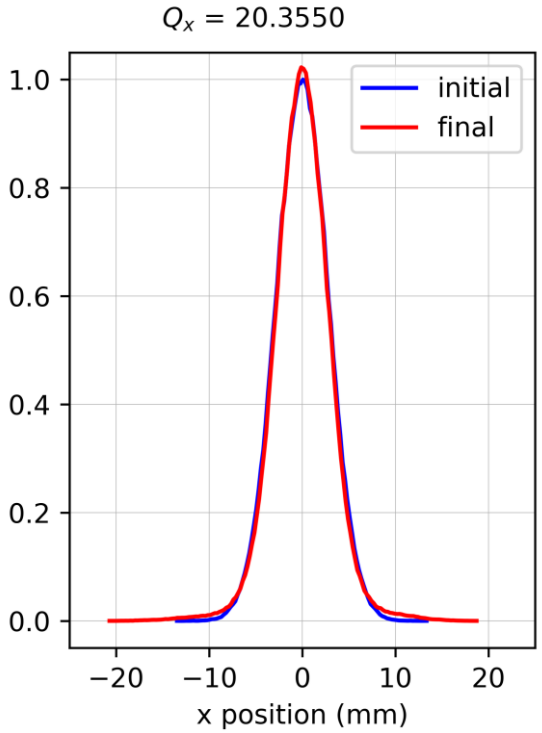
with external tune modulation



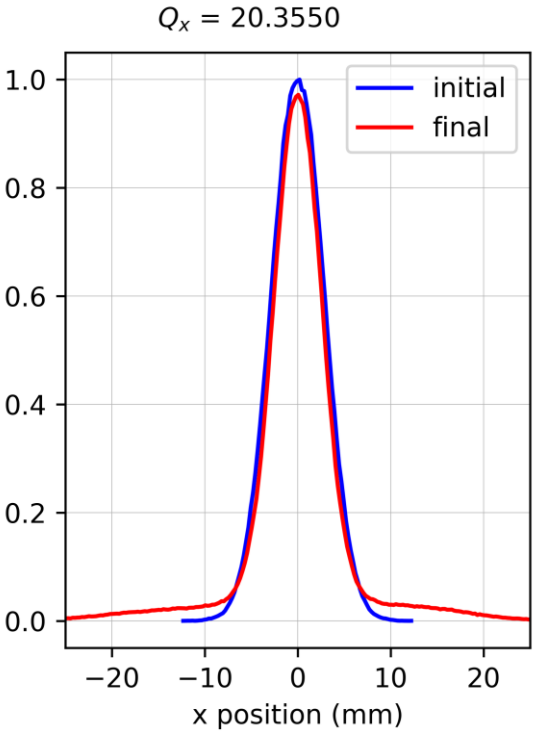
Fast synchrotron tune + moderate modulation

- **SPS model with $1/Q_s$ ~ 99 + external tune modulation with $1/Q_m$ = 880**
- **Scattering can occur on resonance sidebands (from SC → at multiples of 2 Q_s)**
  - Chaotic motion dominates, particles diffuse between sidebands if modulation depth large enough
  - Tail population and emittance growth can be enhanced

w/o external tune modulation



with external tune modulation



Questions addressed in this talk

1. **Why is the beam response in simulations with a frozen model so weak for SPS when tune ripple is not included?**
   - SPS falls in “strong sideband” regime due to fast synchrotron motion ($1/Q_s$ ~ 70 turns)
   - There is not much diffusion since there is no real “resonance crossing”, but rather additional stable islands are created due to resonance sidebands

2. **What happens when combining space charge in a bunched beam with external tune modulation?**
   - **Slow synchrotron tune + fast modulation:** Trapping can occur on resonance sidebands (at multiples of Q_m), resonance sidebands can enhance emittance growth and increase halo size
   - **Fast synchrotron tune + slow modulation:** Trapping can occur on resonance sidebands (at multiples of 2 Q_s), particle excursions determined by amplitude of external tune modulation
   - **Fast synchrotron tune + moderate modulation:** Scattering can occur on resonance sidebands (at multiples of 2 Q_s), chaotic motion dominates and particles diffuse between sidebands if the external modulation depth is large enough, tail population and emittance growth can be enhanced

… this is the regime of the SPS at injection …

Questions to be addressed

1. Could noise from other sources play a similar role for diffusion as the “moderate” external tune modulation in the case of fast synchrotron tunes?

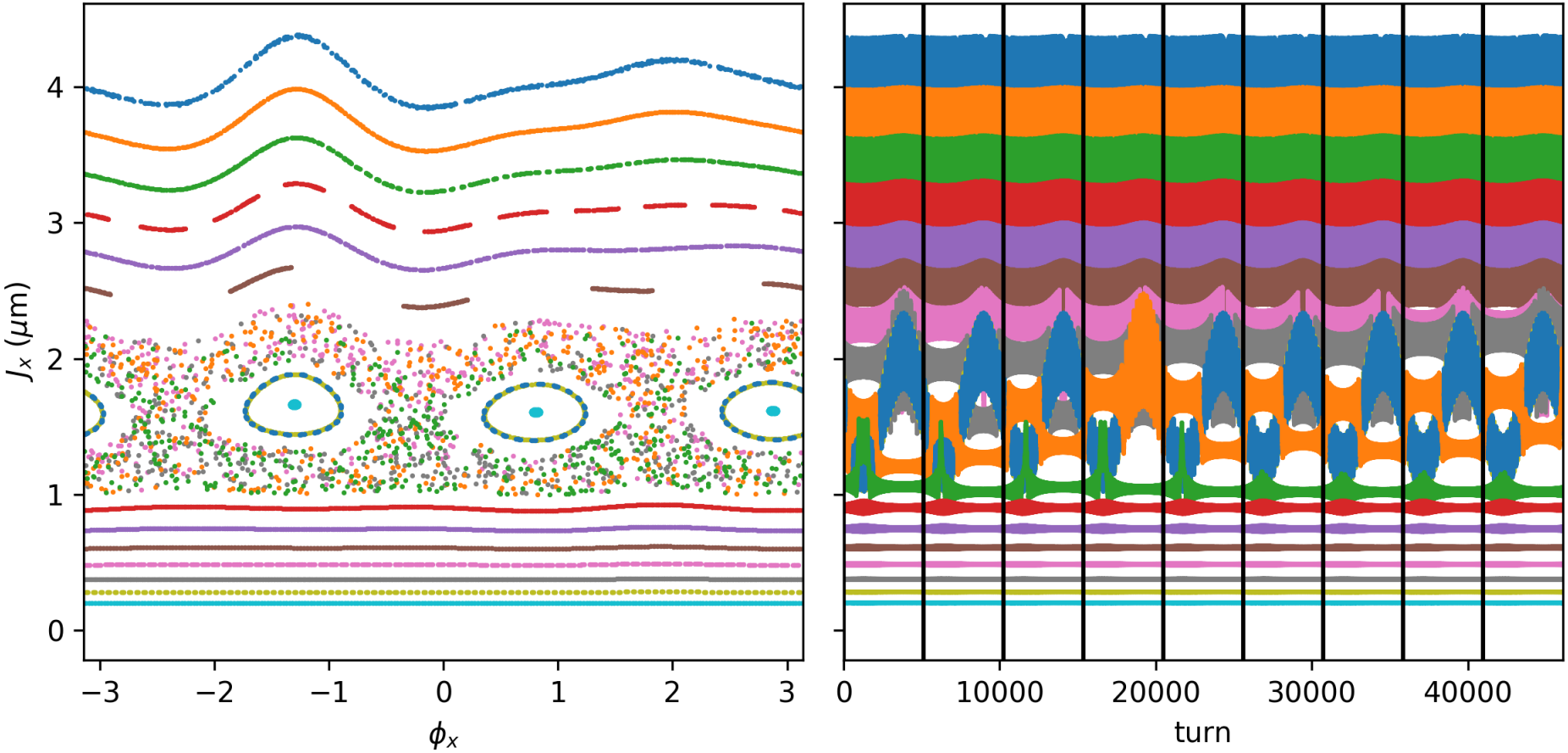
2. Do self consistent simulations (PIC) reproduce the simulation results from the frozen model?

LHC Injectors Upgrade

Thank you for your attention!

Amplitude modulation regime (“trapping”)

- SPS + sextupole + octupoles + external tune modulation (without space charge)
- Stroboscopic view: only one turn per modulation period is plotted



Chaotic regime (“scattering”)

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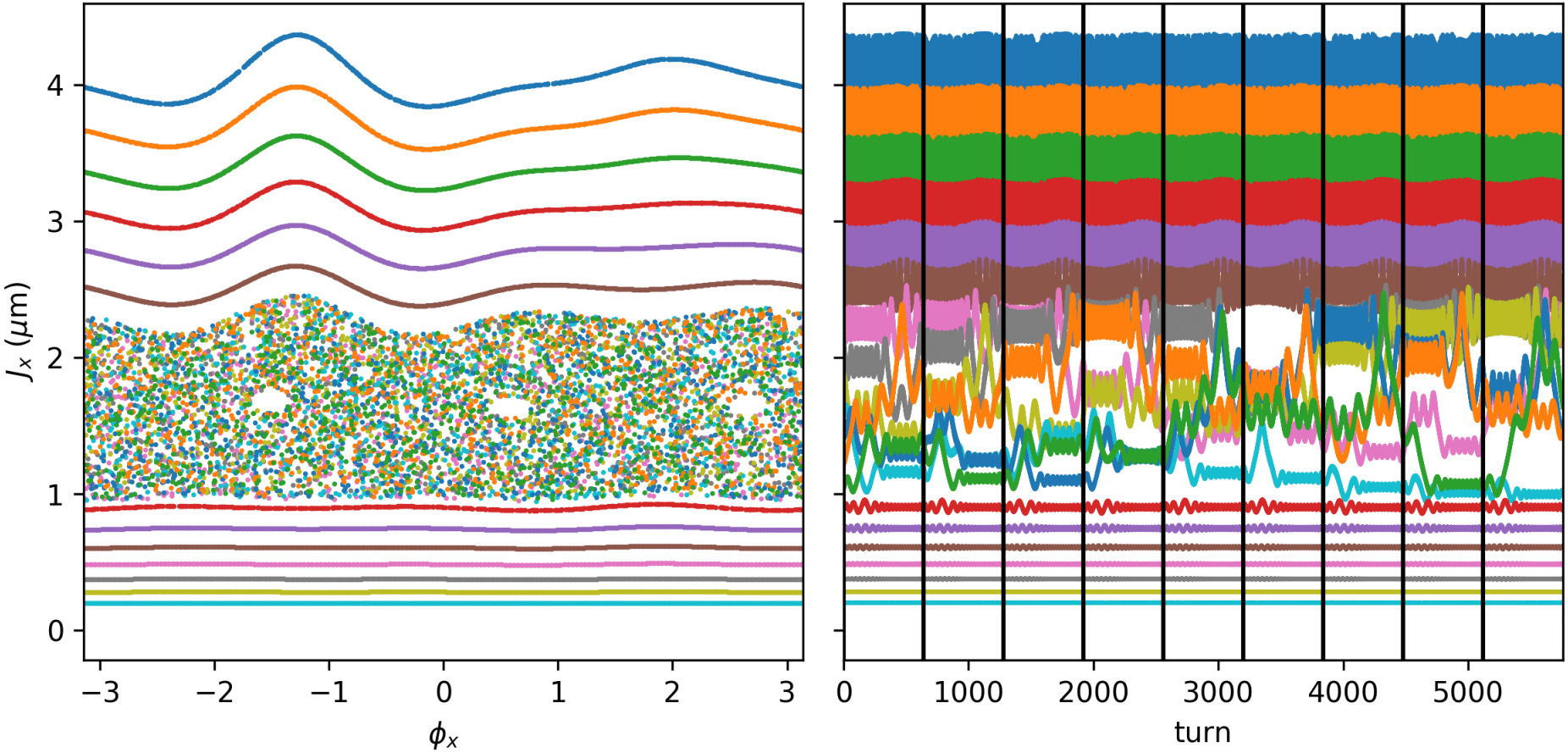
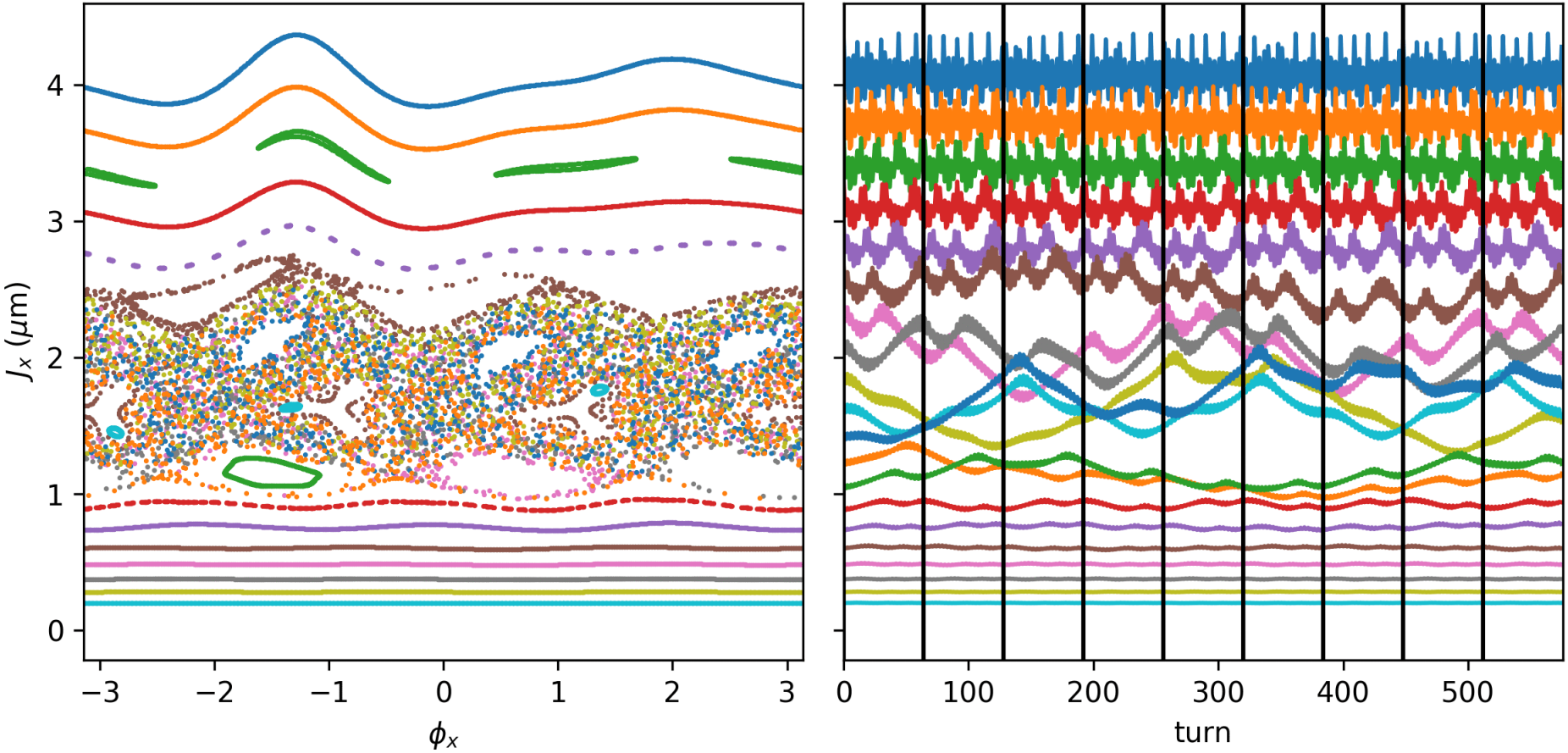


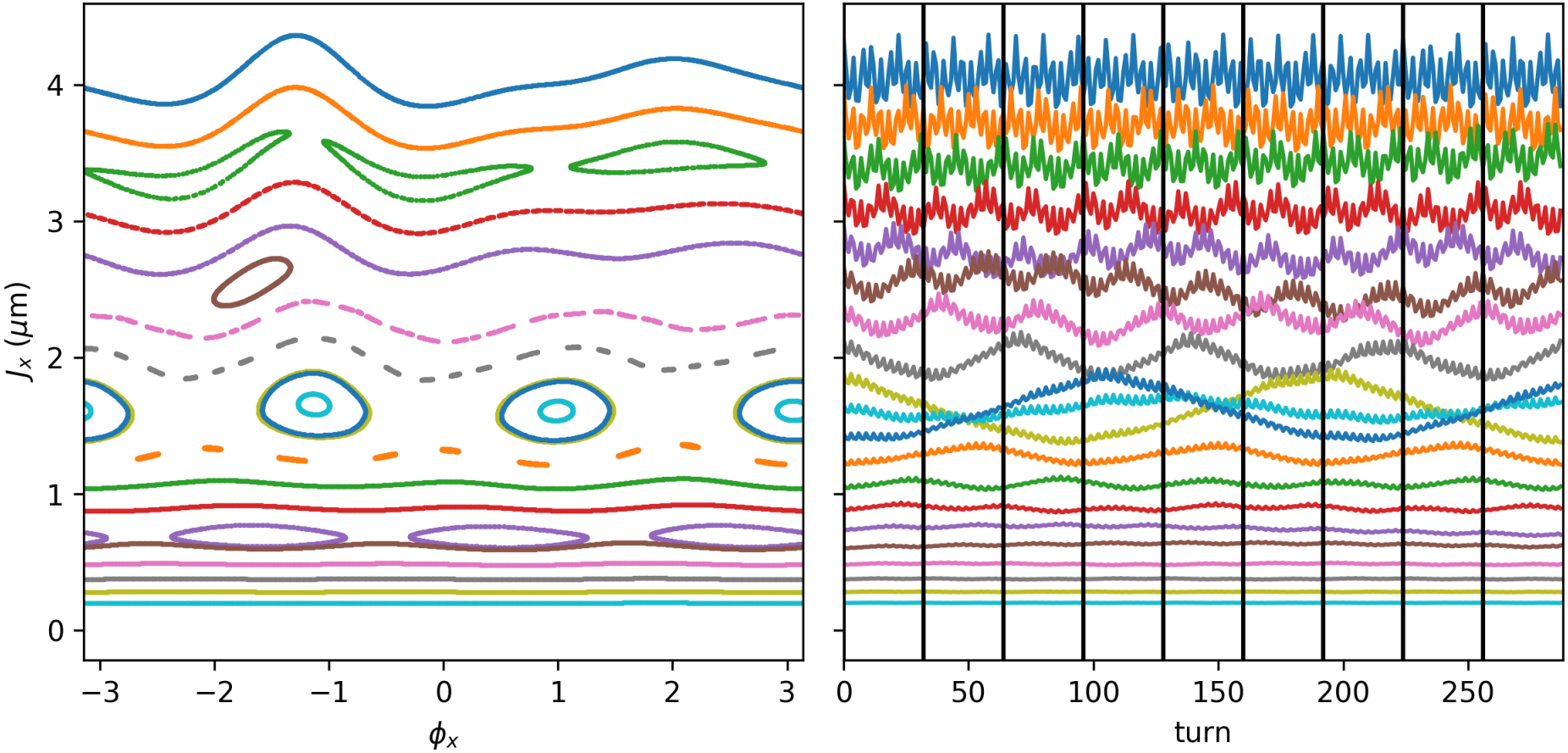
Transition from chaotic to sideband regime

- **SPS + sextupole + octupoles + external tune modulation (without space charge)**
- **Stroboscopic view: only one turn per modulation period is plotted**



Sideband regime

- SPS + sextupole + octupoles + external tune modulation (without space charge)
- Stroboscopic view: only one turn per modulation period is plotted



Slow synchrotron motion + fast modulation

- **SPS model with 1/Qs ~ 12500 + external tune modulation with $1/Q_m$ = 32**
- **Particle trapping can occur also on resonance sidebands (at multiples of Q_m)**