Challenges in understanding space charge effects (in the regime of long storage times)

H. Bartosik

Acknowledgements:

Y. Alexahin, F. Asvesta, E. Benedetto, O. Boine-Frankenheim, S. Cousineau, V. Forte, G. Franchetti, S. Gilardoni, I. Hofmann, J. Holmes, A. Huschauer, S. Machida, E. Métral, Y. Papaphilippou, J. Qiang, A. Saa Hernandez, F. Schmidt, A. Shishlo, E. Stern, R. Wasef, and other colleagues that are part of the CERN space charge collaboration

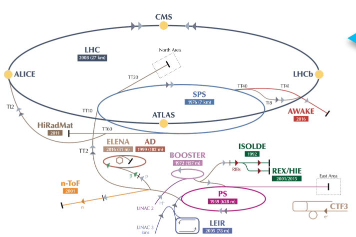
Outline

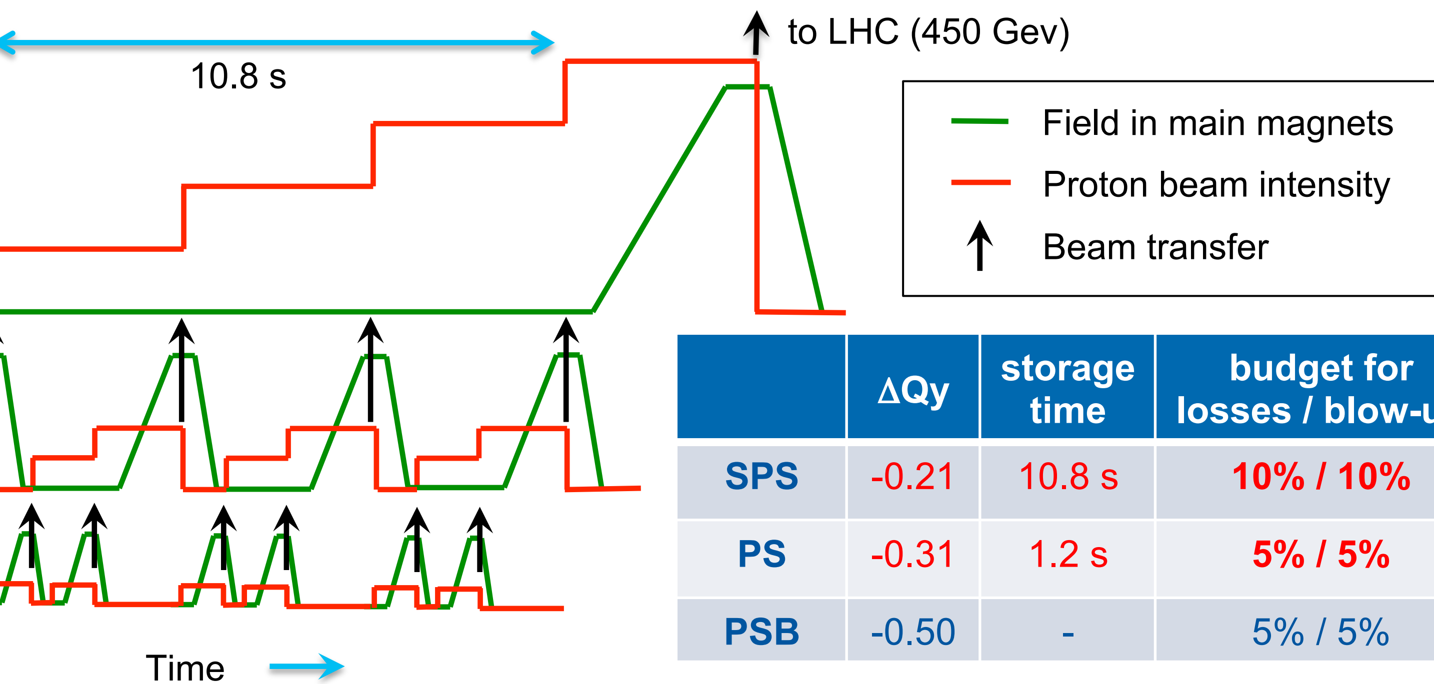
- Introduction
- Overview of studies and present understanding
- (Remaining) challenges
- Code-to-code benchmarking
- Examples from CERN machines
- Conclusions & Outlook

Introduction

- **Space charge effects in high intensity and high brightness synchrotrons can lead to undesired emittance growth, halo formation and particle loss**

- **Will focus here on space charge effects in the <u>regime of long-term storage</u>**
  - **Bunched beam** at injection plateau **stored for ~seconds** (to accumulate injections)
  - Example: **LHC Injector Upgrade (LIU) at CERN** – see talks of G. Rumolo & K. Hanke





	ΔQy	storage time	budget for losses / blow-up
SPS	-0.21	10.8 s	10% / 10%
PS	-0.31	1.2 s	5% / 5%
PSB	-0.50	-	5% / 5%

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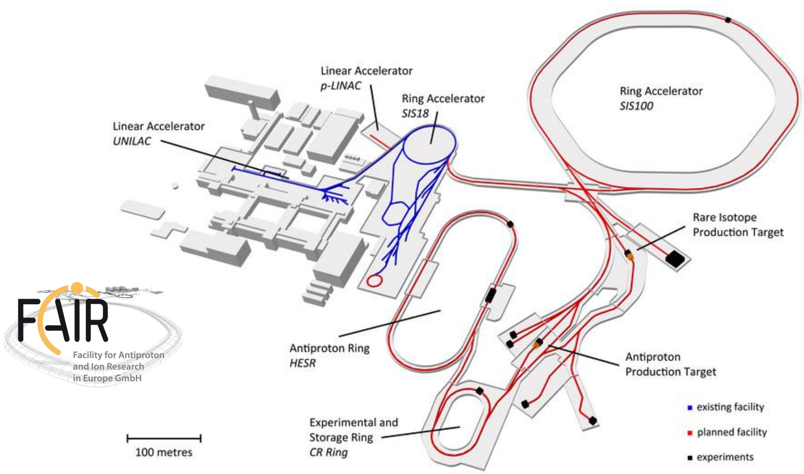
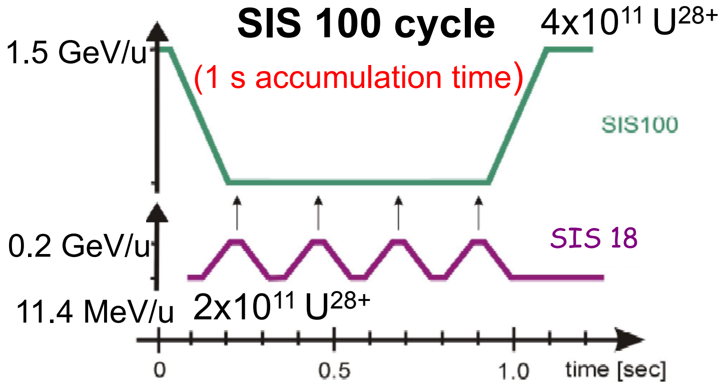
  - Example: **FAIR project at GSI**





	ΔQy	storage time	budget for losses
SIS100	-0.3	1 s	**~5%**

O. Boine-Frankenheim, IPAC2010

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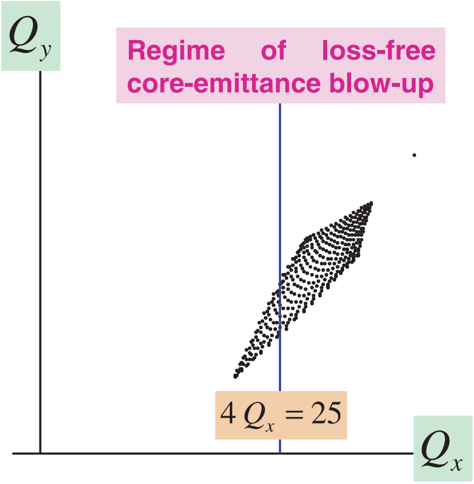
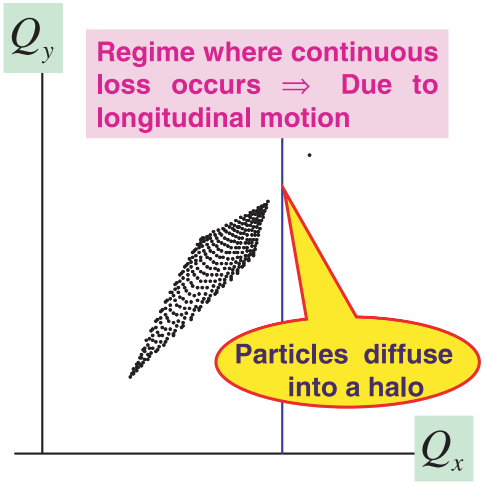
  - Example: **FAIR project at GSI**
  - **Tight budgets on losses and / or emittance growth**

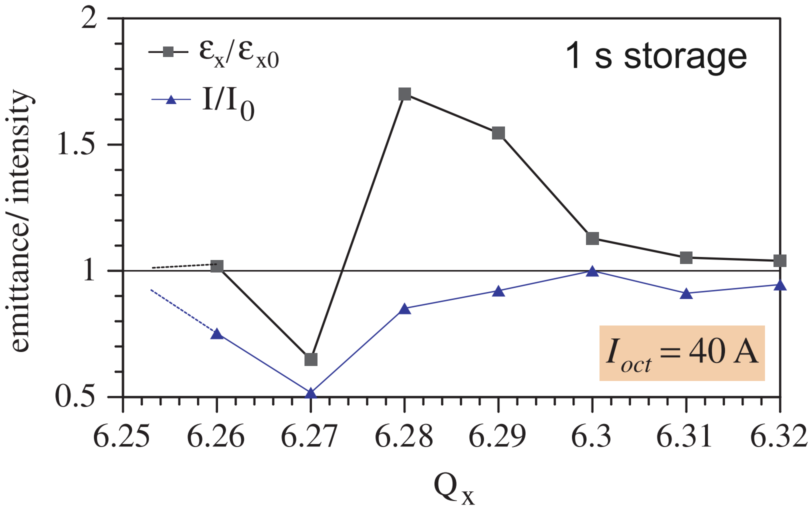
- **Approach to understanding space charge effects**
  - Controlled machine experiments
  - Comparison with simulation models
  - Identification of relevant beam dynamics mechanisms

Pioneering experimental campaign at CERN PS (2002)

- **Systematic measurement campaign on (horizontal) 4th order resonance**
- **Clear identification of two regimes:**
  - Beam loss & bunch shortening for bare machine working points close to or slightly above the resonance
  - Transverse emittance blow-up (of the core) further above the resonance





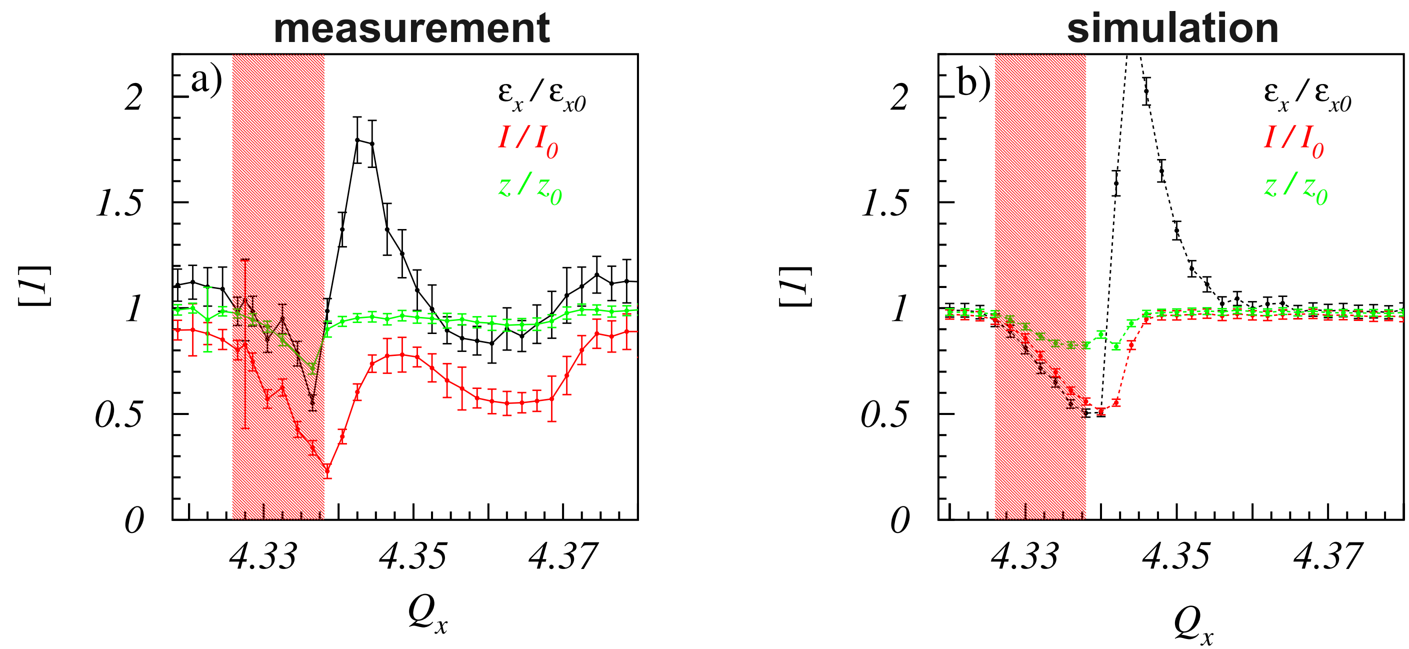


G. Franchetti, M. Giovannozi, I. Hofmann, M. Martini, E. Metral, PhysRevSTAB.6.124201 (2003)

E. Metral, G. Franchetti, M. Giovannozzi, I. Hofmann, M. Martini, R. Steerenberg, NIM A561 (2006) 257

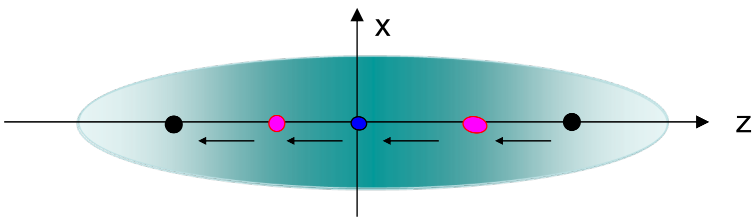
Benchmark experiment at GSI SIS18 (2007)

- **Extensive campaign studying 3rd order resonance**
  - Coasting and bunched beams, low and high intensity
- **For bunched beam same behavior as in PS 4th order resonance experiment**
  - Beam loss and beam growth regimes

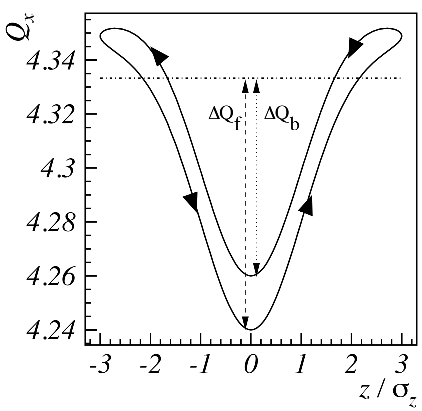


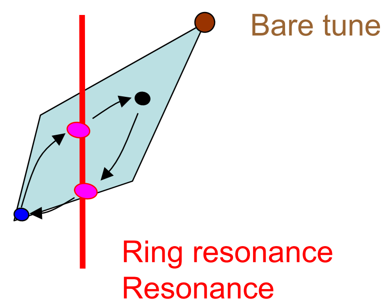
G. Franchetti et al., HB 2008 G. Franchetti et al., Phys. Rev. ST Accel. Beams 13, 114203 (2010)

Mechanism: periodic resonance crossing



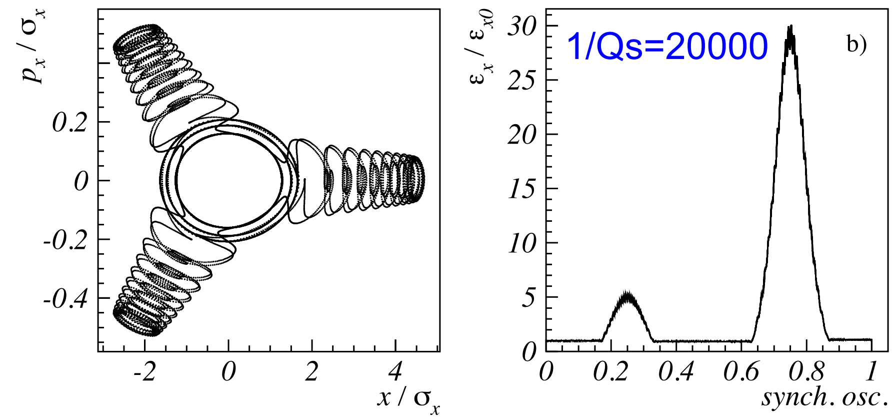
- space charge detuning varies along bunch
- synchrotron motion results in periodic tune modulation of individual particles
- chromaticity enhances tune excursion in one half synchrotron period and reduces it in other half



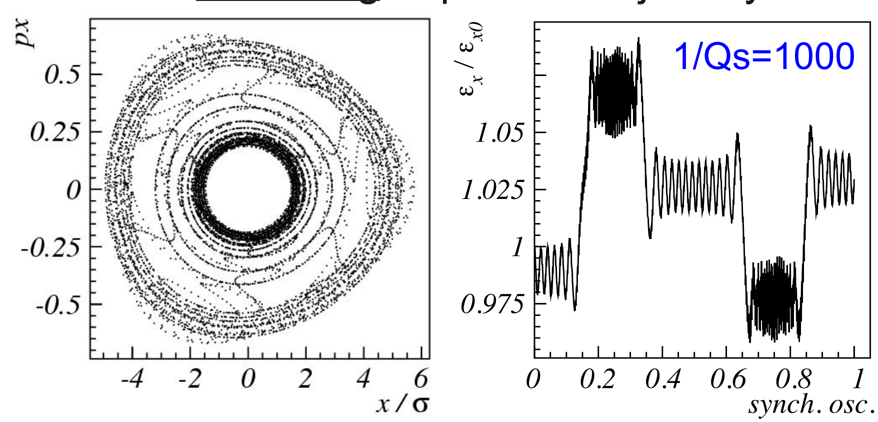


G. Franchetti et. al (2005)

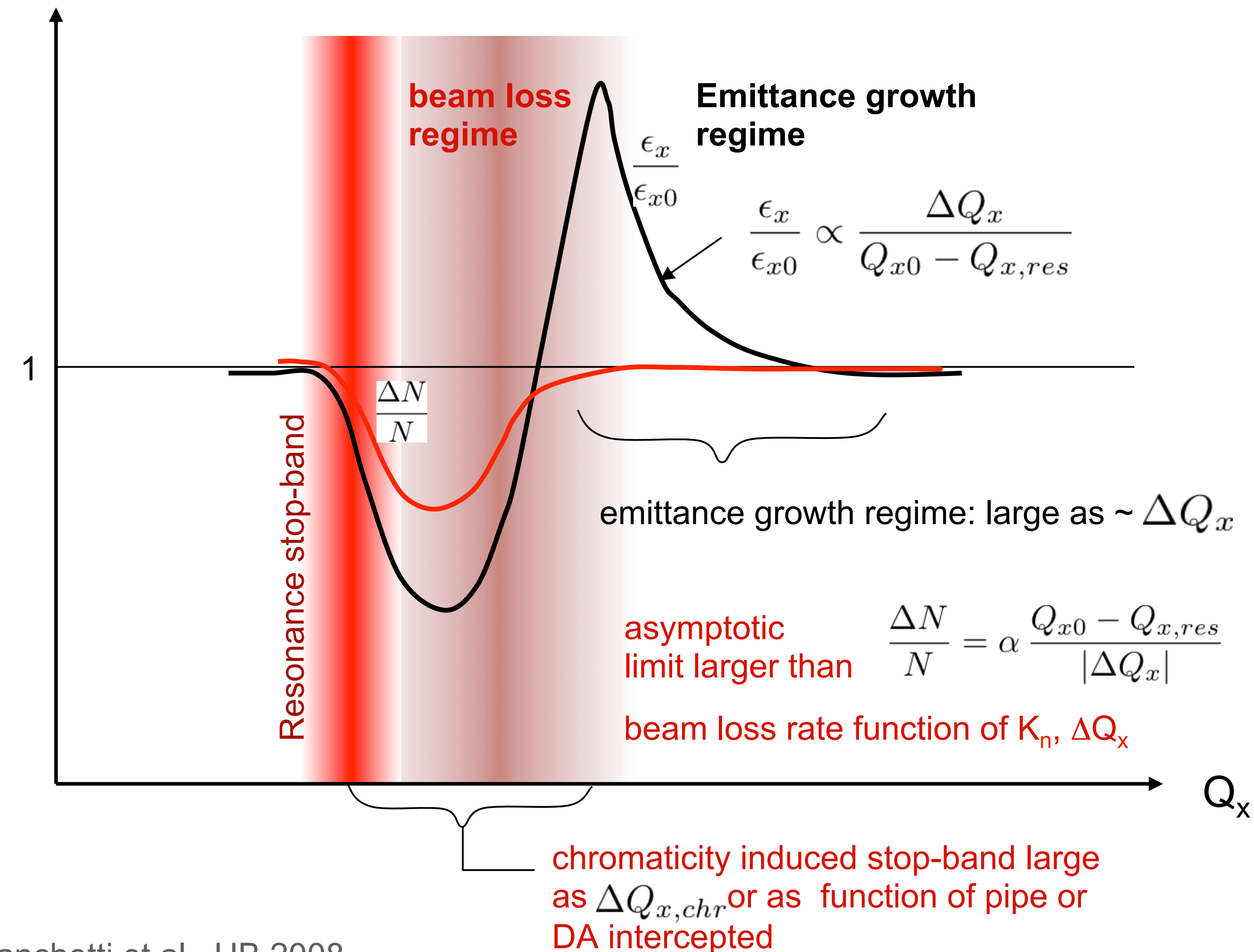
adiabatic limit of resonance crossing:
particle trapping in resonance islands



non-adiabatic resonance crossing:
scattering of particle trajectory



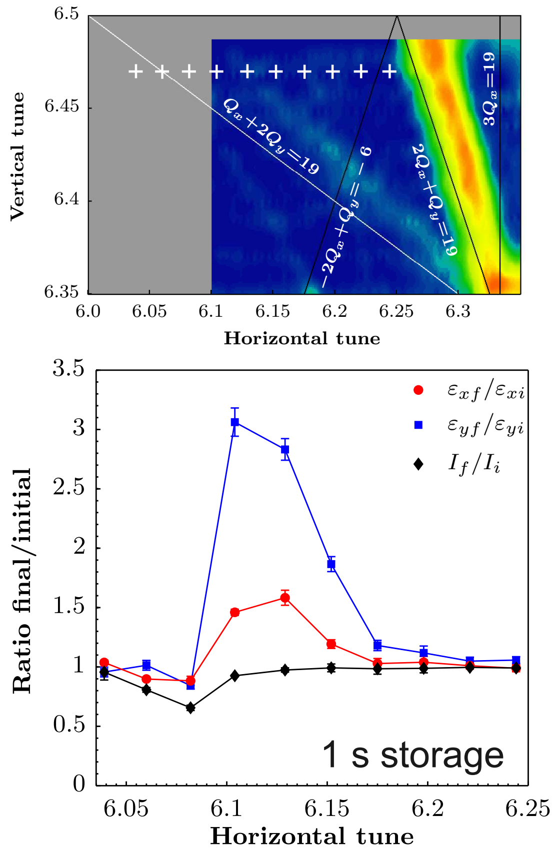
Consequences of periodic resonance crossing

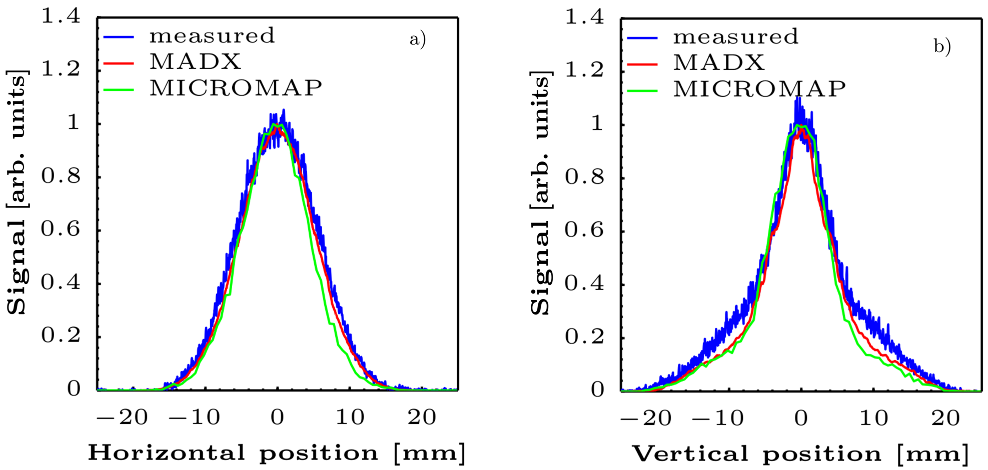


G. Franchetti et al., HB 2008

Experiment on coupled resonance at CERN PS (2012)

- 3rd order coupled sum resonance Qx + 2 Qy
  - Beam loss and emittance growth regimes (as in case of 1D resonance)
  - **Very asymmetric development of tails / halo** – also found in simulations





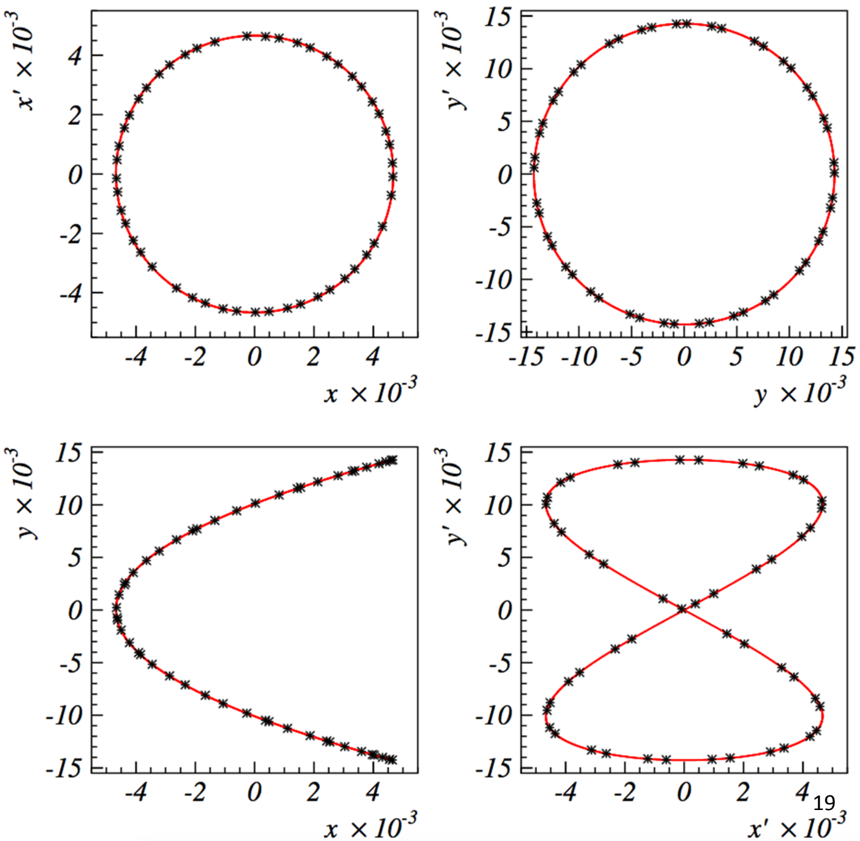
G. Franchetti, S. Gilardoni, A. Huschauer, F. Schmidt, R. Wasef, PRAB 20, 081006 (2017)

See also talk by G. Franchetti

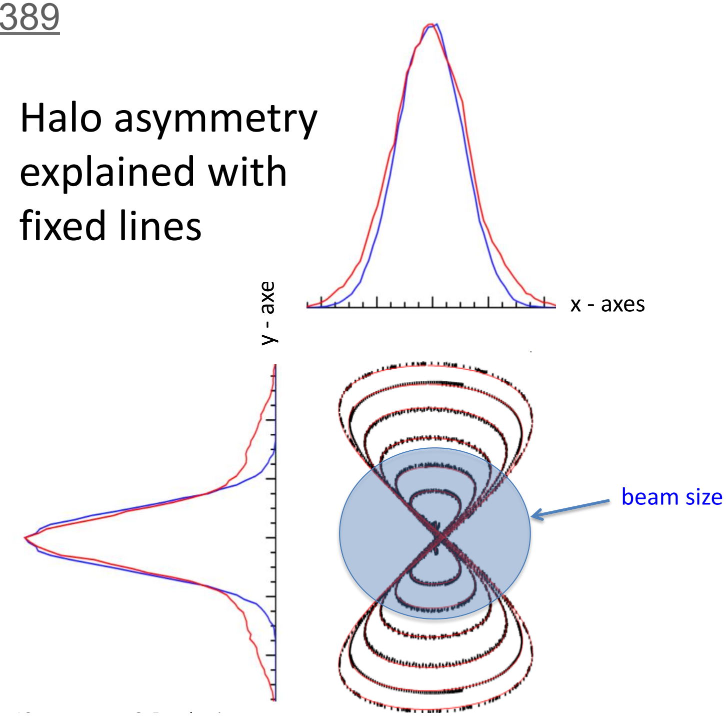
Coupled dynamics on Qx + 2 Qy resonance

- **Resonant tori (“Fixed lines”) in phase space**

  F. Schmidt PhD thesis, and others
  G. Franchetti and F. Schmidt Phys. Rev. Lett. 114, 234801 (2015)
  G. Franchetti and F. Schmidt http://arxiv.org/abs/1504.04389



Halo asymmetry explained with fixed lines



G. Franchetti, S. Gilardoni,A. Huschauer, F. Schmidt, R. Wasef, PRAB 20, 081006 (2017)
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Coupled dynamics on Qx + 2 Qy resonance

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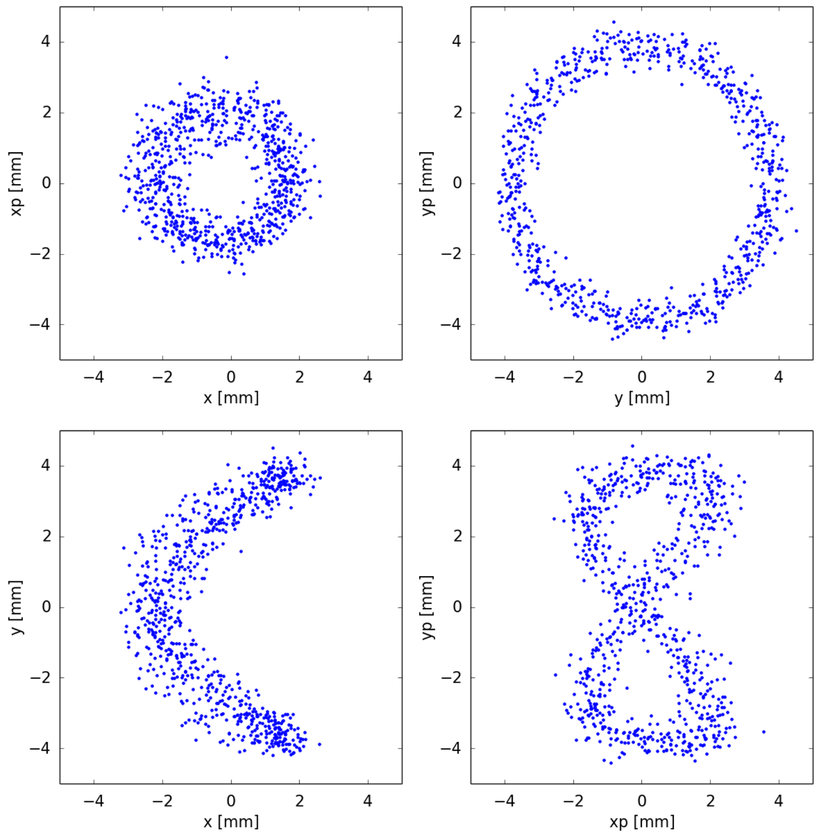
Experimental demonstration in SPS (ongoing)

H. Bartosik, G. Franchetti, F. Schmidt, M. Titze



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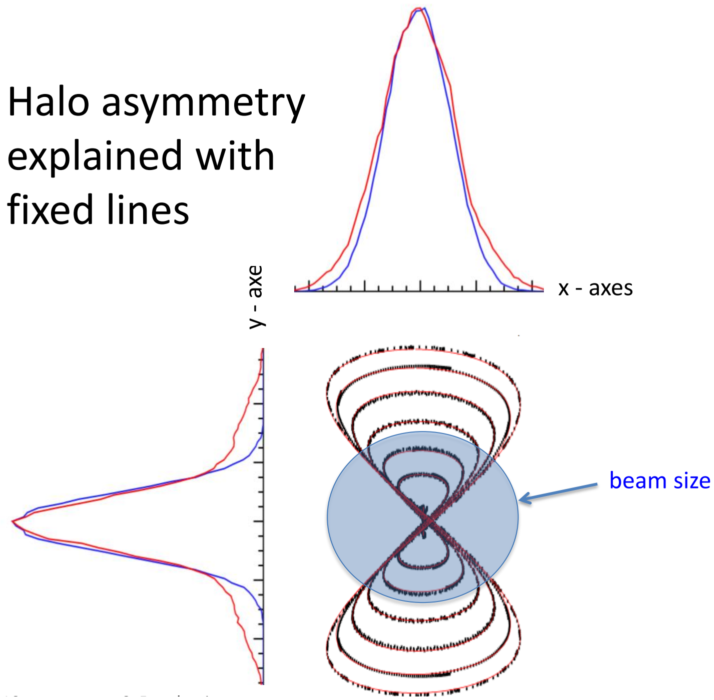


G. Franchetti, S. Gilardoni,A. Huschauer, F. Schmidt, R. Wasef, PRAB 20, 081006 (2017)

See also talk by G. Franchetti

What are the (remaining) challenges?

- **Macroparticle simulations for long storage times**
  - Computationally heavy - approximations have to be made
- **Quantitative agreement between measurements and simulations**
  - Accurate measurement of beam parameters (particularly difficult for beam profiles and beam halo)
  - Good knowledge of machine linear and non-linear errors (much more difficult for old machines)
  - Accurate aperture model including misalignments
  - Properly identifying and accounting for interfering effects (or suppressing them)
- **Interplay with other mechanisms and their identification**
- **Mitigation of beam degradation**
  - Compensation of magnet resonances in presence of space charge
  - Space charge compensation (e.g. using e-lenses studied by O. Boine Frankenheim and W. Stem)

Simulation approaches

- **Space charge is all over the machine - need many space charge ‘kicks‘**
  - Space charge interaction interleaved with particle tracking in magnetic guide field

Particle-In-Cell (PIC)

- Real number of particles represented by ~10^6 macroparticles
- Assign fractional macroparticles charge to spacial grids
- Solve Poisson equation on the grid points to obtain electric field

+ self consistent beam evolution

– computationally heavy – requires large number of macroparticles to avoid artificial emittance growth + only special variants are symplectic*

Frozen potential

- Assuming a fixed charge distribution function (usually Gaussian)
- Calculate space charge force analytically
- Smooth force at any spacial point

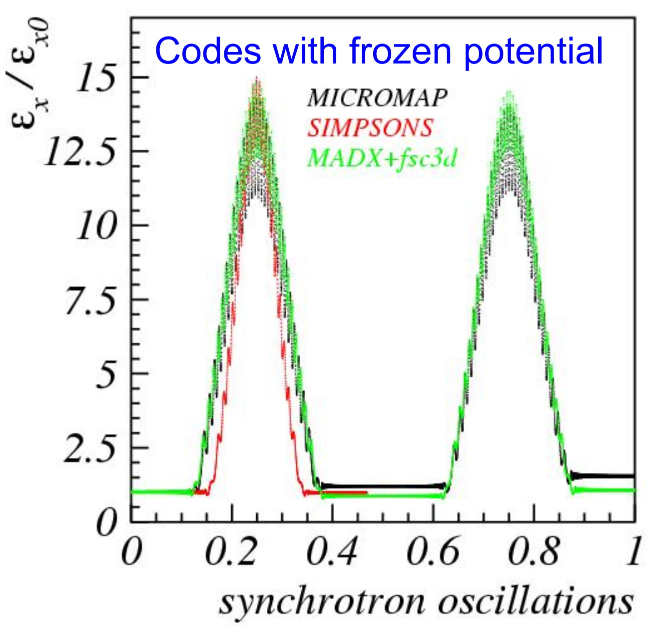
+ no issue with noise - less particles needed for tracking a distribution

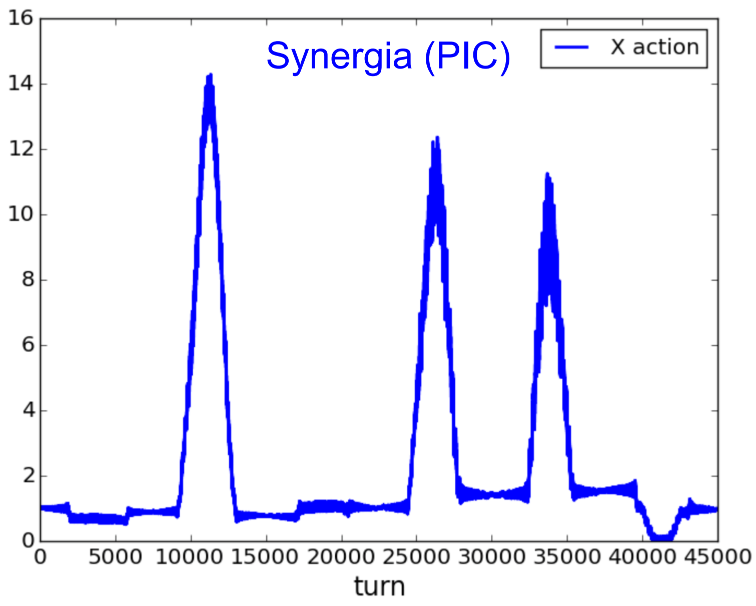
– not self consistent: evolution of charge distribution is not taken into account – semi-self consistency by periodic update of potential

*J. Qiang, “Symplectic multiparticle tracking model for self-consistent space-charge simulation”, PRAB 20, 014203 (2017)

Code-to-code benchmarking

- **GSI SIS18 space charge code benchmarking suite**
  - Originally meant for comparison of particle trapping in 3rd order resonance between MICROMAP (Franchetti) and SIMPSONS (Machida)
  - Later became the standard test case (consisting of 9 steps)
  - **Trapping observed in frozen potential and in self-consistent PIC codes!**





G. Franchetti, J. Holmes, S. Machida, F. Schmidt, E. Stern

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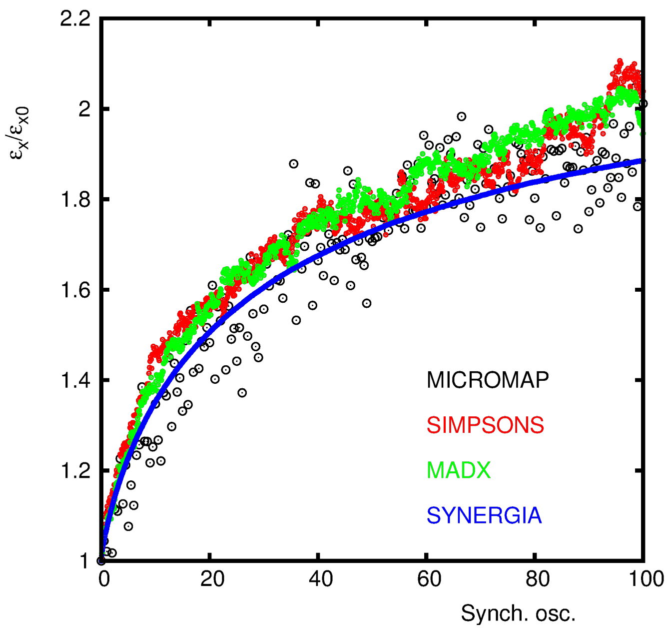

Tracking for 100000 turns
Periodic crossing of Qx = 4.33 resonance in SIS18

The PIC code is self consistent, but required 6M macroparticles (computationally very heavy)

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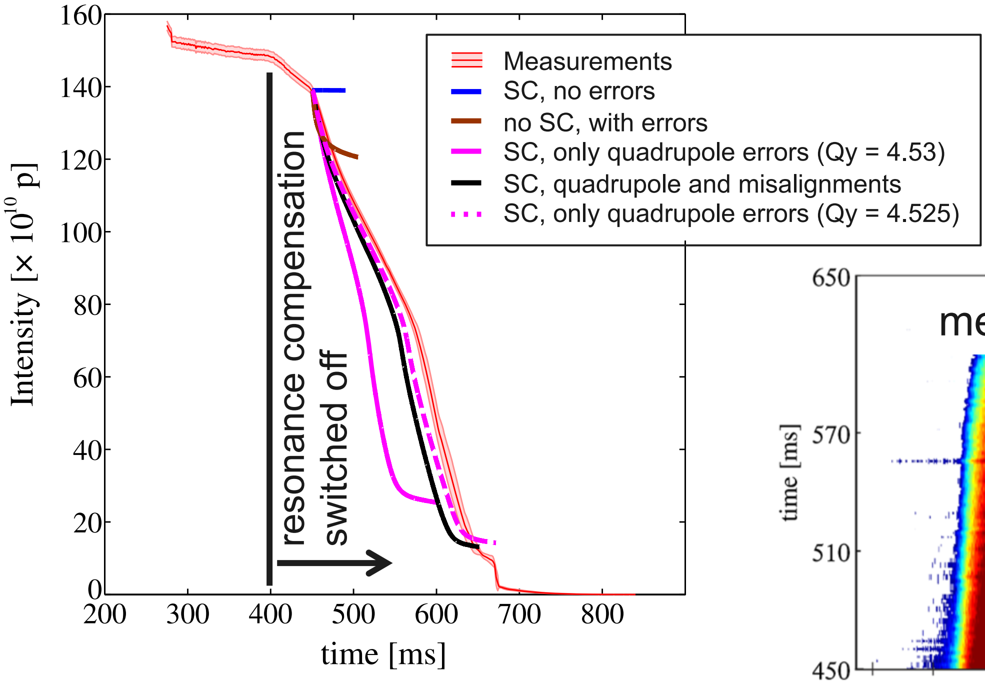
- **Future steps**
  - Discussions ongoing for extending the benchmarking suite with additional test cases (e.g. including a case where losses are expected)

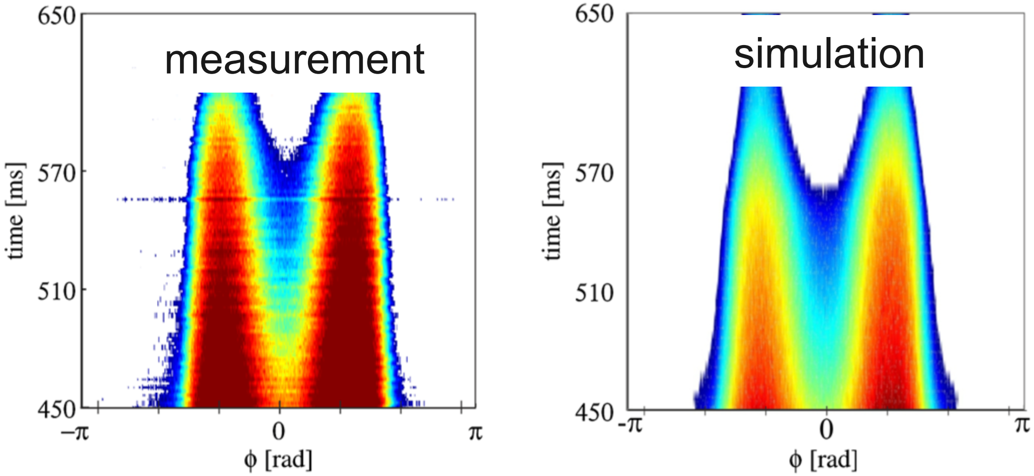
Importance of machine model at the CERN PSB

- **Benchmark campaign on half integer resonance Qy = 4.5**
  - Reproducing losses at half integer resonance at PSB requited accurate (linear) machine model obtained from measurements (LOCO)
  - Bunch shortening in double harmonic RF nicely reproduced in simulations



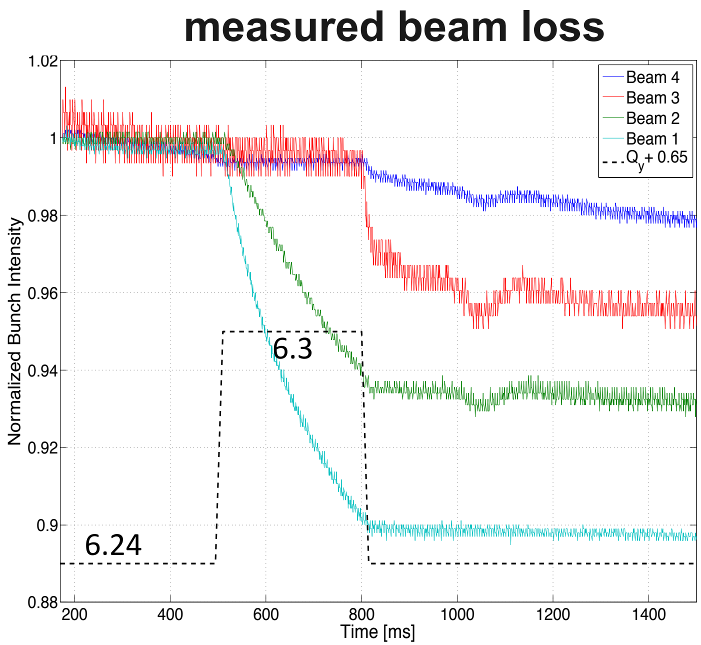
V. Forte, E. Benedotto, M. McAteer, Phys. Rev. Accel. Beams 19, 124202 (2016)

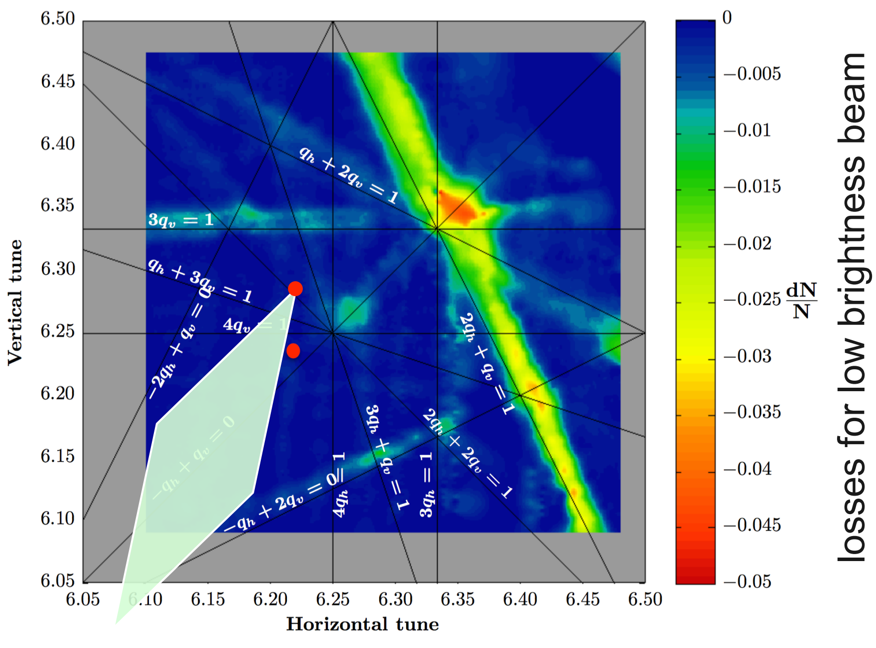
Longitudinal profiles



Resonance(s) at Qy = 6.25 in the CERN PS

- **Losses are observed for high brightness beams for Qy > 6.25**
  - Studies in 2013 indicate that losses occur (mostly) for high brightness beams





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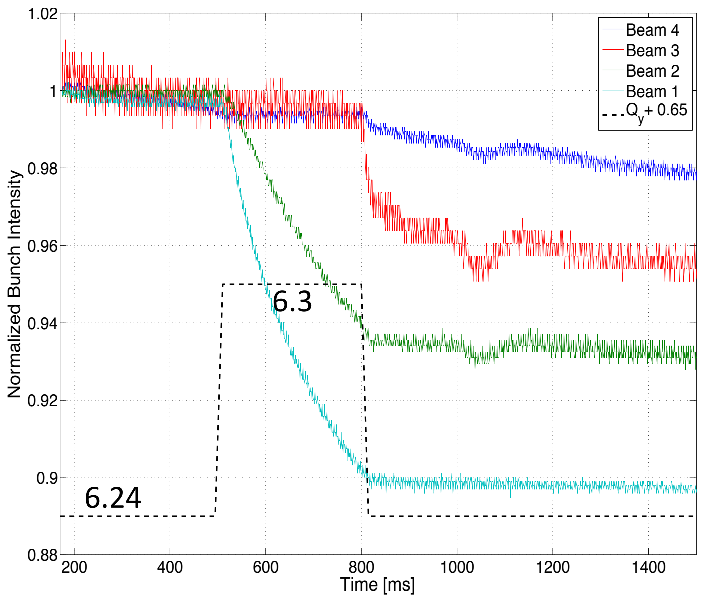
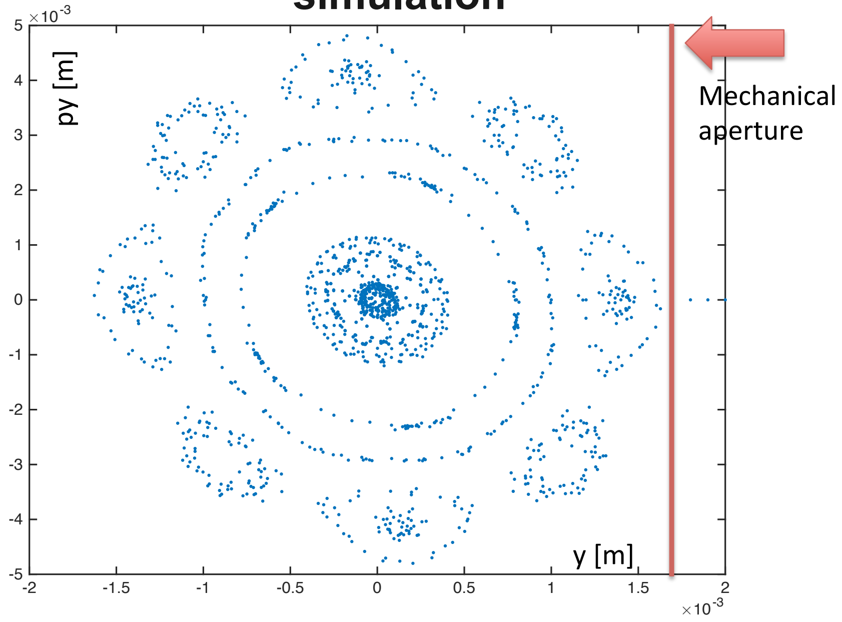
measured beam loss



simulation



S. Machida + R. Wasef, S. Gilardoni, S. Machida

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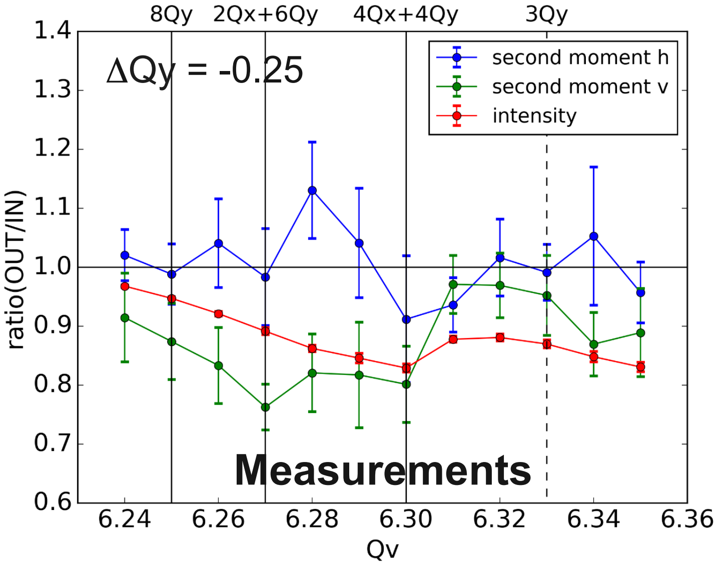
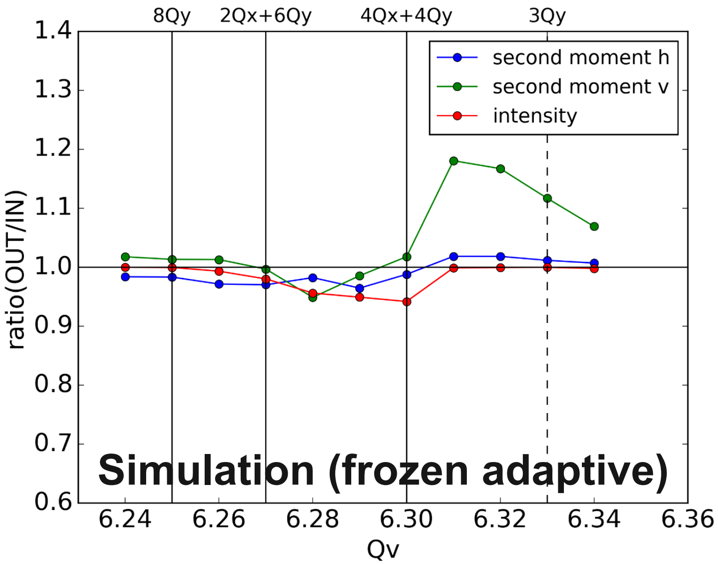
- **Recent campaigns concentrated on tune scans in different beam conditions**
  - **Simulations do not explain the observed losses completely**





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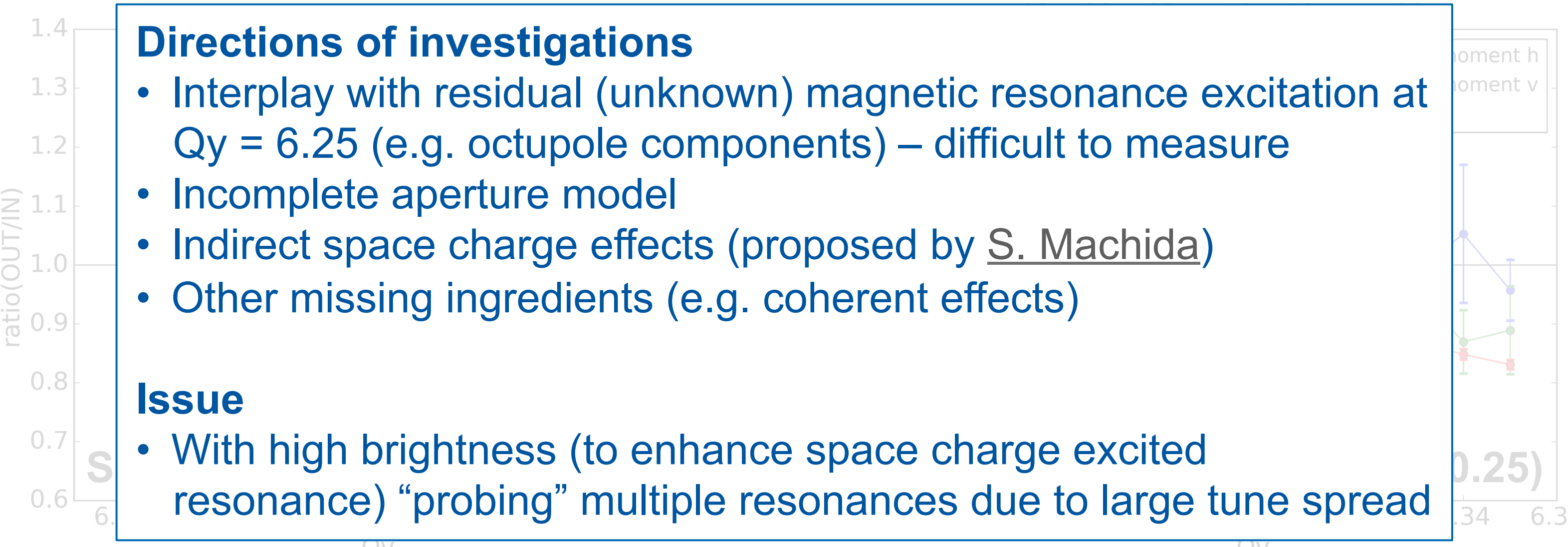


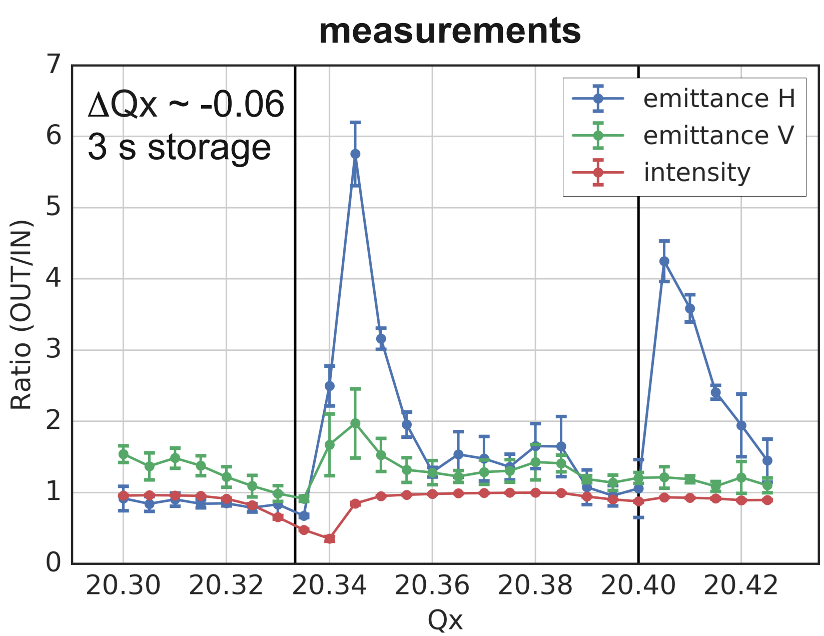
Directions of investigations
- Interplay with residual (unknown) magnetic resonance excitation at Qy = 6.25 (e.g. octupole components) – difficult to measure
- Incomplete aperture model
- Indirect space charge effects (proposed by S. Machida)
- Other missing ingredients (e.g. coherent effects)

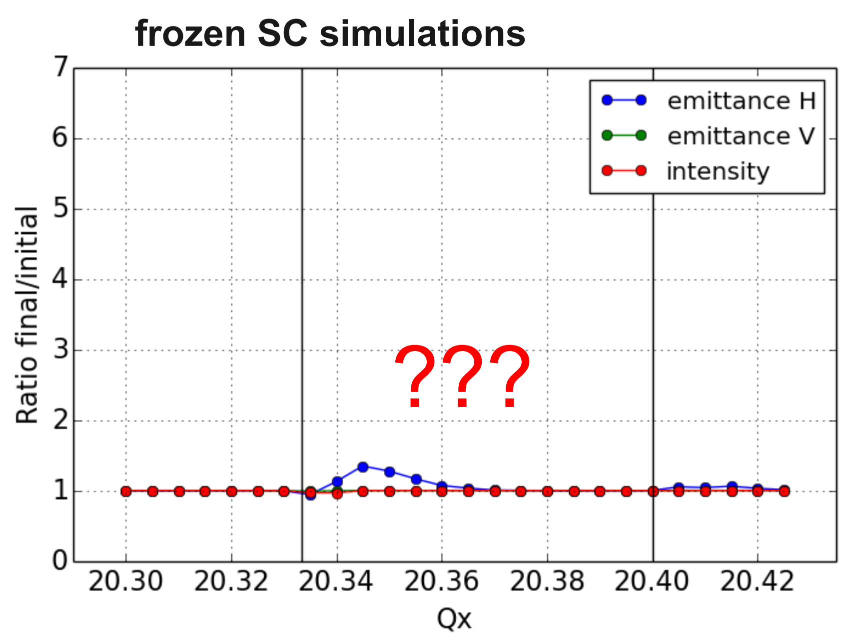
Issue
- With high brightness (to enhance space charge excited resonance) "probing" multiple resonances due to large tune spread

F. Asvesta, H. Bartosik, A. Huschauer, Y. Papaphilippou, A. Saa Hernandez, G. Sterbini

Impact of tune ripple at the CERN SPS

- **Benchmark experiment at CERN SPS (started in 2016)**
  - Horizontal 3rd order resonance at Qx = 20.33 deliberately excited
  - Additional resonance observed at Qx = 20.40 (most likely space charge driven)





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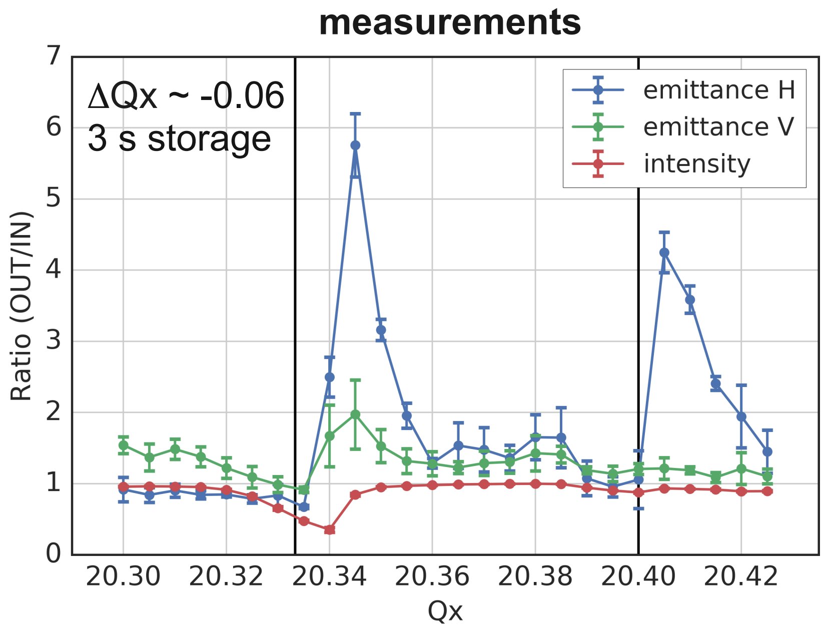

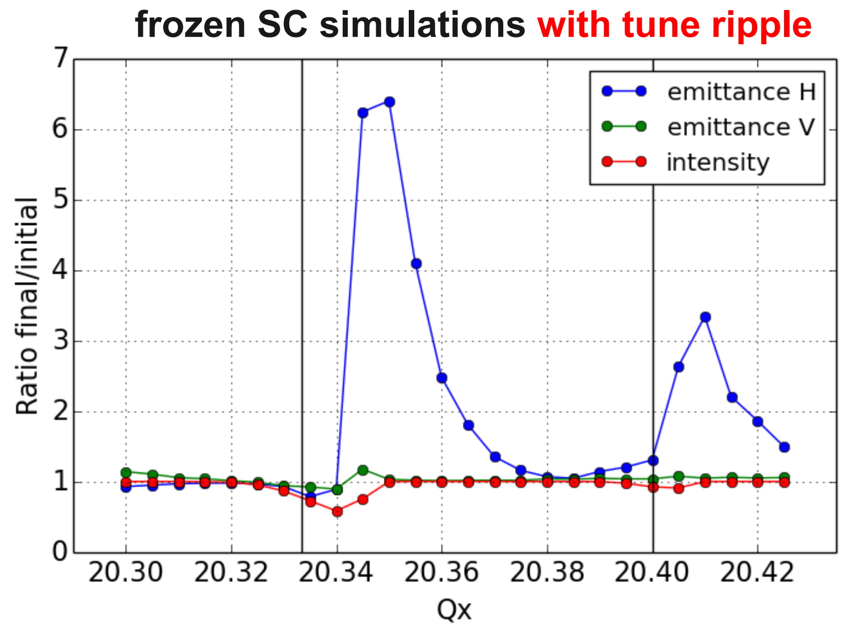

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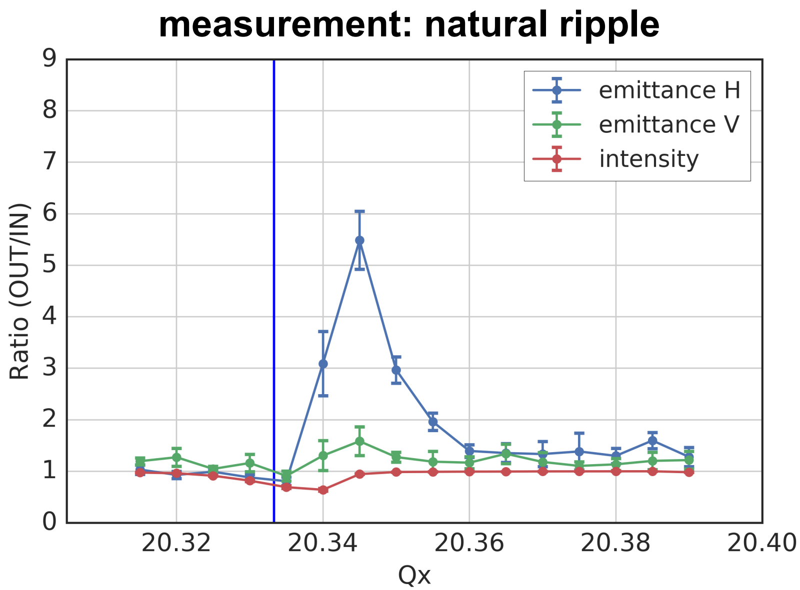
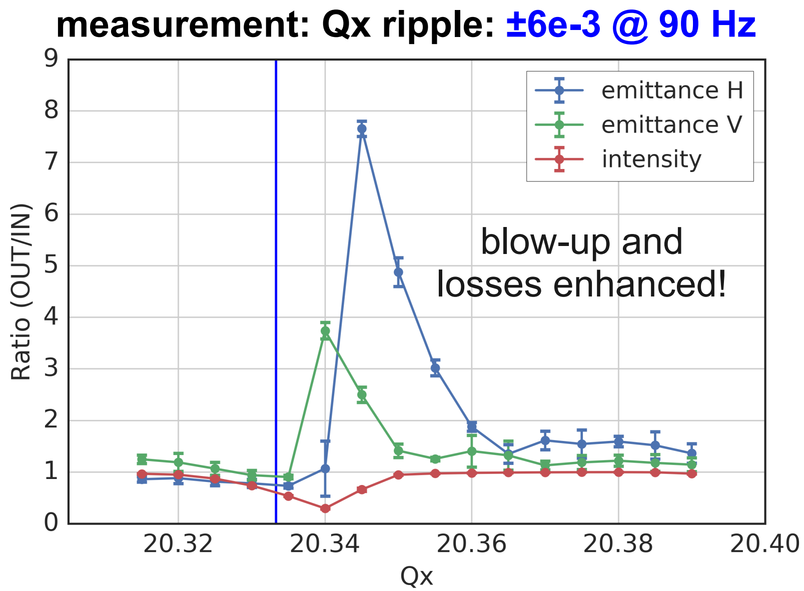
  - **Confirmed in direct experiment** with enhanced tune ripple





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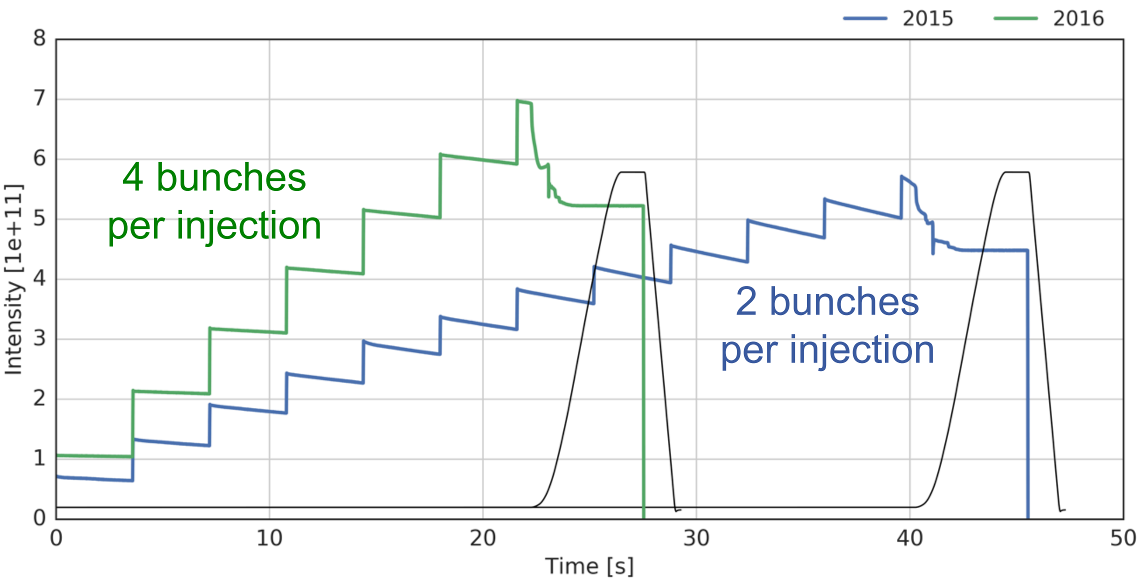
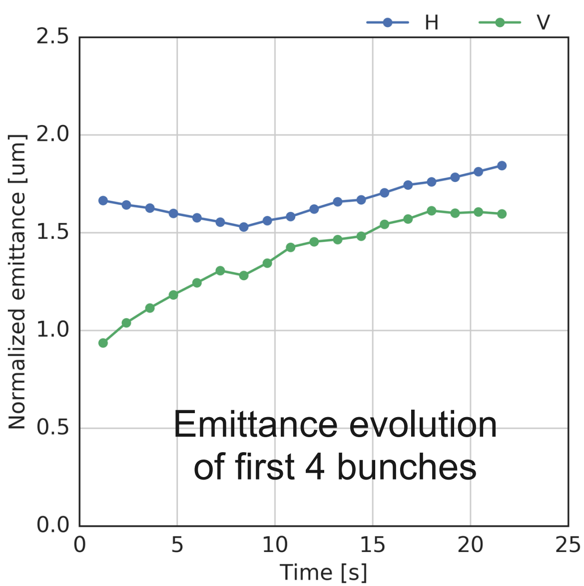
Interplay with IBS for Pb82+ ions at CERN SPS

- **Pb82+ ion bunches have to be accumulated over ~40 s at SPS**
  - ΔQy ~ -0.3 at injection
  - Strong emittance growth, partially from Intra Beam Scattering
  - Biggest concern for this beam is transmission (to maximize luminosity in LHC)
  - Losses maybe due to interplay between space charge and Intra Beam Scattering – *to be studied*





Conclusions & Outlook

- **Space charge effects in the long-term storage regime can result in beam loss and emittance growth due to periodic resonance crossing**
  - Result of systematic experiments and studies performed over the last decade for 1D and more recently also for 2D resonances

- **Overcoming limitations of simulations for long storage times is challenging**
  - Simulations with frozen potential avoid noise issues but are not (fully) self-consistent
  - Good agreement between PIC and frozen potential in code-to-code benchmarking – cases with losses to be checked systematically

- **Quantitative agreement between experiment and simulations is challenging**
  - Requires accurate knowledge of machine aperture and linear / non-linear errors
  - Identify and suppress interfering effects or properly account for them in simulation

- **Future directions: interplay with other mechanisms need to be studied**
  - Tune modulation induced by power converter ripple
  - Intra Beam Scattering (especially for ions)
  - E-cloud (see talk of G. Rumolo)
  - Indirect space charge and impedance

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