Developments in Incoherent vs. Coherent Resonances

ICFA Mini-Workshop SpaceCharge19

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Overview

- Intro: Classification of transverse resonances with space charge
- 90 degree stopband as a „test-bed“
- Higher order coherent resonance effects – role of Landau damping?
- Comparison with SIS18 experiment
- Conclusions

Acknowledgment: O. Boine-Frankenheim, G. Franchetti, A. Oeftiger

Collective – coherent – incoherent

in beams with space charge

Any beam in an external potential with space charge behaves collectively!

Collective effect

- may be on amplitudes of particles (re-arrangement) such that self-field counteracts external field – in synchrotrons „weak“
  - example: „Debye shielding“, or „profile flattening“
  - influencing incoherent resonances

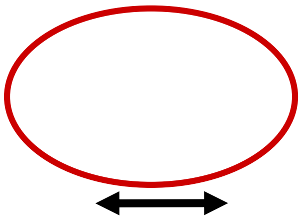
FSM* „good enough“

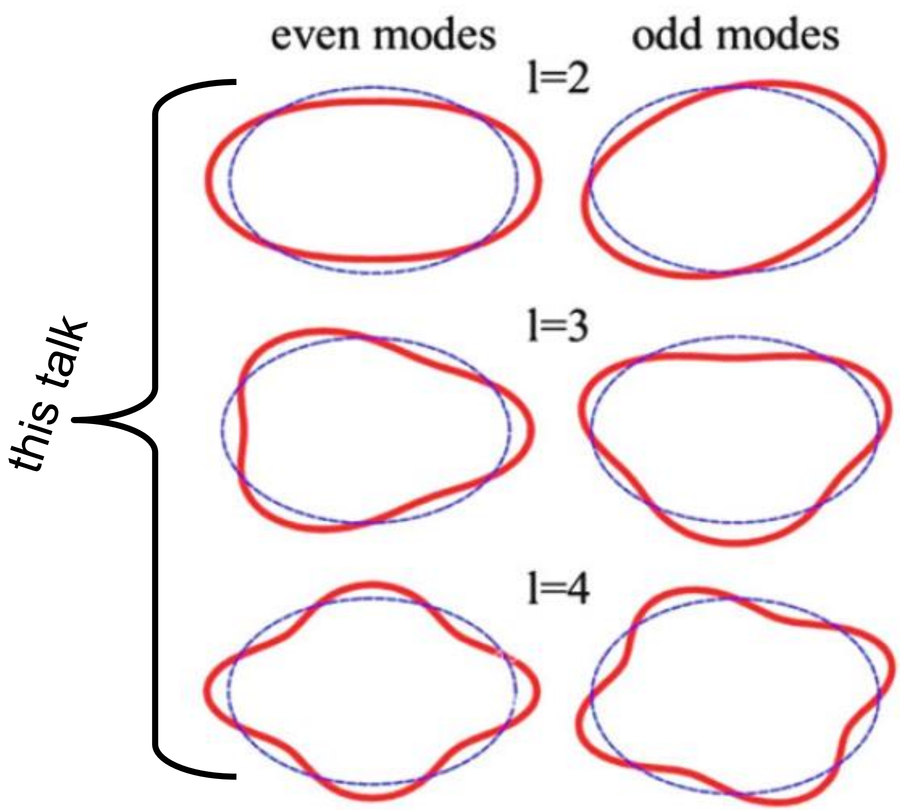
- may be on phases of particles: coherent effects (modes)
  - coherent resonances
  - instabilities
  - shifted frequencies compared with single particles

FSM* fails

FSM*: **F**rozen **S**pace **C**harge **M**odel

Coherent modes



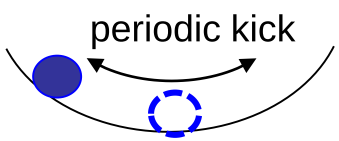


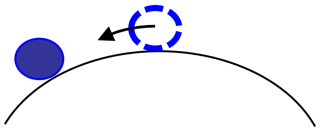
- ✓ Coherent impedance driven instabilities
  - rigid dipolar motion
- ✓ Quadrupolar deformations
- ✓ Higher (3rd or 4th) order coherent modes
  - driven by resonant effects
  - not by impedances!
  - do they exist?

Overview: 3 resonance situations

shifted or **new** frequencies

Incoherent	**coherent**	**coherent parametric**
$l\nu_x + m\nu_y = n$	$l\nu_x + m\nu_y + \Delta\omega_{coh,l,m} = n$	$l\nu_x + m\nu_y + \Delta\omega_{coh,l,m} = n/2$
	weak coherence	„strong“ coherence





resonant excitation

- driven by magnets **and/or** self-fields
- single particle „incoherent“ resonances
- also „coherent resonances“?
- 2nd order example in rings:
  - gradient error resonance – coherent.

parametric resonance

- driven by self-field only
- instability with exponential growth
- example in linacs: envelope instability – not measured - avoided

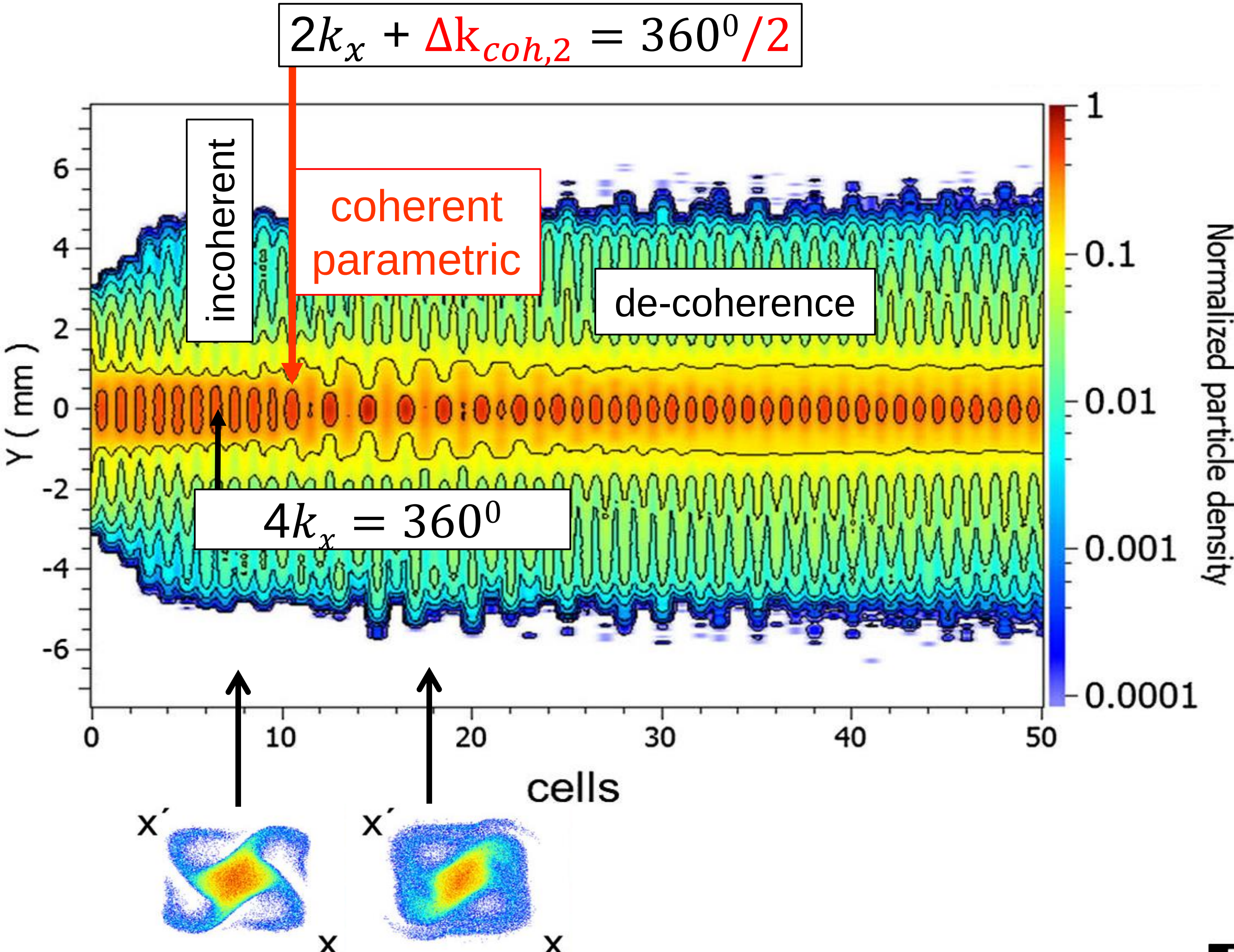
Simulation in linear FODO lattice: short ellipsoidal 3d bunch

showing the two types of resonance in the 90 degree stopband

I.Hofmann, O. Boine-Frankenheim, PRAB 2017

$k_{0x,y} = 120^0$
$k_{xy} = 73^0$

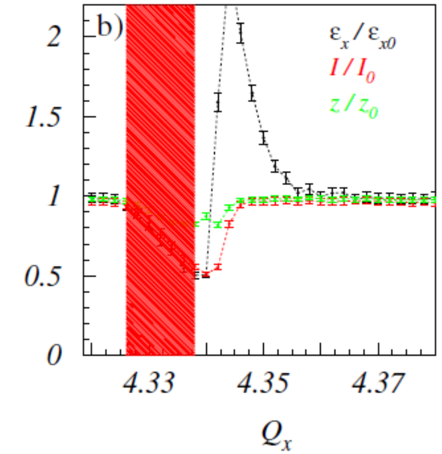
6d Gauss/3σ

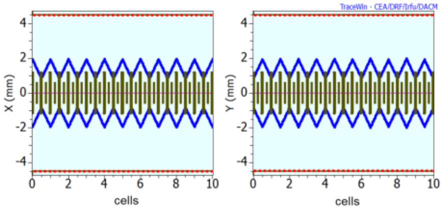


Scan over full regime of resonant response

- use 90^0 band as „test bed“ for higher order and externally driven -

SIS 18
bunched beam – theory
Franchetti et al., PRAB 2010

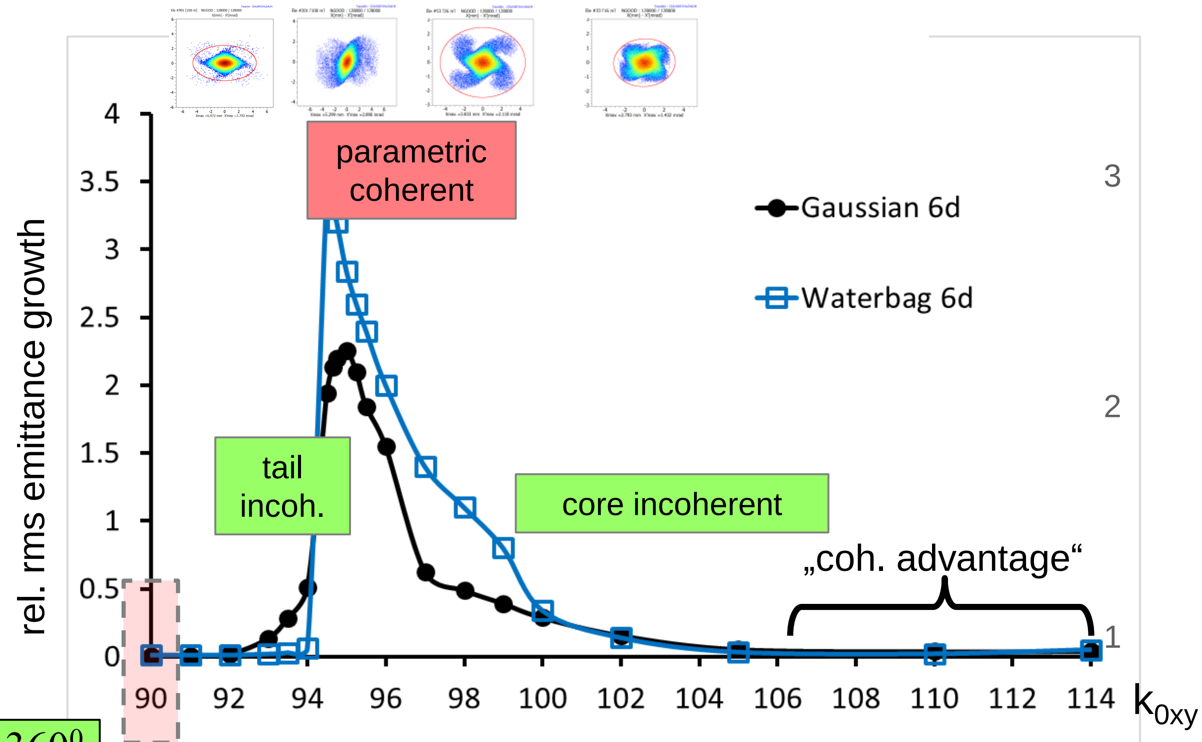




- Need an **integrated** picture over all regimes
  - where incoherent, where coherent? transitions etc.
  - compare with experimental procedures in SIS18 – CERN
- This talk: Elongated 3d Gaussian bunch on 90^0 stopband
  - periodic linear focusing (straight FODO + RF lattice)
  - $T_{synch} \approx 3xT_{beta}$
  - fully self-consistent Poisson solver (TRACEWIN)
  - use a (mechanical) aperture at 7σ to „model“ halo loss regimes

Early (300 cells) response on rms emittance 6d G

on 90^0 stopband - T_{syn}=3x$T_{betatron}$



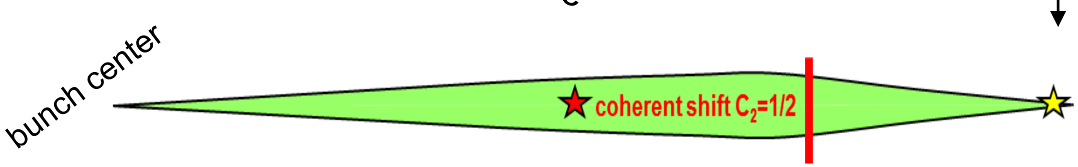
$4\,k_{xy} \approx 360^0$

$2k_{xy} + C_2\Delta k_{xy} = 360^0/2$

coh. frequency on resonance

$k_{xy/rms}$ on resonance

$k_{xy/}$ bunch center on resonance



k_{0xy}

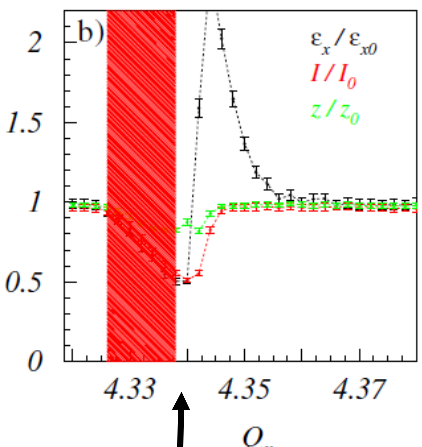
$k_{xy/rms}$

coherent fr.

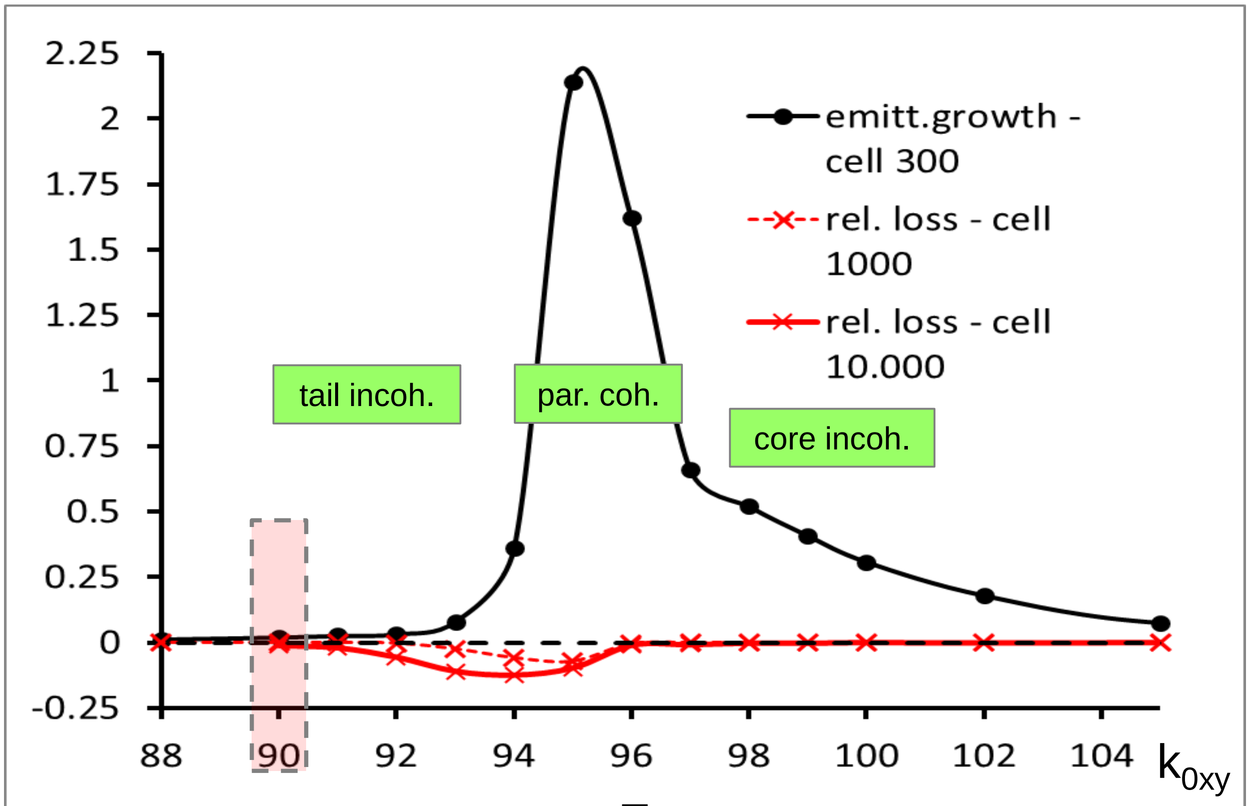
Longer term loss case (6d G - $T_{syn}=3xT_{betatron}$)

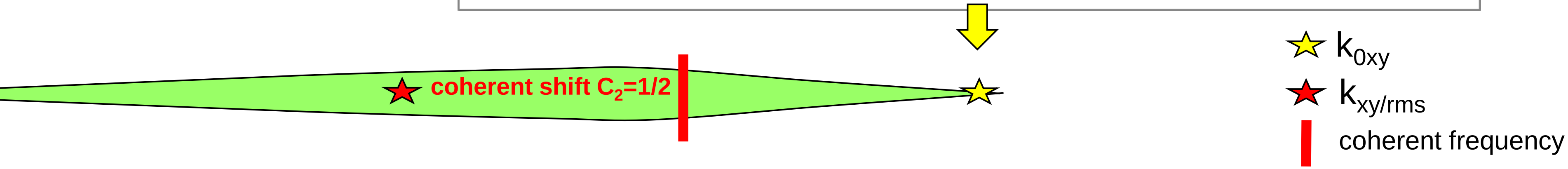
mechanical aperture at 7σ (4.5 mm)

SIS 18 - **sextupolar**
bunched beam – theory FSM



FSM:
- coherent effects absent !
- emittance peaks not coherent, but long-term incoherent





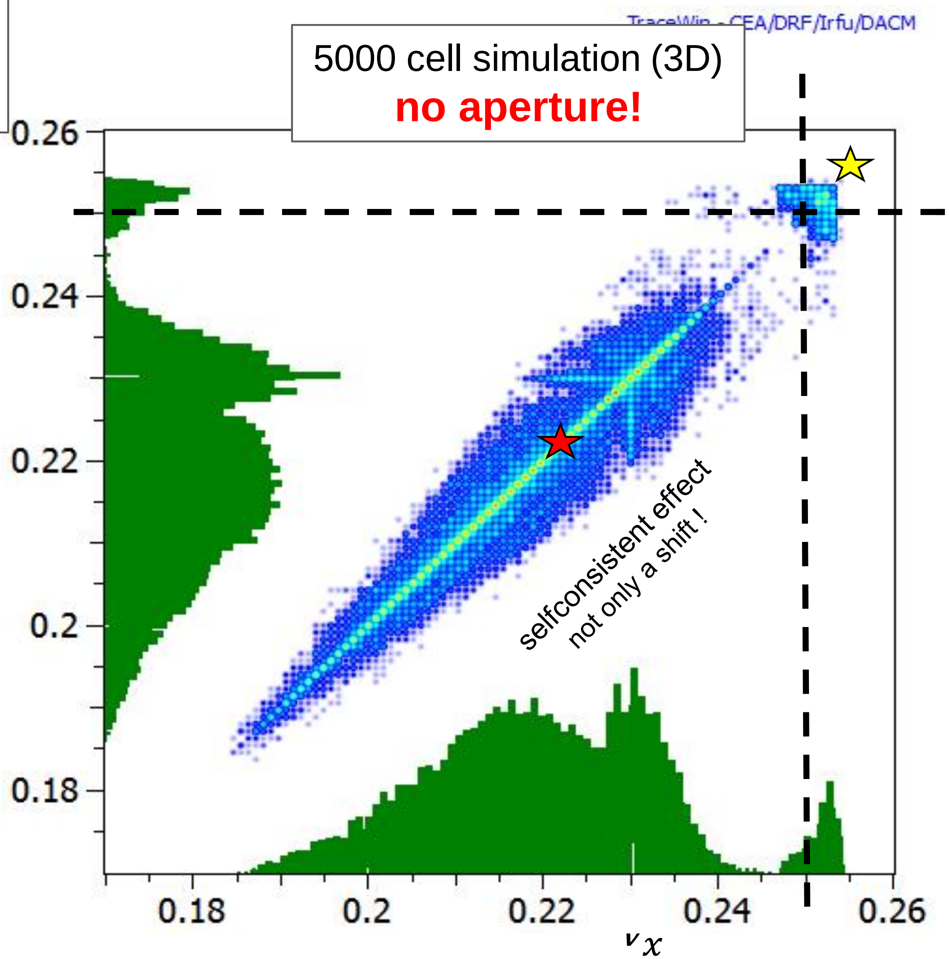
Tail incoherent resonance regime

by periodic crossing of 90^0 resonance during synchrotron motion

*G. Franchetti and I. H., NIM A **261** (2006), G. Franchetti et al. PRAB (2010)*

$k_{0x,y} = 92^0$
$k_{xy} = 80^0$
$k_z = 29^0$

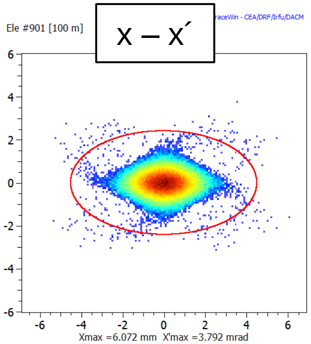
5000 cell simulation (3D)
no aperture!



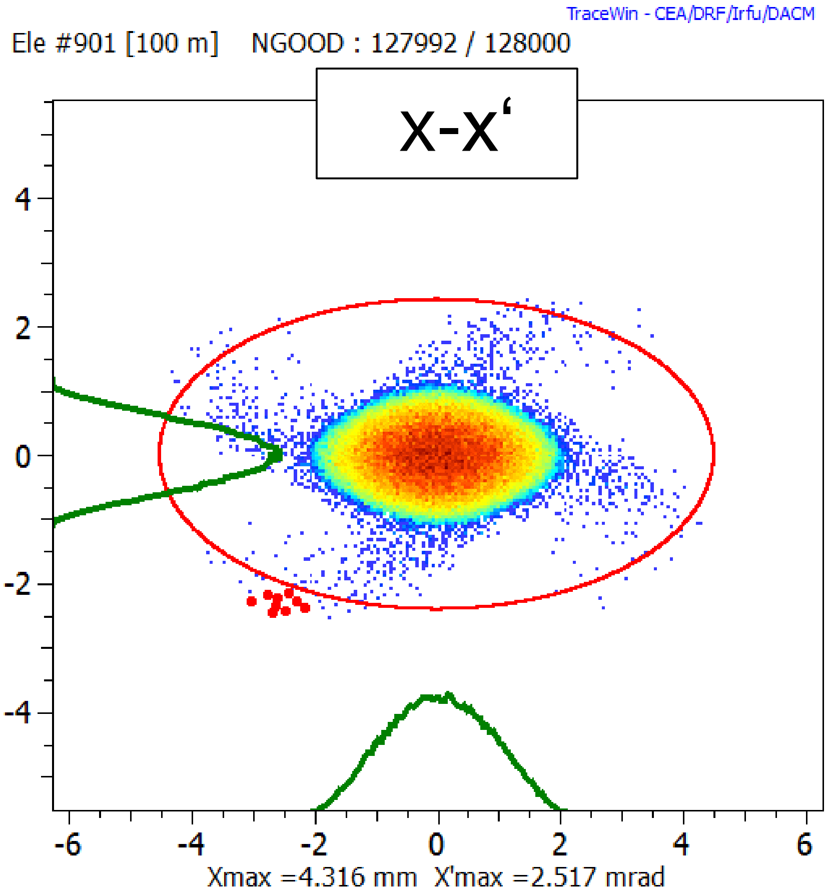
(6d G – $T_{syn} \sim 3xT_{betatron}$)

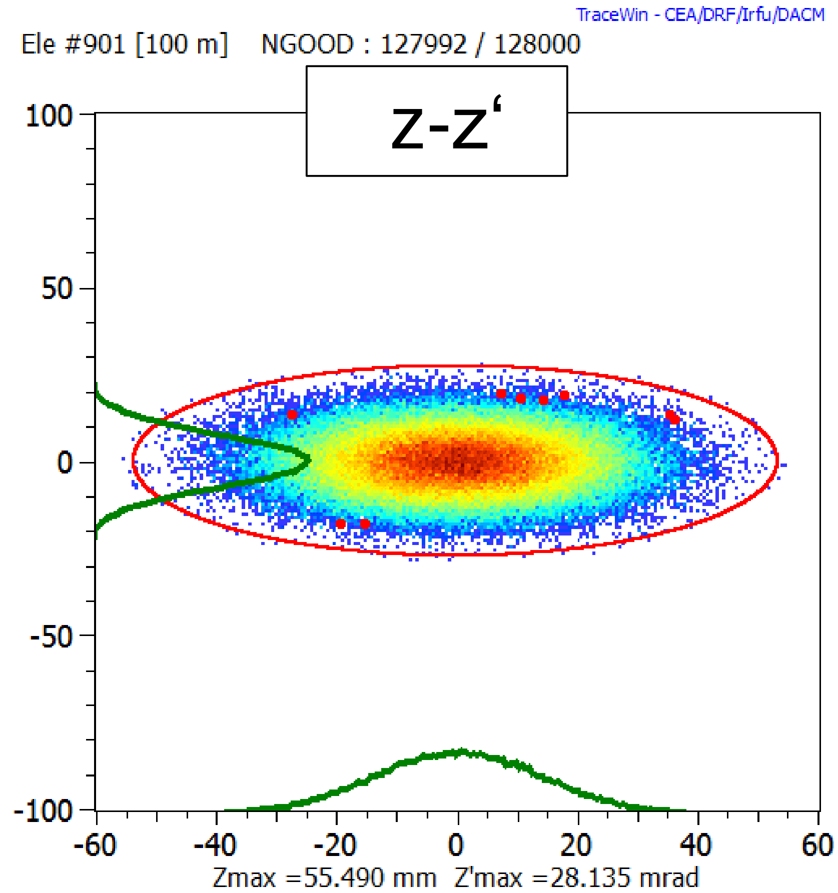
It can be assumed that it

- is an entirely incoherent resonance
- scattering by multiple kicks
- „frozen-in" sp.ch. initially ok
- requires self-consistent treatment if high deviations from initial

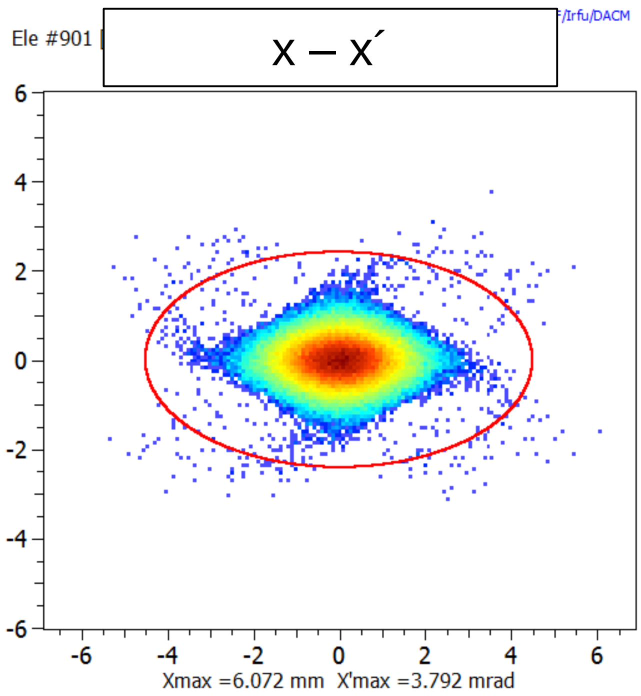


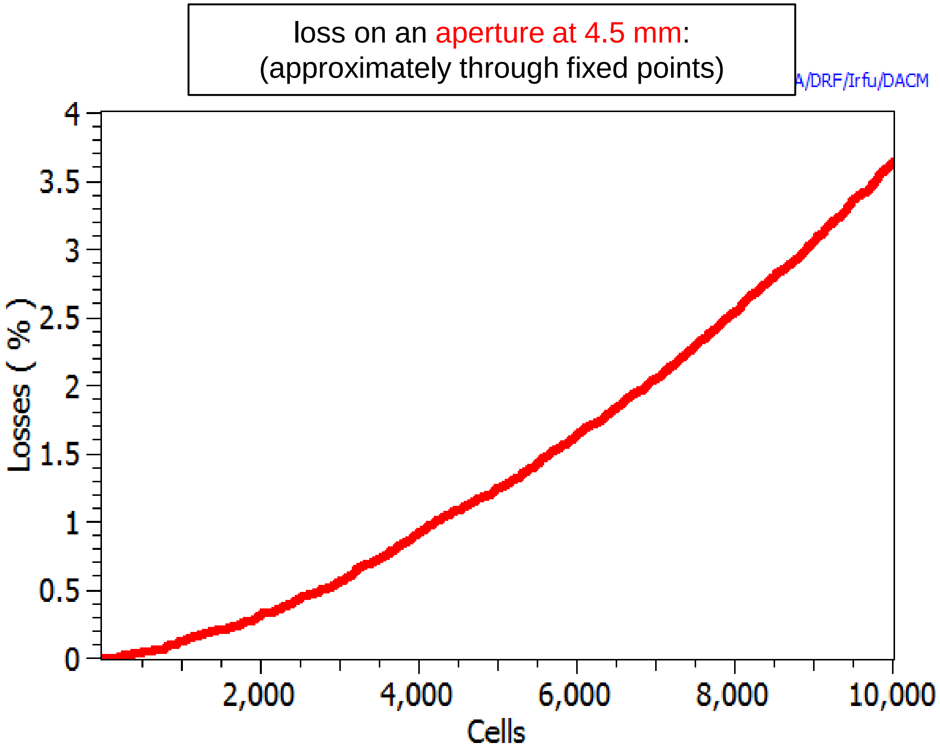
Resonant particles: maximum synchr. amplitudes
→ multiple kicks (G. Franchetti et al., PRSTAB 2010)





Loss curve with assumed mechanical aperture at 7σ





Higher order stopbands? – (6d Gaussian – T_{syn} ~ $3xT_{betatron}$)

Test with slow **tune ramp**:
k_{0xy}: 142 → 135
k_{xy}: 136 → 132

Incoherent:

$\boxed{8\ kxy = 3\cdot 360^0}$

$\boxed{8\ Q_{xy} = \mathrm{m}\cdot N}$ (ring)

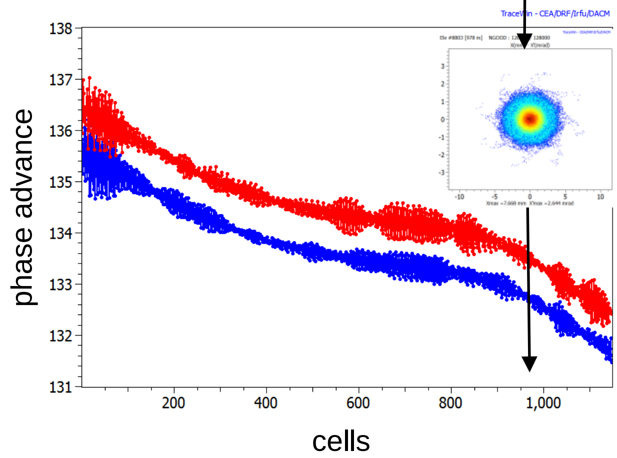
Coherent – „theoretical“:

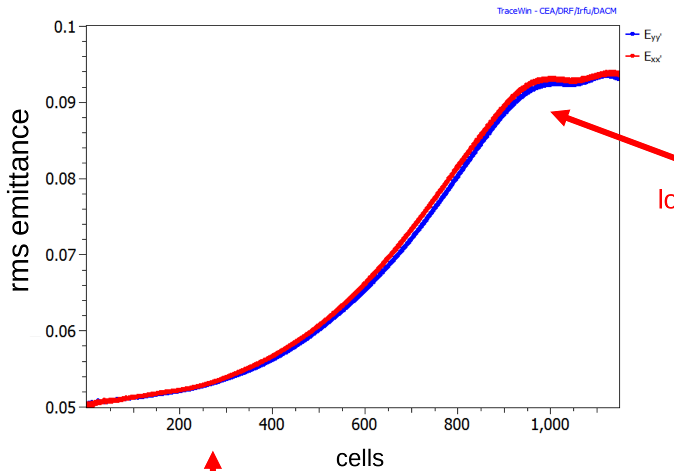
$\boxed{4k_{xy} + \Delta k_{coh,4} = 3\cdot 360^0/2}$

$\boxed{4Q_{xy} + \Delta Q_{coh,4} = \mathrm{mN}/2}$

Incoherent resonance driven by 3rd harmonic of basic FODO cell

compare with CERN PS: $8\ Q_{xy} = 50$





loss from resonance
(too fast scan)

theoretically expected (by theory ignoring LD)
half-integer parametric resonance

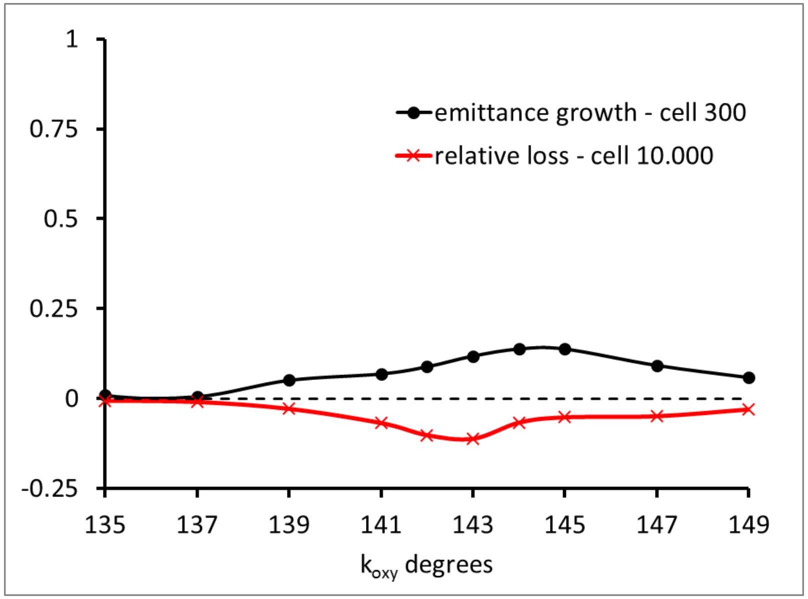
Detailed scan of this 8th order stopband (6d G – T_{syn} ~ 3x$T_{betatron}$)

$8\,kxy = 3\cdot 360^0$

$\rightarrow k_{xy} = 135^0$

incoherent **rms** tune on resonance!

assumed again 7 σ mechanical aperture



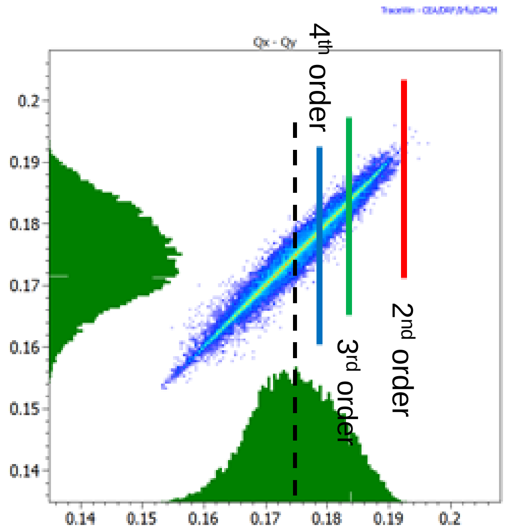
- ✓ **No indication of coherent parametric resonance!**
  - **should show during first 300 cells (exponential growth!)**
- ✓ **rms emittance growth entirely incoherent**

$k_{xy} = 135^0$
$k_{0xy} = 148^0$

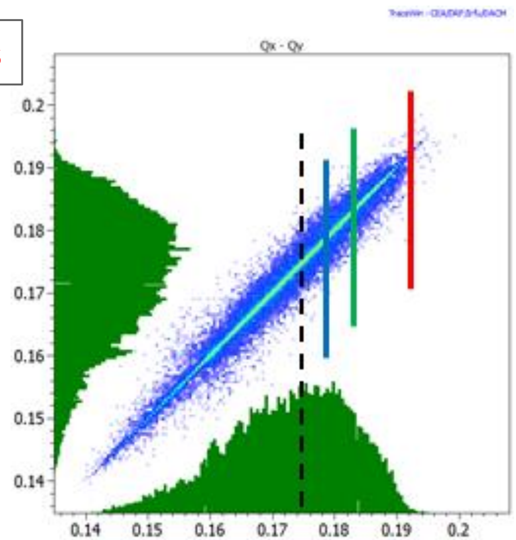
„theoretically“: $\boxed{4\,k_{xy} + \Delta k_{coh,4} = 3\cdot 360^0/2}$

Coherent resonant frequencies and Landau damping

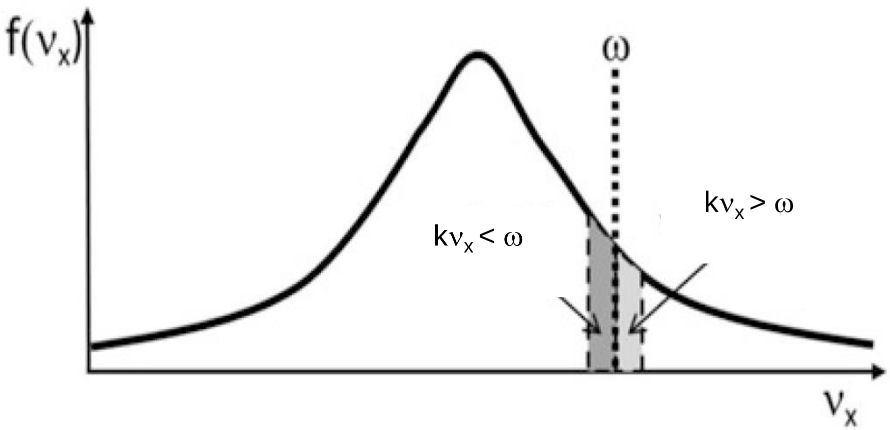
3d WB



3d Gauss



$$\omega = k(\nu_x + C_k \Delta\nu_x)$$



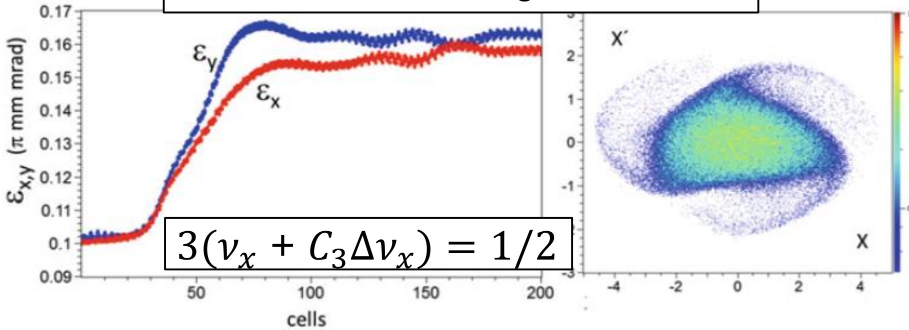
- only second order mode outside spectrum
  - found unstable in 90 deg stopband
- 3rd and 4th within spectrum of G and WB
  - consistent with absence in bunch simulations
  - in 2d found for WB!

Confirmed 3rd and 4th order parametric resonances

in WB (!) coasting beam

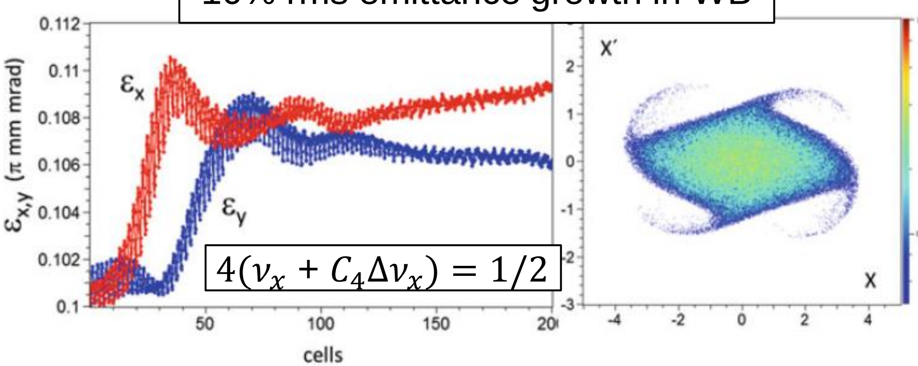
source: I.H., Springer, 2017

60% rms emittance growth in WB

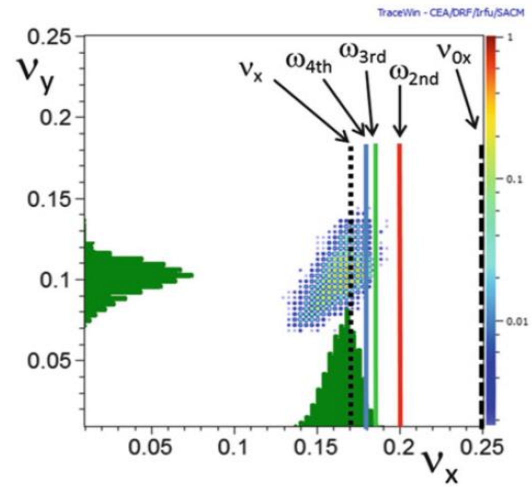


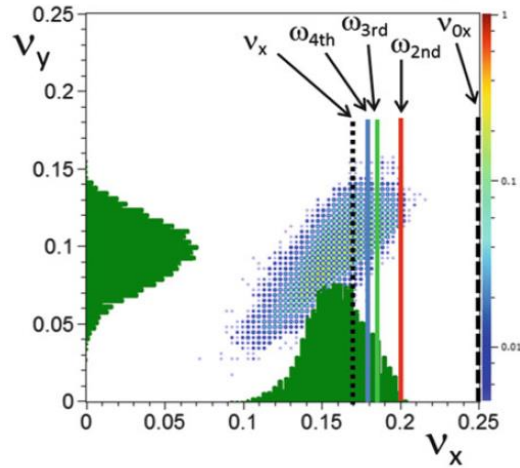
$3(\nu_x + C_3\Delta\nu_x) = 1/2$

10% rms emittance growth in WB



$4(\nu_x + C_4\Delta\nu_x) = 1/2$





Not found for Gaussian

- < 1% emittance growth

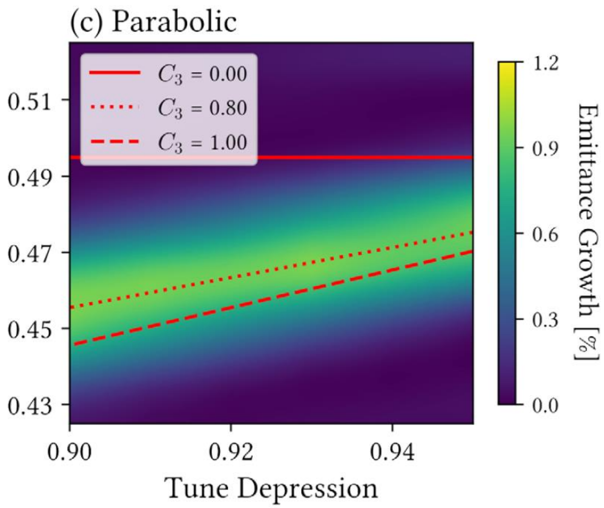
Recent suggestion by Hiroshima-group (2019):

Employ *only coherent* resonance conditions in resonance diagrams
(Kojima, Okamoto et al. / S-POD experiment)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 074201 (2019)

Empirical condition of betatron resonances with space charge

K. Kojima, H. Okamoto,* and Y. Tokashiki
Graduate School of Advanced Sciences of Matter, Hiroshima University,
1-3-1 Kagamiyama, Higashi-Hiroshima 739-8530, Japan



$$k(\nu_{0x} - C_m \Delta\nu_x) + l\,(\nu_{0y} - C_m \Delta\nu_y) = n$$

$$k(\nu_{0x} - C_m \Delta\nu_x) + l\,(\nu_{0y} - C_m \Delta\nu_y) = n'/2$$

$n'/2$: for even n' parametric instability
would nearly double # of lines

WARP-code: 2D coasting beam

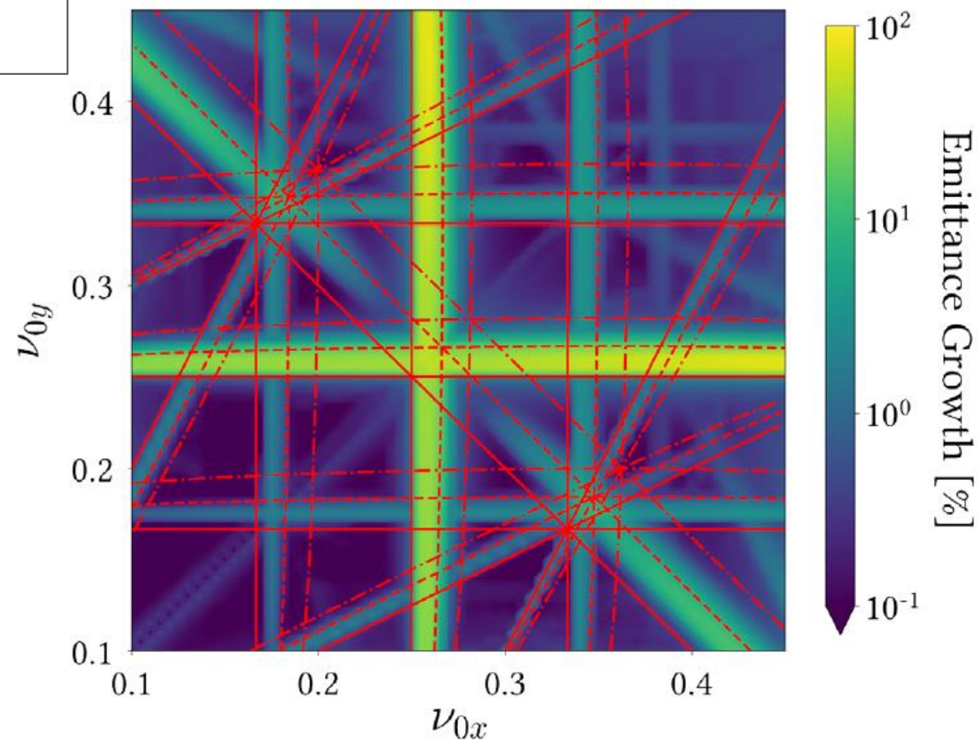


FIG. 4. Tune diagram obtained from 2D WARP simulations with a fixed beam intensity and fixed rms emittances at injection. The

SIS18 high intensity measurements:
→ no indication of coherent resonance shifts

G. Franchetti et al., PR-STAB 13 (2010)

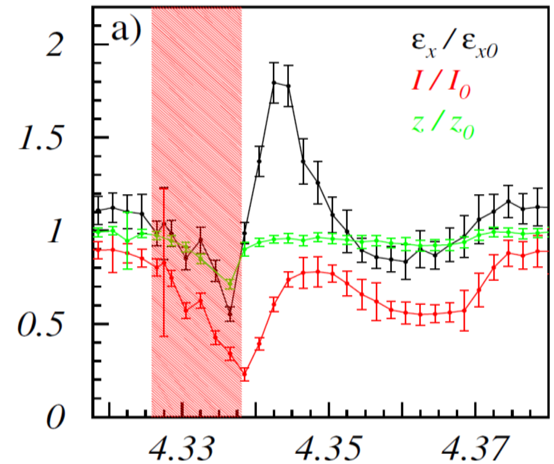
bunched beam 1 sec storage
$\Delta \nu_{x/y}$ = *-0.04/-0.045*

- ✓ **No indication** of coherent shifts
- ✓ dominated by long-term emittance growth and loss
- ✓ if any: measurement peaks should be more to the left

$$3(\nu_x + \cancel{C_s}\Delta\nu_x) = 13$$

- ✓ quantitative loss with „frozen“ sp.ch. underestimates long-term loss
  - could be due to lack of self-consistency

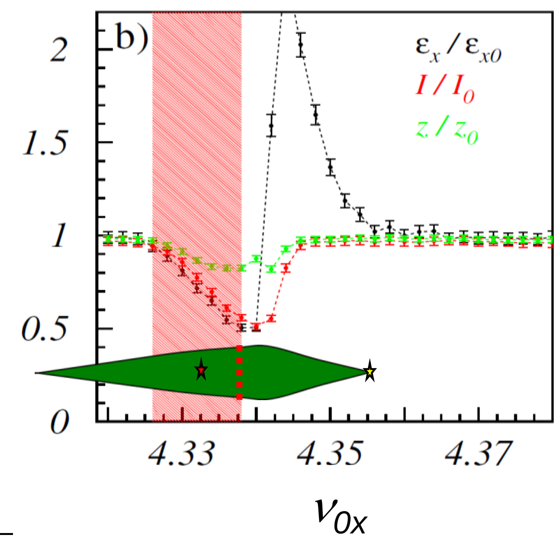
Measurement



Simulation

with „frozen“ space charge
(no coherent effects!)

coherent frequency (from theory)



Conclusions

- ✓ Distinguish incoherent – coherent – parametric
  - latter would increase # of resonance lines – **no evidence > 2nd order** (except for WB – coasting beam)
- ✓ 90 degree „test-bed“ describing 3 regimes:
  - core + coherent (half-integer) + tail
- ✓ 135 degree stopband – free of 4th order coherent half-integer!!
  - rms emittance growth only from 8th order
- ✓ Coherent part Landau damped for Gaussian and higher order
- ✓ No evidence of „coherent“ in SIS18 experiments (+ CERN)
- ✓ Future work should carefully consider LD and possibly loss of LD