# SIMULATION STUDY OF TRANSVERSE COHERENT INSTABILITIES IN INTENSE BUNCHES WITH SPACE CHARGE AND IMAGE CURRENTS

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# INTRODUCTION

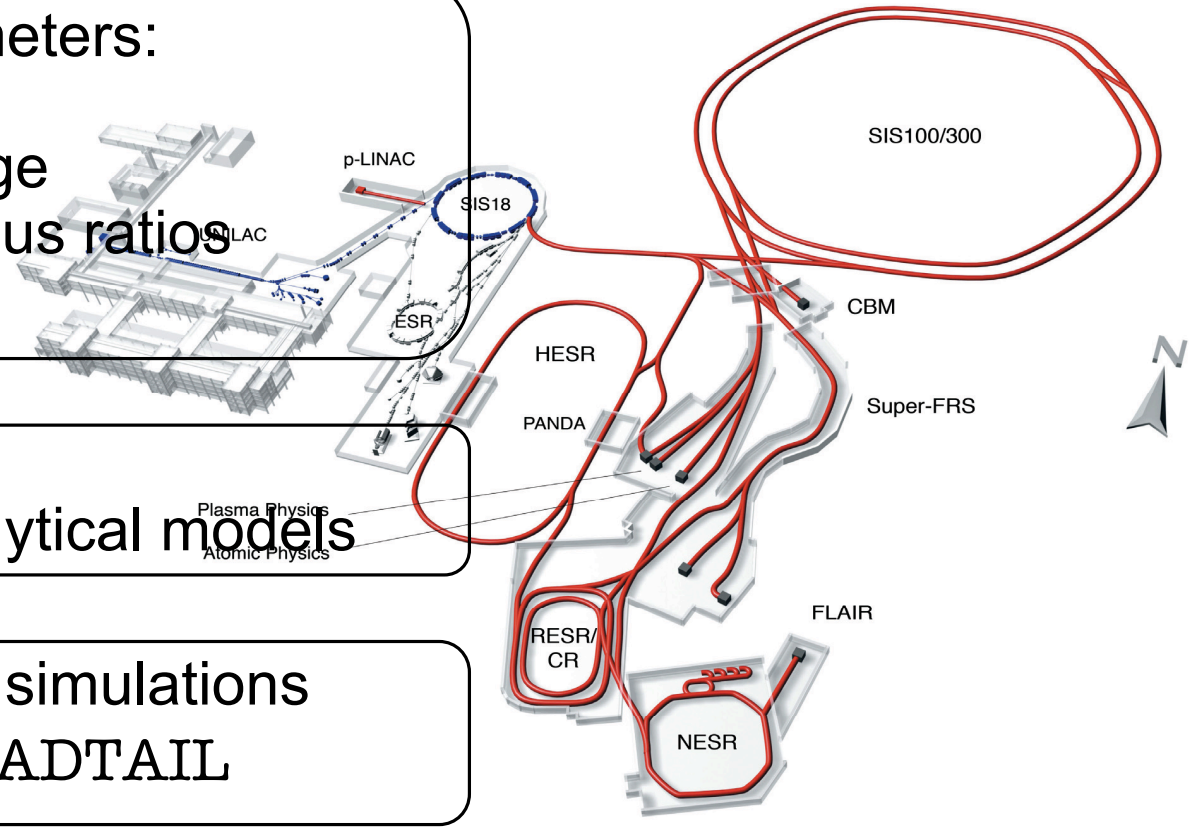
Head-Tail modes can limit the
high-current operation of SIS-100,
especially during the 1 sec accumulation at injection

specific FAIR parameters:

- strong space charge
- small aperture/radius ratios
- long bunches

lack of adequate analytical models

particle tracking simulations
PATRIC, HEADTAIL



# SIS-100 PARAMETERS

| | |
|---|---|
| circumf. | 1083 m |
| $Q_v$ | 18.73 |
| $Q_s$ | 0.0017 |
| $\gamma_t$ | 23.14 |

at injection

| | |
|---|---|
| $U^{28+}$ | $N_b = 0.625 \times 10^{11}$ |
| $\mathcal{E}_{beam} = 200\,\mathrm{MeV/u}$ | $\delta p/p = 3.0 \times 10^{-4}$ |
| $\beta = 0.566$ | $\gamma = 1.21$ |
| $f_0 = 156\,\mathrm{kHz}$ | $\eta = -0.67$ |
| $\epsilon_v = 13\,\mathrm{mm\,mrad}$ | $\epsilon_h = 36\,\mathrm{mm\,mrad}$ |

Space Charge tune shift: 0.25

Bunch length: 61 m $\Rightarrow$ $\phi_m \approx 100°$

Beam radius: 13 mm (vert, KV-equiv.)

Chamber radius: 30 mm (vert, dipole ch.) $\Rightarrow$ 20% of SC

$\Downarrow$

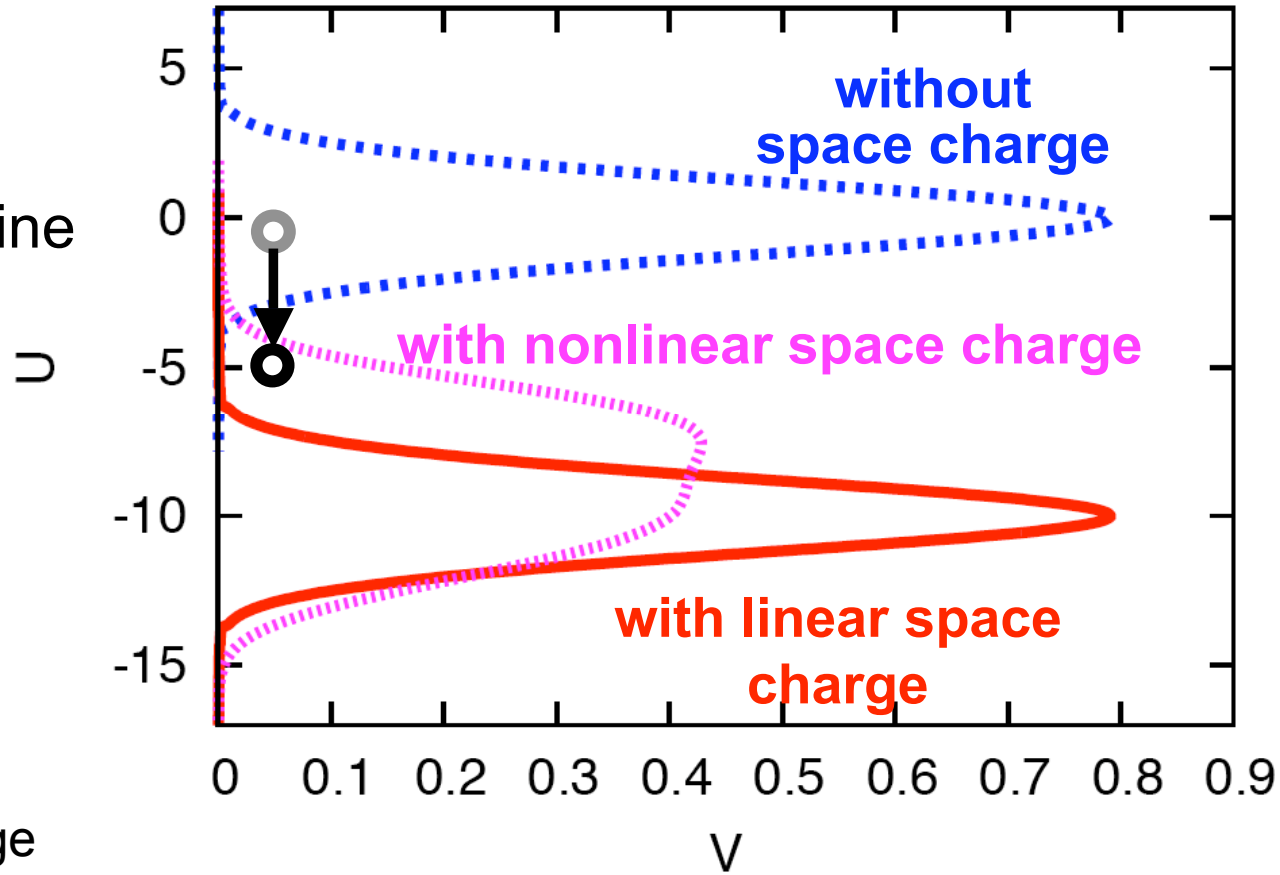
Head-Tail Dynamics changed by:
- Image Charges (coher)
- Space Charge (incoh)
- Synchr. Nonlinearity

# COASTING BEAM

- linear Space Charge:
  loss of Landau damping
- nonlinearity in SC:
  enhances stability
  from ξ or octupoles
- Image Charges:
  shift of the coherent line

$$U = \frac{\mathrm{Re}(\Delta Q_{\mathrm{coh}})}{\delta Q_\xi} \propto \mathrm{Im}(Z_{\mathrm{ext}})$$

$$V = \frac{\mathrm{Im}(\Delta Q_{\mathrm{coh}})}{\delta Q_\xi} \propto \mathrm{Re}(Z_{\mathrm{ext}})$$

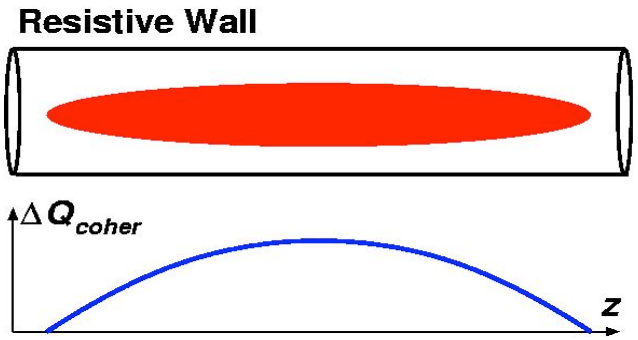



stability diagram from dispersion relation

has been confirmed by PIC simulations with the PATRIC code (recent PRSTAB paper), but: non-self-consistent approaches for space charge are not always applicable

# FROM 2D TO 3D

A shift provides tune spread,
both for Image Charges and Space Charge




$$\delta\Omega_{coher} = \Delta\Omega_{max}$$

Coupling with synchrotron dynamics provides
new mechanisms and changes damping characteristics

3D description is more involved,
especially for long simulations with Space Charge

Threshold behaviour of instabilities
(Had-Tail → TMCI) limits the scaling of impedance and CPU time

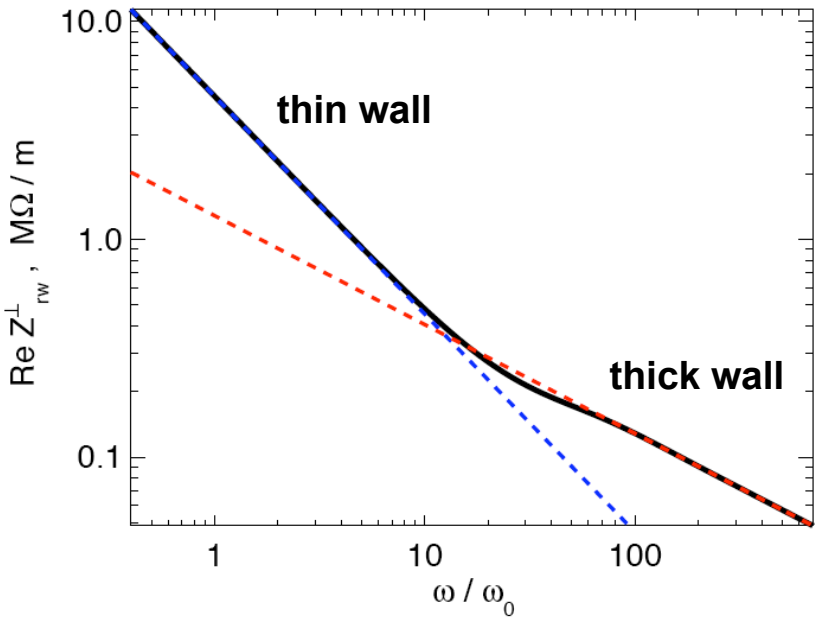
# HEAD-TAIL

Sacherer Theory:

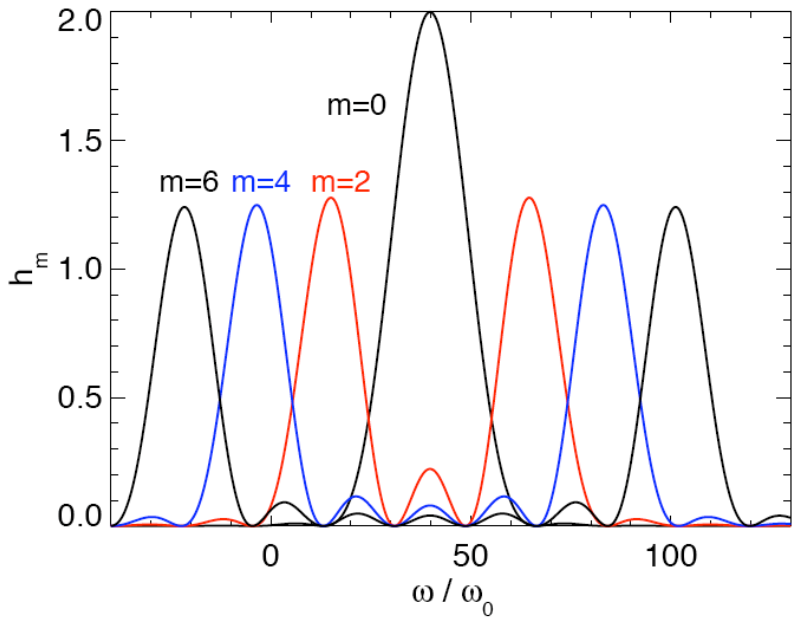
$$\Delta\Omega_m = \frac{\omega_0}{Y_0}\frac{1}{1+m}\frac{C}{L_b}\frac{\sum_p(-i)Z^{\perp}(\omega_p)\ h_m(\omega_p-\omega_\xi)}{\sum_p h_m(\omega_p-\omega_\xi)}$$

$$\omega_p = (p+Q_0)\omega_0 + m\omega_s \qquad \omega_\xi = \frac{Q_0\xi}{\eta}\omega_0$$

SIS100 Resistive-Wall impedance




Power spectrum of Head-Tail modes




for SIS100: a head-tail mode *m*=4 with $\tau \approx 70$ms

the theory not valid for strong image charges $\Delta Q_{coh} \gg Q_s$ and space charge $\Delta Q_{SC} \gg Q_s$

# TWO TOOLS: PIC CODES

**our strategy on the way to a correct description of these effects on Head-Tail instability: two different tools**

| PATRIC | HEADTAIL |
|---|---|
| (development at GSI) | (joint work with G.Rumolo) |
| short-term simulation: resolve betatron oscillations | long-term simulations: once per turn |
| impedances $Z_\perp(\Omega)$ [add. $W_\perp(s)$] | wake fields $W_\perp(s)$ |
| self-consistent SC | beam-beam SC |
| static space grid | flexible space grid |
| coasting / long bunches | short bunches |

Head-Tail modes: consistency with the Sacherer theory was confirmed in the recent work (E.Metral,G.Rumolo,R.Steerenberg,B.Salvant,PAC'07)

# WAKE-FIELD MODULE

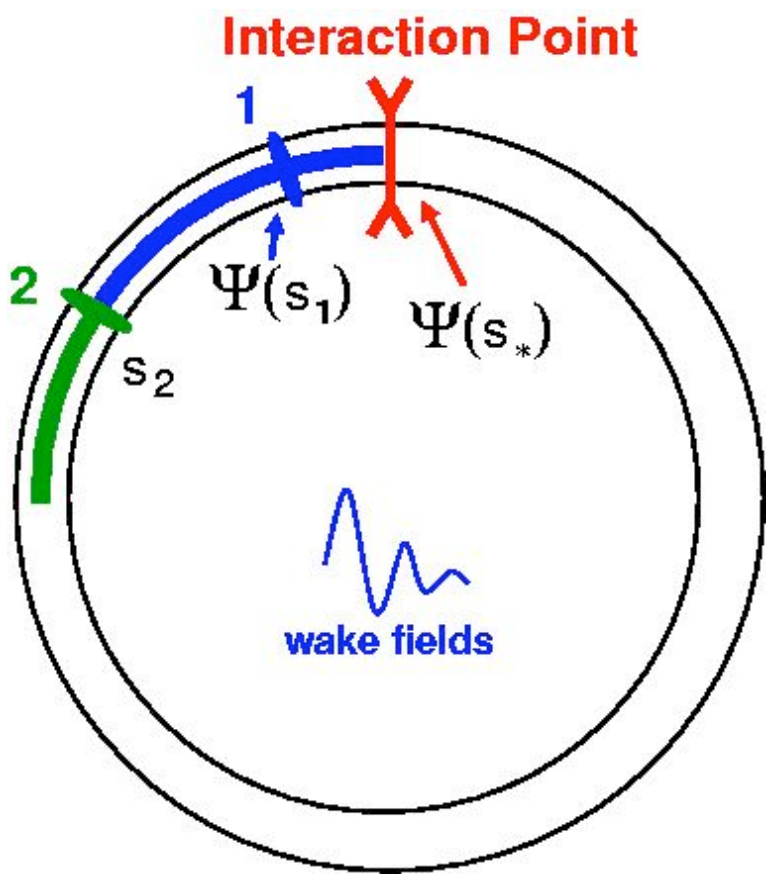
Resistive wall (thick-wall) wake field

$$W_{\mathrm{RW}}(z) = -\frac{cL_{\mathrm{wall}}}{b^3}\sqrt{\frac{Z_0}{z\ \sigma_{\mathrm{wall}}}\left(\frac{\beta}{\pi}\right)^3}$$

$$\Delta p_y = \int \Psi(s)\ W_{\mathrm{RW}}(z)\mathrm{d}z$$

$$\Psi = k\ n_{\mathrm{p}}\overline{x}$$

$$z = s_1 - s_2$$




**take into account the phase advance:**

instead of

$$\Delta p_{12} = \Psi(s_1)\ W_{\mathrm{RW}}(z)$$

we use

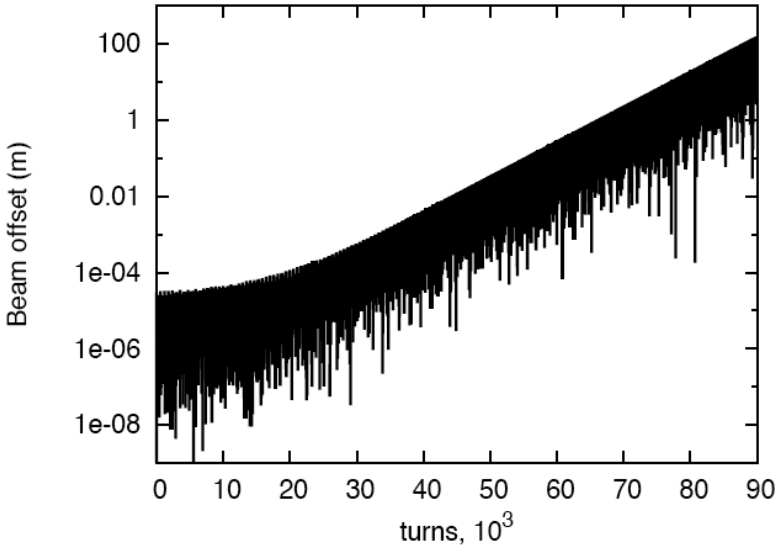
$$\Delta p_{12} = \Psi(s_*)\ W_{\mathrm{RW}}(z)$$

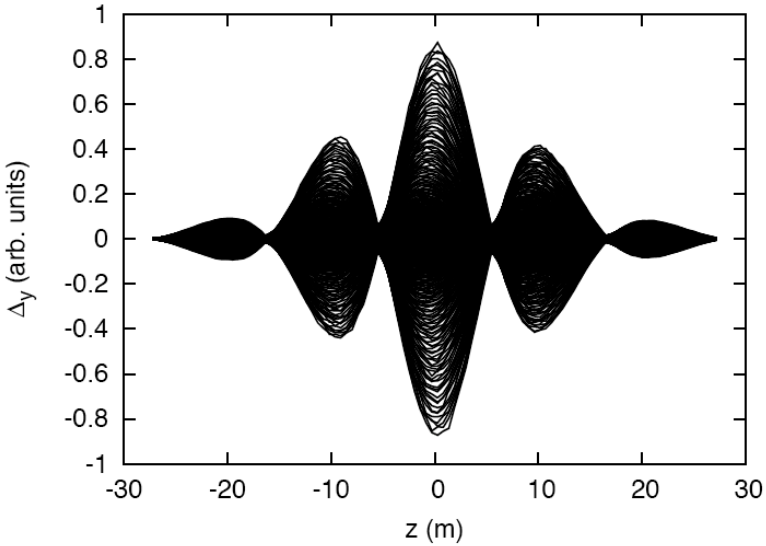
(verified with the coasting beam)

# HEAD-TAIL MODE

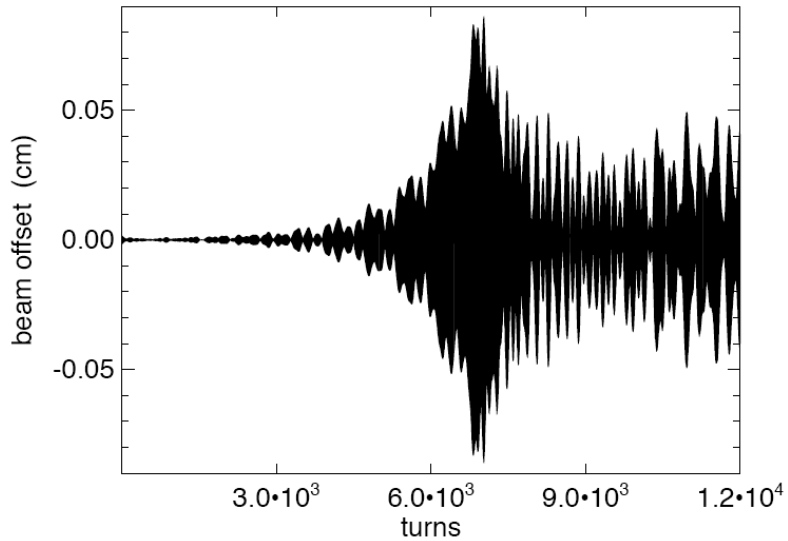
HT mode example for SIS100
(scaled impedance)

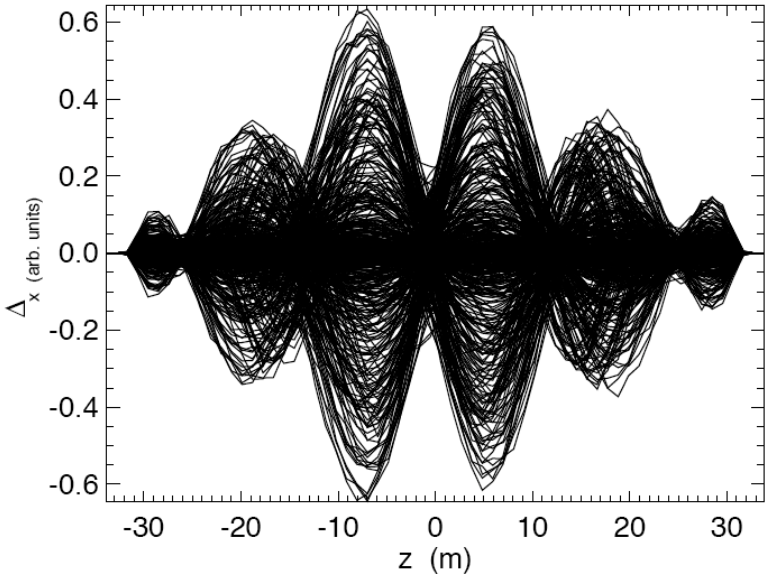
HEADTAIL



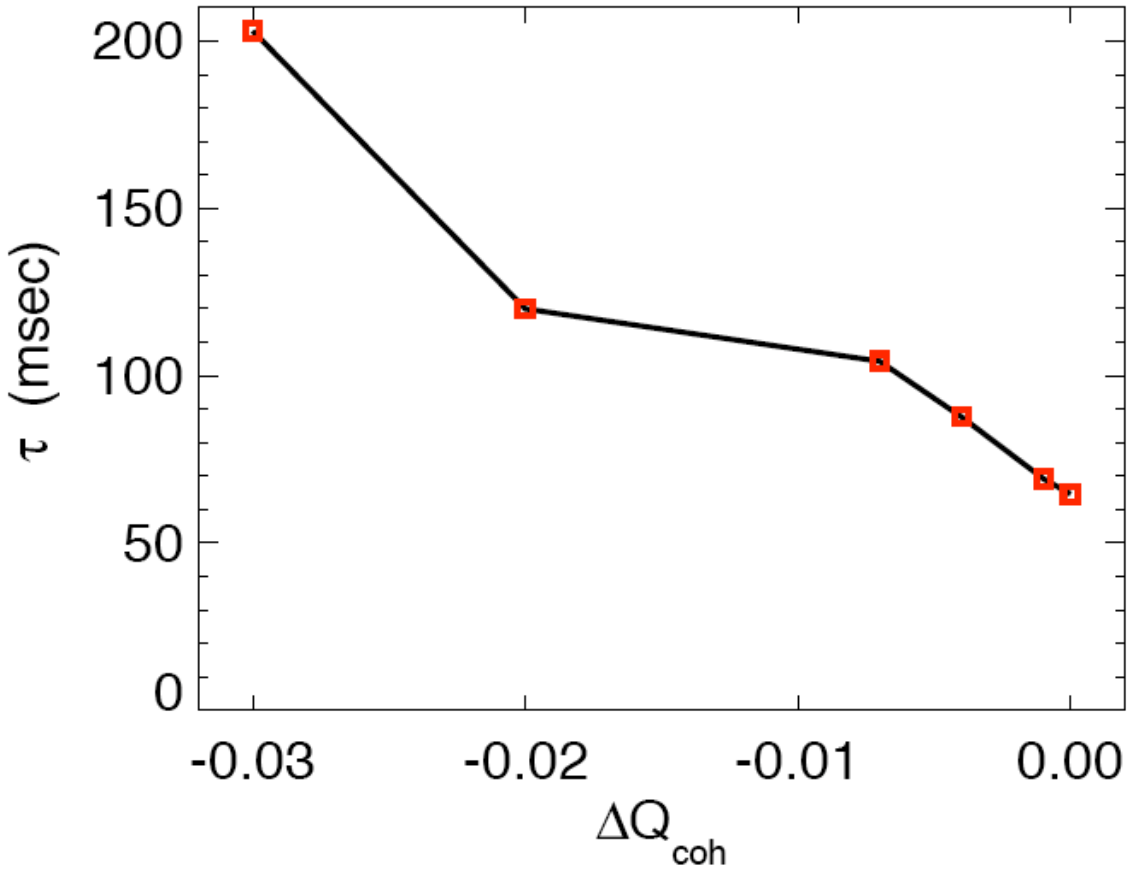

PATRIC



# IMAGE CHARGES

Effect of Image Charges
on Head-Tail modes



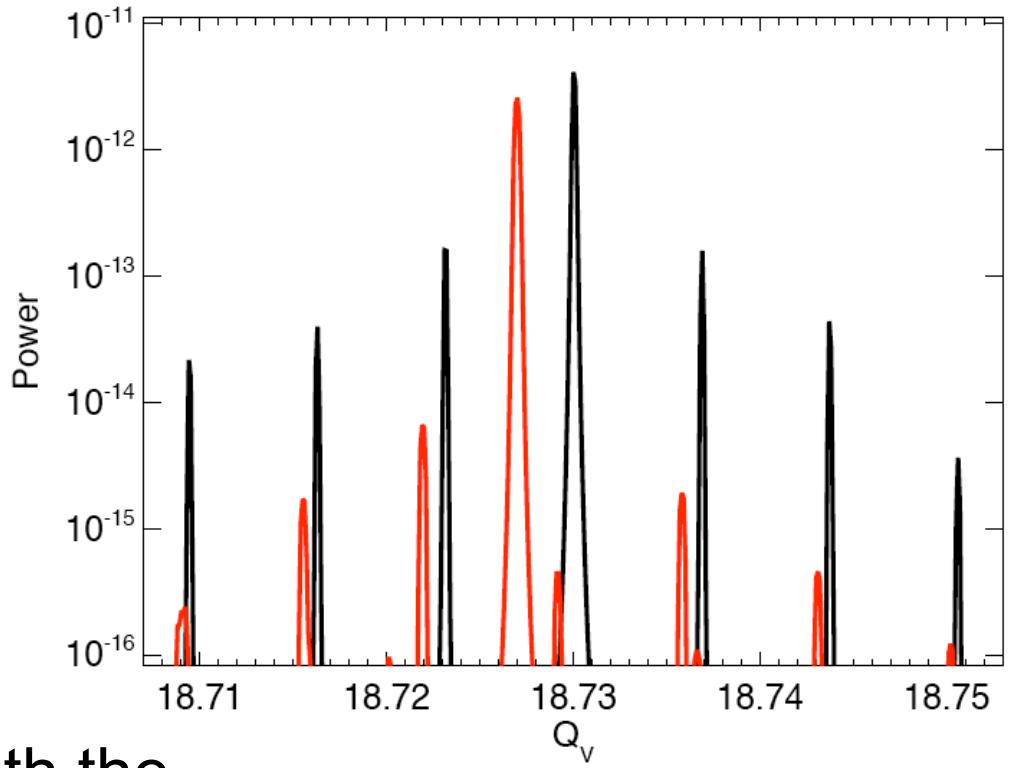

simulations with the HEADTAIL code,
$\Delta Q_{coh}$ at the bunch center ($Q_s$=0.0017)

# IMAGE CHARGES

Coherent Spectrum of the transverse bunch oscillations with Image Charges included

large synchr. freq.
$Q_s$=0.00686
$\Delta Q_{coh}$ = -0.004

black: without $\Delta Q_{coh}$
red: with $\Delta Q_{coh}$




shifts are consistent with the perturbation theory (A.Chao book), however, no Strong Head-Tail set in with large $\Delta Q_{coh}$

# SPACE CHARGE

Effect of Direct Space Charge
on Head-Tail modes
**preliminary results**

| PATRIC | HEADTAIL |
| --- | --- |
| frozen Space Charge for KV beam | beam-beam Space Charge module |
| ↓ | ↓ |
| damping effect | no effect |

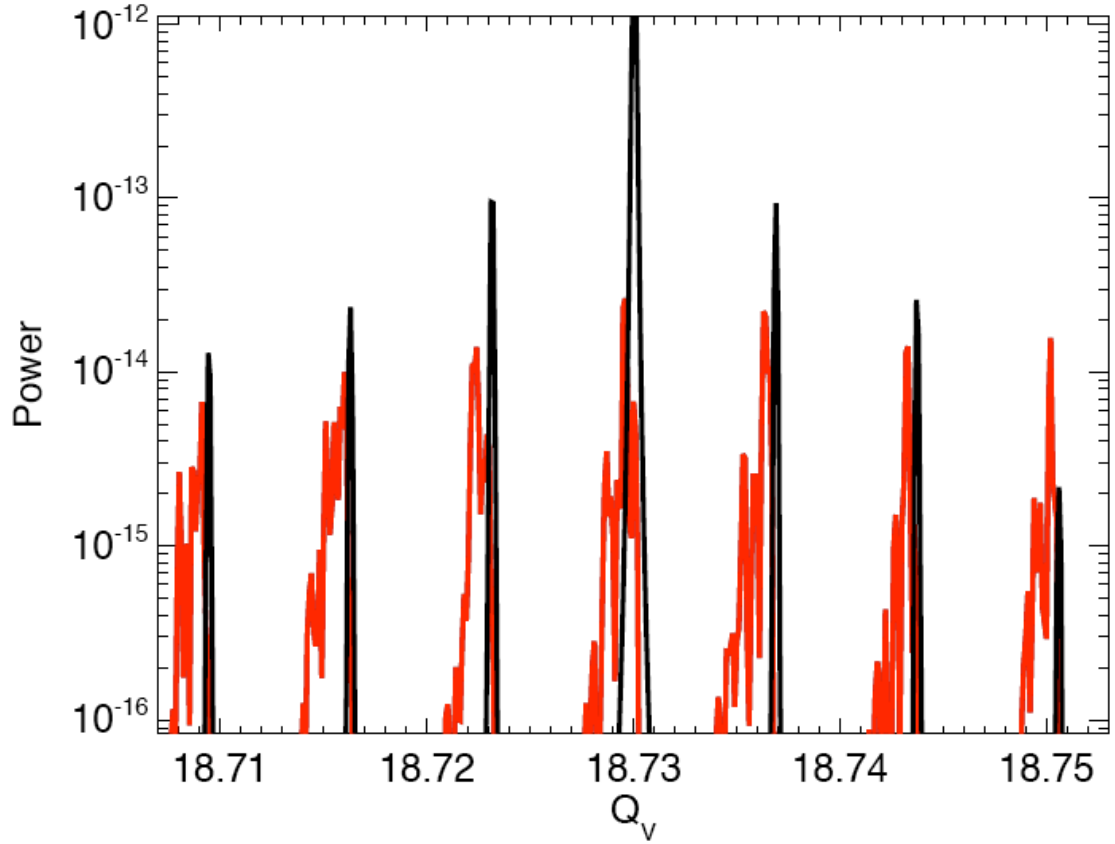
to be clarified:
- applicability of the beam-beam module
- applicability of non-self-consistent approaches

# SPACE CHARGE

Coherent Spectrum of the transverse bunch oscillations with Space Charge included

$Q_s$=0.00686
$\Delta Q_{SC}$ =-0.03

black: without SC
red: with SC




the coupling (uniform bunch) theory predicts shifts of $m \neq 0$ coherent lines

# NONLINEAR HF

Effect of nonlinear HF
on Head-Tail modes
**preliminary results**

**literature: statements that nonlinearity in synchrotron oscillation damp all Head-Tail modes for certain chromaticities**

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Sacherer theory only predicts independency of $\tau$ from the value of $Q_s$ (small $Q_s$) confirmed in simulation

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HEADTAIL: no effect from the nonlinearity
PATRIC: a damping effect

**the discrepancy to be clarified**

# NONLINEAR HF

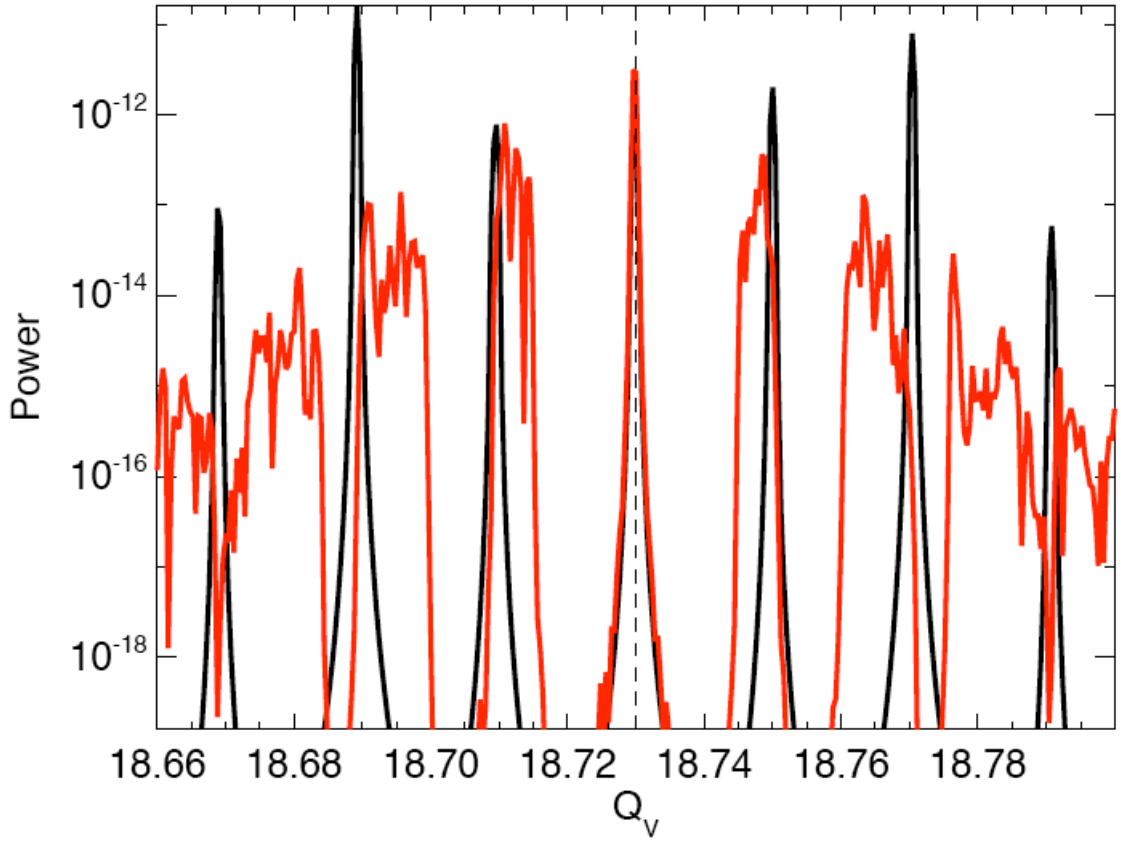
Coherent Spectrum of the transverse bunch oscillations with Nonlinearity in synchrotron oscillations included

$Q_s$=0.02

$\phi_m \approx 100°$

black: linear $\omega_s$

red: nonlinear




simulations with the PATRIC code

# SUMMARY

Head-Tail modes for FAIR synchrotron SIS100 must be studies taking into account:

- Image Currents
- Space Charge
- Nonlinearity in synchrotron oscillations

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Particle tracking simulations employing two different tools is chosen to deal with the problem

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Simulations with Image Currents taken into account suggest a damping effect, without triggering TMCI

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First simulations with non-self-consistent approaches for Space Charge reveal discrepancies

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The role of synchrotron nonlinearity should be clarified