Status of collective effects at GSI

Oliver Boine-Frankenheim

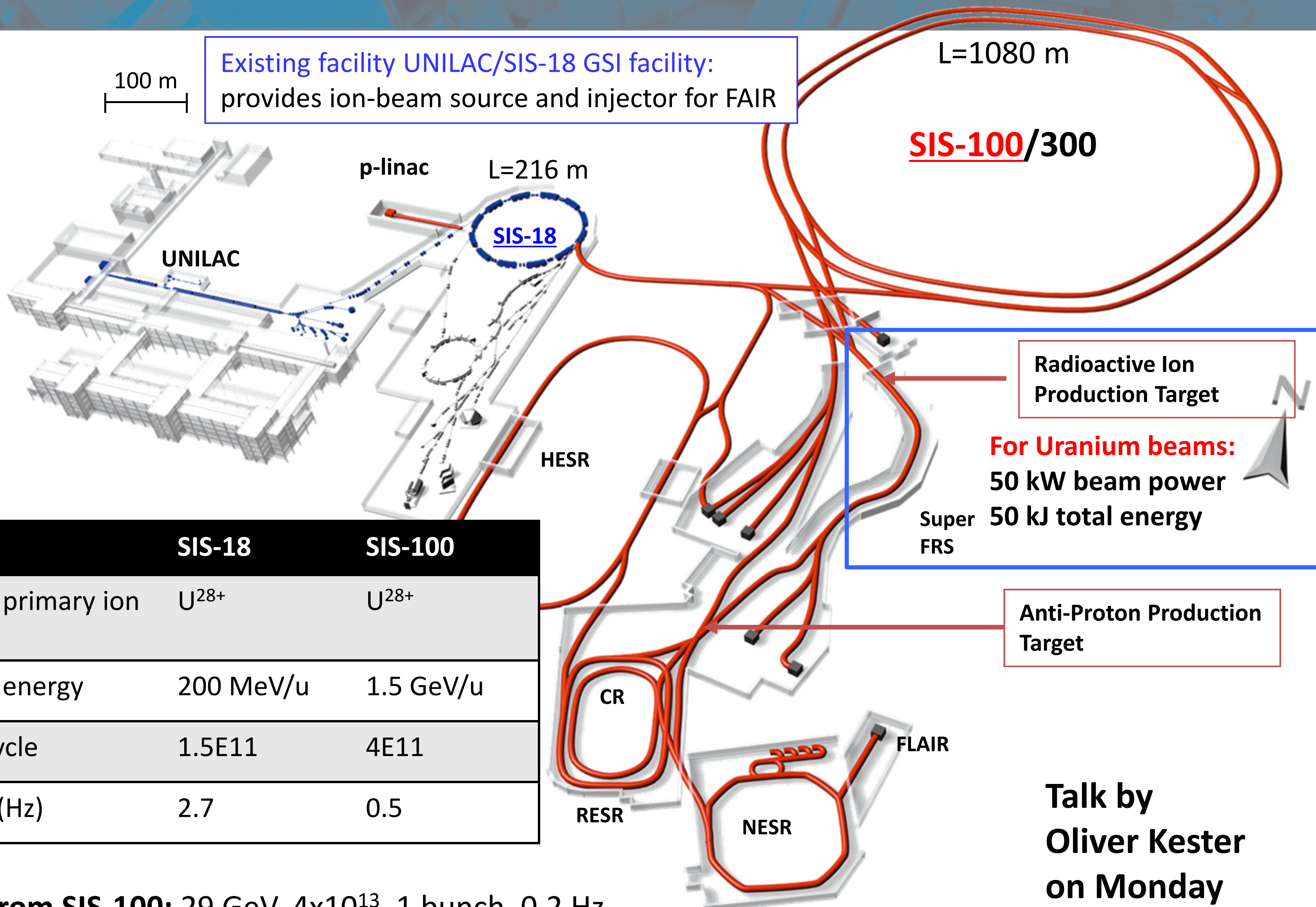
Beam physics department, GSI, Darmstadt *and* Computational electromagnetics laboratory, TU Darmstadt

Contents

- Collective effects at FAIR
- Simulation codes for collective effects in rings at GSI
- Impedances and expected transverse coherent instabilities
- Beam diagnostics: Interpretation of tune spectra using head-tail modes
- Conclusions

The FAIR accelerator facility

Existing facility UNILAC/SIS-18 GSI facility:
provides ion-beam source and injector for FAIR



	SIS-18	SIS-100
Reference primary ion	U^{28+}	U^{28+}
Reference energy	200 MeV/u	1.5 GeV/u
Ions per cycle	1.5E11	4E11
cycle rate (Hz)	2.7	0.5

Protons from SIS-100: 29 GeV, $4\text{x}10^{13}$, 1 bunch, 0.2 Hz

Talk by Oliver Kester on Monday

Collective effects in the FAIR rings

Incoherent space charge:

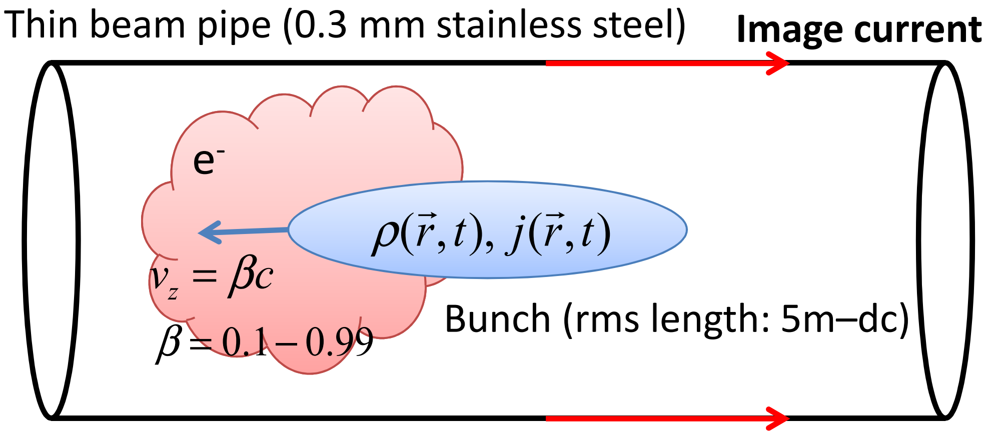
$\varepsilon_0 \nabla\cdot\vec{E} = \rho$ (in the rest system of the beam)

-> tune shift: $\Delta Q_y^{sc} \propto -\frac{q^2}{m}\frac{N}{B_f}\frac{4}{\varepsilon_y\beta_0^2\gamma_0^3}\frac{1}{1+\sqrt{\varepsilon_y/\varepsilon_x}}$

-> $\Delta Q^{sc} \lesssim 0.4$

-> beam loss and modification of coherent effects

Thin beam pipe (0.3 mm stainless steel)



Impedances:

$$\nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} \quad \nabla\times\vec{B} = \mu_0\vec{j} + \frac{1}{c^2}\frac{\partial\vec{E}}{\partial t}$$ (laboratory system)

-> image currents in the beam pipe

-> magnetic/resistive materials: ferrite, magnetic alloy

-> coherent instabilities and feedback requirements

Intrabeam scattering:

-> Beam cooling equilibrium in the HESR

Secondary particles:

electron clouds created by residual gas ionization and SEY.

-> trapping of electron during slow extraction, two-stream instability.

In the FAIR synchrotrons SIS-18 and SIS-100 different incoherent/coherent effects occur simultaneously.

Beam loss in SIS-100 has be limited below 5 % (injection energy) and 1-2 % (extraction energy)

-> Computer modeling in combination with dedicated experiments (model validation) is essential.

TECHNISCHE UNIVERSITÄT DARMSTADT

Simulation codes for collective effects in rings at GSI

MICROMAP (G. Franchetti):
- 3D particle tracking with error multipoles, 2D self-consistent, 3D adaptable space charge.
- **see presentation on Wednesday**

G. Franchetti et al., *Experiment on space charge driven nonlinear resonance crossing in an ion synchrotron*, PRST-AB 2010

PATRIC (O. Boine-F., V. Kornilov, et al.):
- 3D particle tracking with self-consistent 2.5D space charge solver and wake fields
- MADX maps, arbitrary rf bucket forms
- Implemented for multi-core CPUs using MPI.

V. Kornilov, O. Boine-F., *Head-tail instability and Landau damping in bunches with space charge*, PRST-AB 2010

External tracking codes with collective effects:
HEADTAIL, PTC/Orbit (CERN) + **pyorbit** (SNS)

CST EM and Particle Studio® (CST AG, Darmstadt)
+ 3D EM frequency domain solver for impedances
poster by U. Niedermayer (Monday)

U. Niedermayer, O. Boine-F., *Analytical and numerical calculations of resistive wall impedances for thin beam pipe structures at low frequencies*, NIM A 2012

LOBO (O. Boine-F.):
- Longitudinal beam dynamics with space charge, impedances, cooling, IBS, internal targets
- direct Vlasov-Fokker-Planck solver or PIC

O. Boine-F., *rf barrier compression with space charge*, PRST-AB 2010
O. Boine-F., A. Lehrach, et al., *Cooling equilibrium and beam loss with internal targets in the HESR*, NIM A 2006

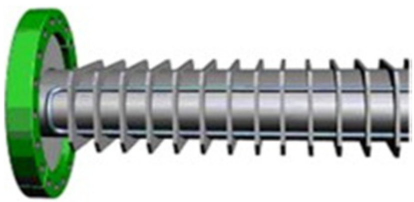
VORPAL (Tech-X) 3D EM PIC + 2D e-cloud codes

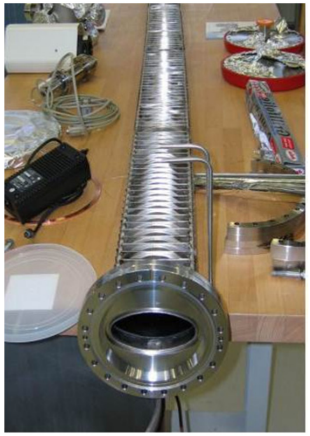
O. Boine-F., E. Gjonaj, F. Petrov, F. Yaman, T. Weiland, G. Rumolo, *Energy loss and longitudinal wakefield of short proton bunches in electron clouds*, PRST-AB 2012

Transverse SIS-100 beam pipe impedance

CST® EM Studio + frequency domain solvers

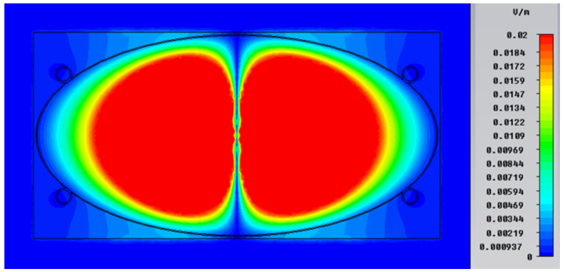
SIS-100 thin (**0.3 mm**) stainless steel beam pipewith cooling tubes attached.

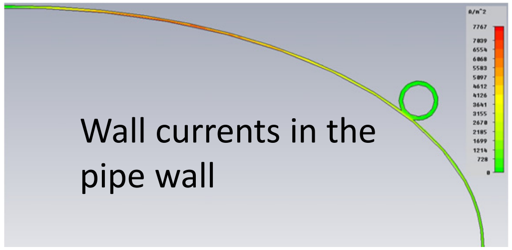




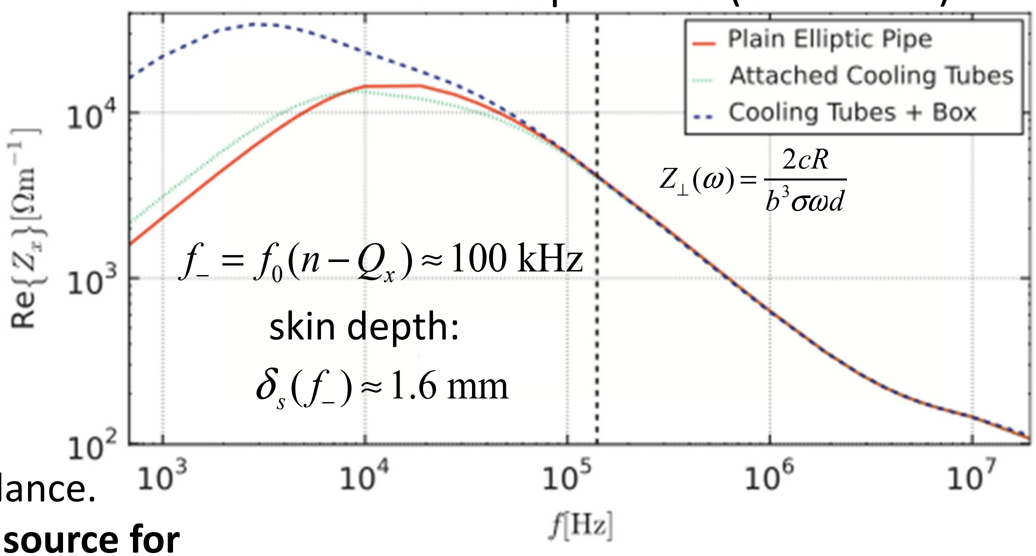
U. Niedermayer, O. Boine-F., *Analytical and numerical calculations of resistive wall impedances for thin beam pipe structures at low frequencies*, NIM A 2012

Longitudinal electric field in the SIS100 pipe structure resulting from a dipolar excitation (300 kHz).





Transverse impedance (horizontal)

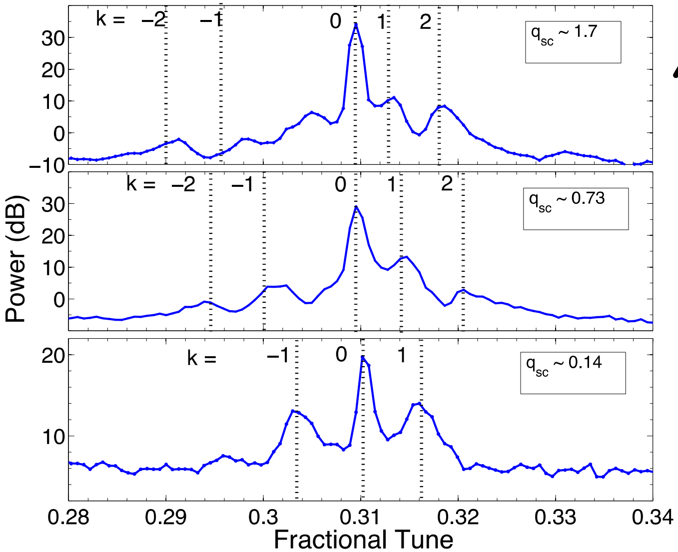


- In the frequency range of interest outside structures do not contribute to the impedance.
- **The thin resistive beam pipe is the major source for the expected head-tail instabilities in SIS-100**.

Next step: ferrite kickers and bench measurements (**see poster by Uwe Niedermayer**)

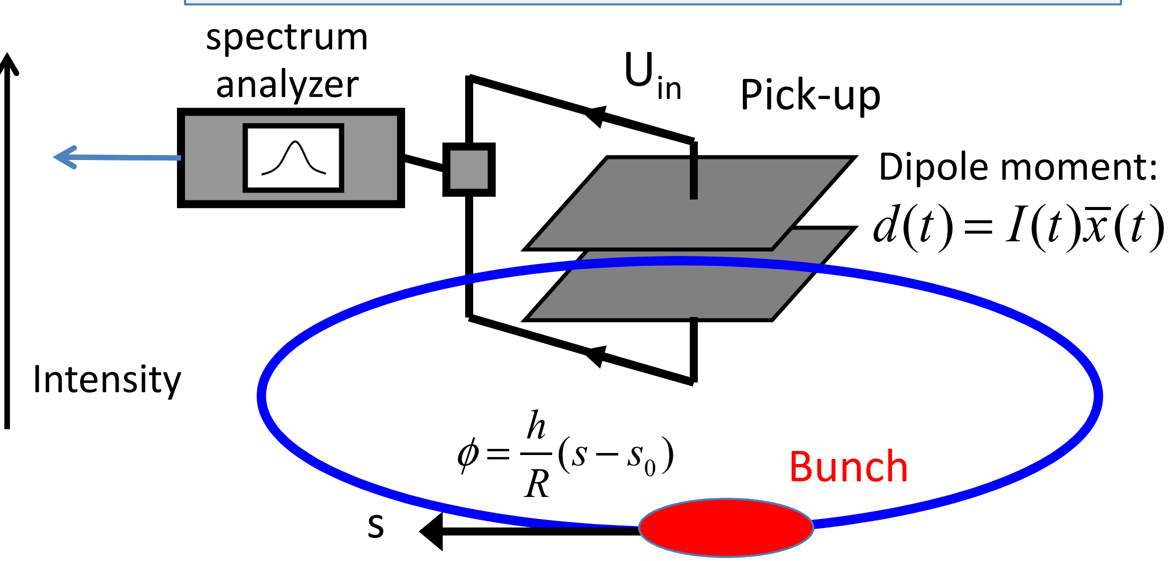
Tune spectra (low intensity bunches)

Tune spectrum: FFT[Dipole moment per turn]



R. Singh, P. Forck, et al.

Difference signal U_Δ : beam 'offset' fluctuations $\bar{x}$



local dipole moment: $I(\phi)\bar{x}_k(\phi) \propto e^{-i\chi\phi/\phi_b} e^{-iQ_k t}$

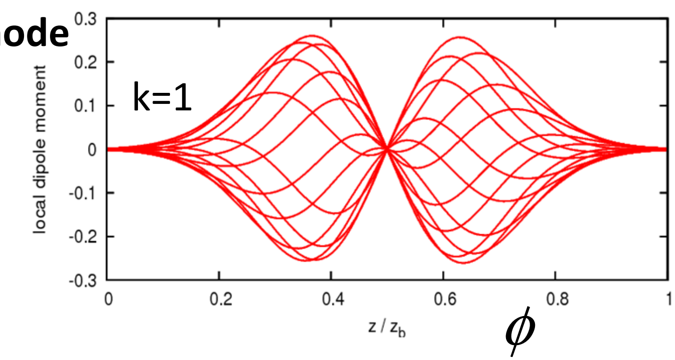
Synchrotron satellites (synchrotron tune Q_s):

$$Q_k = Q_0 + kQ_s \quad \text{or} \quad \Delta Q_k = kQ_s$$

Tune spread in a rf bucket (rms bunch length σ):

$$\delta Q \approx kQ_s \frac{\sigma_\phi^2}{4}$$

head-tail mode



tune spectra -> measure and control the tune (e.g. to avoid resonances)

TECHNISCHE UNIVERSITÄT DARMSTADT

Tune spectra for high intensities: Theory

Simplified transverse particle equation of motion (e.g. D. Möhl, 1995):

$$x''(\phi,s)+\frac{Q_{x0}^2}{R^2}x-\frac{2Q_{x0}\Delta Q_x^{sc}}{R^2}(x-\bar{x})=\frac{2Q_x\Delta Q_x^c}{R^2}\bar{x}$$

(bare betatron tune) (space charge) (image current/charges)

$$\bar{x}(\phi,s)=\int x\rho(x,y,\phi,s)dxdy$$

(local offset)

SIS-18/100: q_{sc}=10-20

CERN PSB/PS: q_{sc} ≥100

Longitudinal (synchrotron) oscillations: $\phi''(s)=\hat{\phi}\sin(Q_{s0}s/R)$

Coherent shift due to image currents: $\Delta Q^c\approx\frac{a^2}{b^2}\Delta Q^{sc}$

-> important for thick beams ! (a: beam radius, b: pipe ra

space charge and image current parameters: $q_{sc}=\frac{\Delta Q^{sc}}{Q_{s0}}$ $q_c=\frac{\Delta Q^c}{Q_{s0}}$

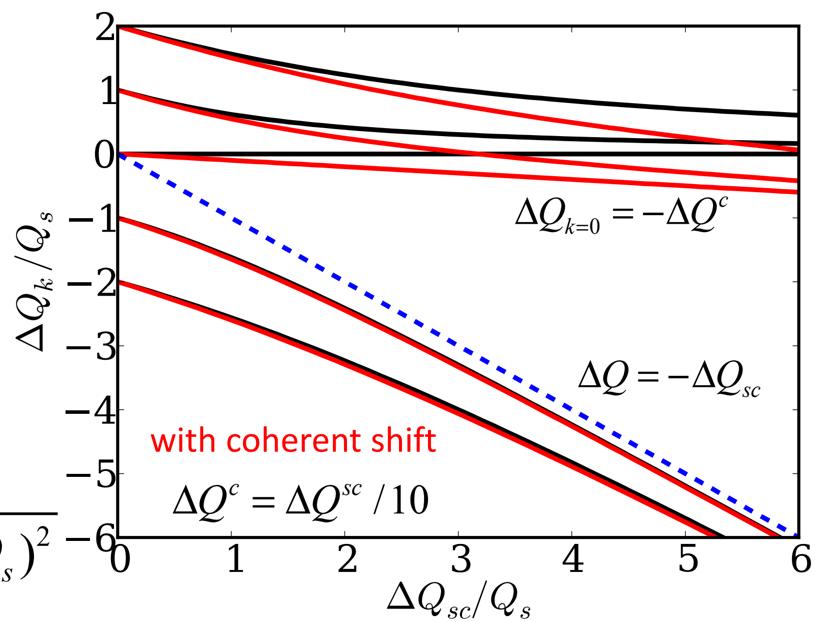
head-tail tune shifts (longitudinal **airbag distribution)**:

$$\Delta Q_k=-\frac{\Delta Q_{sc}}{2}\pm\sqrt{(\Delta Q_{sc}/2)^2+(kQ_s)^2}$$

$\Delta Q^{sc}=0:\quad \Delta Q_k=kQ_s$

$\Delta Q^c>0:$

$$\Delta Q_k=-\frac{\Delta Q_{sc}+\Delta Q_c}{2}\pm\sqrt{(\Delta Q_{sc}-\Delta Q_c)^2/4+(kQ_s)^2}$$



Blaskiewicz, Phys. Rev. ST Accel. Beams (1998)

Boine-F., Kornilov, Phys. Rev. ST Accel. Beams (2009), Burov (2009), Balbekov (2009)

Tune spectra from real bunches

The airbag model shows good agreement with tune spectra for Gaussian bunches (PATRIC simulations and SIS-18 measurements) -> V. Kornilov, O. Boine-F., arXiv (2012)

Modified airbag model:

$$\Delta Q_k = -\frac{\Delta Q_{sc}}{2} \pm \sqrt{(\Delta Q_{sc}/2)^2 + (k Q_{s1})^2}$$

$$\Delta Q_{sc} = \frac{q I_p R}{4\pi\epsilon_0 c E_0 \gamma_0^2 \beta_0^3 \varepsilon_x}$$

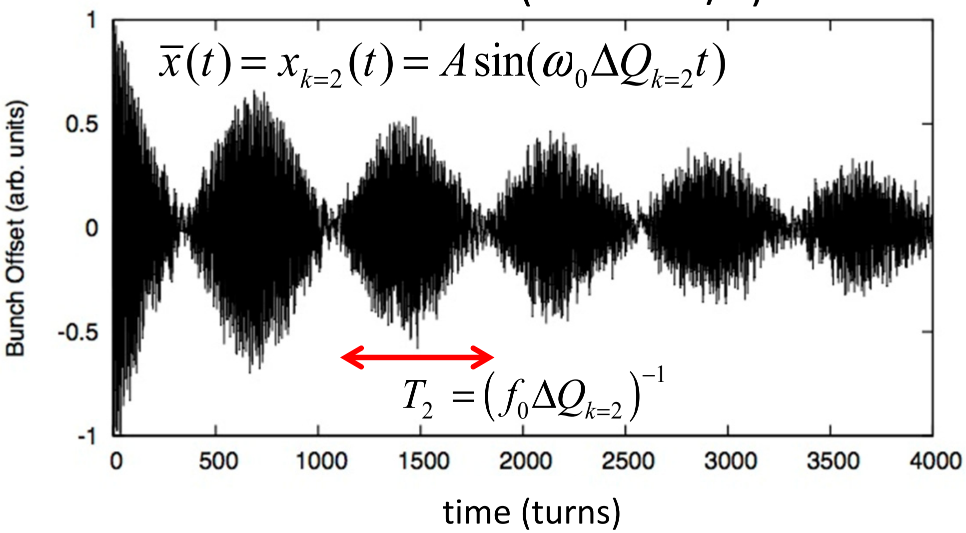
(sc tune shift in the bunch center)

$$\frac{Q_{s1}}{Q_{s0}} = \sqrt{1 - \frac{\sigma_\phi^2}{2}}$$

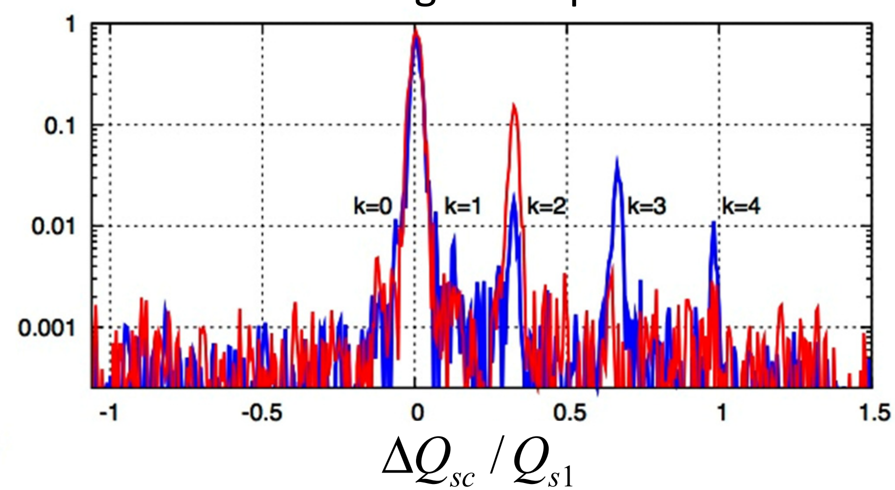
(longitudinal dipole tune)

Measured decoherence signal from a kicked Ar^{18+} bunch (100 MeV/u)

$$q_{sc} \approx 10, \quad q_c \ll 1$$



Resulting tune spectrum



Thin beam (a<<b): coherent tune shift can be neglected

TECHNISCHE UNIVERSITÄT DARMSTADT

Measured SIS-18 tune spectra (noise excitation)

11.4 MeV/u (injection energy), 0.3-1.0 x 10^{10} N^{7+} bunches

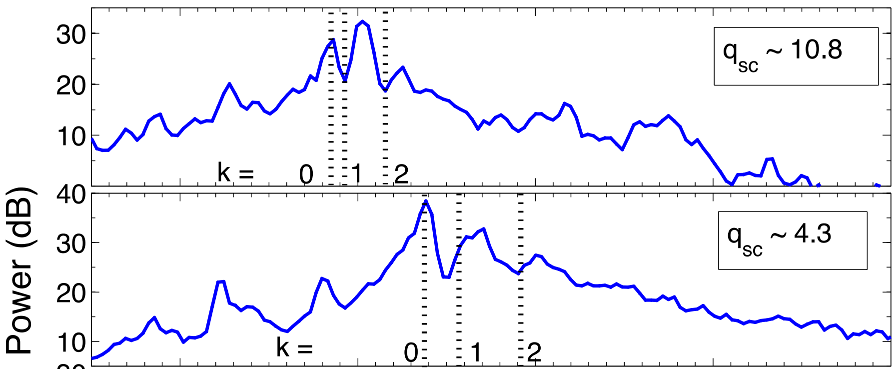
Thick beams (a≈b/3): coherent tune shift is important

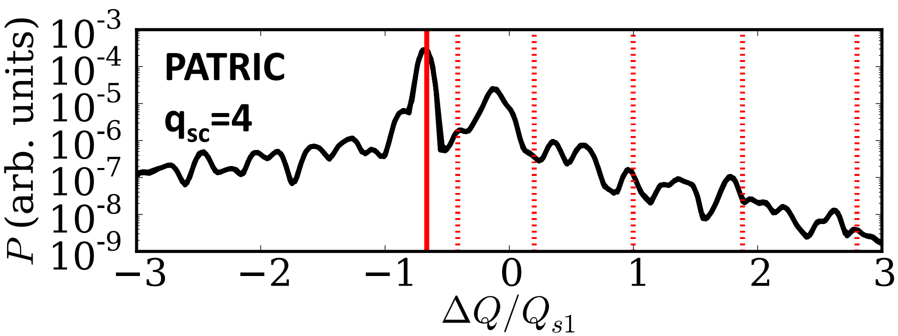
$$\Delta Q_k = -\frac{\Delta Q_{sc} + \Delta Q_c}{2} \pm \sqrt{(\Delta Q_{sc} - \Delta Q_c)^2 / 4 + (kQ_{s1})^2}$$

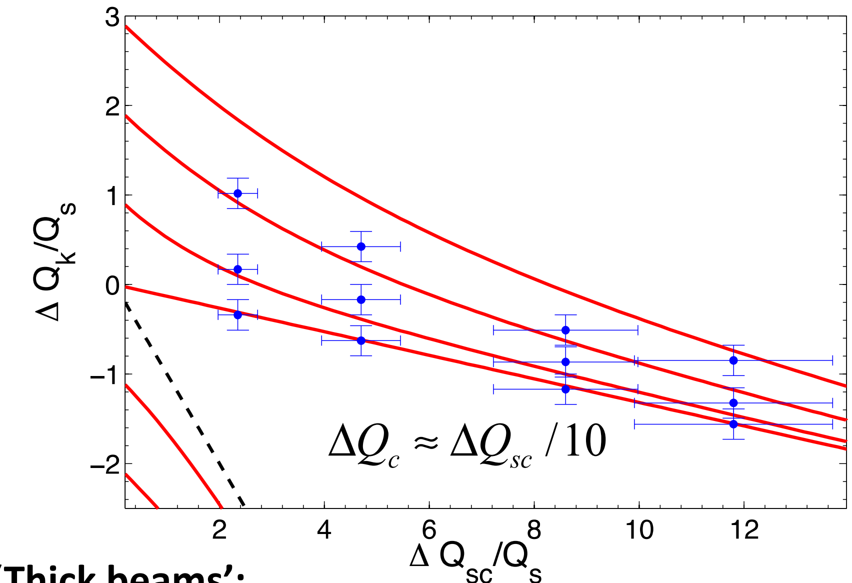
ΔQ_{sc} : from beam profile measurement (IPM)

Q_{s1} : from longitudinal Schottky signal

ΔQ_c : from the shift of the k=0 line.







'Thick beams':

- deviation from the modified airbag model.
- broadening of the lines -> intrinsic Landau damping (Burov 2009, Balbekov 2009)

R. Singh, P.Forck, P. Kowina, O. Boine-F., et al., *Interpretation of tune spectra for high intensity*, to be published

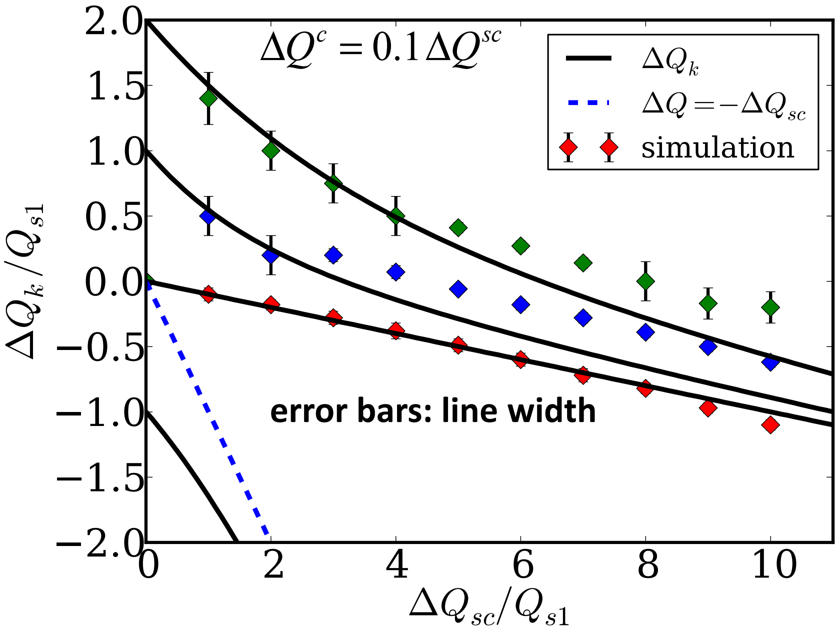
-> **see presentation by Oleksandr Chorniy**

Computer tune spectra

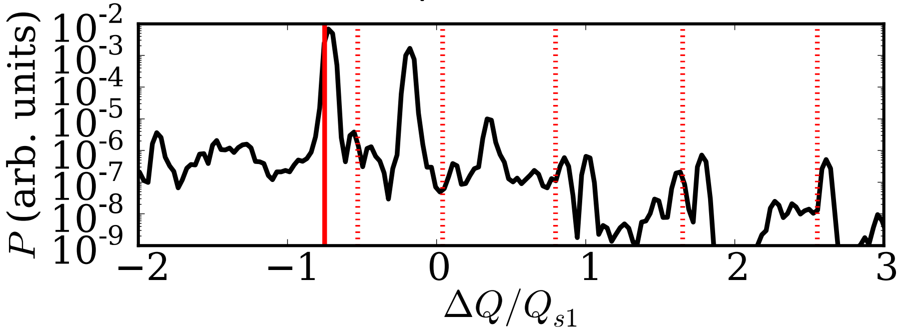
self-consistent space charge

PATRIC: 3D tracking with 2.5D self-consistent space charge solver, pipe with circular boundary.

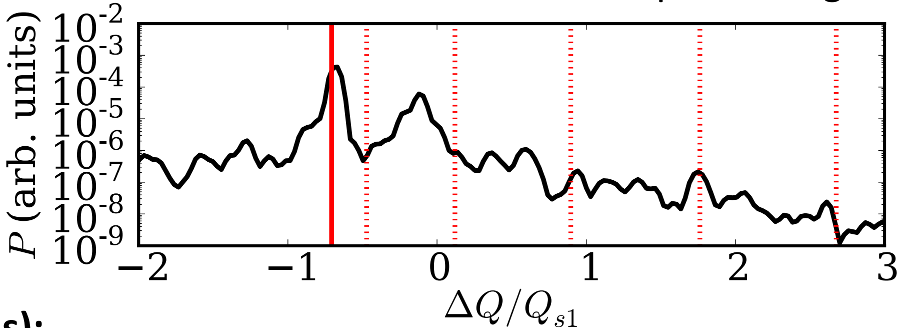
$$\Delta Q_k = -\frac{\Delta Q_{sc}}{2} \pm \sqrt{(\Delta Q_{sc}/2)^2 + (k Q_{s1})^2}$$



PATRIC: Möhl's equation for $q_{sc} = 4, \quad q_c = 0.1$



PATRIC: 2.5D self-consistent space charge



In the presence of a coherent tune shift (thick beams):

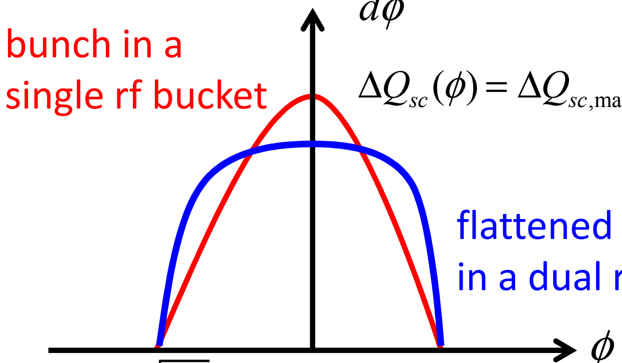
- Agreement with the measurements (positions and widths of the lines)
- Similar deviations from the modified airbag model.
- Self-consistent space charge model is required !

Computer tune spectrum in dual rf buckets

Dual rf voltage: $V_{rf}(\phi) = V_0(\sin(\phi) + \frac{1}{2}\sin(2\phi))$

$$\lambda(\phi) = \frac{dN}{d\phi}$$

$$\Delta Q_{sc}(\phi) = \Delta Q_{sc,\max}\frac{\lambda(\phi)}{\lambda(0)}$$



$$\frac{Q_{s1}}{Q_{s0}} \approx \sqrt{\frac{10}{7}}\sigma_\phi$$ (synchrotron dipole mode)

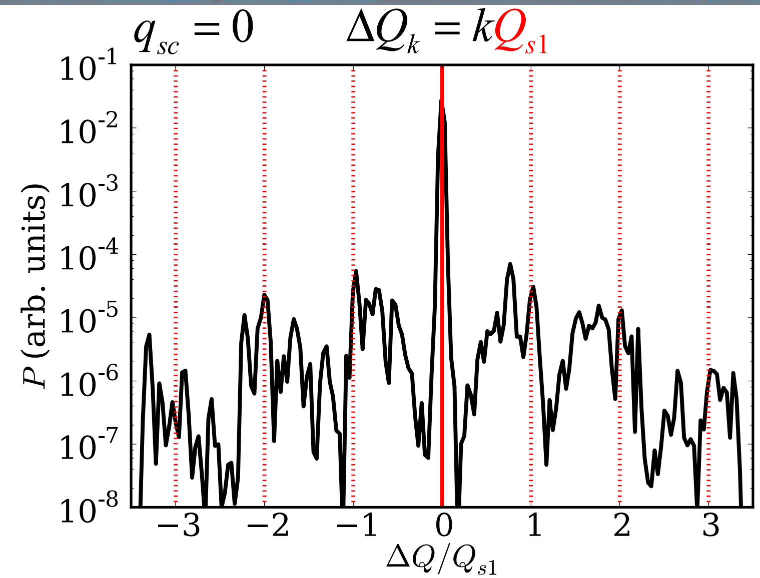
-> poster by Monika Mehler

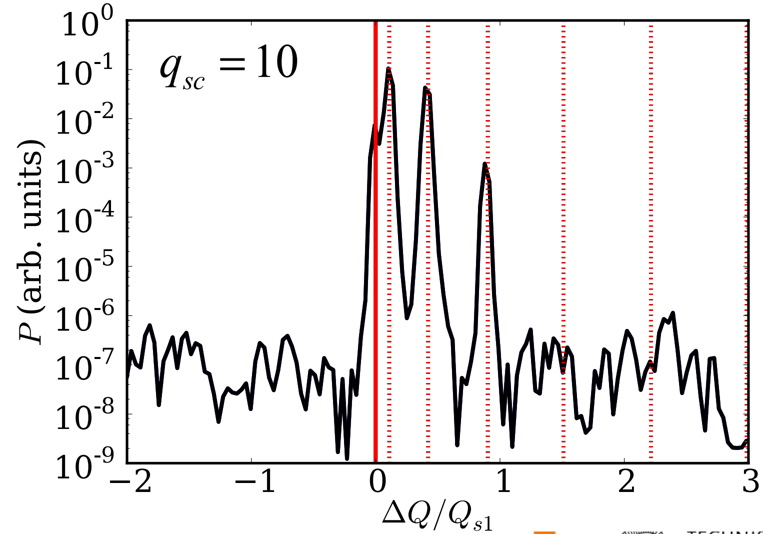
$$\Delta Q_k = -\frac{\Delta Q_{sc}}{2} \pm \sqrt{(\Delta Q_{sc}/2)^2 + (kQ_{s1})^2}$$

Preliminary results for dual rf:

- Good agreement with modified airbag model (thin beams).
- No space charge: strongly damped head-tail modes
- Space charge: undamped (k < 4) head-tail modes

-> Compare to observed head-tail instability thresholds in the CERN PSB (V. Kornilov, et al.)





TECHNISCHE UNIVERSITÄT DARMSTADT

Conclusions

- For the optimization of the GSI and FAIR rings, including **the important interplay of incoherent and coherent collective effects**, different **simulations codes** are employed, in combination with **dedicated beam physics experiments in the GSI SIS-18 and in the CERN PSB/PS**.

- For the interpretation of tune spectra in the presence of space charge we successfully used the PATRIC simulation code together with a modified 'airbag' model for head-tail oscillations.
  -> direct measurements of the **incoherent space charge tune shift** from the **coherent tune spectrum** !

- Measurements, simulations (with self-consistent sc) indicate that **the coherent tune shift caused by the image currents (-> thick beams) in the pipe can strongly increase the damping of head-tail modes**.

- From simulations: **In a dual rf bucket the tune spectrum shows pronounced (low-order) head-tail modes** in the presence of space charge (similar indications from CERN PSB experiments)

For the FAIR synchrotrons (SIS-18/100) -> additional intrinsic damping of head-tail modes expected.

Next step (for the FAIR synchrotrons):
- Systematic **simulation+experimental studies** of head-tail modes, instability thresholds with space charge, including the pipe impedance, **dual rf buckets and dampers/octupoles**.