Transverse Schottky spectra and beam transfer functions of coasting ion beams with space charge

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Outline

- FAIR and SIS-18
- Schottky diagnostics and beam transfer functions
  - Effect of linear space charge
- Measurement of space-charge effects
- Simulation of space-charge effects
- Summary

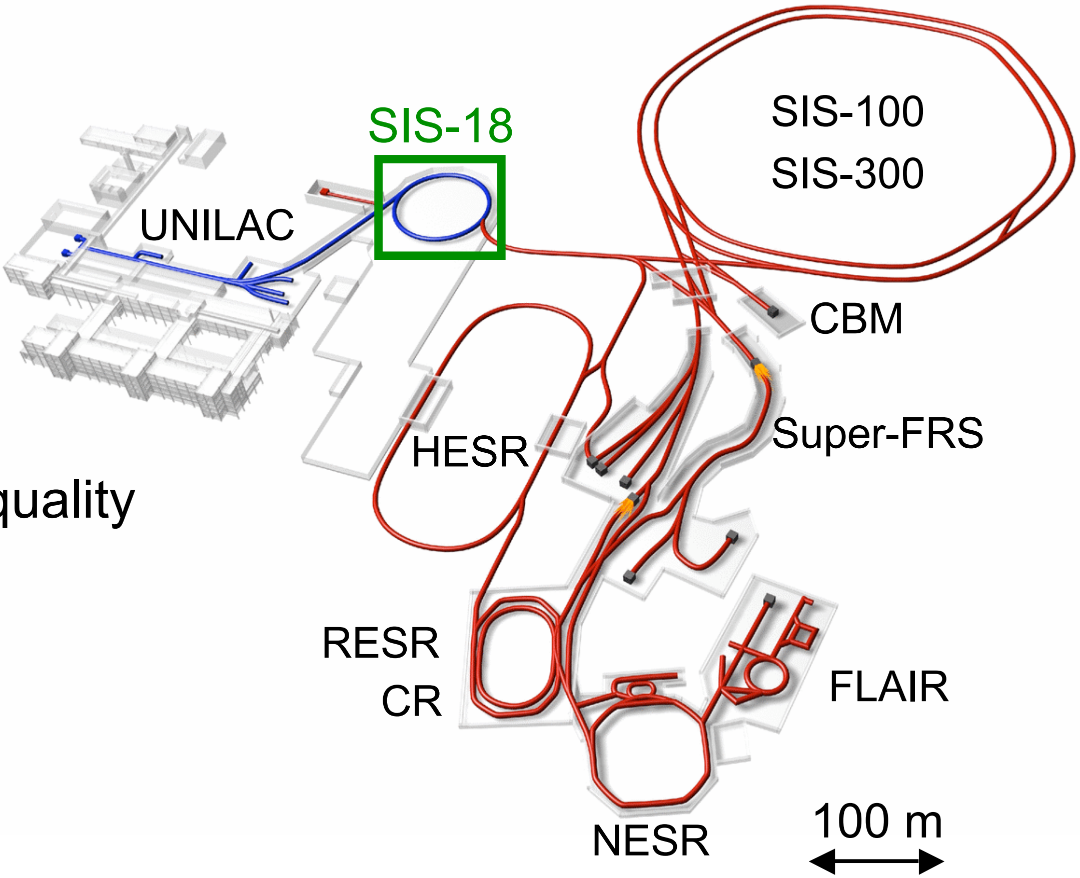
FAIR at GSI

FAIR: experiments with high quality and high intensity beams

SIS-18 becomes booster

- Increase of beam intensity
- Arise of collective effects
  → Degradation of beam quality and particle losses

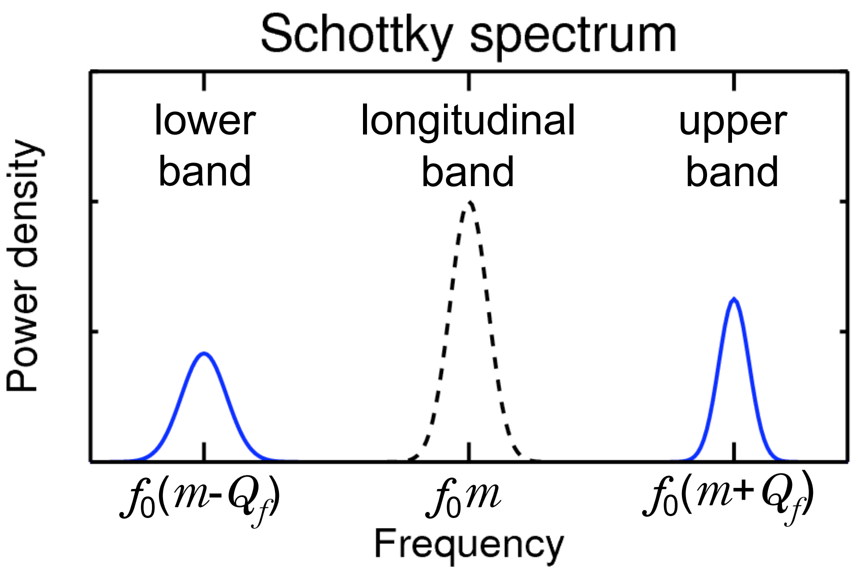
Low energy
→ strong space charge



P. Spiller, MOIC01

Low intensity Schottky spectrum

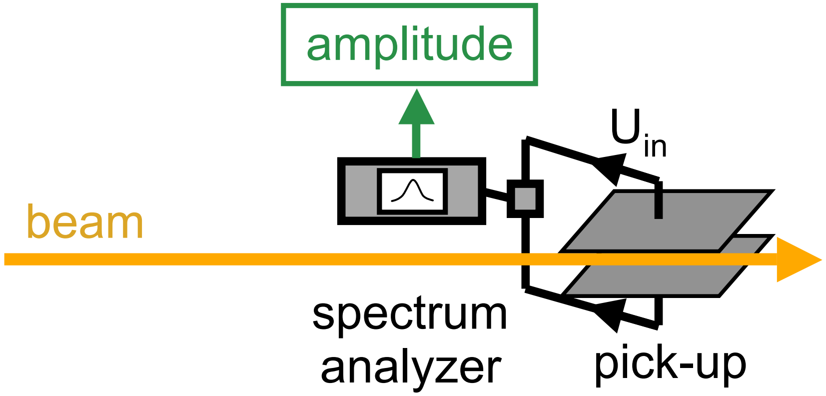
- Based on statistical fluctuations of local beam current and current dipole moment
- Non-destructive measurement of
  - Revolution frequency f_0
  - Fractional tune Q_f
  - Momentum spread
- Features
  - Longitudinal bands peaking at $f_0 m$
  - Side bands $P_0(f)$ centered around $f_0(m \pm Q_f)$
  - Width of sidebands $\sigma_m^{\pm}$

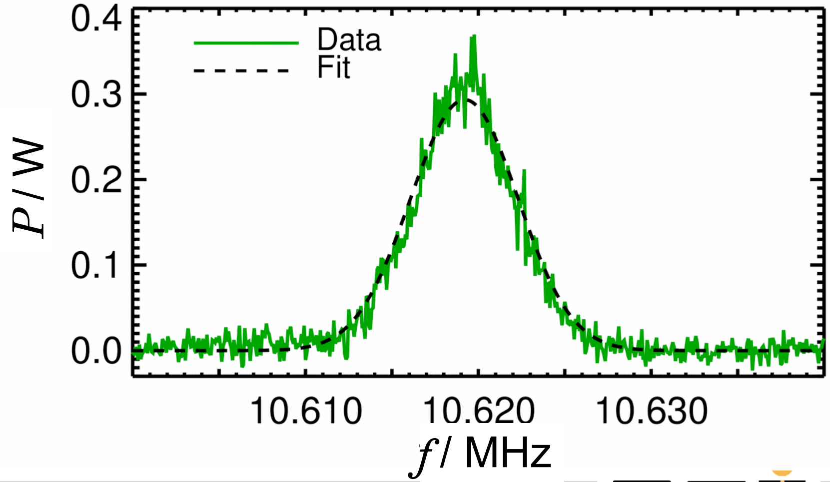


Schottky detection

Requires

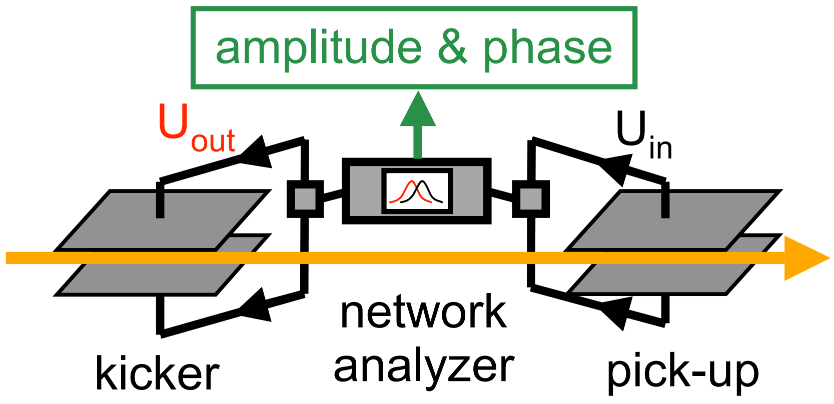
- Pick-up
- Sum amplifier for longitudinal spectrum
- Difference amplifier for transverse spectrum
- Spectrum analyzer

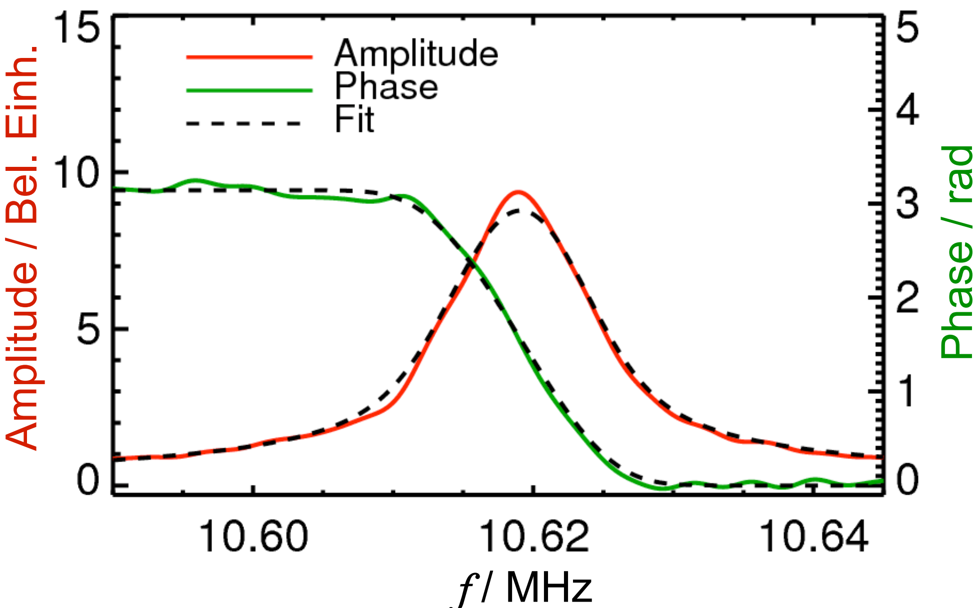




Transverse beam transfer functions (BTFs)

- BTF $r_0(f)$ defined as ratio of beam response to excitation
- Requires
  - Network analyzer
  - Exciter (kicker)
  - Pick-up
  - Difference amplifier
- Alternative to Schottky diagnosis
- Stability analysis

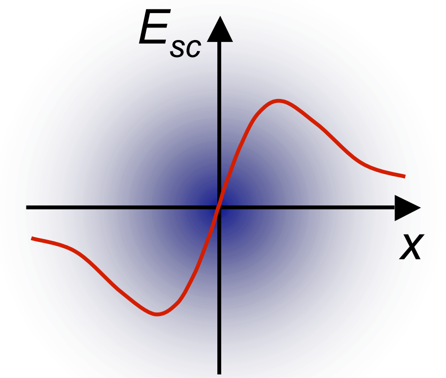




Impedance and space charge

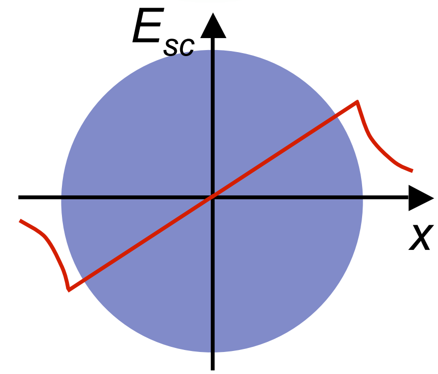
- Impact of transverse dipolar impedances
  - Coherent tune shift ΔQ_{coh}
  - Coherent dipolar instability with growth rate τ—if not Landau damped
  - Impedance parameters

$$\Delta U_{coh} = \frac{\Delta Q_{coh} f_0}{\sigma_m^{\pm}} \text{ and } \Delta V = \frac{1}{\tau \sigma_m^{\pm}}$$



- (Direct) space charge
  - Non-linear self-field, very difficult to model $\rightarrow$ tune spread
  - Linearized self-field (of K-V beam) $\rightarrow$ incoherent tune shift

$$\Delta Q_{sc} \propto \frac{N}{\epsilon}$$



Diagnostics with collective effects

High intensity BTF [1] and Schottky band [2]

$$r(f) = \frac{r_0(f_{sc})}{1 - (\Delta U_{coh} + \mathrm{i}\Delta V - \Delta U_{sc})r_0(f_{sc})}$$

$$P(f) = \frac{P_0(f_{sc})}{|1 - (\Delta U_{coh} + \mathrm{i}\Delta V - \Delta U_{sc})r_0(f_{sc})|^2}$$

with $\Delta U_{sc} = \frac{\Delta Q_{sc} f_0}{\sigma_m^{\pm}}$ and $f_{sc} = f \mp \Delta U_{sc}\sigma_m^{\pm}$

[1] D. V. Pestrikov, NIM A, **578**, 1, 2007; S. Paret et al., PRST-AB, **13**, 2, 2010

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deformation
impedance and space charge

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deformation
impedance and space charge

shift
space charge only

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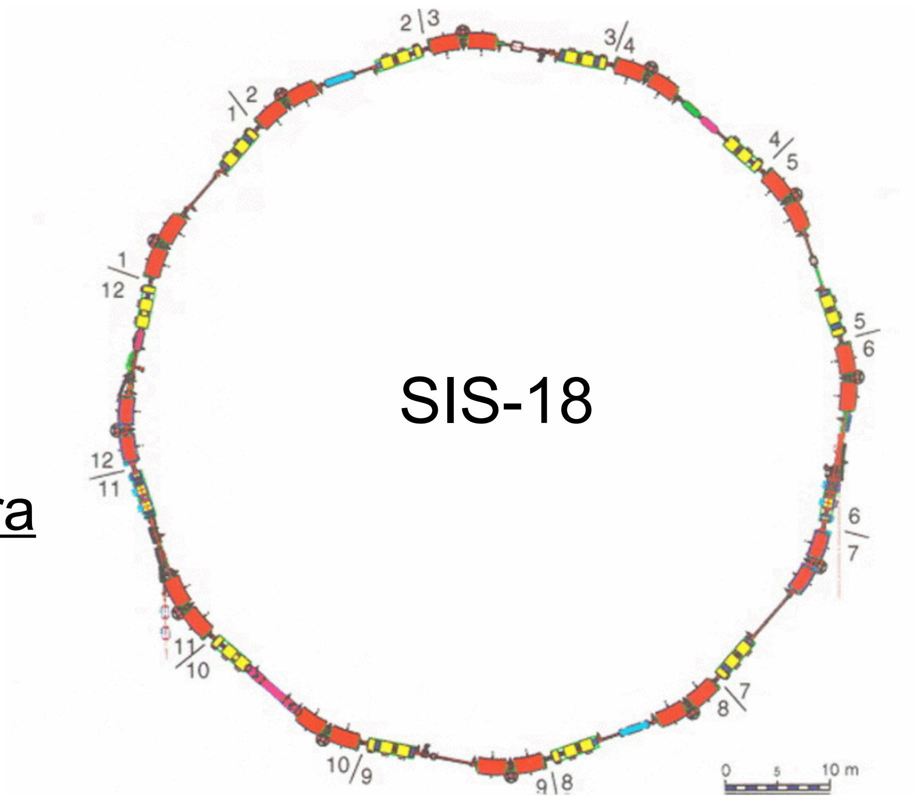
Experimental setup

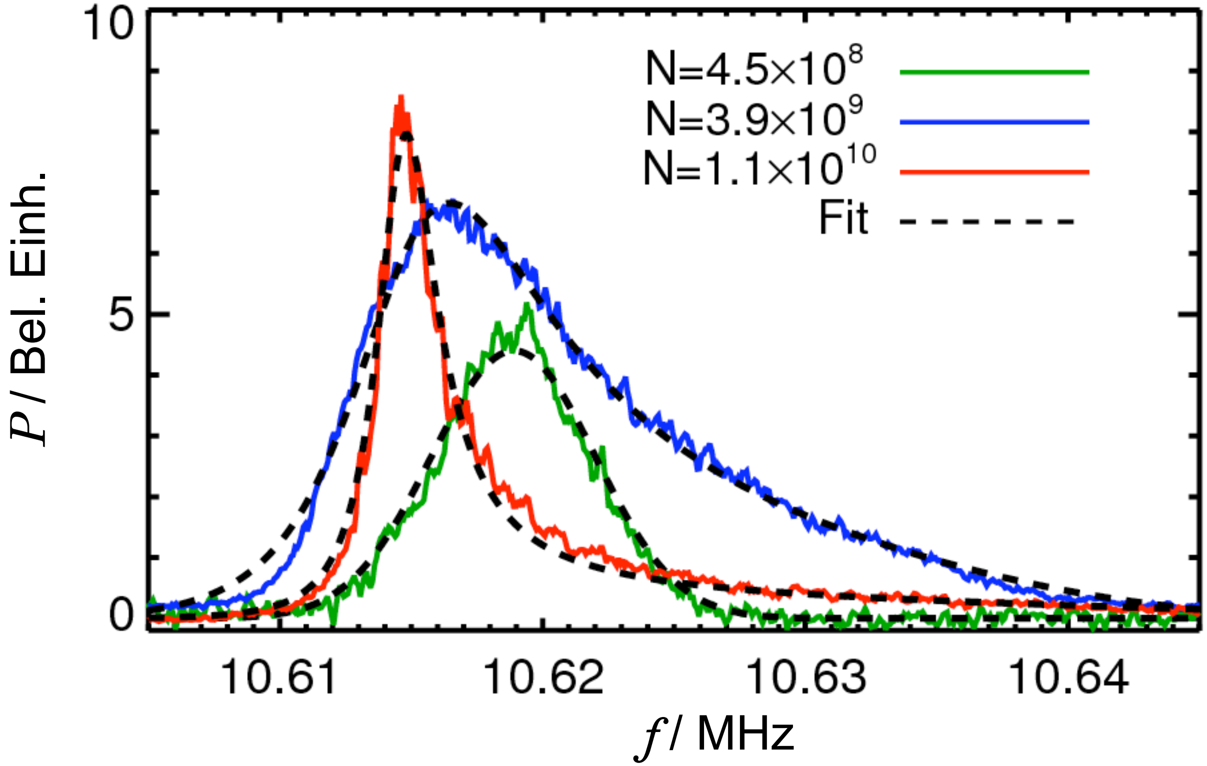
- Energy 11.4 MeV/nucleon
- Detection of
  - Ion number N
    varied from 2.5×10^{8} to 1.1×10^{10} Ar^{18+} ions
  - Longitudinal Schottky Spectra
    → Gaussian momentum distribution
  - Beam profiles
    with ionization profile monitor → emittance
- ΔU_{coh}, $\Delta V \ll \Delta U_{sc}$ → only ΔU_{sc} taken into account



Measured Schottky bands

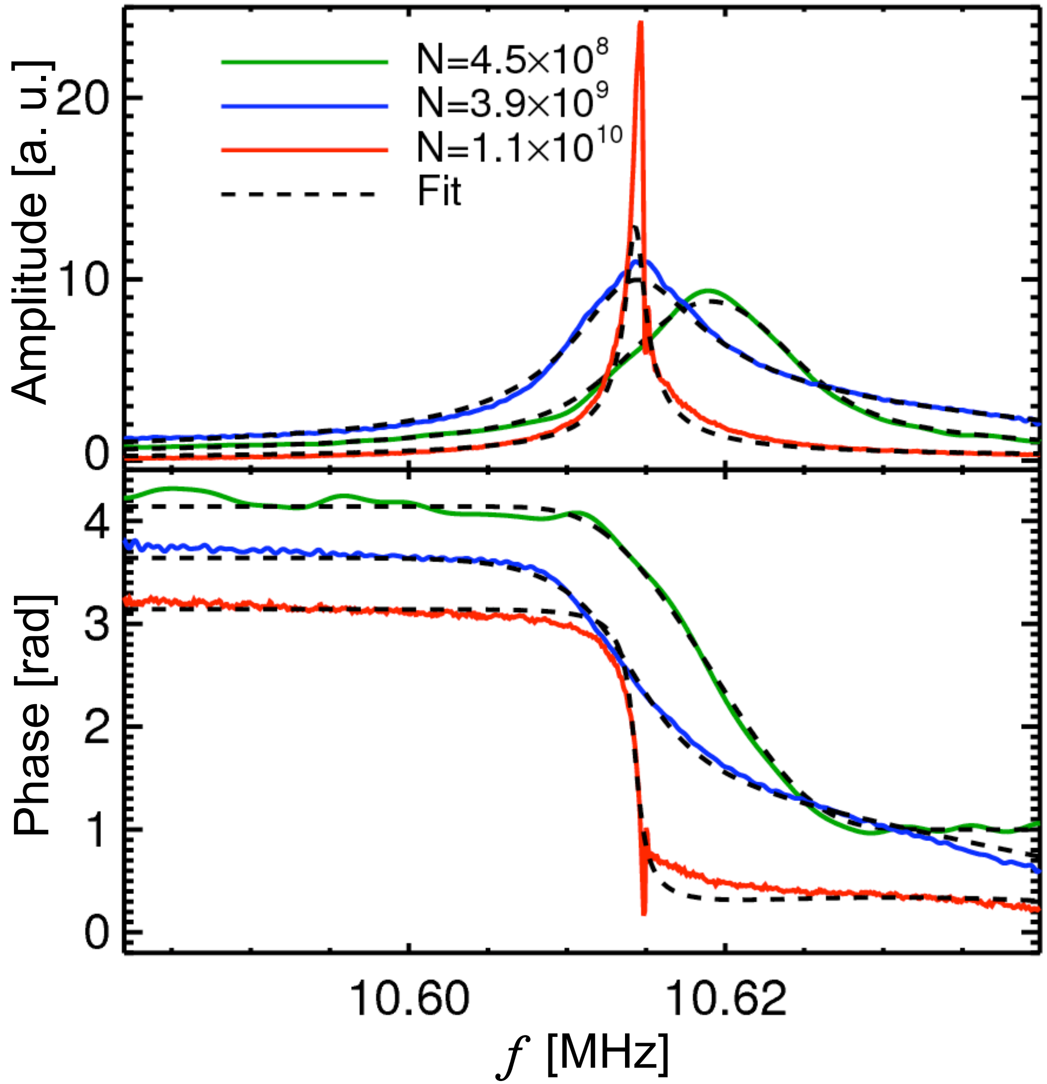
- Fit of $$P(f) = \frac{P_0(f_{sc})}{|1 + \Delta U_{sc} r_0(f_{sc})|^2}$$

- Good agreement at low, medium and maximal intensity



Measured BTFs

- Noise suppression via time gating
- Fit of $r(f)$
  - Good agreement at low intensity
  - Deviations at high intensity

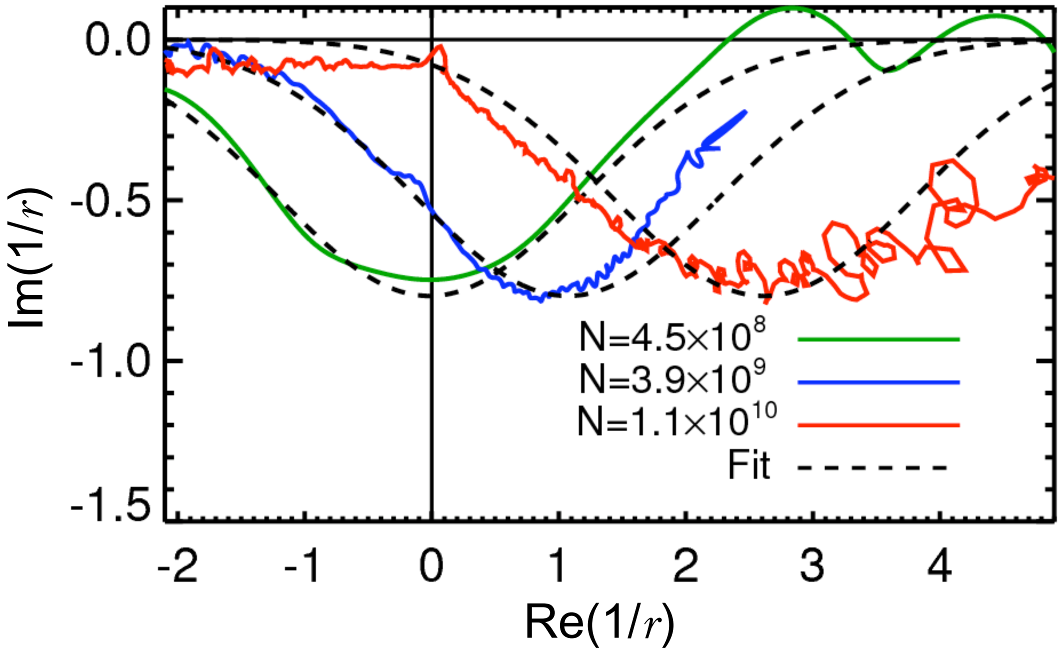


Measured stability diagrams

- Stability diagram with space charge

$$\frac{1}{r(f)} = \frac{1}{r_0(f_{sc})} + \Delta U_{sc}$$

- Shifted as expected
- Approximately shaped as expected
- Disturbed by noise at high intensity

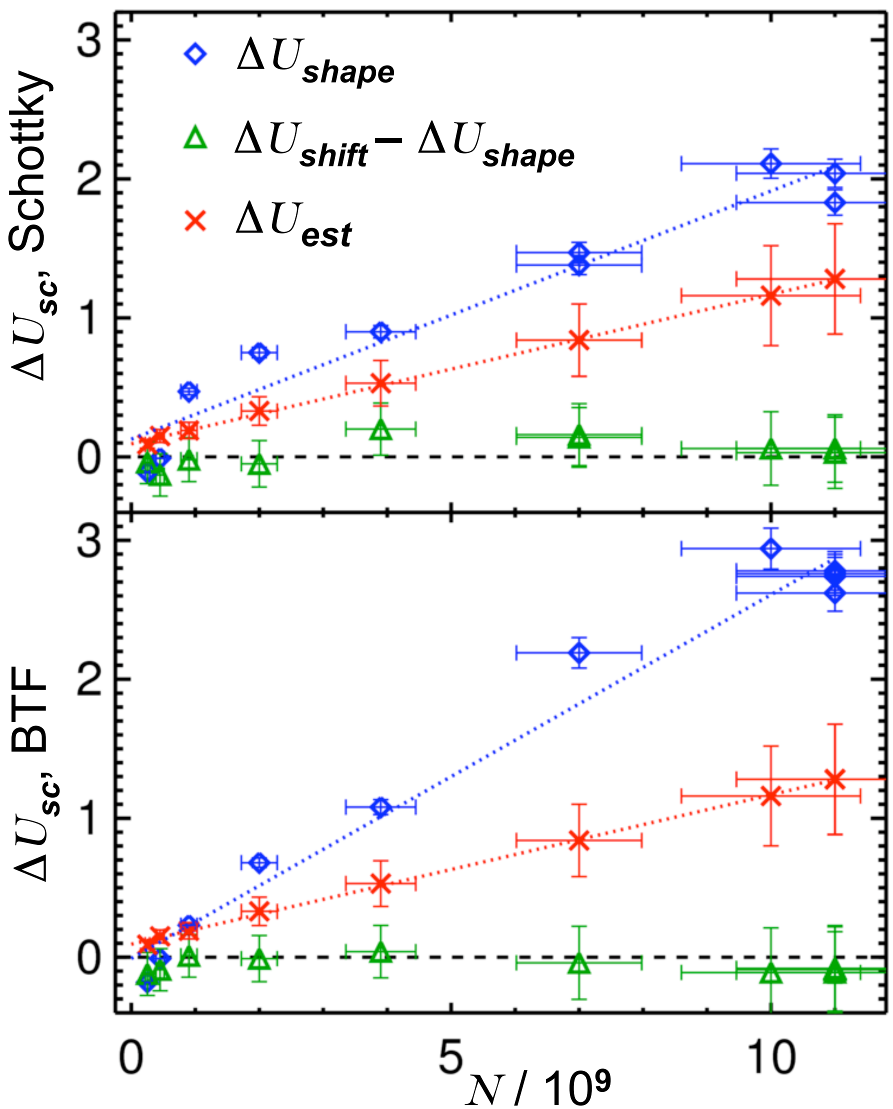


Measured space-charge parameter

- Estimation with beam parameters → ΔU_{est}
- Deformation of signal → ΔU_{shape}
- Position of signal (f_{sc}) → ΔU_{shift}

  Consistency → ΔU_{shift}-ΔU_{shape} = 0

- ΔU_{sc} grows linearly with N
- Measured ΔU_{sc} larger than estimation
- Larger ΔU_{sc} for BTF



Possible error sources

Beam parameters

- Uncertainty of beta function at profile monitor
- Degradation of detector components

BTFs

Beam of high intensity close to coherent instability

- Nonlinear response to excitation?
- Perturbation by resonance?

PIC simulations

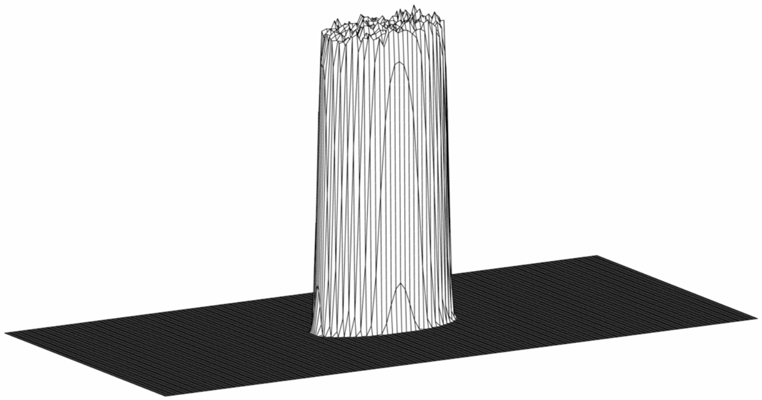
- Random macro particle distribution in phase space

  Fluctuation of dipole moment → transverse Schottky spectrum

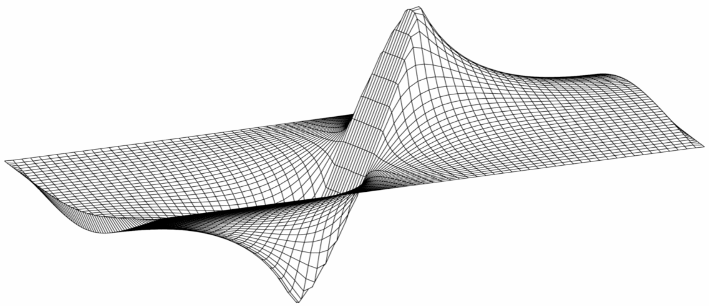
- Self-consistent field computation in 2D
- Options:
  - Excitation with noise for BTF
  - Impedance kicks
- Transverse profiles: K-V beam or Gaussian
- Maximal $\Delta U_{sc} = 2$

K-V beam

density

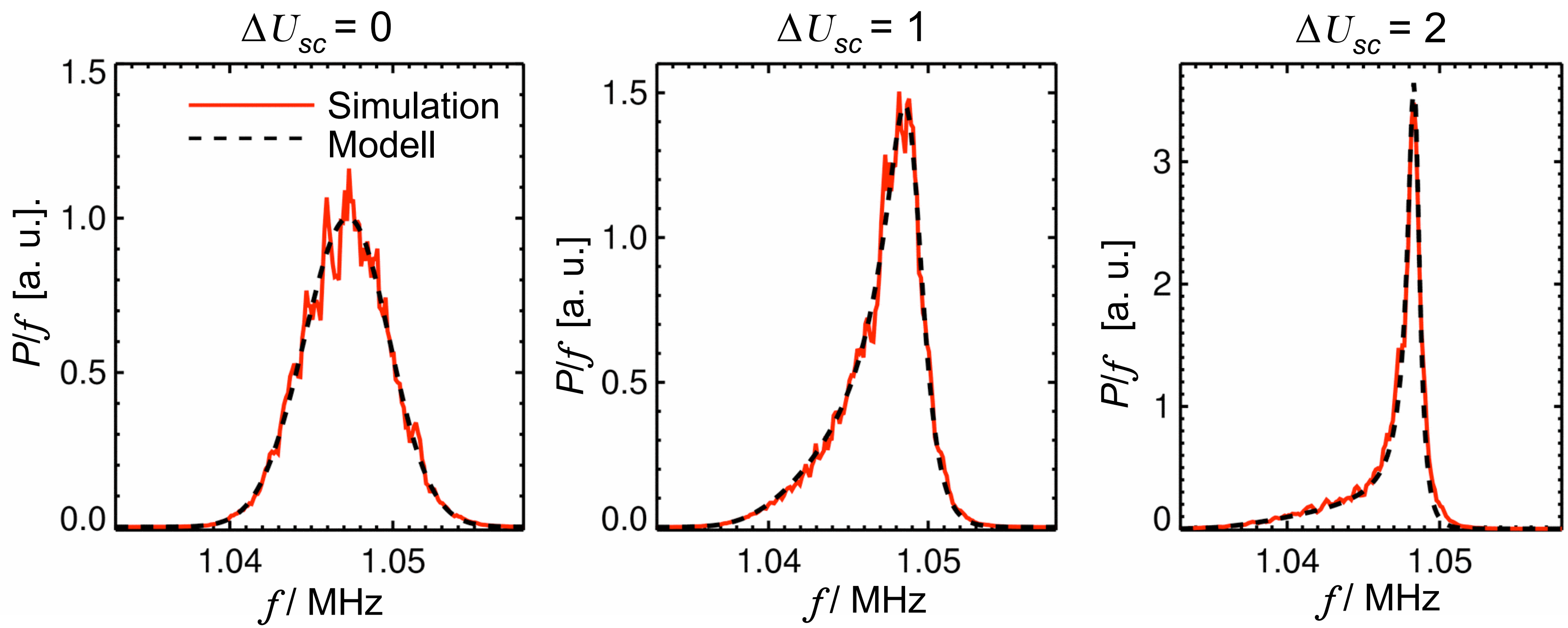


electric field



Schottky simulations

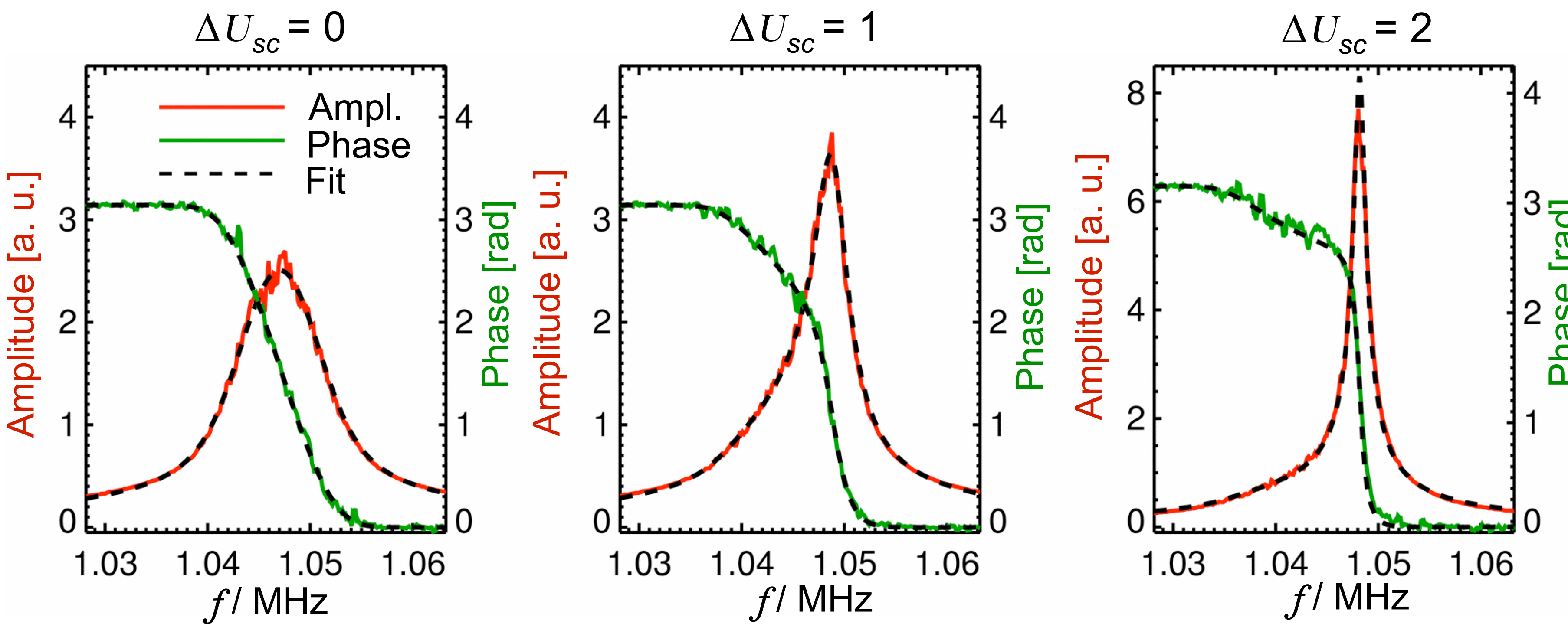
Results for beam with Gaussian transverse profile



- ΔU_{sc} fitted to data
- Excellent agreement with data and expected ΔU_{sc}
- Similar results for K-V und Gaussian profiles

BTF simulations

Results for beam with Gaussian transverse profile



- ΔU_{sc} fitted to data
- Excellent agreement with data and expected ΔU_{sc}
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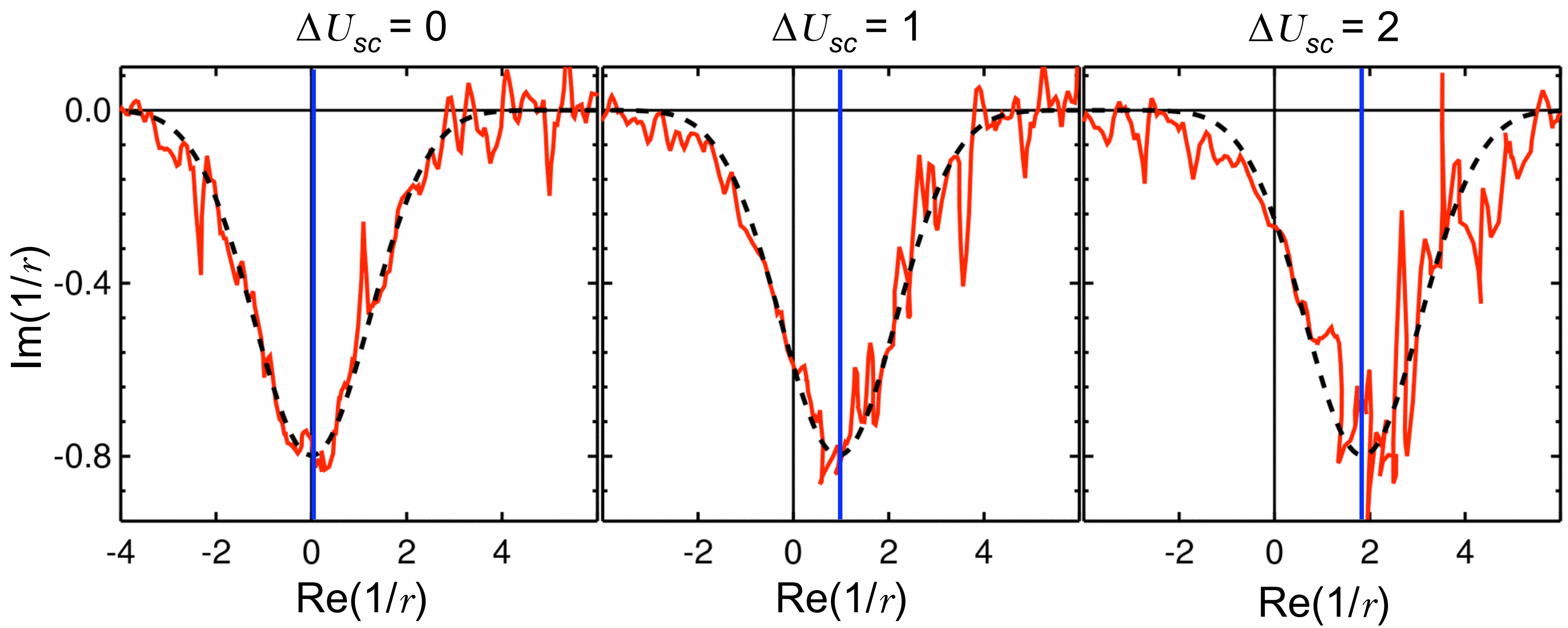
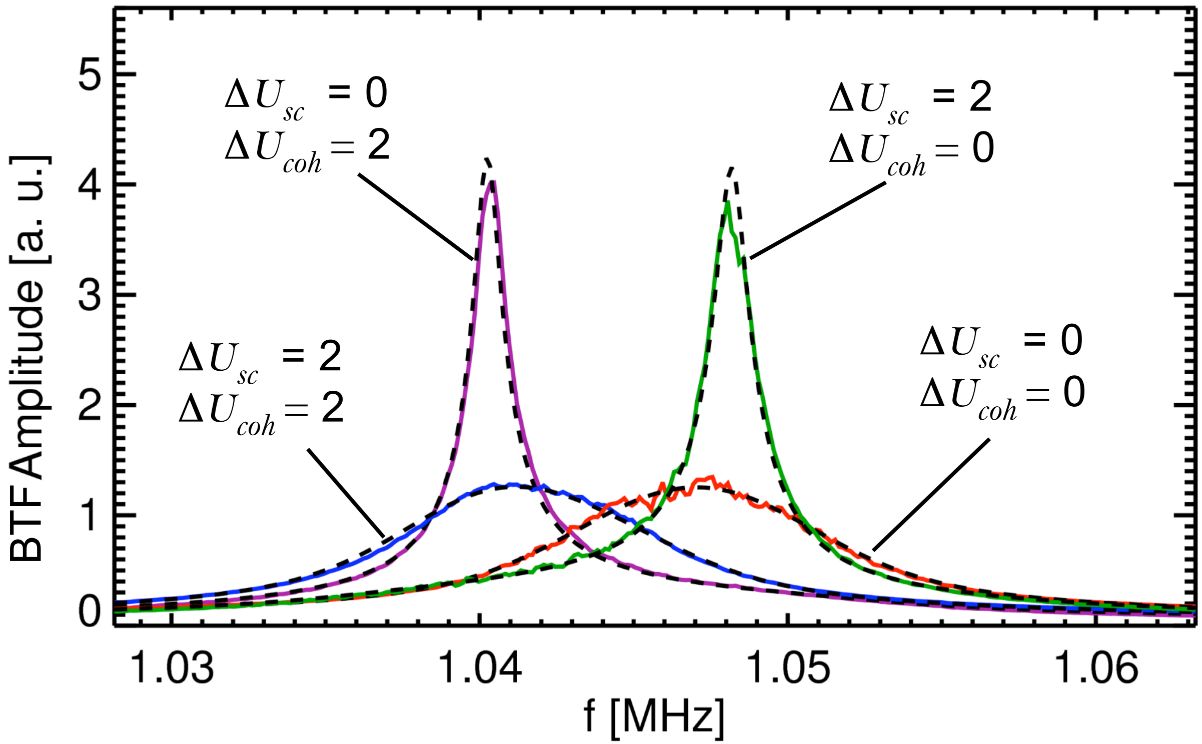
Simulated stability diagrams

- Good agreement with model
- More noise at high intensity



Simulation with impedance

Variation of ΔU_{coh} and ΔU_{sc} for direct comparison



Shift and deformation agree with model

Summary

Analytic linear space-charge model

- Different from dipolar impedance

Experiment

- Measurement of transverse Schottky spectra and BTFs
- Verification of model despite deviations in some parts
- Direct measurement of Q, ΔQ_{sc} und ΔU_{sc}

Simulation

- Transverse Schottky spectra and BTFs with space charge and imaginary impedances
- Excellent agreement with model

Thank you for your attention

Measured ΔQ