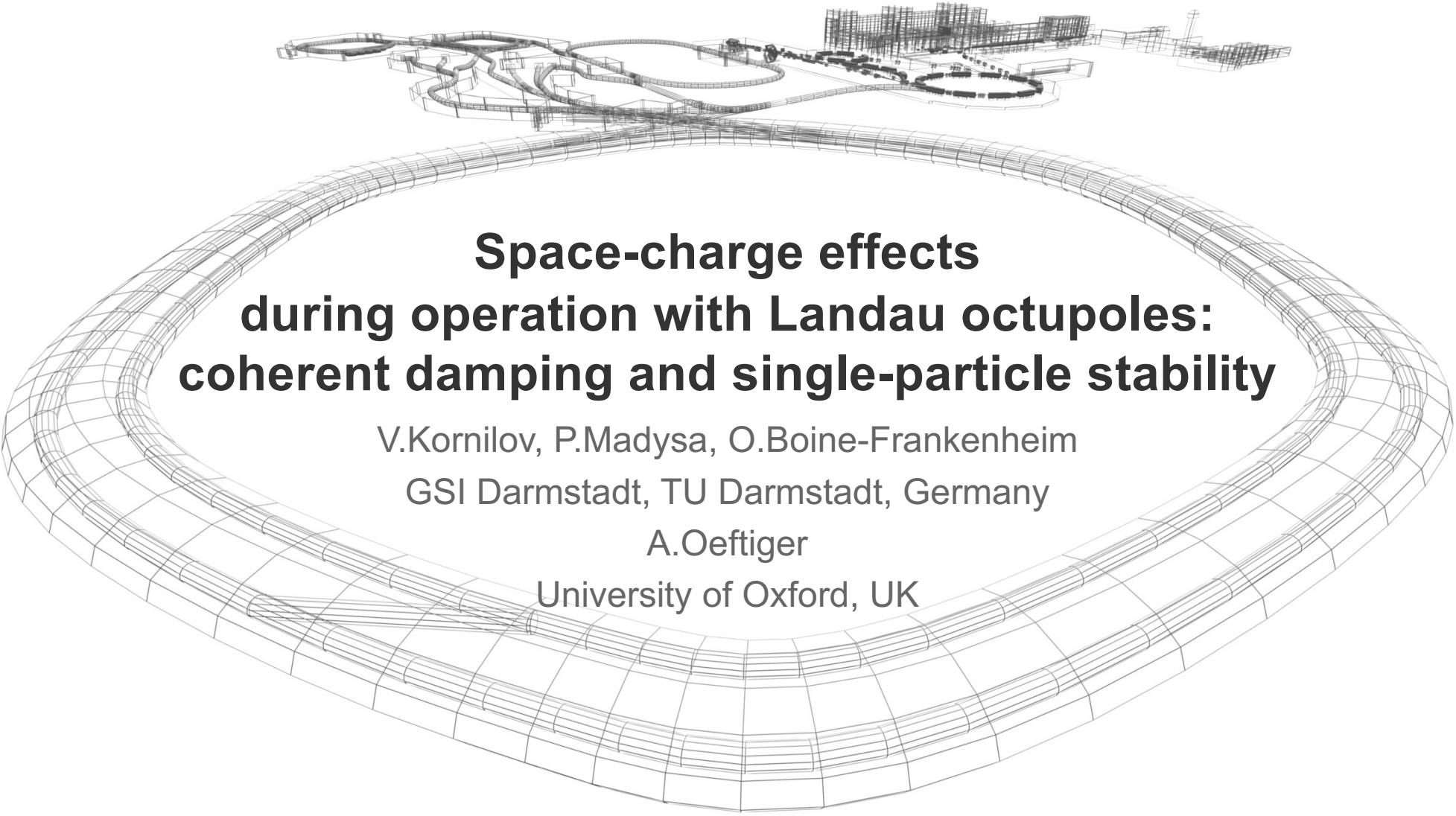




# **Space-charge effects during operation with Landau octupoles: coherent damping and single-particle stability**

V.Kornilov, P.Madysa, O.Boine-Frankenheim

GSI Darmstadt, TU Darmstadt, Germany

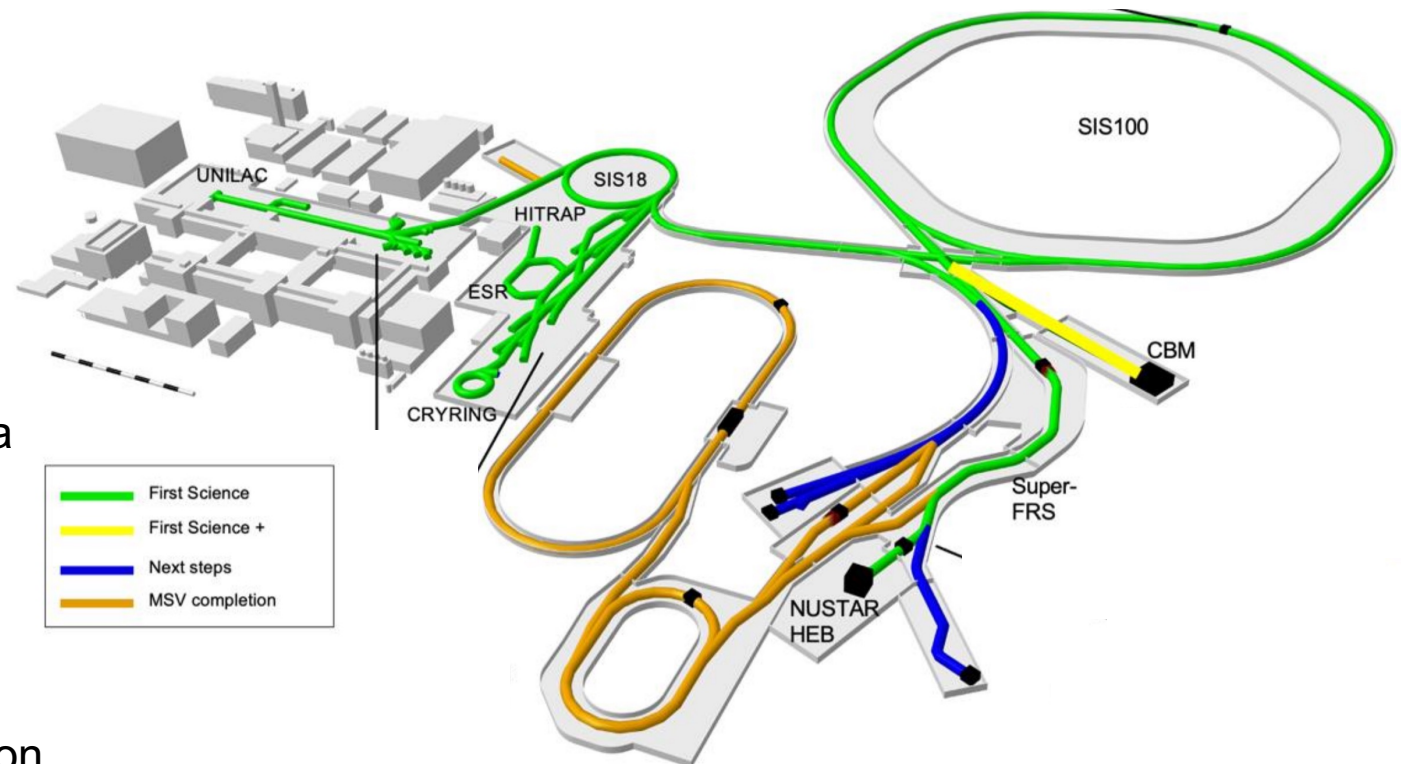
A.Oeftiger

University of Oxford, UK

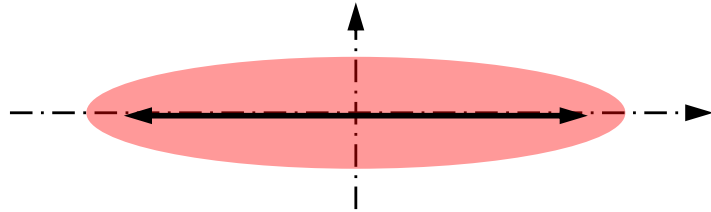
# FAIR project at GSI, Darmstadt, Germany

## SIS18 and SIS100 Synchrotrons

- C:  $\text{SIS100} = 5 \times \text{SIS18} = 1083.6 \text{ m}$
- Ions H–U.
- $\text{U}^{28+} 0.2 \rightarrow 1.5 \text{ GeV/u}$
- High-intensity, low-loss (5%) operation
- Coherent instabilities is a potential danger
- Space charge  $\Delta Q_{\text{sc}}$  up to  $-0.3$
- SIS100 under construction, SIS18 in shutdown.

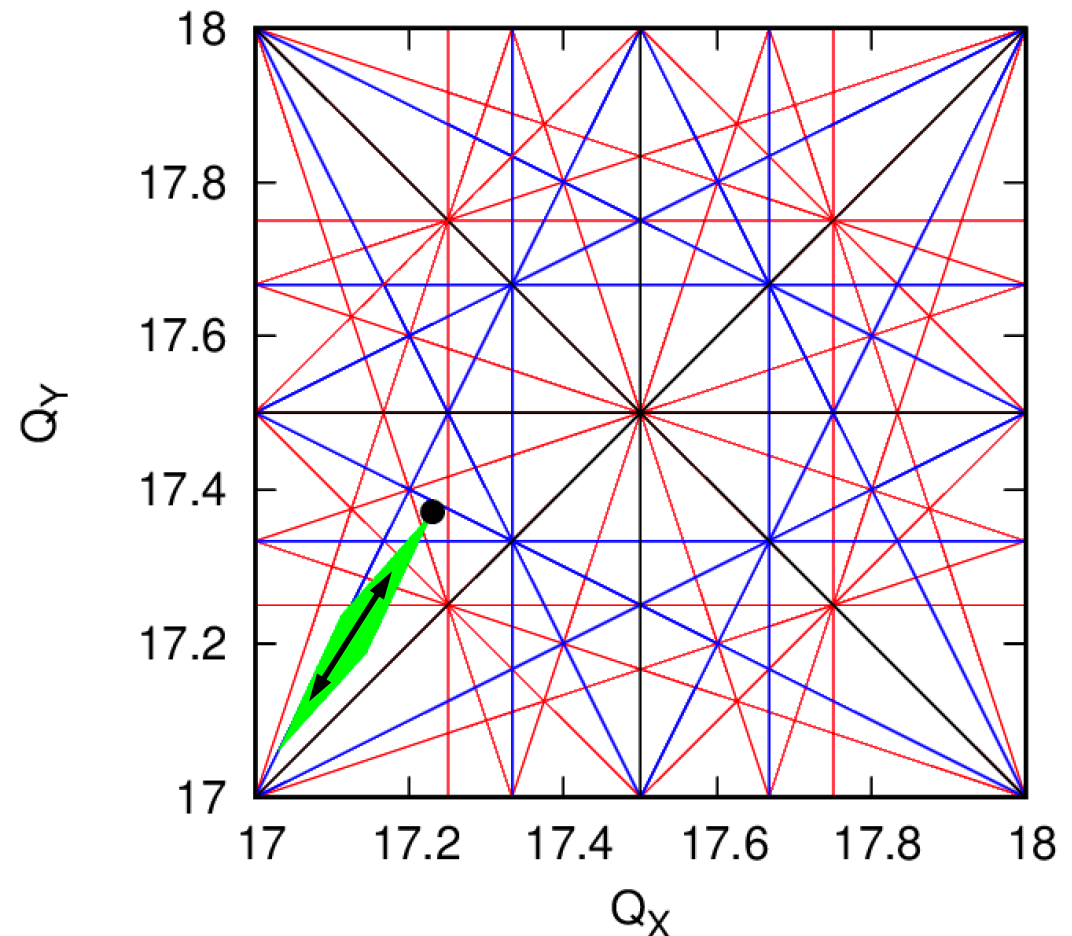


# SPACE CHARGE IN SIS100



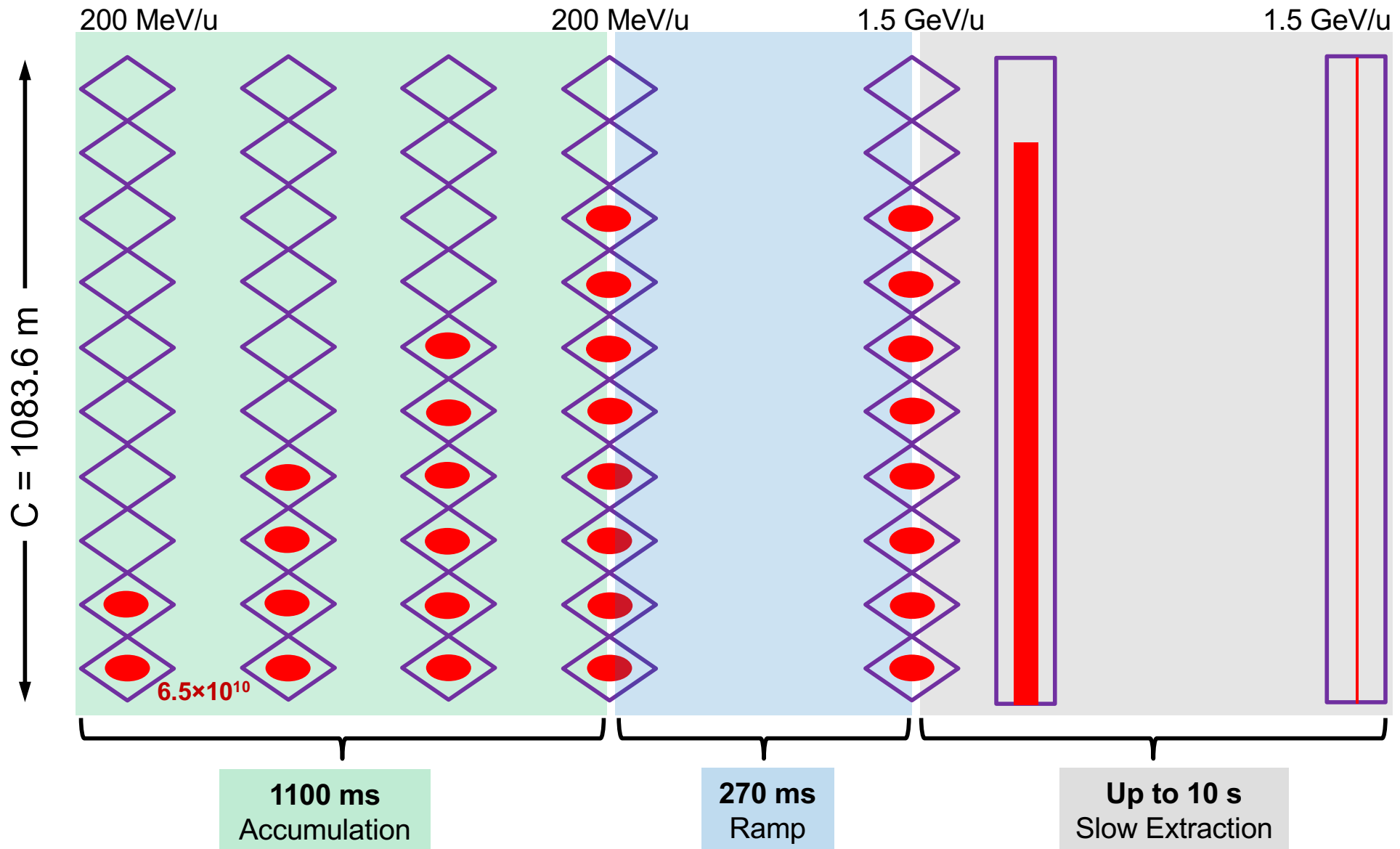
| Parameter           | Quantity    | Plane | Value  |
|---------------------|-------------|-------|--------|
| Space charge        | max shift   | $x$   | -0.2   |
| Space charge        | max shift   | $y$   | -0.3   |
| Chromaticity        | max span    | both  | 0.04   |
| Magnet Field Errors | max span    | both  | 0.004  |
| Fastest instability | growth rate | $y$   | 0.002  |
| Synchrotron tune    | $Q_s$       |       | 0.0045 |

Resonance-crossing and coherent instabilities: the key aspects for SIS100 beam dynamics are dominated by space-charge

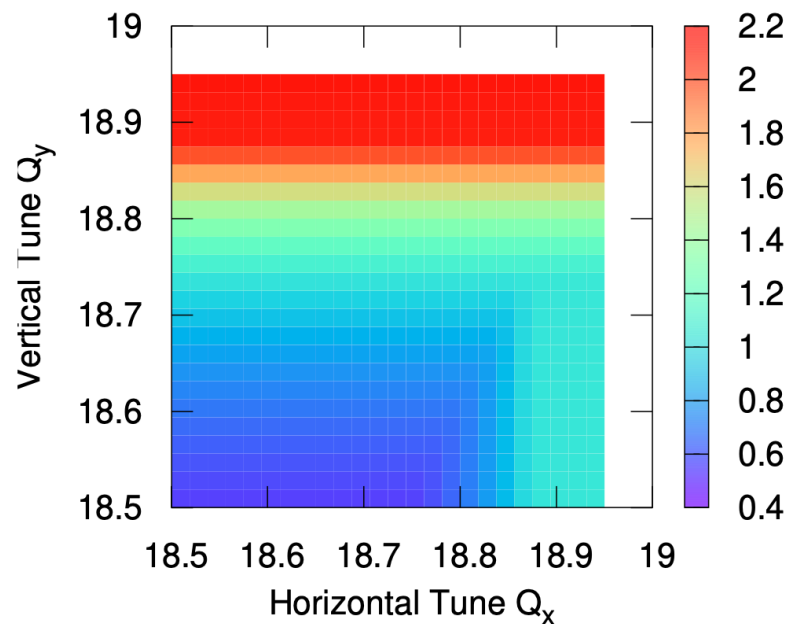


Resonances:  $kQ_x + mQ_y = n$   
 2<sup>nd</sup> order, 3<sup>rd</sup> order, 4<sup>th</sup> order

# Reference Cycle: $U^{28+}$ slow extraction



# Coupled-Bunch Head-Tail Instability



Color: Growth Rate  $\Delta Q$ ,  $10^{-3}$  of the most unstable mode.

Vert, horiz,  $k=0$

Sacherer Theory and the Resistive Wall Impedance

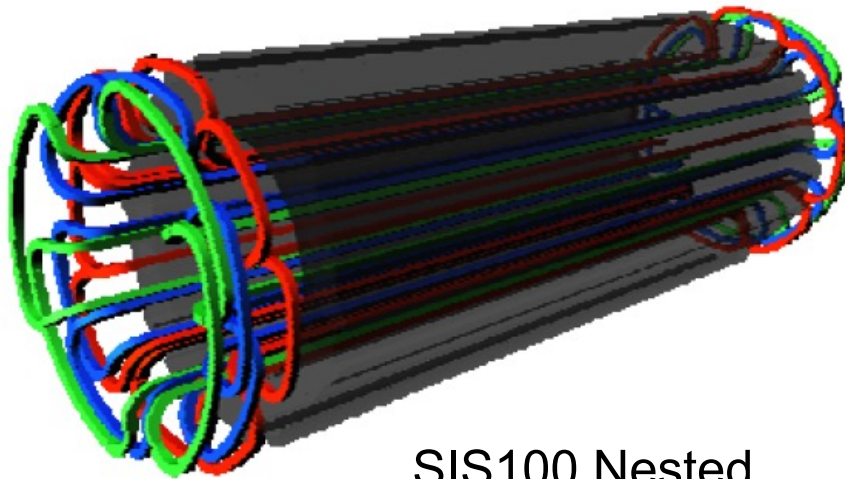
$$\Delta\Omega_m = \frac{\omega_0}{Y_0} \frac{1}{1+m} \frac{C}{L_b} \frac{\sum_p (-i) Z^\perp(\omega_p) h_m(\omega_p - \omega_\xi)}{\sum_p h_m(\omega_p - \omega_\xi)}$$

For  $U^{28+}$  bunches at the injection

$\Delta Q = 2 \times 10^{-3}$  corresponds to the growth time 0.5ms.

Conservative calculation.

## Mitigation: octupole magnets

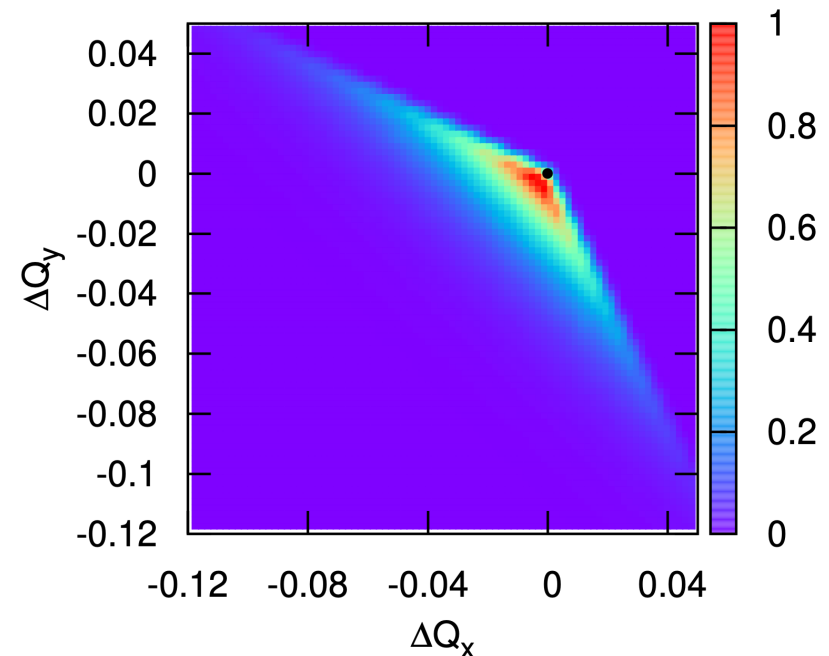


SIS100 Nested  
Corrector Magnets (12)

### Octupoles for Landau damping in SIS100

- Max power:  $K_3=100 \text{ m}^{-4}$
- 12 octupoles, 2 magnet groups
- “f”-group: x beta function,  
“g”-group: y beta function

### Example for an octupole tune footprint



What is the sufficient octupole power to suppress the instabilities?

# Octupoles for Landau damping

## A possible recipe:

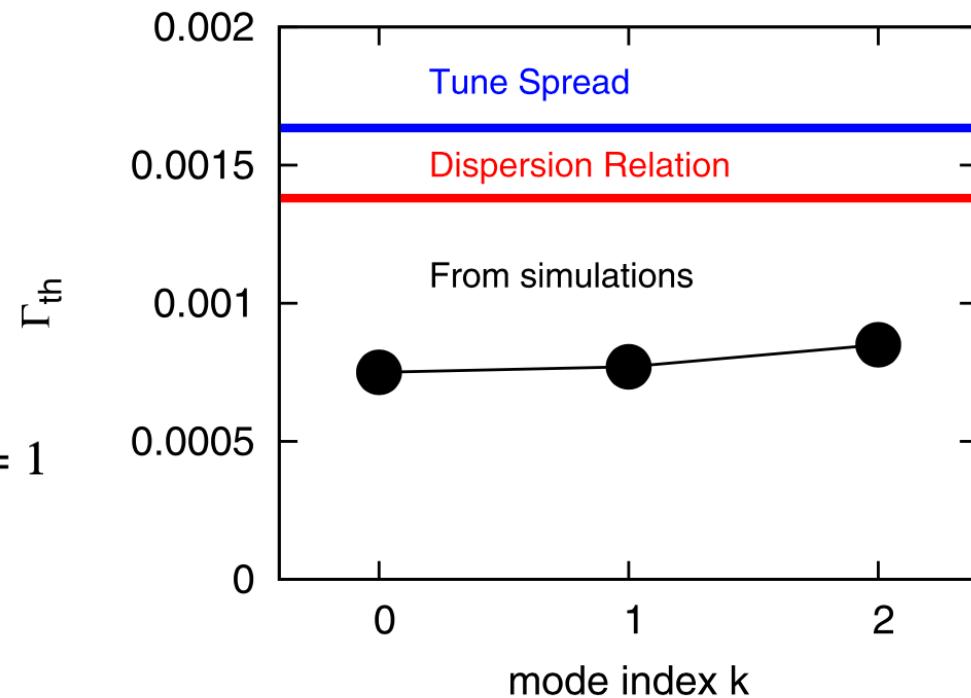
- The instability growth rates from the analysis without space-charge
- A potential effect of space-charge on the instability drive
- Landau damping due to octupoles without space-charge
- Modifications of Landau damping due to space-charge
- Determination of the sufficient octupole power for Landau damping
- Check the single-particle stability due to resonance crossing with space-charge and octupoles

# Octupoles for Landau damping

$$\Delta S = \left[ \left( \epsilon_x \frac{\partial Q}{\partial J_x} \right)^2 + \left( \epsilon_y \frac{\partial Q}{\partial J_y} \right)^2 \right]^{1/2}$$

$$\Delta Q_{\text{coh}} \int \frac{1}{\Delta Q_{\text{oct}} - \Omega/\omega_0} J_x \frac{\partial \psi_{\perp}}{\partial J_x} dJ_x dJ_y = 1$$

Stability threshold for a fixed octupole strength

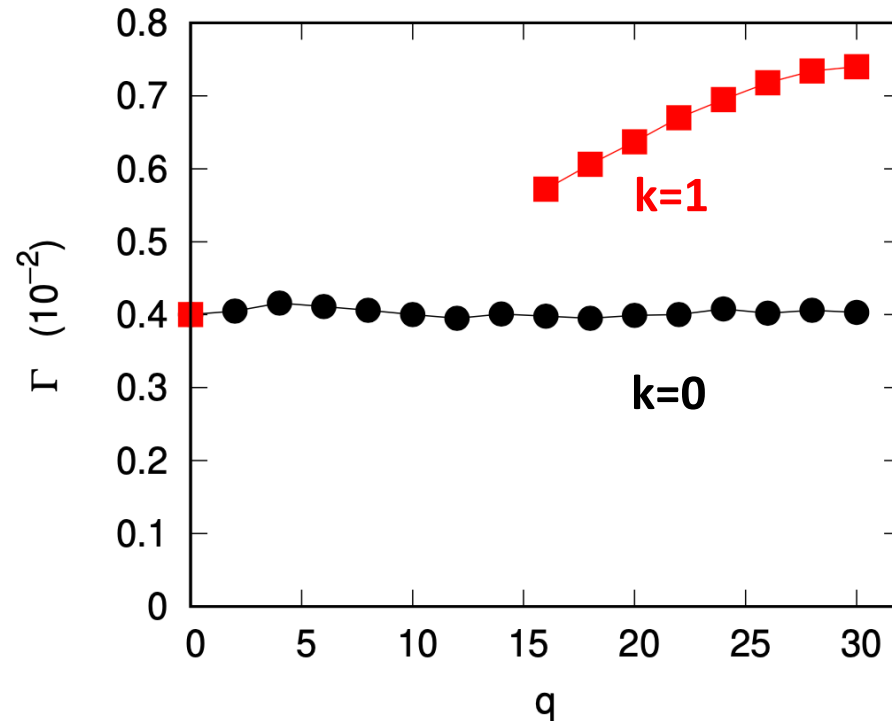


Consideration without space-charge

D. Möhl, H. Schönauer, 1974,

V. Kornilov, O. Boine-Frankenheim, NIM A 951 (2020) 163042

# Simulations with Space-Charge



- The PATRIC code
- Self-consistent space-charge
- Resistive-wall wake field

$$q = \frac{\Delta Q_{sc}}{Q_s}$$

## Instability growth rate

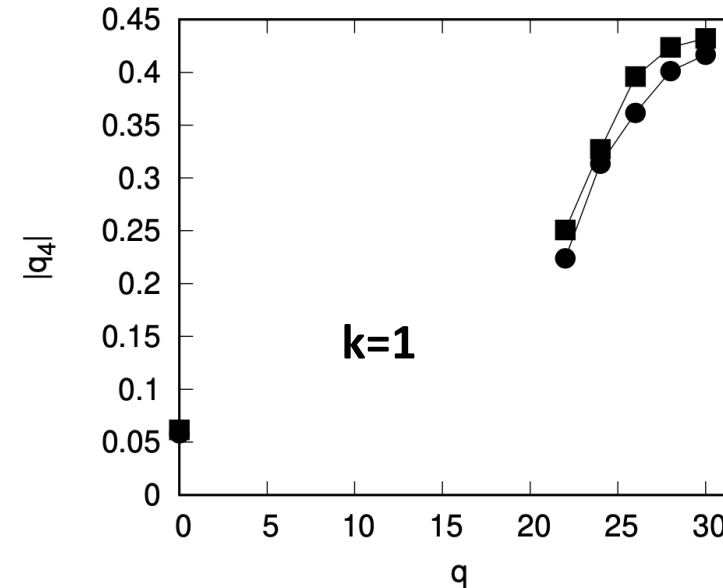
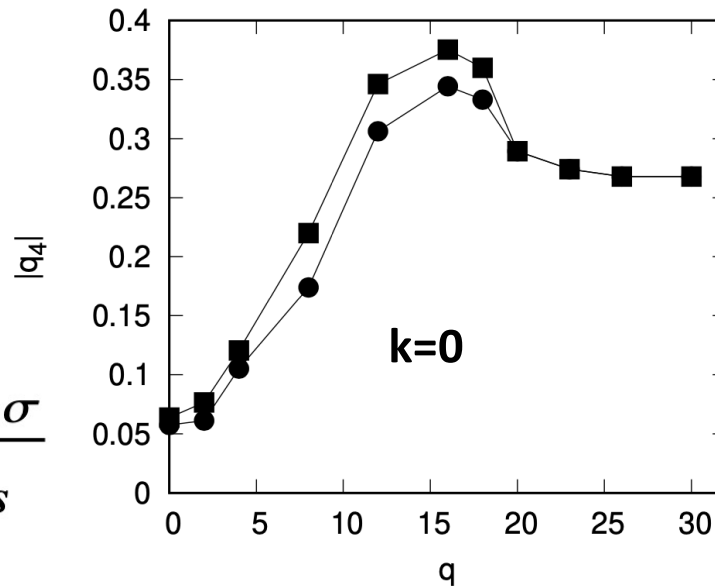
Effect of space-charge on the instability drive:

- Higher-order modes strongly affected
- Landau damping due to space-charge
- Moderate growth rate modifications

# Simulations with Space-Charge

$$q_4 = \frac{\Delta Q_\sigma}{Q_s}$$

$$q = \frac{\Delta Q_{sc}}{Q_s}$$



## Stability threshold of the octupole power

- Landau damping for  $k>0$  modes
- Loss of Landau damping
- Stronger octupoles are needed due to space-charge
- No clear sensitivity to the octupole polarity
- For SIS100:  $K_3=50 \text{ m}^{-4}$  should be sufficient,  $q \approx 30$

# Particle Tracking Simulations

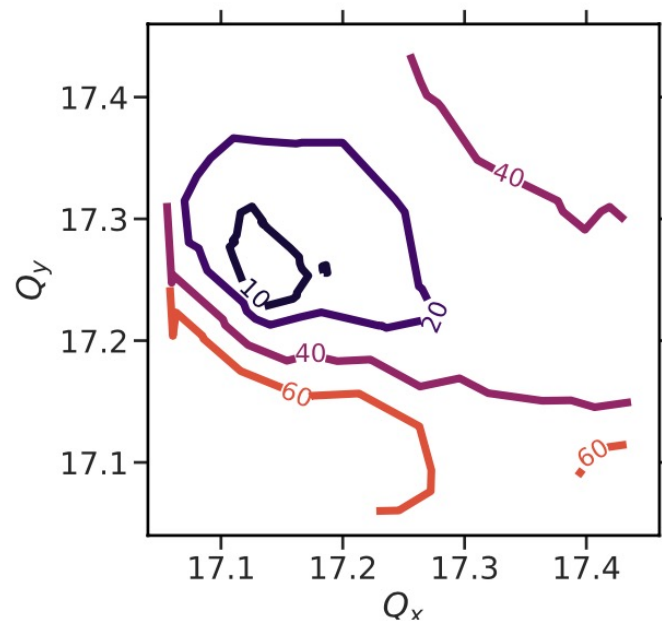
Particle tracking simulations using the code SixTrackLib [A. Oeftiger et al, PRAB 25, 054402 (2022)]

- Nominal  $U^{28+}$  bunch during the 1 sec accumulation at the injection energy: 160 000 turns
- Symplectic 6D tracking
- Complete nonlinear lattice
- Field errors set ( $B_n, A_n$ ) for each magnet from the series measurements
- Fringe fields
- Nonlinear frozen space-charge
- 6D Gaussian bunch
- Nonlinear rf effects
- Chromaticity effects
- Multi-core simulations on the Green IT Cube at GSI

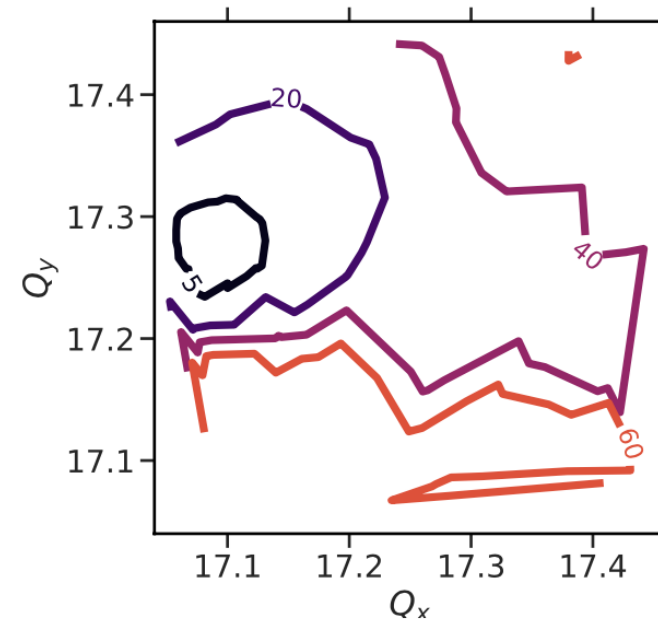
At the moment, the most complete description of the SIS100 accelerator and the high-intensity effects for reliable predictions

# Beam Loss Simulations

With octupoles:  $K_{3f,d}=(+50,+50) \text{ m}^{-4}$   
Beam loss contours



With octupoles:  $K_{3f,d}=(+50,-50) \text{ m}^{-4}$   
Beam loss contours



There are octupole configurations which allow for the low-loss (below 5%) operation

## Octupoles for SIS18

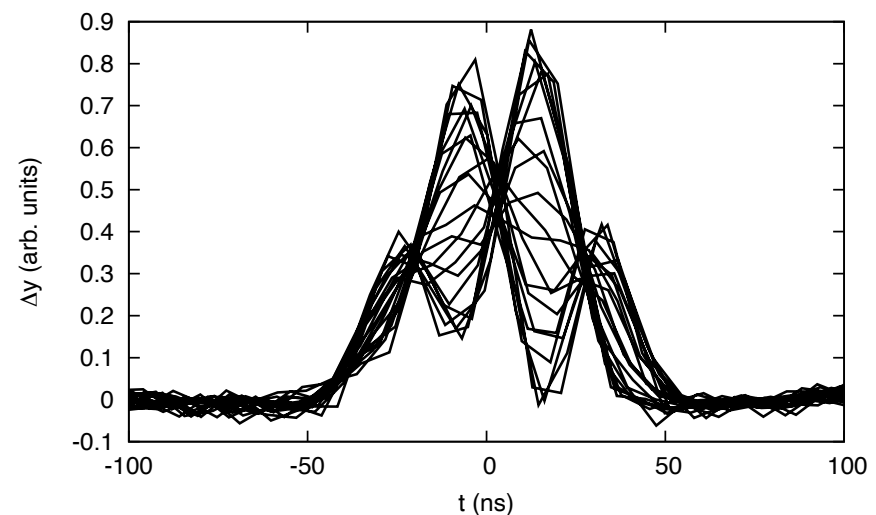
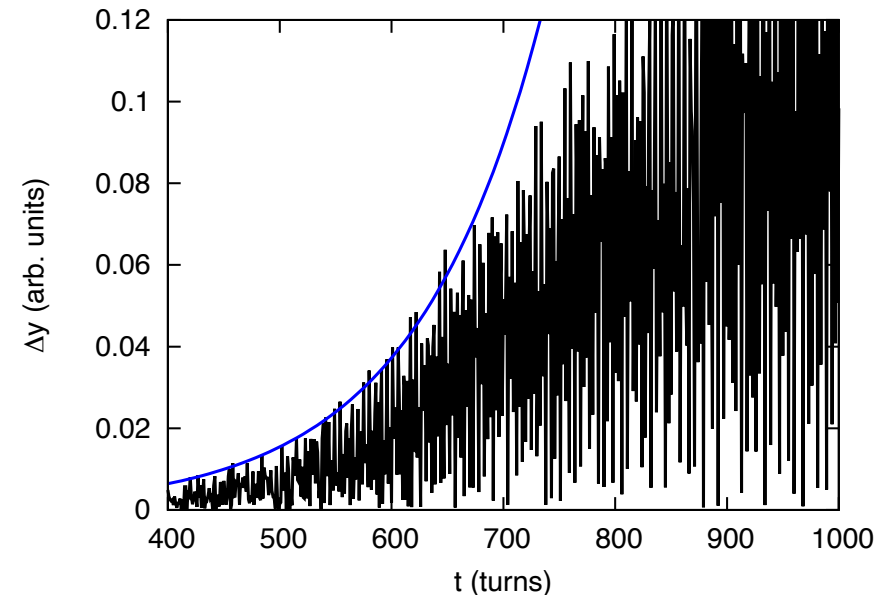
High-intensity tunes above  $Q_y \approx 3.6$ :  
strong collective oscillations,  
fast beam loss

Instability with the growth time  
 $\tau = 0.11$  ms

$N^{7+}$  ions,  $1.2 \times 10^{10}$

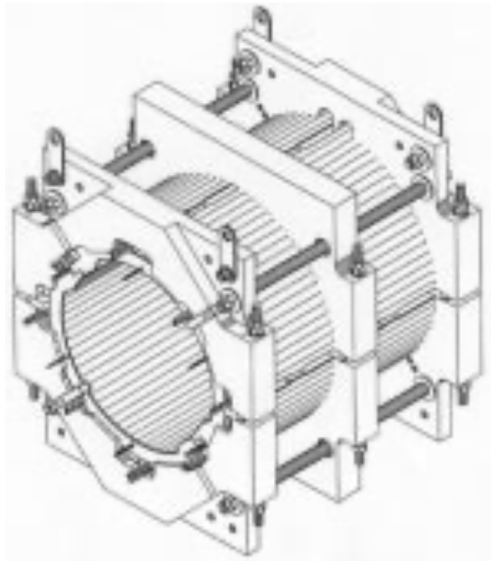
1 turn = 0.989  $\mu$ s

Applying the recipe for octupole  
Landau damping with space-charge:  
 $\Delta Q_{\text{oct}} \approx 0.02$



## Octupoles for SIS18

A present idea: replacement of some of the eight corrector magnets (having normal quadrupole, skew quadrupole, and skew sextupole)



| N of octupoles | $K_3L$              | $gL$                   |
|----------------|---------------------|------------------------|
| 4              | $72 \text{ m}^{-3}$ | $300 \text{ T m}^{-2}$ |
| 6              | $48 \text{ m}^{-3}$ | $200 \text{ T m}^{-2}$ |

Two configurations under consideration:  
technical feasibility study

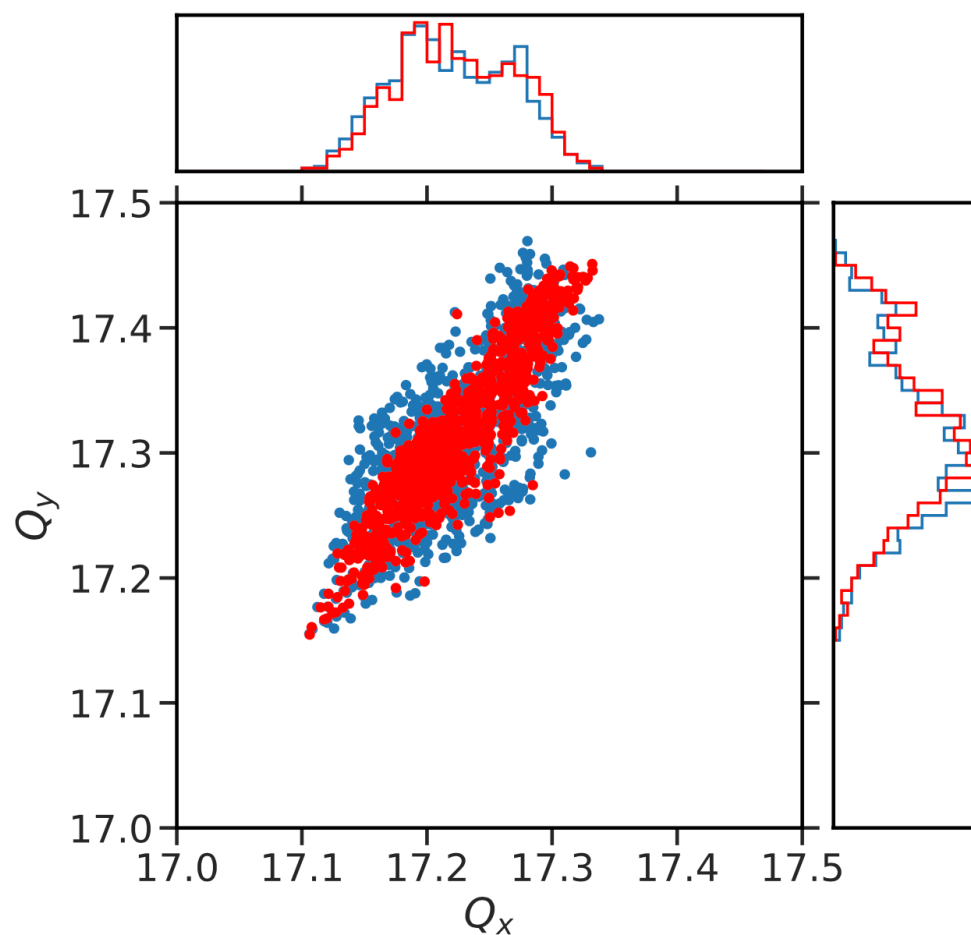
## Summary

- Space-charge strongly modifies Octupole Landau damping
- A recipe to determine the sufficient octupole power for instability suppression with the effect of space-charge
- Application for the octupole configurations in SIS100 and SIS18
- Particle tracking simulations for safe tune areas in SIS100 confirm the acceptability of  $K_3=50 \text{ m}^{-4}$  Landau octupoles
- Technical feasibility study for octupole installation in SIS18

# Tune Footprints

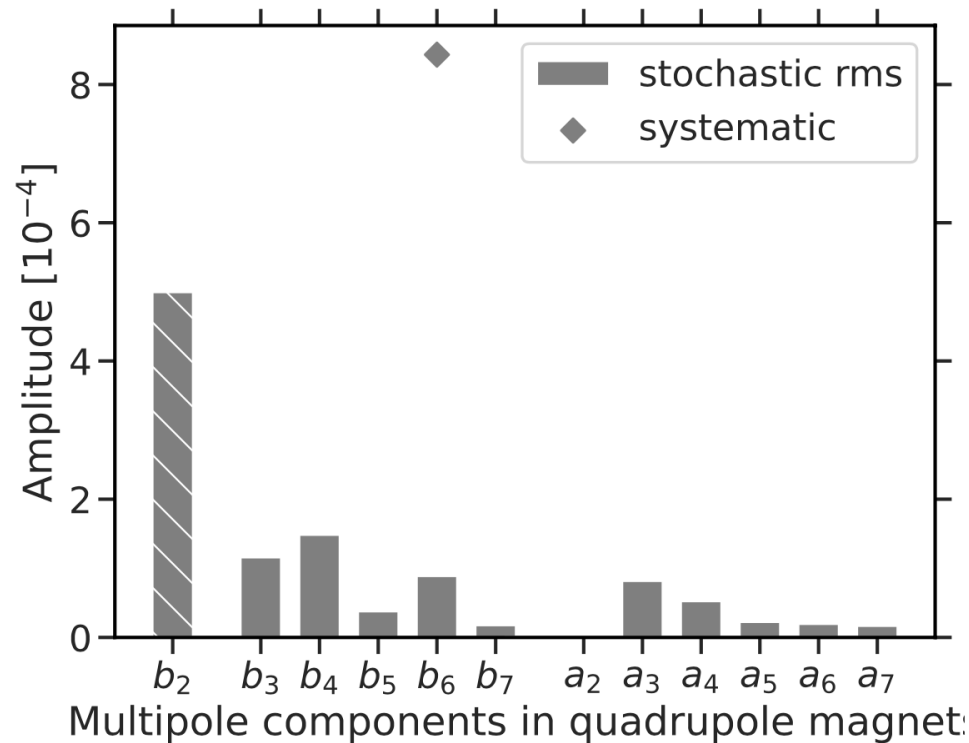
With  $K_{3f}=+50 \text{ m}^{-4}$ ,  $K_{3d}=+50 \text{ m}^{-4}$

With  $K_{3f}=+50 \text{ m}^{-4}$ ,  $K_{3d}=-50 \text{ m}^{-4}$



# SIS100 Quadrupole Magnet Model

The field measurements of the quadrupole series provide the model of the quadrupole magnets for particle tracking simulations



$b_n$  normal  
 $a_n$  skew  
 $b_2, a_2$  quadrupole  
 $b_3, a_3$  sextupole  
 $b_4, a_4$  octupole

**Assumptions for the magnet model:**

1. Only the allowed ( $b_6$ ) systematic component is nonzero
2. The random errors = sample standard deviations

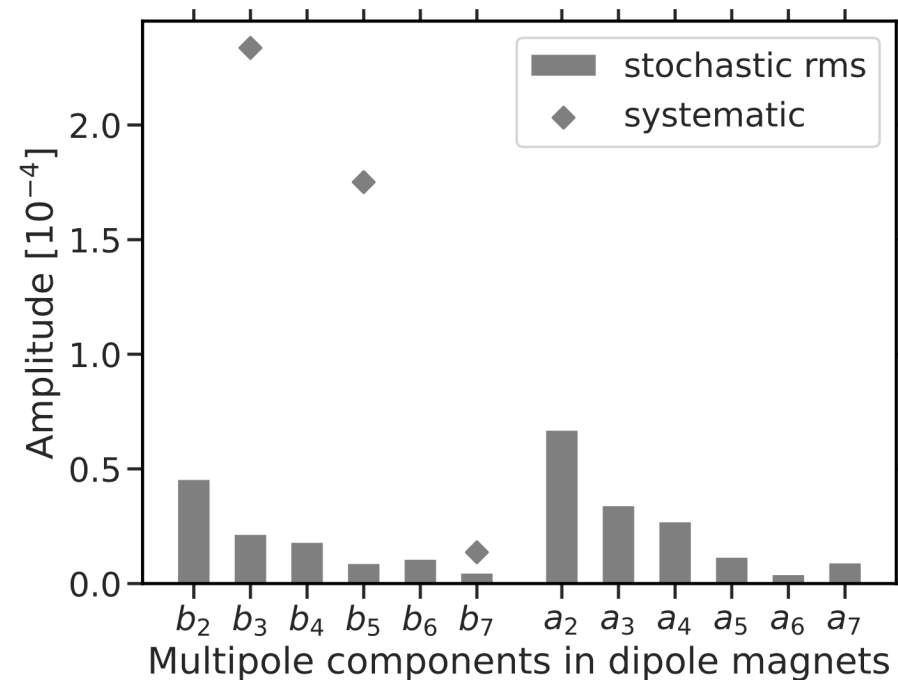
$r_0 = 40\text{mm}$   
 Plot:  $\pm 2\sigma$  bars  
 1 unit =  $10^{-4}$

The model used in simulations.  
From the 83 (total 166) of the series magnets

# SIS100 Dipole Magnet Model

The field measurements of the dipole series provide the model of the dipole magnets for particle tracking simulations

$b_n$  normal  
 $a_n$  skew  
 $b_2, a_2$  quadrupole  
 $b_3, a_3$  sextupole  
 $b_4, a_4$  octupole



**Assumptions for the magnet model:**

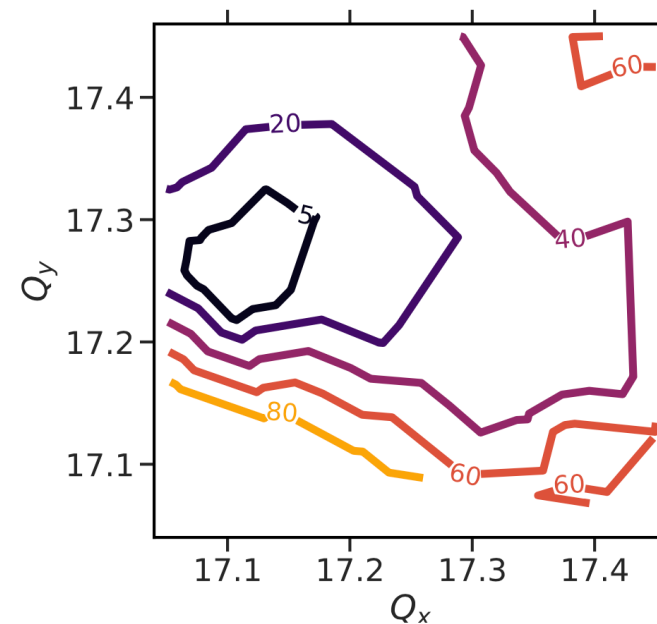
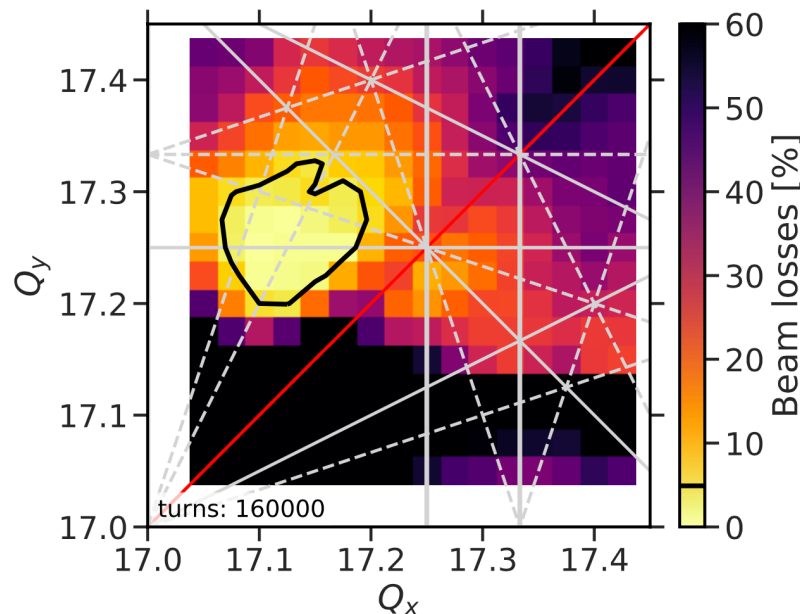
1. Only the allowed ( $B_3$ ,  $B_5$ ,  $B_7$ ) systematic components are nonzero
2. The random errors = sample standard deviations

$r_0=30\text{mm}$   
 Plot:  $\pm 2\sigma$  bars  
 1 unit =  $10^{-4}$

The model used in simulations.  
 From the 108 series magnets

# Beam Loss Simulations

## Bayesian optimization using Gaussian process



Bayesian Optimization vs Tune Scan: much less simulations.  
For commissioning, optimization, etc

Currently used for the magnet quality assessment:  
confirmation of a good quality of the SIS100 dipoles and quadrupoles