SIS100 high-intensity beam dynamics

Vladimir Kornilov, WPL “SIS100 Beam Dynamics”

20th FAIR Machine Advisory Committee Meeting

Work package description
2.8.1 SIS100 Beam Dynamics

- The focus: design of the high-intensity low-loss operation
- Beam survival and beam quality preservation with magnet field errors and space-charge
- Instabilities & Mitigation
- WP: O.Boine-Frankenheim, V.Chetvertkova, V.Kornilov, S.Sorge

Recommendations addressed

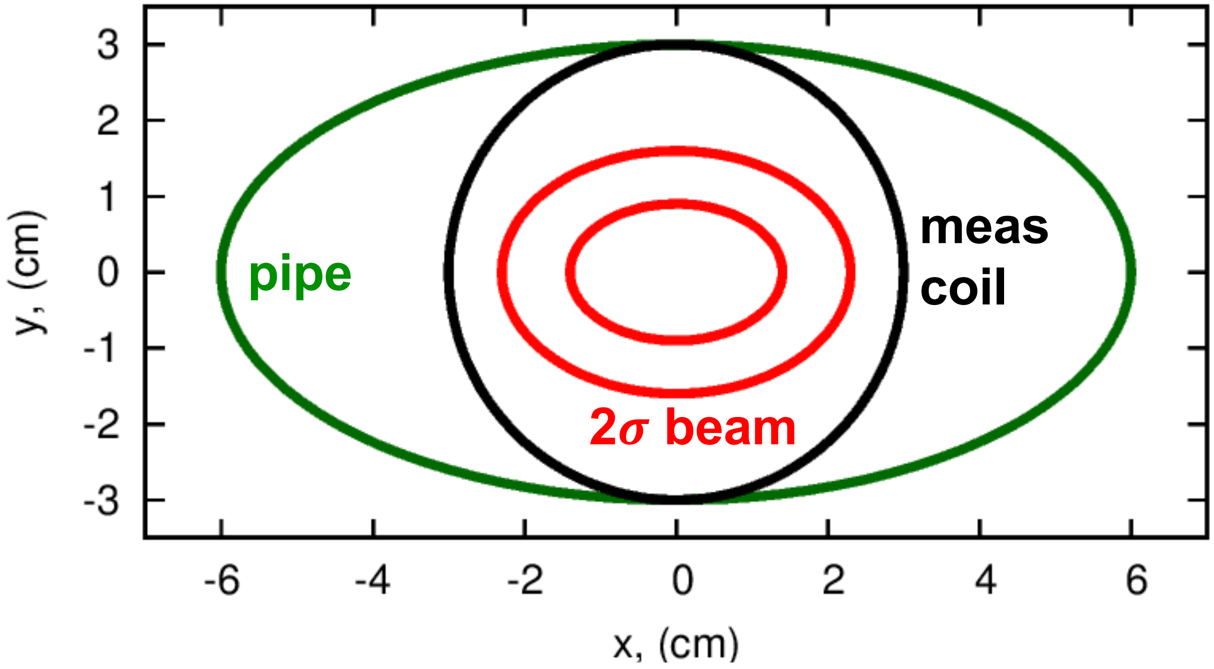
Report from the 19th FAIR MAC

- We encourage the SIS100 3D machine model and beam tracking simulations with full space charge with the objective of reduced beam-loss and emittance preservation during the 1-s accumulation after injection.
- We support investigations into how to mitigate space-charge effects with choice of beam parameters and of (Q_x, Q_y), dual-rf bucket, and correction magnets.
- **R8** Investigate the possibility of a resistive-wall instability damper.
- **R9** Consider performing a field measurement of a dipole magnet with and without the vacuum chamber installed.
- **P5** The present single particle beam-dynamics simulations related to the vacuum chamber … should be supplemented with an assessment of the multi-particle effects (RW instability).

SIS100 Dipole Magnets

Series dipole magnet measurements:

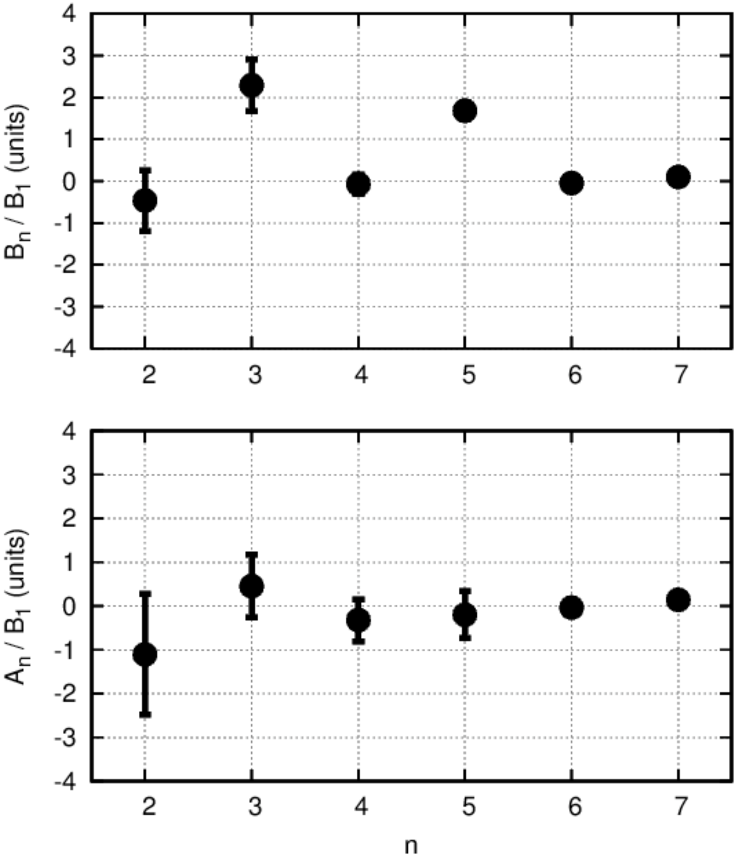
- A large coil R=30 mm
- At the moment: data from 21 series magnets



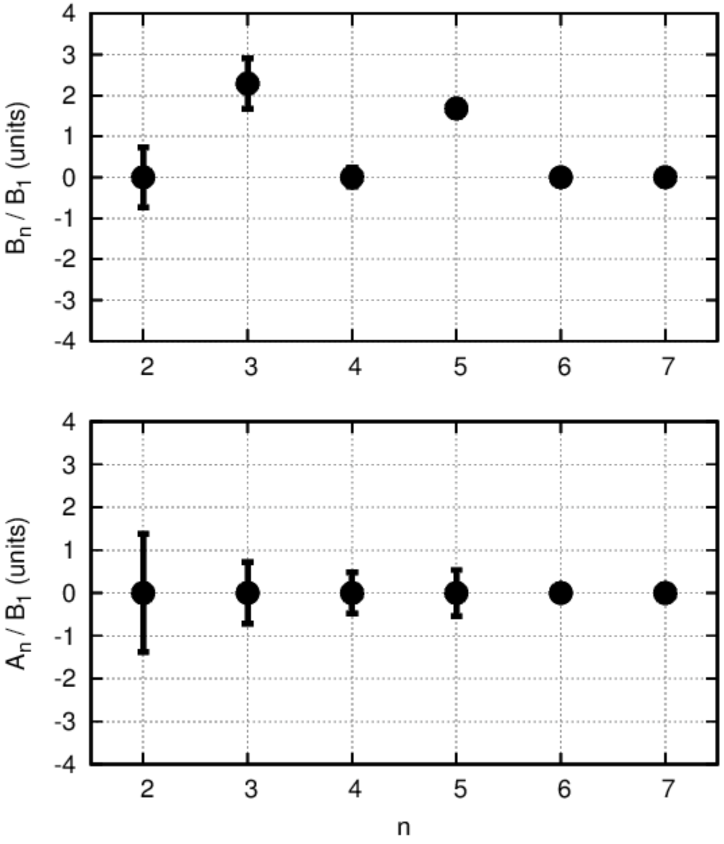
$$B_y + iB_x = (B_n + iA_n)\left(\frac{x+iy}{r_0}\right)^{n-1}$$

SIS100 Dipole Magnet Model

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



From the 21 series magnets



The model used in simulations

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

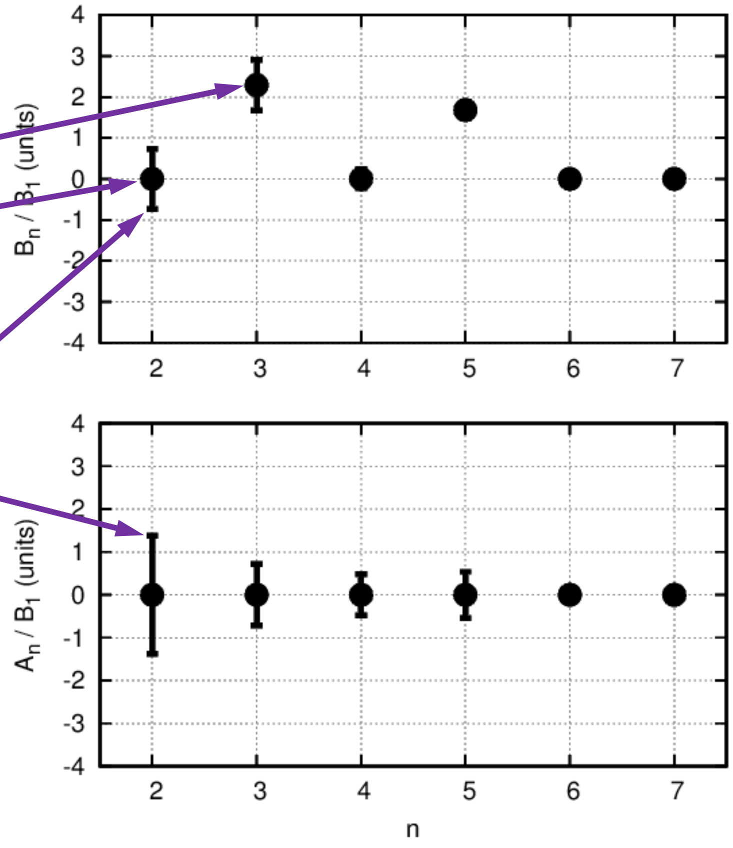
SIS100 Dipole Magnet Model

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

Fixed values are the systematic components

The bars show the random components, i.e. the amplitude of the Gaussian distribution among magnets

B_n normal ; A_n skew
B_2 , A_2 quadrupole
B_3 , A_3 sextupole
B_4 , A_4 octupole



The model used in simulations

Assumptions for the magnet model:

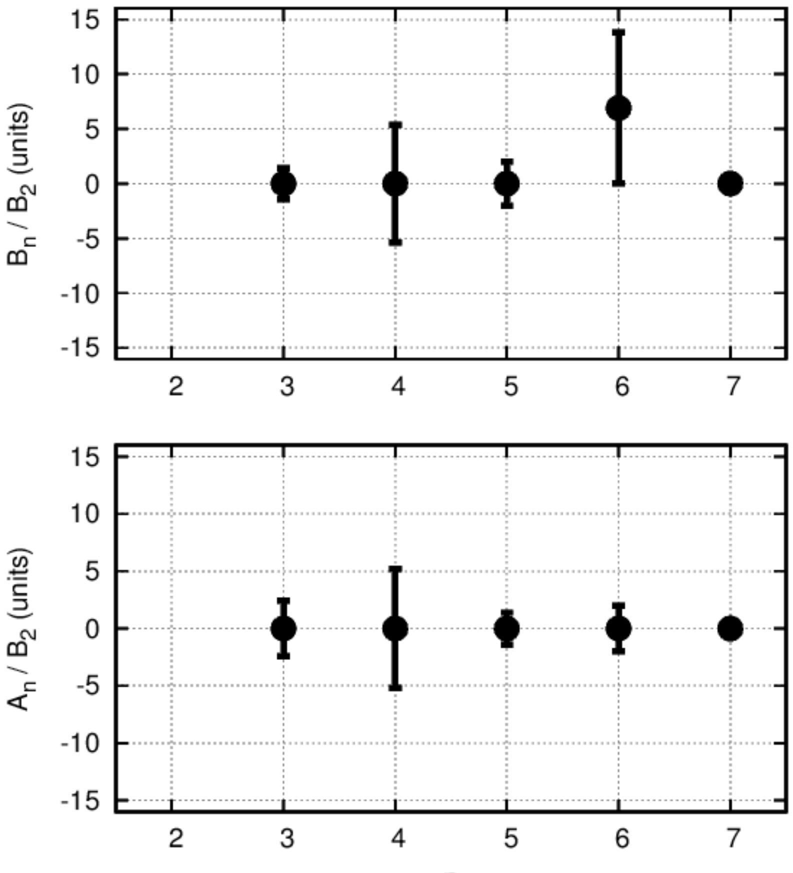
1. Only the allowed (B_3, B_5, B_7) systematic components are nonzero
2. The random errors = sample standard deviations

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

SIS100 Quadrupole Magnets

This model is based on first measurements of one magnet
(the unmilled).

There is another (milled) magnet with stronger errors.

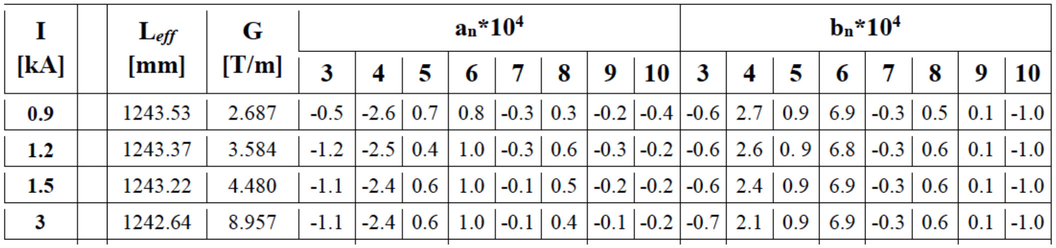


Assumptions for the magnet model:

1. Only the allowed (B_6) systematic components are nonzero
2. The random errors = from the measurement (conservative model)

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

Table 1: Main data for F2 magnet (a_n, b_n – integrated values)



I [kA]		L_{eff} [mm]	G [T/m]	a_n*10^4								b_n*10^4							
				3	4	5	6	7	8	9	10	3	4	5	6	7	8	9	10
0.9		1243.53	2.687	-0.5	-2.6	0.7	0.8	-0.3	0.3	-0.2	-0.4	-0.6	2.7	0.9	6.9	-0.3	0.5	0.1	-1.0
1.2		1243.37	3.584	-1.2	-2.5	0.4	1.0	-0.3	0.6	-0.3	-0.2	-0.6	2.6	0. 9	6.8	-0.3	0.6	0.1	-1.0
1.5		1243.22	4.480	-1.1	-2.4	0.6	1.0	-0.1	0.5	-0.2	-0.2	-0.6	2.4	0.9	6.9	-0.3	0.6	0.1	-1.0
3		1242.64	8.957	-1.1	-2.4	0.6	1.0	-0.1	0.4	-0.1	-0.2	-0.7	2.1	0.9	6.9	-0.3	0.6	0.1	-1.0

A.Shemchuk, M.Shandov,
Report 2018-02-16

SIS100 RESONANCE DIAGRAM

Resonances in transverse oscillations:

$kQ_x + mQ_y = n$

2nd order (quadrupole)

3rd order (sextupole)

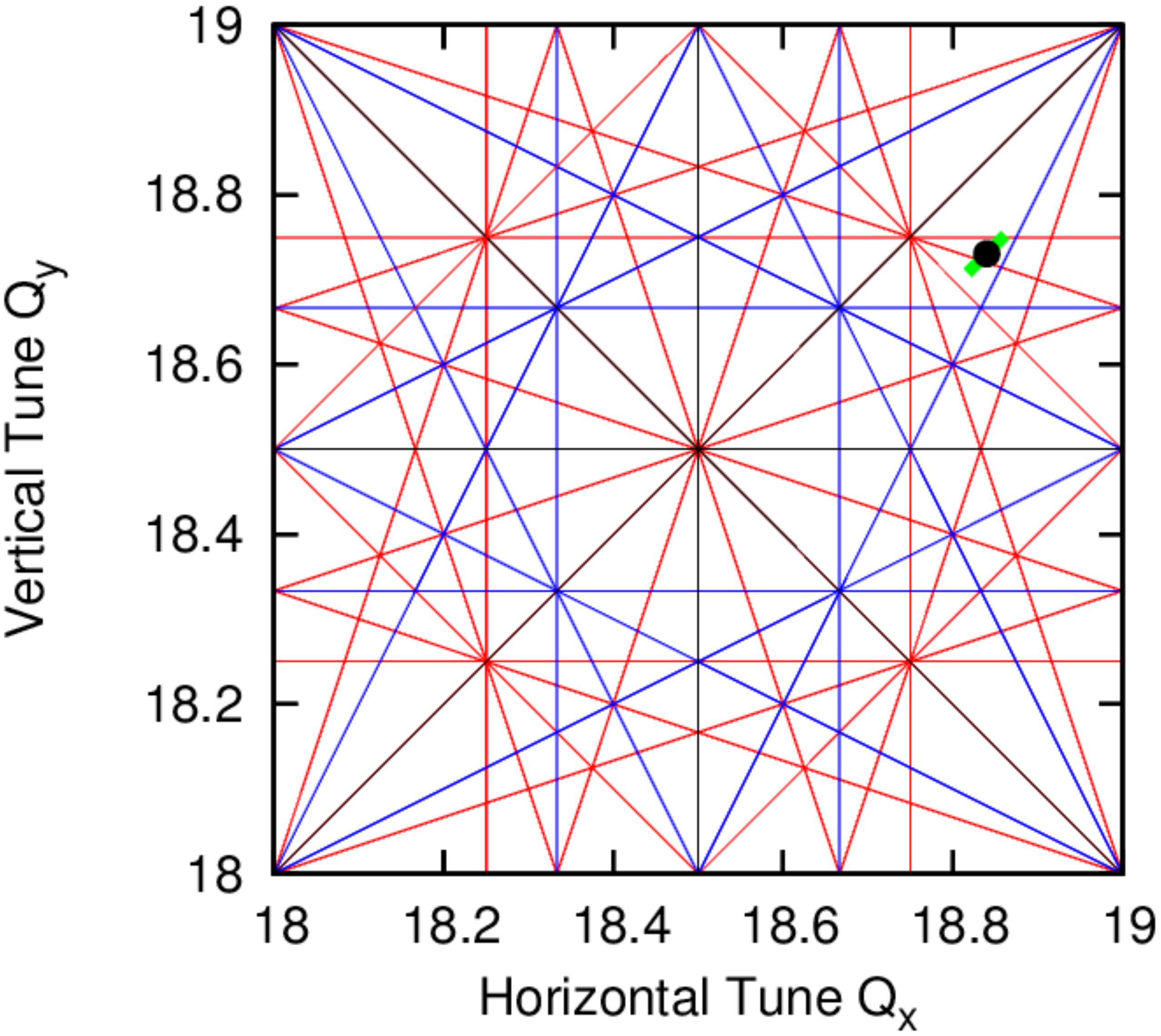
4th order (octupole)

Nominal tune (heavy ions, fast extraction):

$Q_{x0} = 18.84$

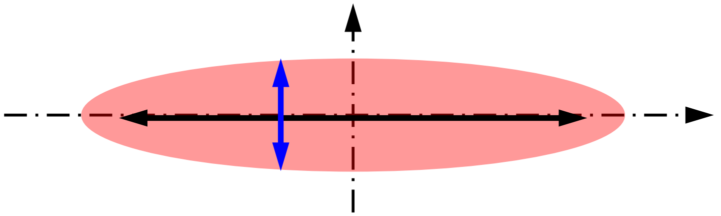
$Q_{y0} = 18.73$

Green area: tune spread, here due to the chromaticity ξ

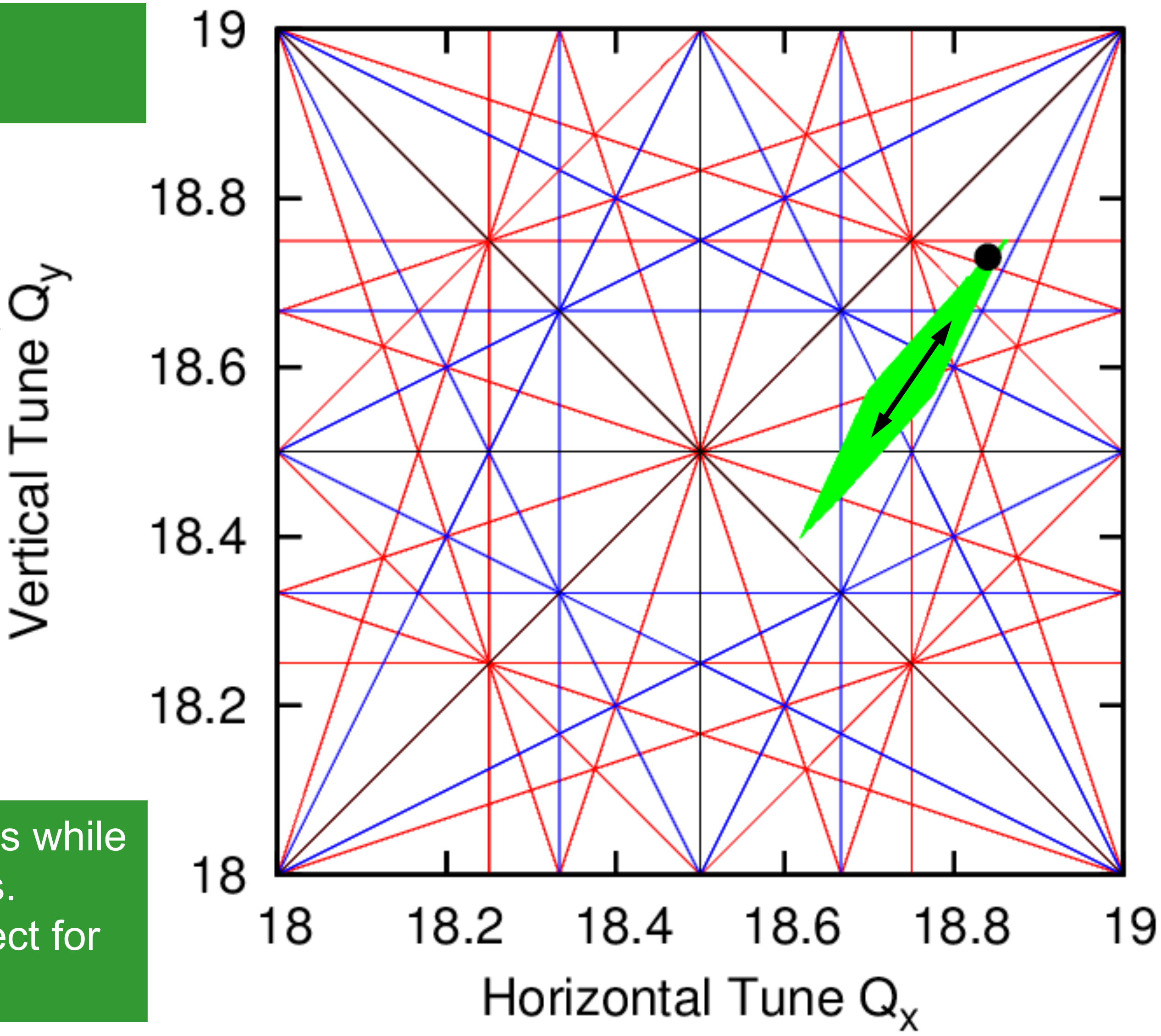


SIS100 RESONANCE DIAGRAM

Special situation for SIS100:
Tune spread due to space-charge



$f_{\text{longitudinal}} \approx 1.5$ kHz
(T ≈ 600 us)
$f_{\text{transverse}} \approx 5$ MHz
(T ≈ 0.2 us)



Particles cross different resonances while performing synchrotron oscillations.
Errors + Space-charge: a key aspect for SIS100 beam dynamics

Simulations: Code “elegant”

Particle tracking simulations using the code Elegant

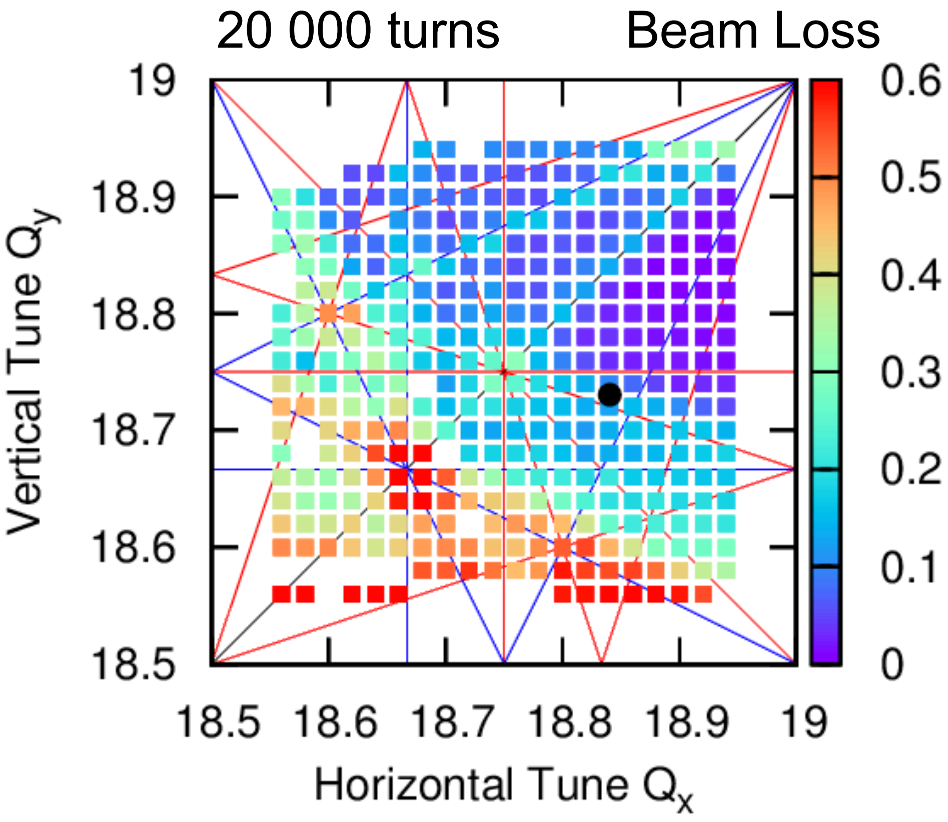
M. Borland, "*elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation*" Advanced Photon Source LS-287, September 2000. Y. Wang and M. Borland, "*Pelegant: A Parallel Accelerator Simulation Code for Electron Generation and Tracking*", Proceedings of the 12th Advanced Accelerator Concepts Workshop, AIP Conf. Proc. 877, 241 (2006)

- Nominal U^{28+} bunch during the 1 sec accumulation at the injection energy
- 6D particle dynamics in the complete SIS100 lattice with the errors
- High intensity: frozen nonlinear space-charge model
- Multi-core simulations on the Green IT Cube at GSI
- Other tools (MADX, PATRIC) under active development

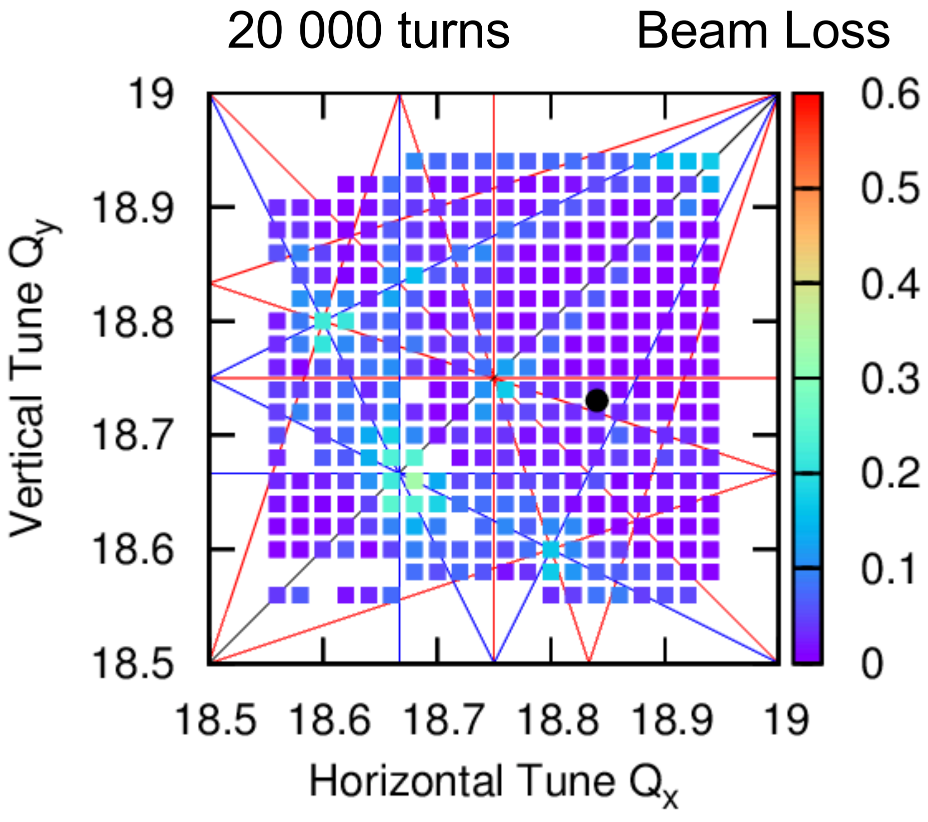
At the moment, the most complete description of the SIS100 accelerator and of the high-intensity effects for reliable predictions

Simulations: Tune Scans

Every square: beam loss (color, 1 is 100%)
after tracking a bunch for 20 000 turns



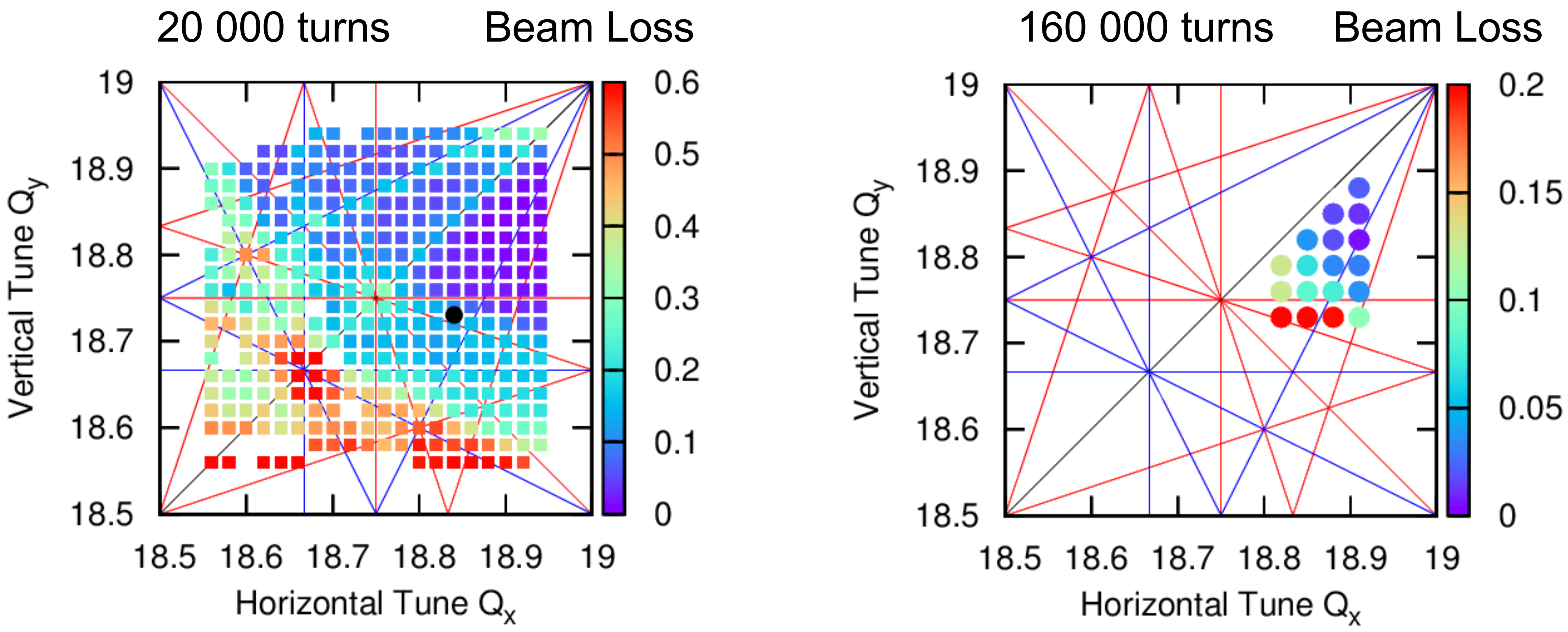
With space charge



No space charge

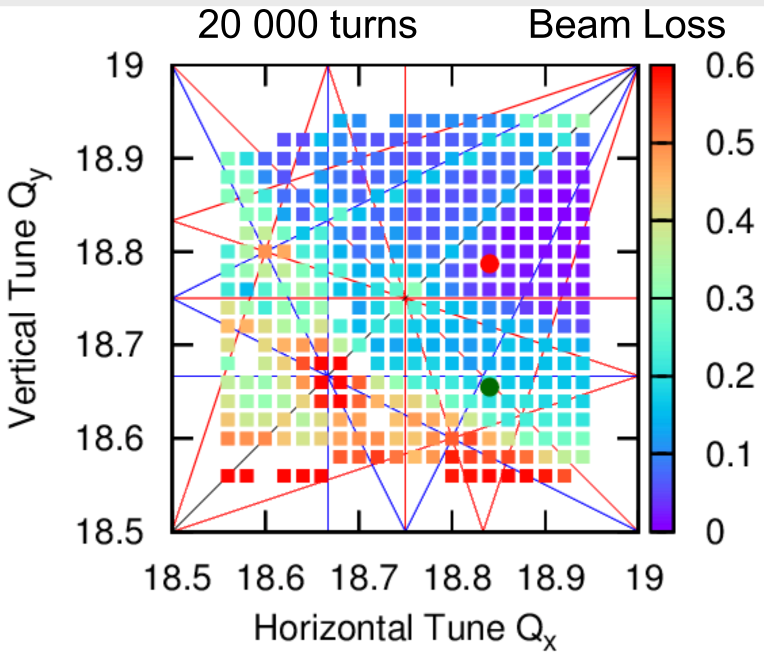
Long simulations for the good tunes

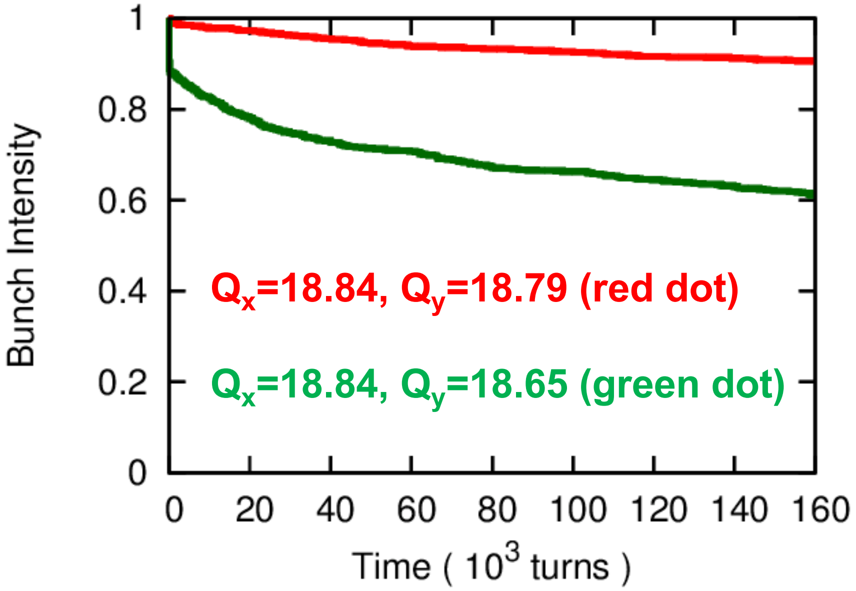
There is a good tune area.
Longer simulations (160 000 turns = 1 sec) confirm low losses.



note different color scale

Simulations: Beam Loss

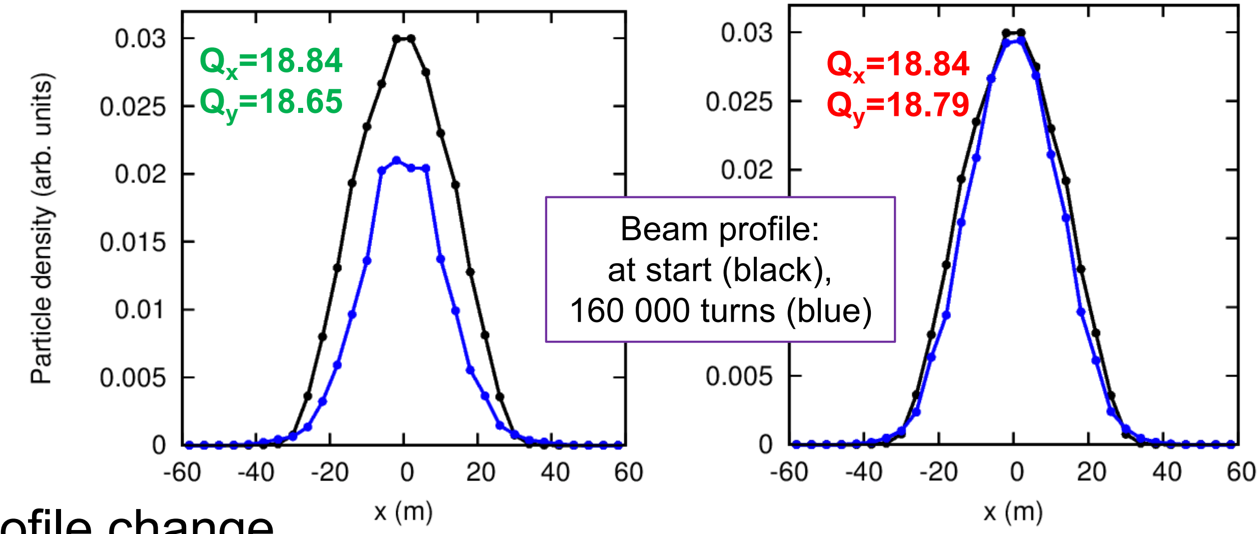




An example for the RIB cycle (1sec, 4 inj × 2 bunches): first 2 bunches 9% Loss → 5.5% Total Beam loss

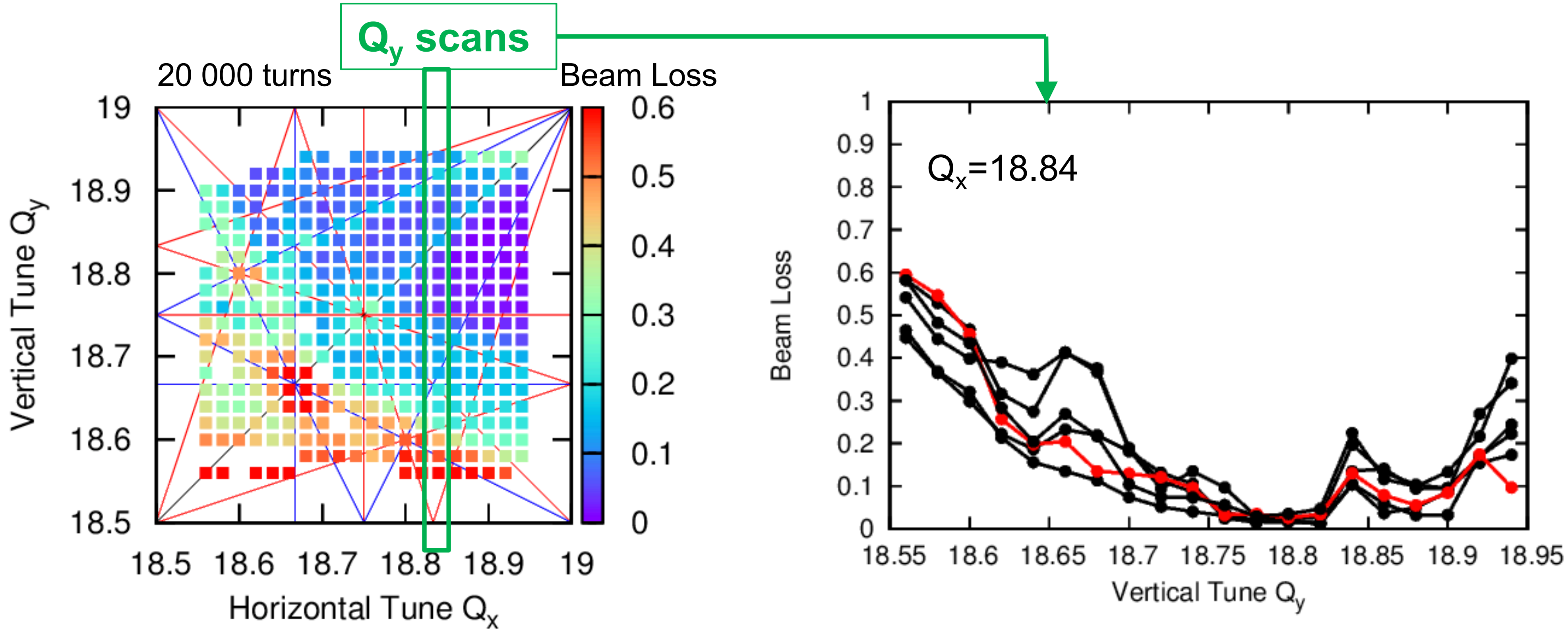
160 000 turns = 1 sec.

For tunes with less losses: no profile change.



Beam profile:
at start (black),
160 000 turns (blue)

Different Random Seeds

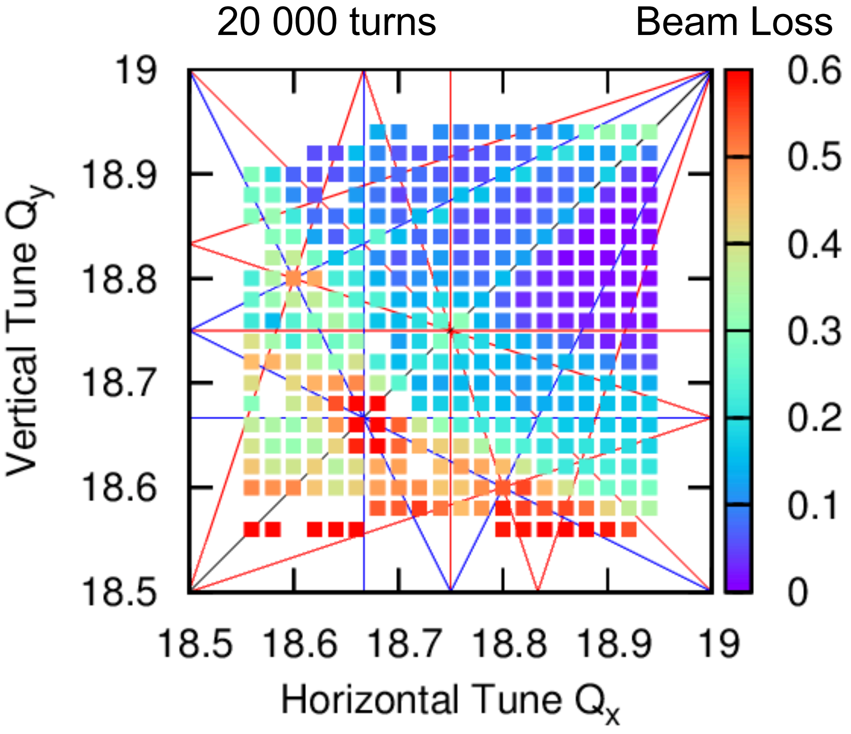


In the good tune area,
beam losses are small irrespective the random error seed

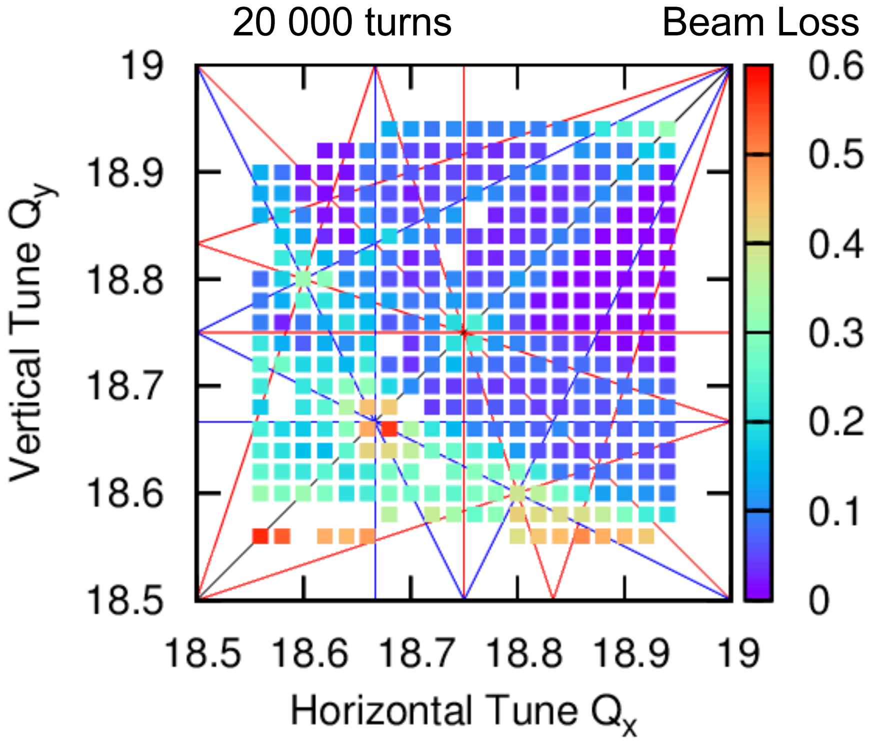
Dual-RF operation

First check for a weaker space-charge due to dual-rf bucket.
Here: the single-rf bucket, effects of the dual-rf synchrotron frequency distribution are not take into account

Full space charge



0.6 space charge

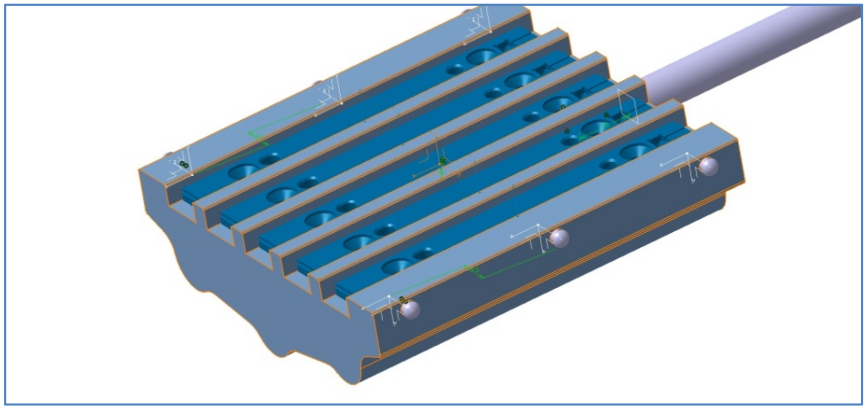


This issue, and in general for the beam-loss predictions:
Simulations↔Measurements comparisons for SIS18 are needed

Response to R9: measurements with/without vacuum chamber

There are only field measurement of a dipole magnet with and without the vacuum chamber in 2016 with the FoS magnet before the error reduction.

“Assel” system: 5 coils



V.Marusov, PBMT.

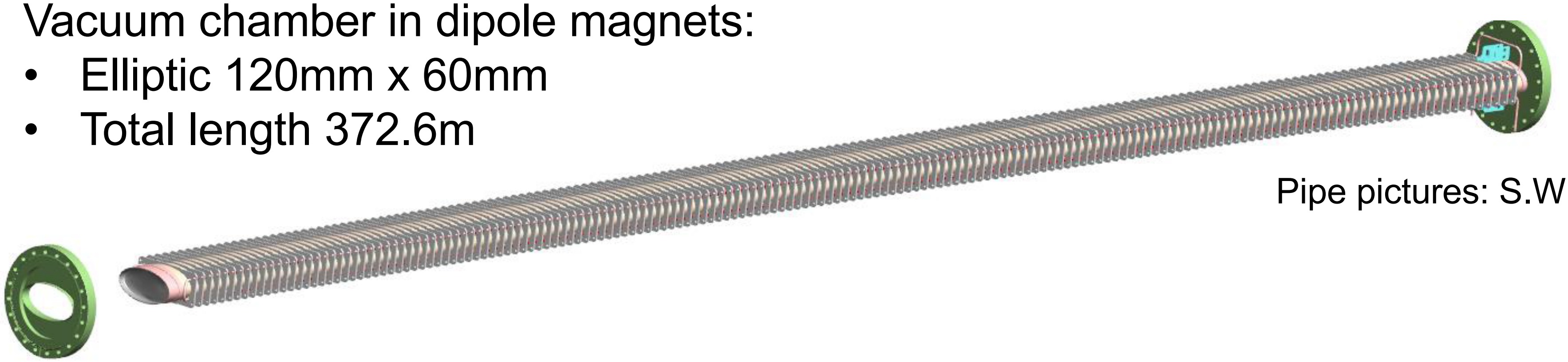
Conclusions

- **within accuracy of the measurements chambers are identical**
- **field distortion introduced by either chamber is negligible compare to the field inhomogeneity of the SIS100 dipole magnet itself**

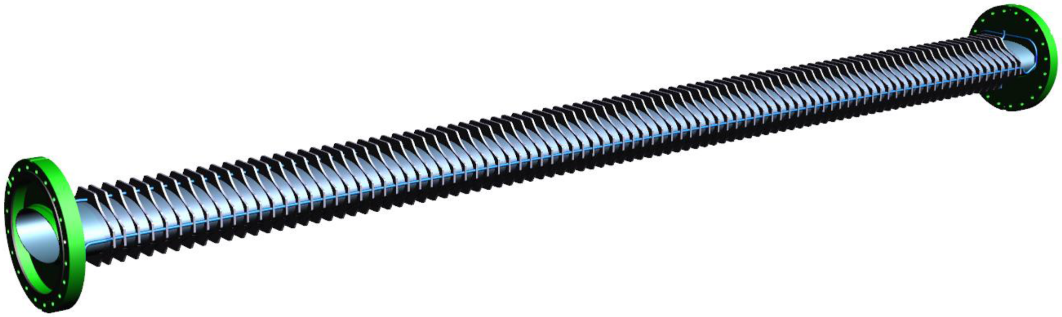
Resistive-Wall Instability

Vacuum chamber in dipole magnets:

- Elliptic 120mm x 60mm
- Total length 372.6m



Pipe pictures: S.Wilfert, MAC19

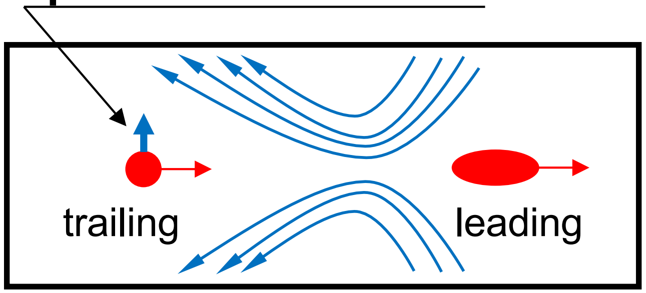


Vacuum chamber in quadrupoles:

- Elliptic 133.4mm x 65.2mm
- Total length 282.5 m

(reminder) a high-intensity problem:
self-induced EM-fields couple to the
beam surroundings and cause instabilities:
Description using the IMPEDANCES Z(f)

experiences the induced fields



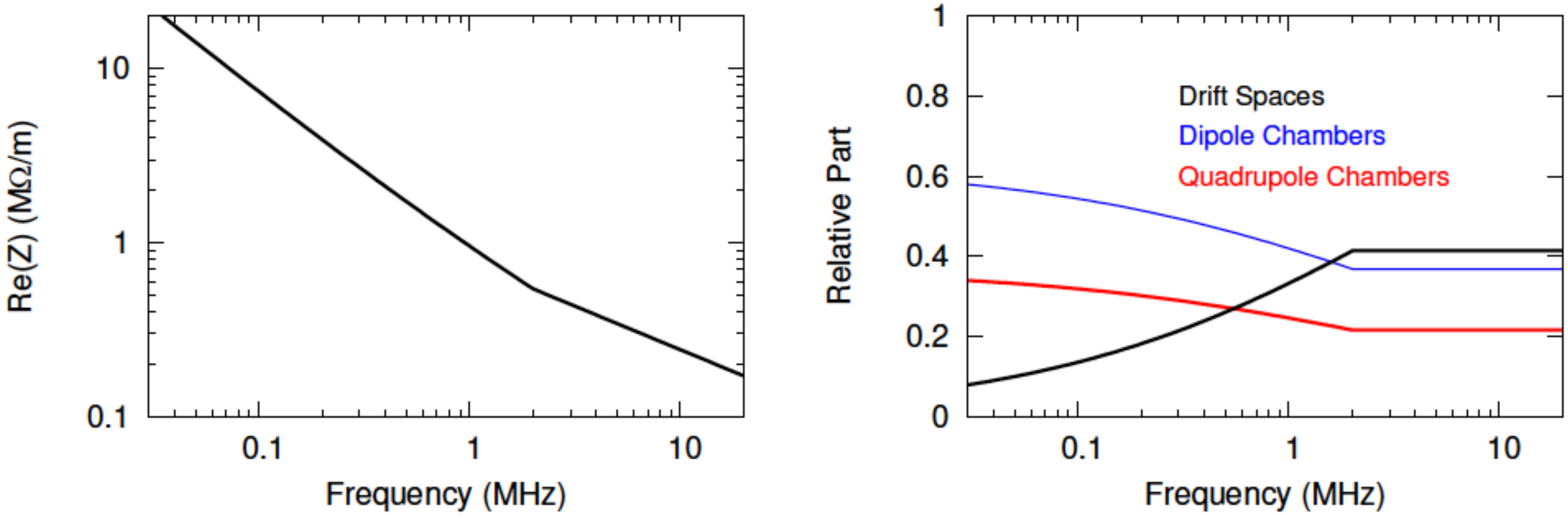
$$V_x \propto Z_x \times I_{\text{beam}}$$

SIS100 Resistive-Wall Impedance

	Horizontal Diameter $2b_x$	Vertical Diameter $2b_y$	Wall thickness d_{pipe}	Length
Quadrupole Chambers	133.44 mm	65.21 mm	0.3 mm	282.5 m
Dipole Chambers	120 mm	60 mm	0.3 mm	372.6 m
Drift Spaces	135 mm	65 mm	3 mm	428.48 m

Simplified, conservative model for the drift spaces, other devices.
Impedance for elliptic pipes U.Niedermaier, et al, NIM 687 51-61 (2012)

Vertical resistive-wall impedance of the SIS100 vacuum pipes



Head-Tail Instability

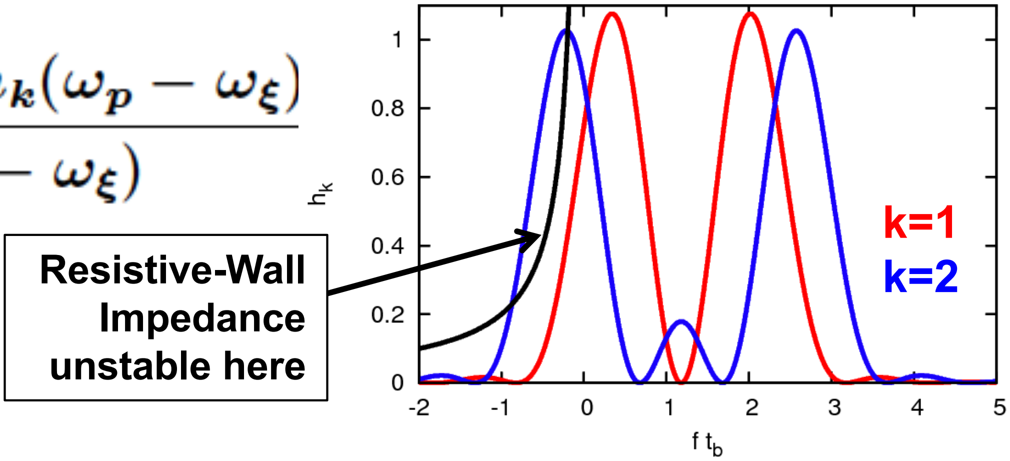
The approach by F. Sacherer 1974

$$\Delta Q_k = \frac{\Upsilon}{1+k} \frac{\sum(-i) Z_\perp(\omega_p) h_k(\omega_p - \omega_\xi)}{\sum h_k(\omega_p - \omega_\xi)}$$

$$\omega_p = (p + Q_0)\omega_0 + k\omega_s$$

$$\Upsilon = \frac{I_0 q_{\text{ion}}}{4\pi\gamma m c Q_0 \omega_0}$$

$$\omega_\xi = \frac{Q_0 \xi}{\eta} \omega_0$$



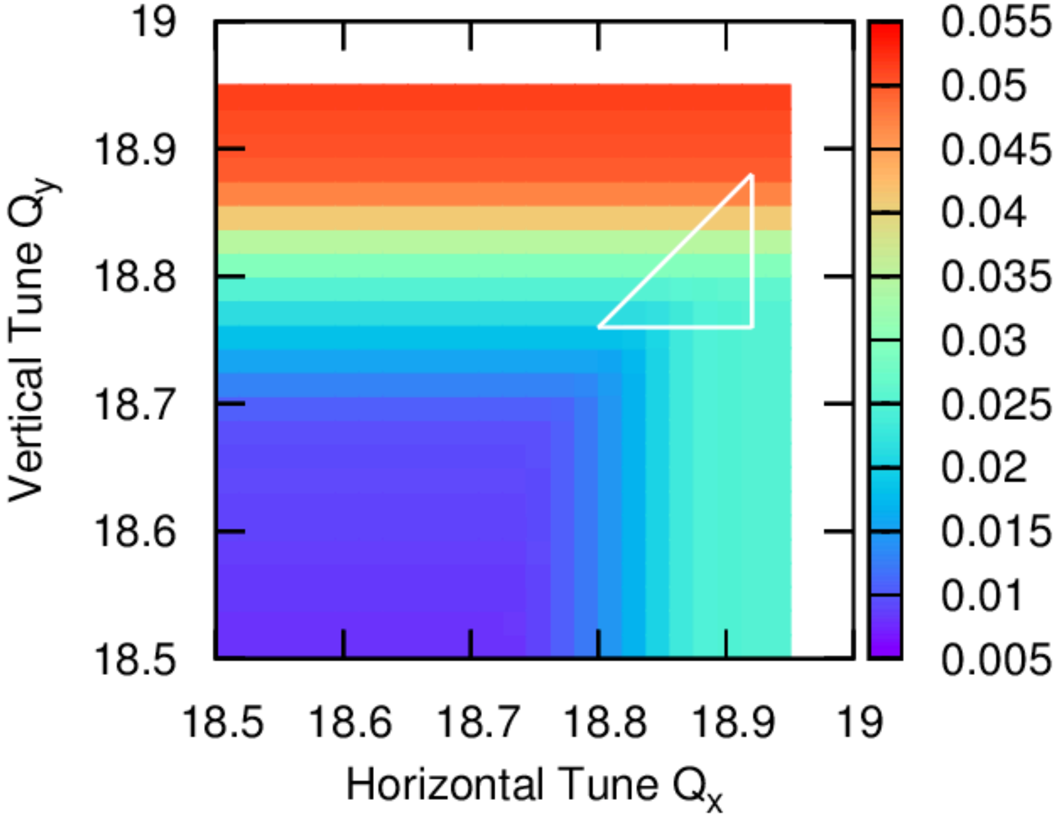
Resistive-Wall Impedance unstable here

k: mode index
Q_0: betatron tune
ξ: chromaticity
h_k: bunch eigenmode spectrum

Sacherer theory predicts:

- Resistive-Wall Impedance is the main drive for the single-bunch and coupled-bunch head-tail instability
- Dependencies on the tunes and on the chromaticity machine settings

Head-Tail Instability



Color: Growth Rate ΔQ, 10^{-3} of the most unstable mode.

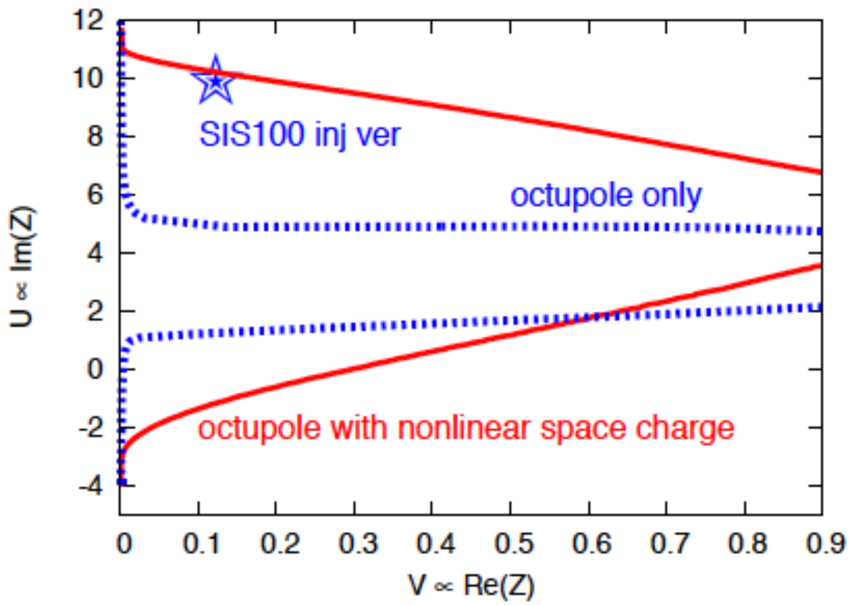
0.04 corresponds to the growth time 25ms. Conservative model for the vacuum pipe impedance

White triangle: schematic for the good area from the beam-loss simulations

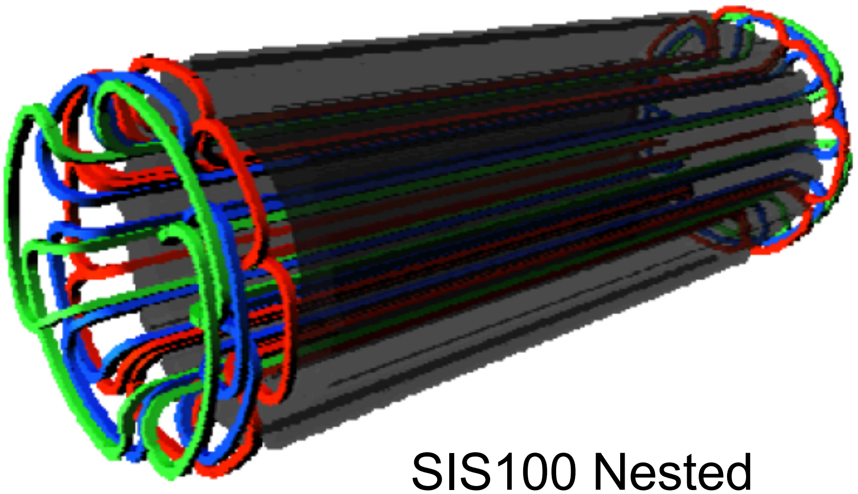
! Experience at many synchrotrons shows much faster instabilities.
Safety margin is needed!

Head-Tail Instability

Octupoles Magnets in SIS100



V.Kornilov et al, prstab 11, 014201 (2008)



SIS100 Nested
Corrector Magnets (12)

Simplified estimations imply stability with the SIS100 octupoles, but:

- the safety margin is small
- octupoles degrade the single-particle stability (under further study)

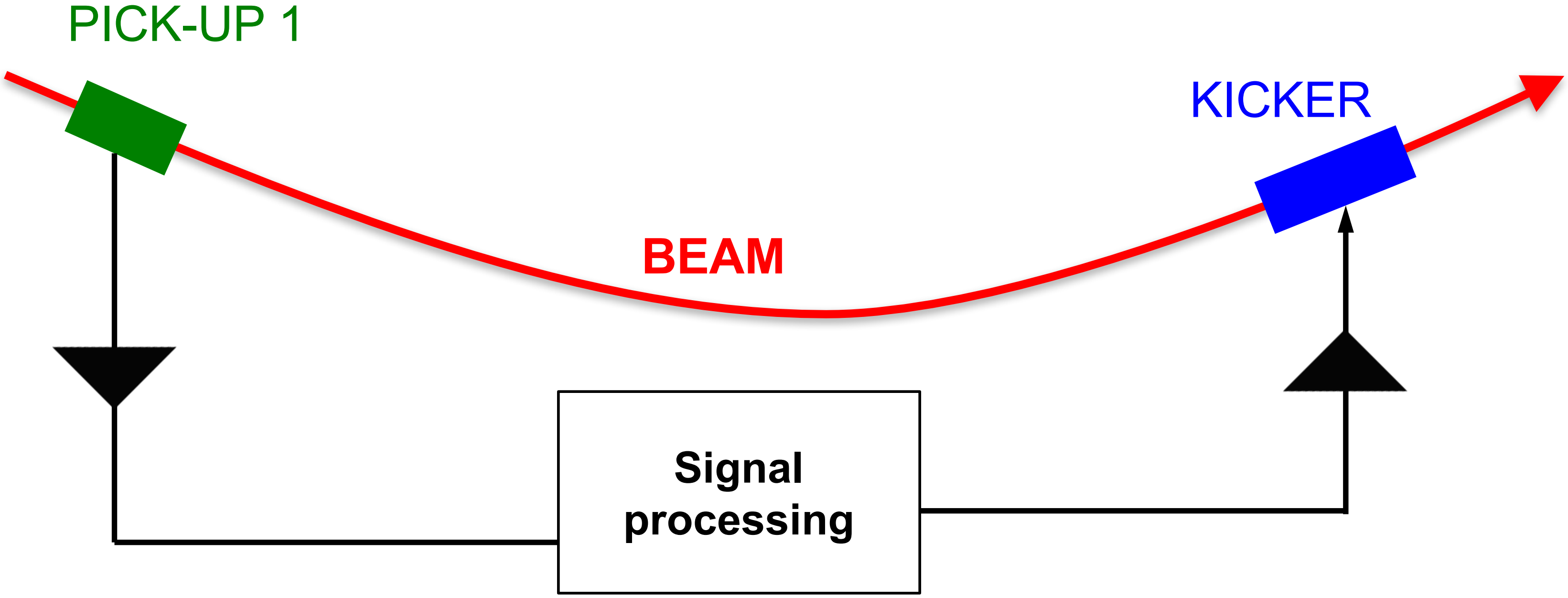
Transverse Feedback System (Damper)

Further tasks:

- Completing the geometrical model of the SIS100 vacuum chambers
- Continue to identify other sources of the impedances
- Update of the studies for the effect of the octupoles on the beam stability and on the beam-loss (previous study positive, V.Kornilov et al, IPAC2010).
- Comparisons calculations ↔ measurements in SIS18

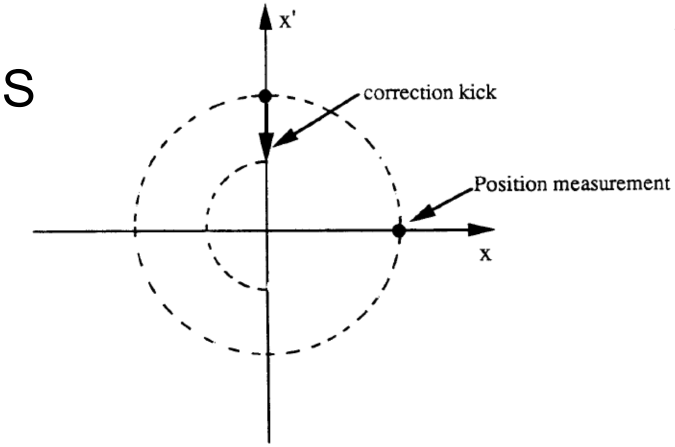
Meanwhile:

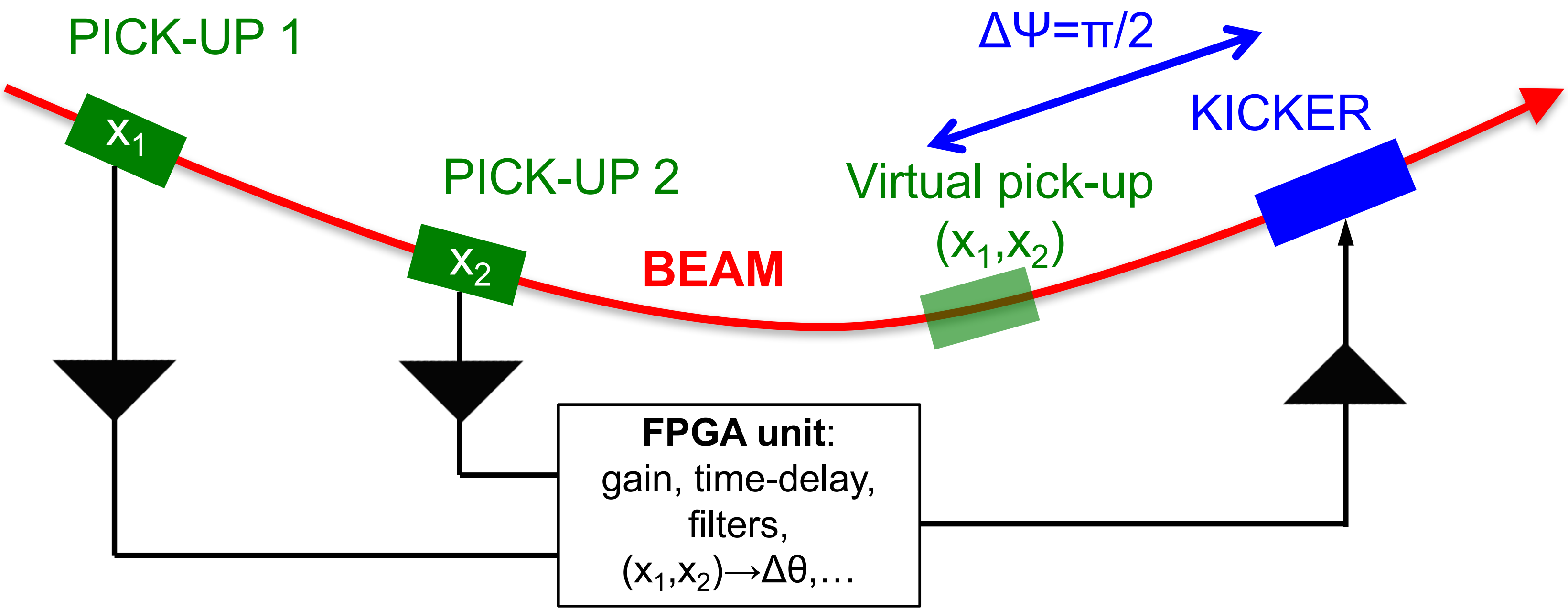
Consider the active suppression of the collective oscillations



Transverse Feedback System (Damper)

- Restriction: special (warm) Pick-Ups are needed for TFS
- 2 Pick-Ups for TFS (preliminary)
- Can also operate with one Pick-Up:
  PICK-UP2 is PICK-UP1 one turn later





PICK-UP 1

x_1

PICK-UP 2

x_2

BEAM

$\Delta\Psi=\pi/2$

Virtual pick-up

(x_1,x_2)

KICKER

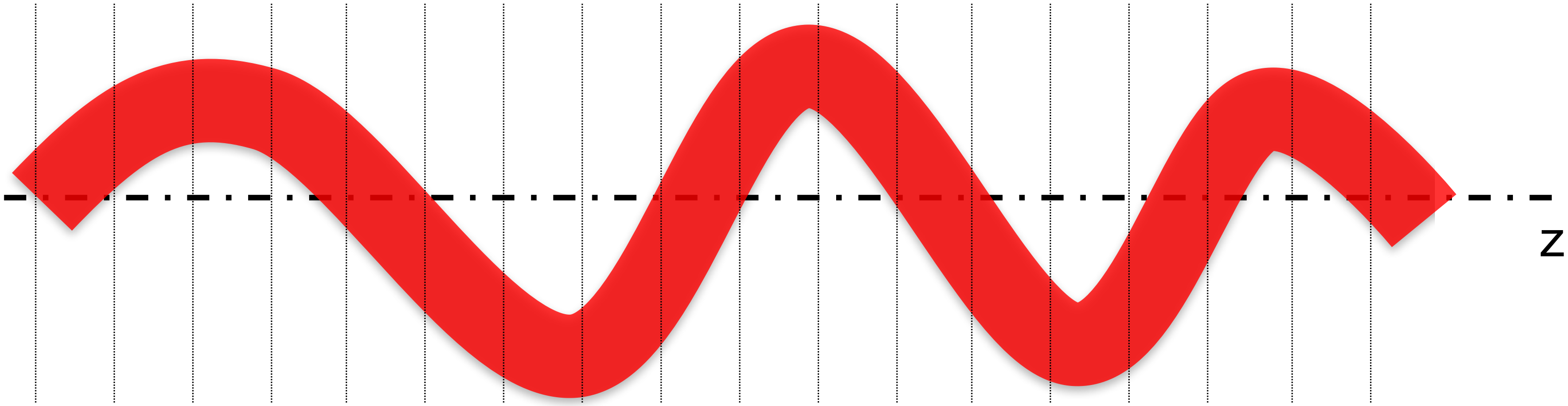
FPGA unit:
gain, time-delay,
filters,
$(x_1,x_2)\rightarrow\Delta\theta$,…

Transverse Feedback System (Damper)

SIS100: Chromaticity, and higher-order modes in long bunches.
The average offset is smaller that the local offset along the bunch

$$\langle \Delta x \rangle \ll \Delta x(s)$$

Thus: multi-sampling per bunch is necessary



Transverse Feedback System (Damper)

TFS for SIS100: physics-based specs

Present assumption: the function as an injection error damper is not needed

Instability damping time: 100 turns, $\Delta\theta$ = 16 μrad
Bandwidth: 25kHz → 10MHz
Multi-sampling along the bunch.
Sampling rate 8 ns.
Kicker: L=2.5 m; d=135 mm; U_{peak}=0.3 kV
for a 50Ω−equivalent strip-line: P_{rms} = 2.1 kW

The feedback system alone would ensure beam stability.
The octupoles will be used additionally / optionally (exper LHC)

Summary

- The field data from the 21 series dipole magnets demonstrate a sufficiently good field quality.
- The field data from the (unmilled) FoS quadrupole, and linear error/shifts assumptions, are used to construct a conservative SIS100 magnet model.
- The 160 000 turns (1 sec) bunch simulations with the “elegant” code, and the 2D tune scans, demonstrates important role of space-charge and the existence of safe tune areas.
- Especially in the good tune area the Resistive-Wall Instabilities have to be damped efficiently.
- In addition to the octupole system, a TFS is desirable to secure the beam stability. Physics-based specs for a TFS are formulated.
- Experiments (MD) at SIS18 are needed for reliable predictions.