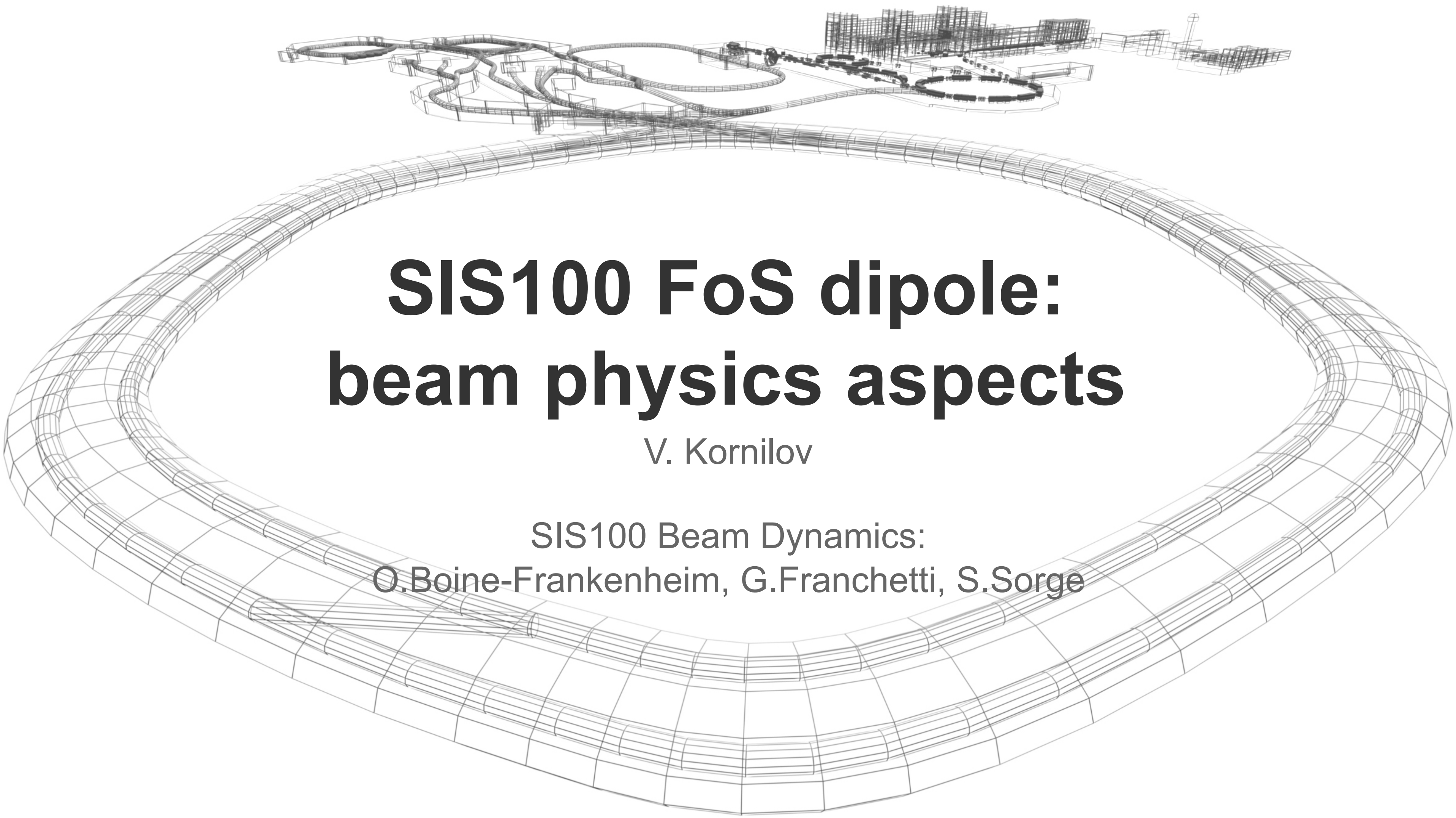


SIS100 FoS dipole: beam physics aspects

V. Kornilov

SIS100 Beam Dynamics:
O.Boine-Frankenheim, G.Franchetti, S.Sorge

SIS100 BEAM DYNAMICS SO FAR

Dynamic Aperture (DA), Beam Loss studies with the Computational Model Magnets (B_n, A_n):

- 1st MAC 2009: nonlinear dynamics, DA scans (talk Franchetti)
- 4th MAC 2010: beam loss simulations, slow extraction (talks Franchetti, Sorge)
- 5th MAC 2011: beam loss during ramp (talk Franchetti)

Main conclusions:
with the Computational Model Magnets and 30% random error ($\delta B_{n\ RMS}=0.3B_n$)

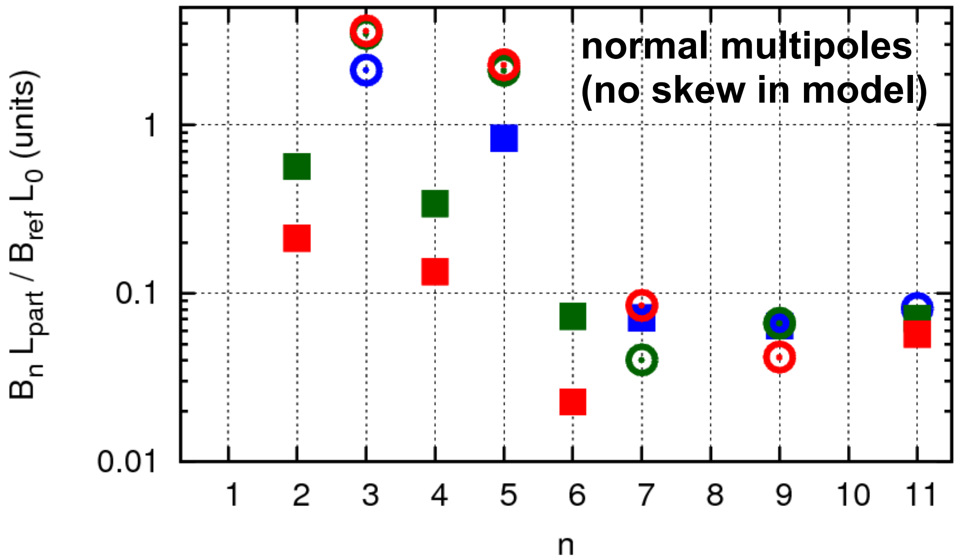
- DA is generally safe (>3ε), beam loss ≈5%
- beam loss is due to **combination** Space-Charge with Field-Errors + beam width (contrary to Nuclotron)
- resonance compensation necessary

Discussion at 10th MAC 2013:
Comparison of (B_n,A_n) for FoS Magnet vs. Computational Model is the base.
In the case of a good agreement (below $2\sigma_{meas}$), the satisfactory field quality can be concluded.

SIS100 MAGNETS: COMPUTATIONAL MODEL

Dipole Magnet (108 in SIS100)
Computational Model Akishin et.al. 2010, Kapin et.al. 2010

Center (red), Conn-End (blue), Nonconn-End (green)
circle O: positive (+)
square ■: negative (−)



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

$B_n^{error} = B_n^{syst} + B_n^{random} = B_n + \delta B_n \times$Gaussian
δB_n is the rms spread of the error

Our assumption so far: $\delta B_n = 0.3\ B_n$:

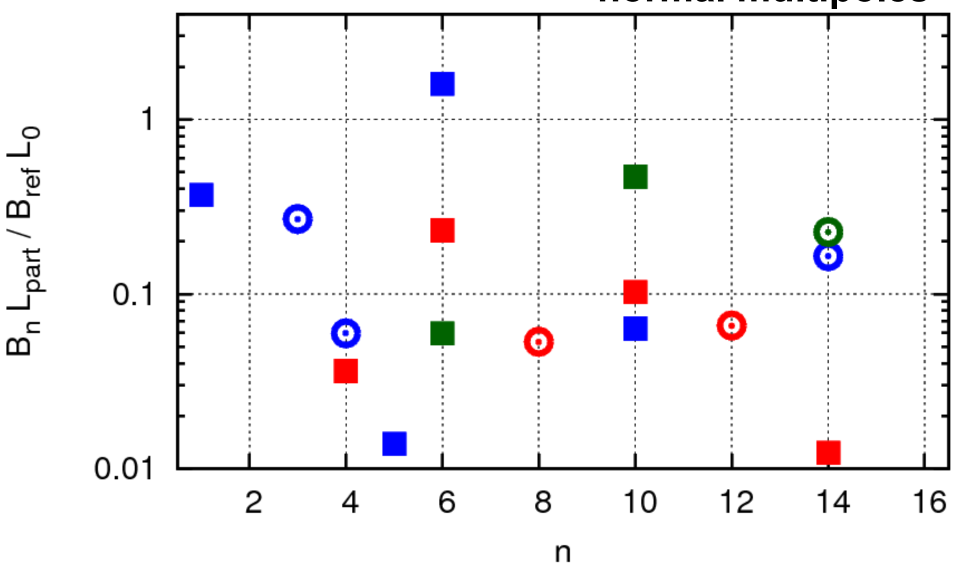
- Is it appropriate, to relate δB_n to B_n ?
- Is the number 0.3 appropriate?

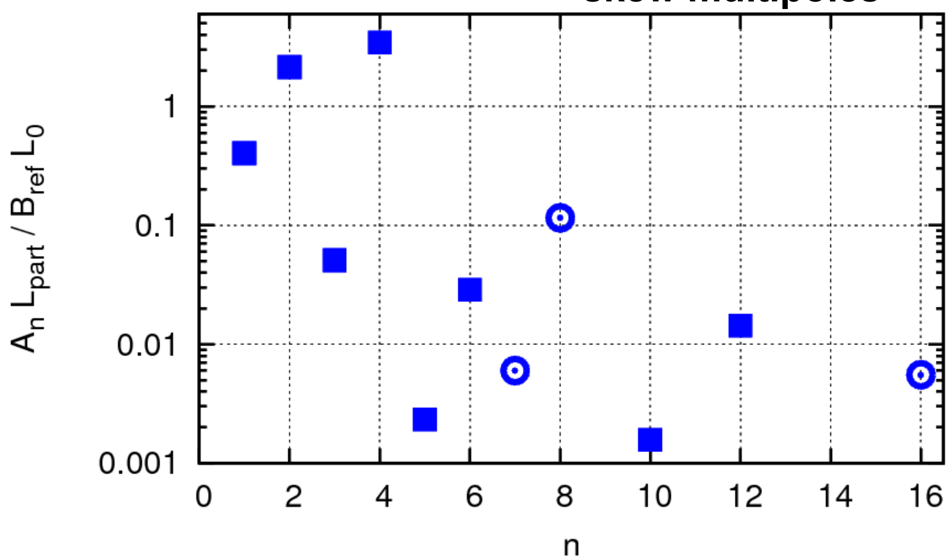
n=1 dipole, n=2 quadrupole,…
r_0=40mm
1 unit = 10^{-4}

averaged over
L_{center}=2.52m, L_{end}=0.4m

SIS100 MAGNETS: COMPUTATIONAL MODEL

Quadrupole Magnet (166 in SIS100 + 2 warm)
Computational Model Akishin et.al. 2010, Sugita 2013
Center (red), Conn-End (blue), Nonconn-End (green)
circle **O**: positive (+)
square ■: negative (−)





n=1 dipole, n=2 quadrupole,…
r_0=40mm, 1 unit = 10^{-4}

averaged over
L_{center}=0.96m, L_{end}=0.35m

skew multipoles for the nonconnection-end from the recent simulations by K.Sugita; center, conn-end: no skews

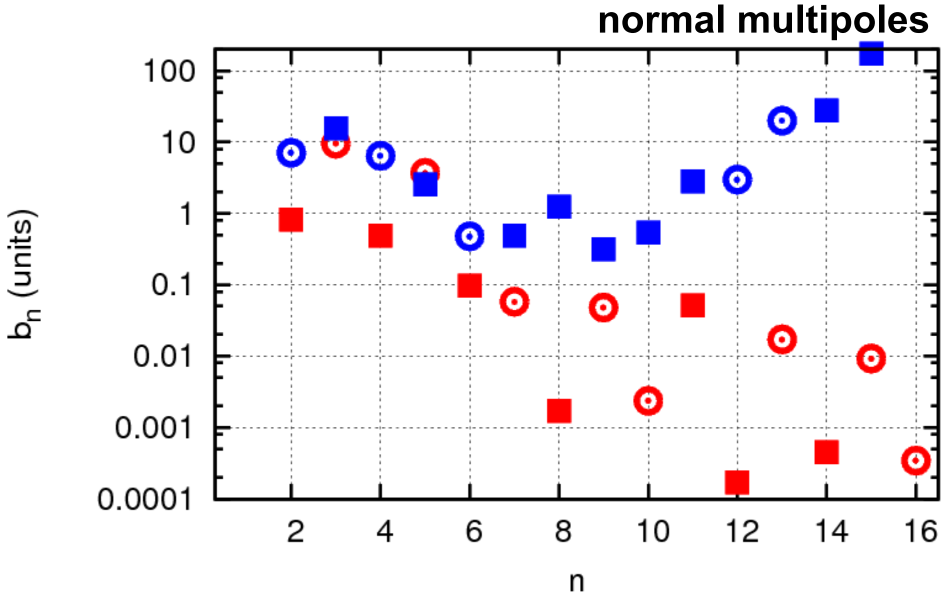
COMPARISON FOS VS COMP.MODEL

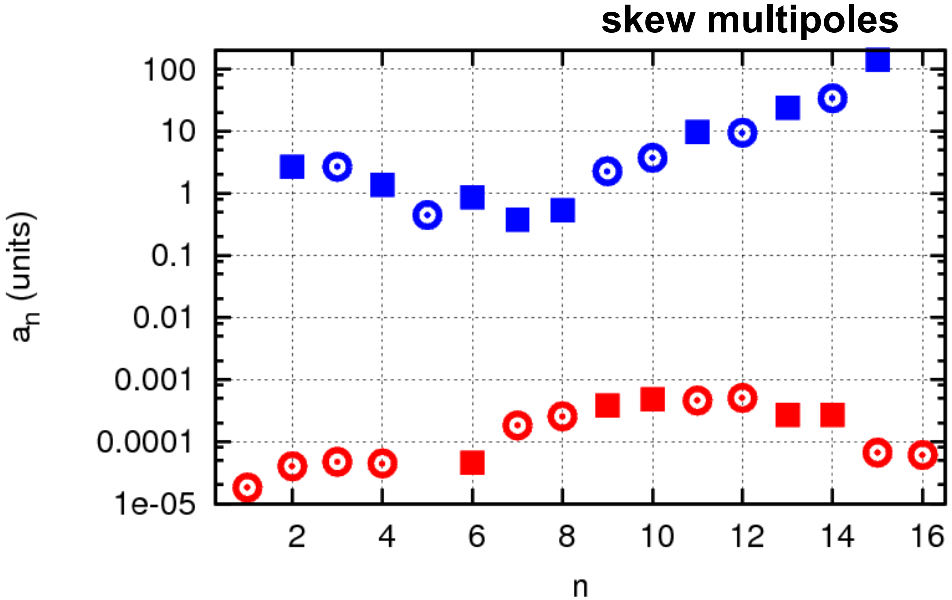
Complete Dipole Magnet Bρ=15.8Tm

Computational Model (red), Measurements 1Coil FoS (blue)

circle O: positive (+)

square ■: negative (−)





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

n=1 dipole, n=2 quadrupole,…

r_0=40mm

$b_n=B_n/B_1$, $a_n=A_n/B_1$

1 unit = 10^{-4}

averaged over L_0=3.6m

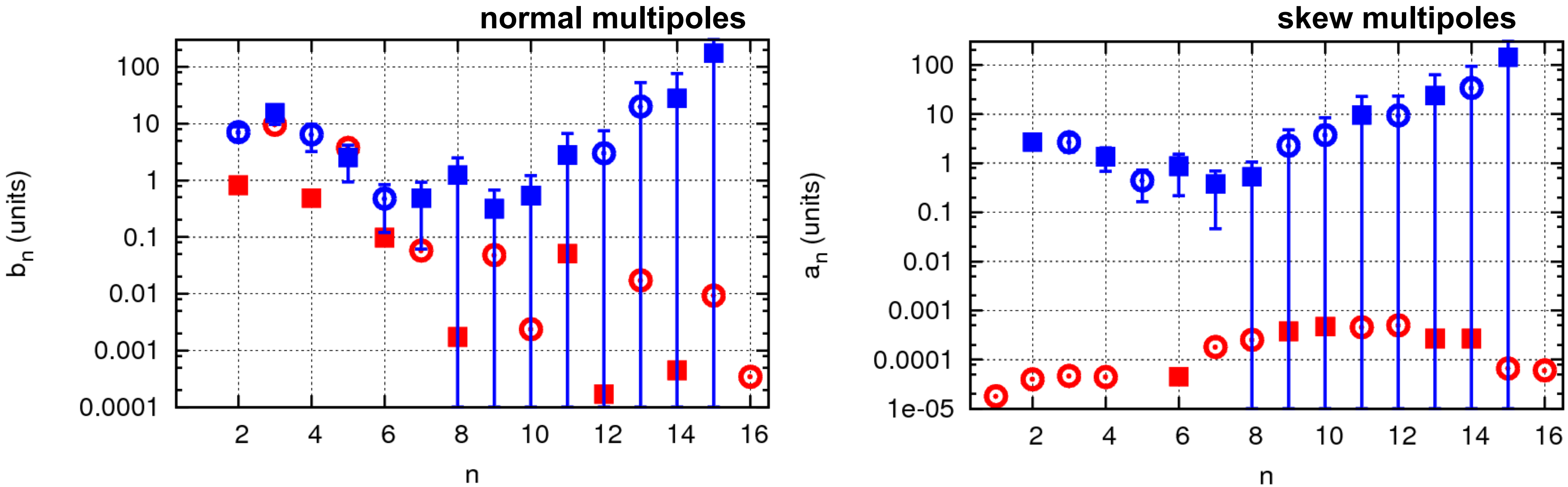
COMPARISON FOS VS COMP.MODEL

Complete Dipole Magnet Bρ=15.8Tm

Computational Model (red), Measurements 1Coil FoS (blue) with the Error Bars

circle **O**: positive (+)

square ■: negative (−)



n=1 dipole, n=2 quadrupole,…

r_0=40mm, 1 unit = 10^{-4}, $b_n=B_n/B_1$, $a_n=A_n/B_1$

Conclusion: consider only n≤7.
the magnet differs from the computational model.

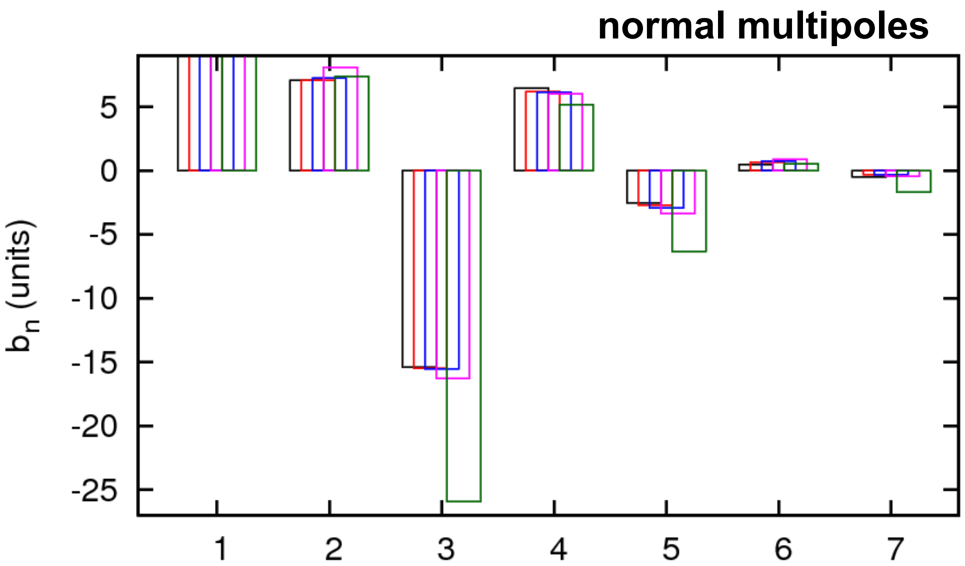
FOS MAGNET MULTIPOLES

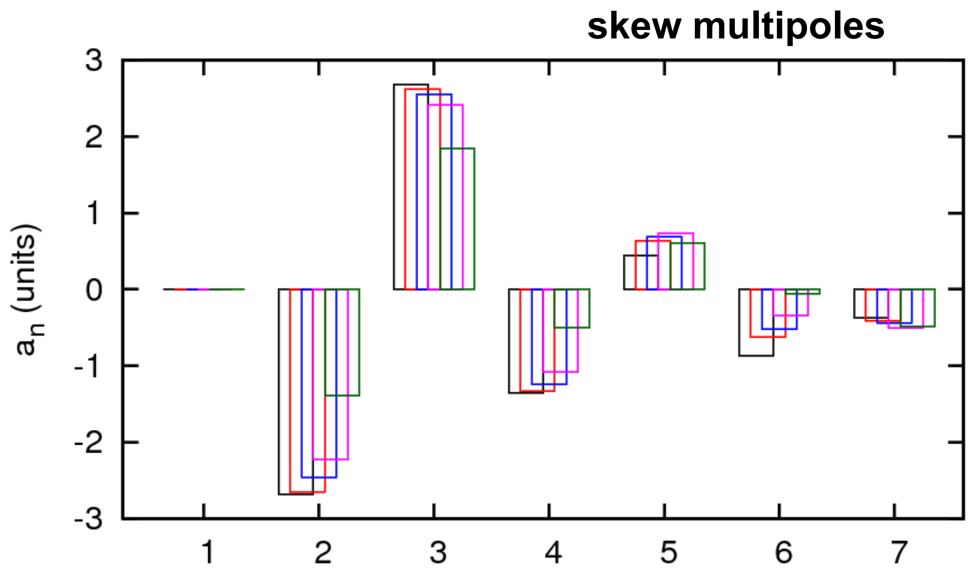
Complete magnet: Measurements with 1 (central) coil without end-block optimization

Current (kA): **2, 4, 6, 10, 13.1**

Bρ(Tm): **15.8, 31.5, 47.3, 79, 103**

SIS100 Operation: from Bρ=18Tm to Bρ=100Tm





n=1 dipole, n=2 quadrupole,…

r_0=40mm, 1 unit = 10^{-4}, $b_n=B_n/B_1$, $a_n=A_n/B_1$

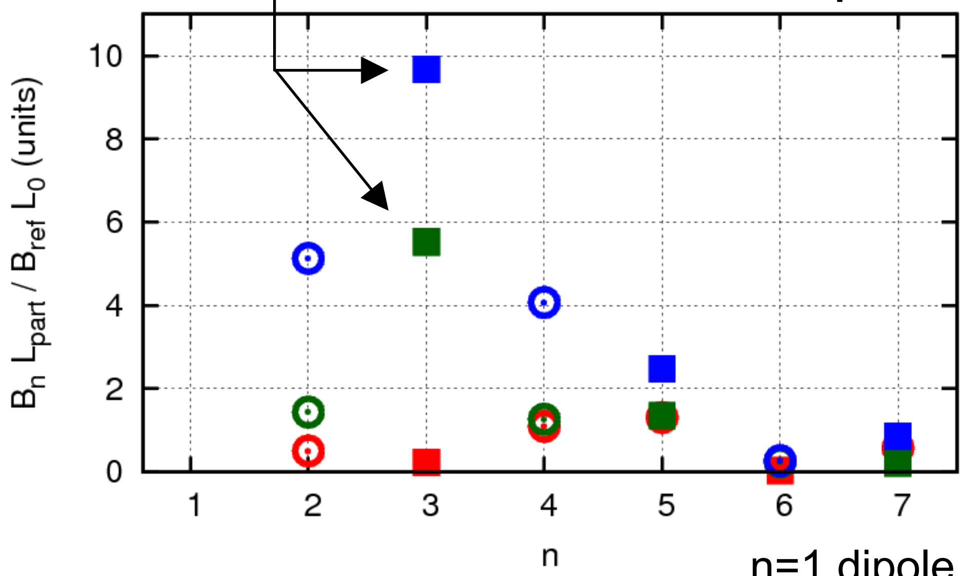
Multipoles do not change significantly with the increasing current

FOS DIPOLE MAGNET MULTIPOLES

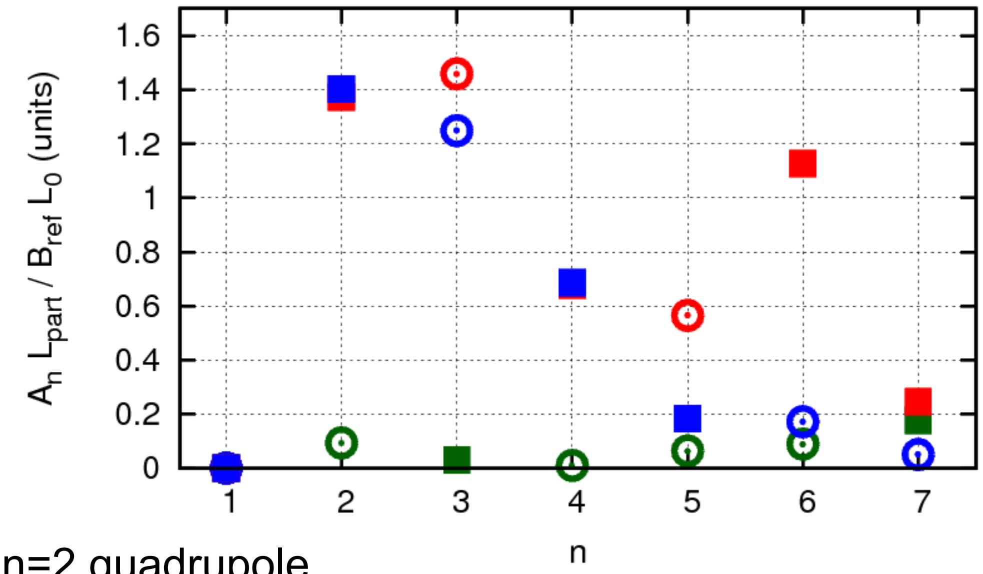
Measurements with 1 (central) coil without end-block optimization
Center (red), NonConn-End (blue), Conn-End (green)
circle O: positive (+)
square ■: negative (−)

will be reduced by the end-block optimization

normal multipoles



skew multipoles



n=1 dipole, n=2 quadrupole,…

r_0=40mm, 1 unit = 10^{-4}, averaged over L_{center}=2.4m, L_{end}=0.6m

Consider only n≤7.
Confirmed by other magnetic measurements (talk P.Schnizer)

Assumption: these are the **systematic** multipoles

FOS DIPOLE MAGNET MULTIPOLES

$B_2^{error} = B_2^{syst} + B_2^{random}$

B_2^{syst}-Component produces **tune shift**:

$\Delta Q_x = 18.74-18.84 = -0.1$

$\Delta Q_y = 18.81-18.73 = +0.08$

Fully compensated with the Main Quadrupoles.

A_2^{syst} produces linear coupling

B_2^{random} excites 2nd order resonances

A_2^{random} excites 2nd order coupling resonances

$B_3^{error} = B_3^{syst} + B_3^{random}$

B_3^{syst} produces **chromaticity shift**:

$\Delta Q\xi_x = -34.8-(-25.8) = -9.0$ (non-optimized)

$\Delta Q\xi_y = -18.5-(-25.7) = +7.2$ (non-optimized)

$\Delta(SL_{eff})_x = -17$T/m; $\Delta(SL_{eff})_y = -21$T/m

(magnet strength 175T/m, 170T/m for full ξ compensation)

B_3^{random} excites 3rd order resonances

A_3^{random} excites 3rd order coupling resonances

$B_4^{error} = B_4^{syst} + B_4^{random}$

B_4^{syst} produces ampl.-dependent tune shift:

$\Delta Q_x (a_{x,\ beam}) = 0.044$

$\Delta Q_y (a_{y,\ beam}) = 0.018$

(12 Corrector octupoles 3× stronger)

A_4^{syst} does not produce 1st order ΔQ

$B_n^{error} = B_n^{syst} + B_n^{random}$

$A_n^{error} = A_n^{syst} + A_n^{random}$

B_n^{random} excites nth order resonances

A_n^{random} excites nth order coupling resonances

RESONANCES

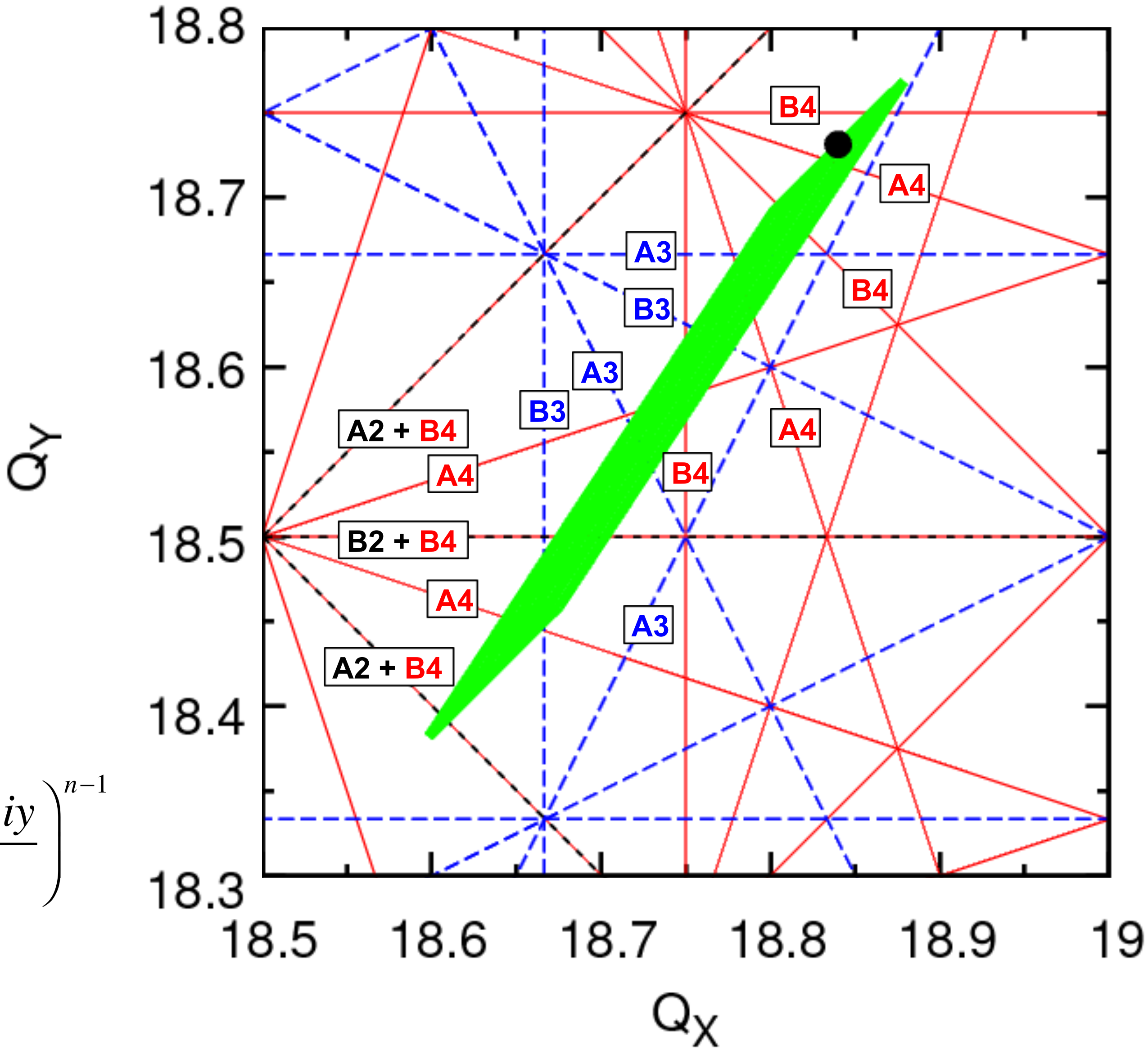
Ions Fast Extraction
Q_{X0} = 18.84
Q_{Y0} = 18.73

The tune footprint due to space charge and chromaticity with δp

B2: normal quadrupole
A2: skew quadrupole
B3: normal sextupole
A3: skew sextupole
B4: normal octupole
A4: skew octupole

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

╲ coupling sum
╱ coupling difference



RESONANCES

Resonance Compensation at SIS100

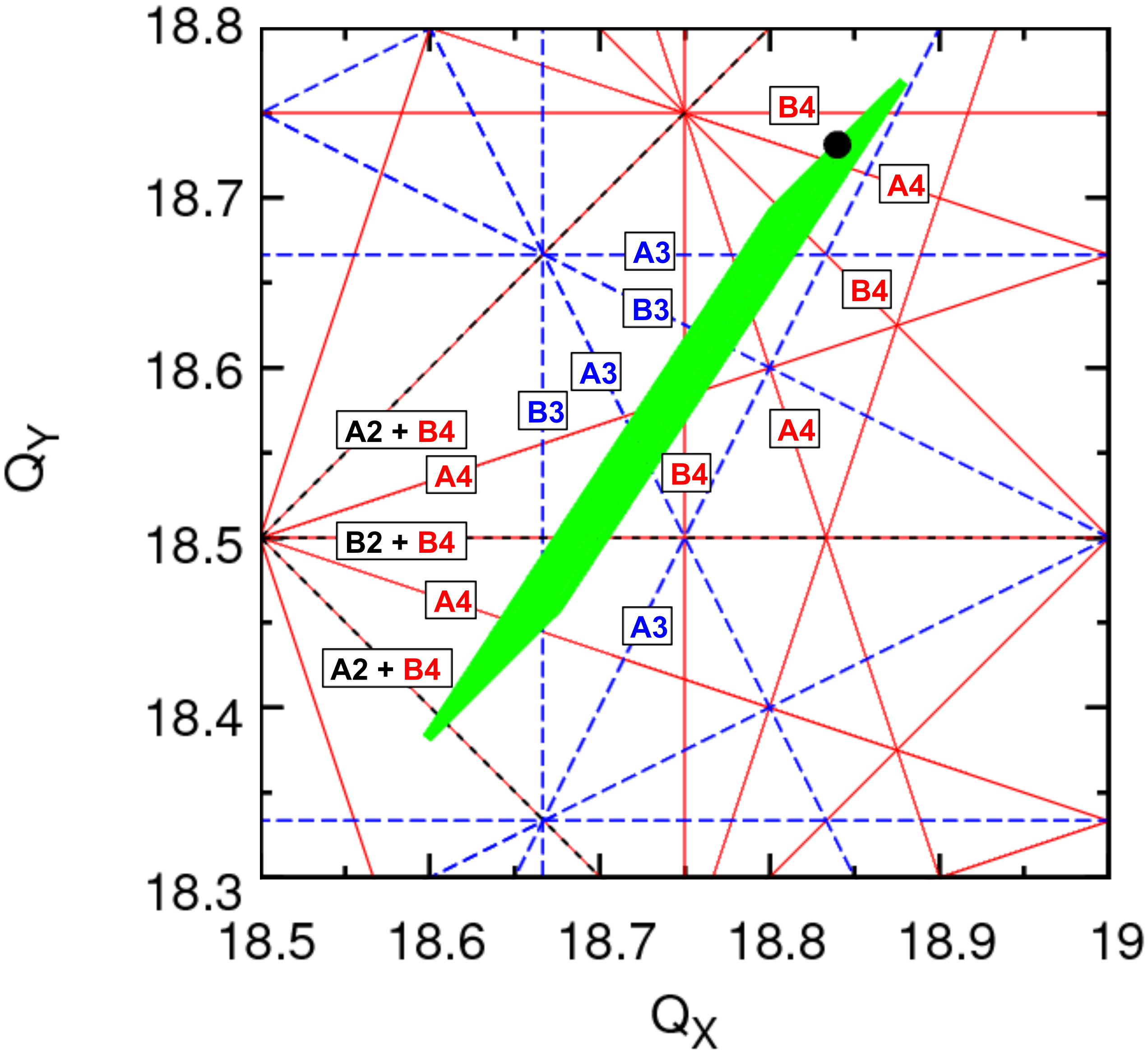
12 Corrector Quadrupoles (**B2**) 0.75T/m, 0.75m
30× stronger than $B_2^{syst\ FoS}$

no skew Quadrupoles (~~**A2**~~)

42 ξ−Sextupoles (**B3**)
350T/m², 0.5m
176× stronger than $B_3^{syst\ FoS}$
(plus 6 Resonance Sext)

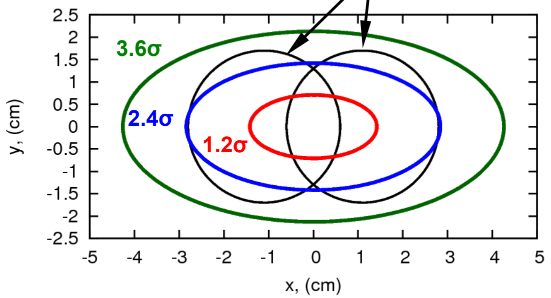
12 Correstor Skew Sext (**A3**)
50T/m², 0.75m
145× stronger than $A_3^{syst\ FoS}$

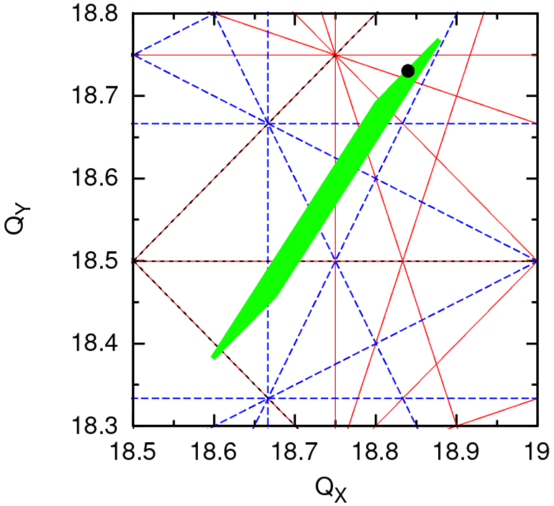
12 Corrector Octupoles (**B4**)
2000T/m³, 0.75m
25× stronger than $B_4^{syst\ FoS}$

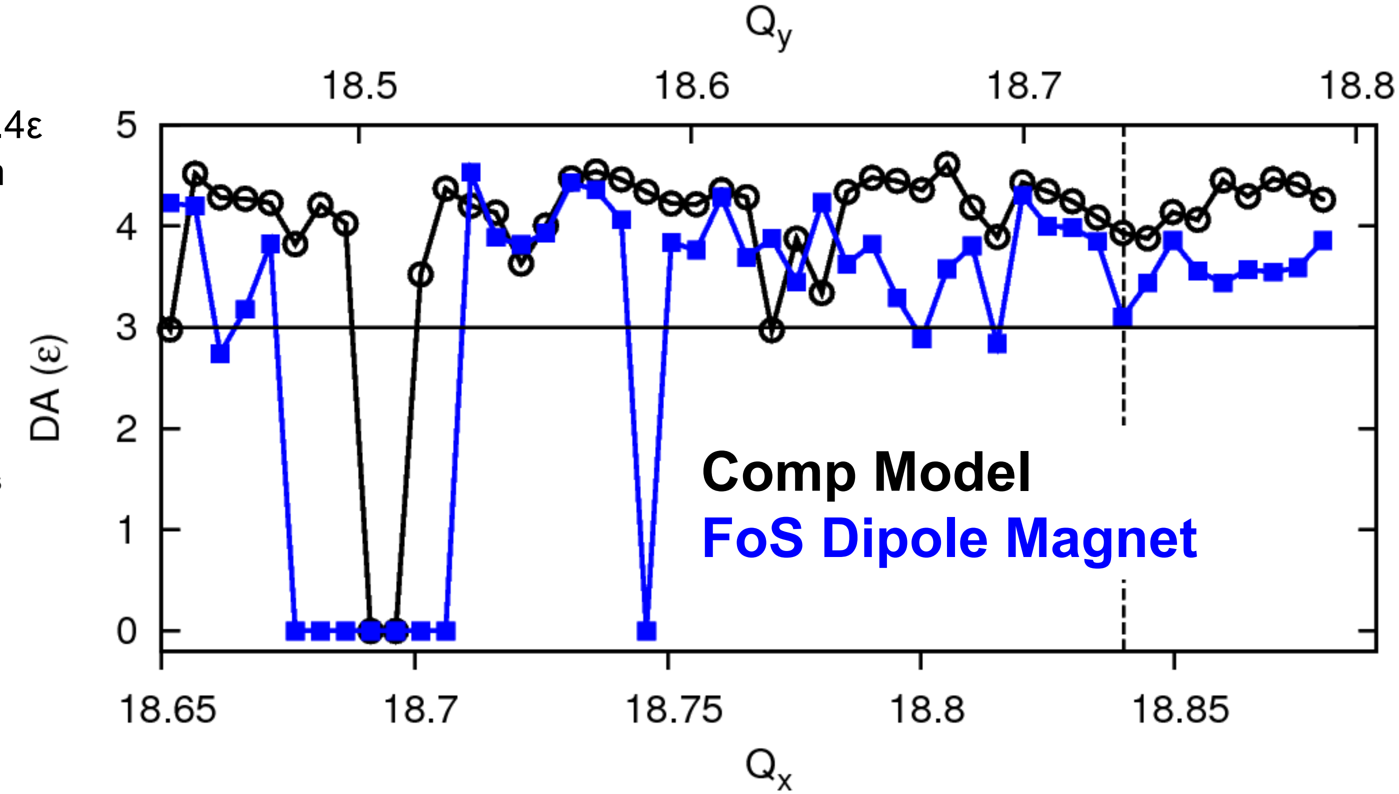


DYNAMIC APERTURE SCANS

Beam **1σ** = 11.8mm (hor)
Measurement area ≈2.4σ→1.4ε
Measurement coil: r=1.7cm



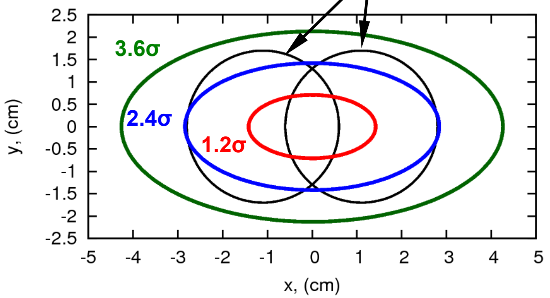


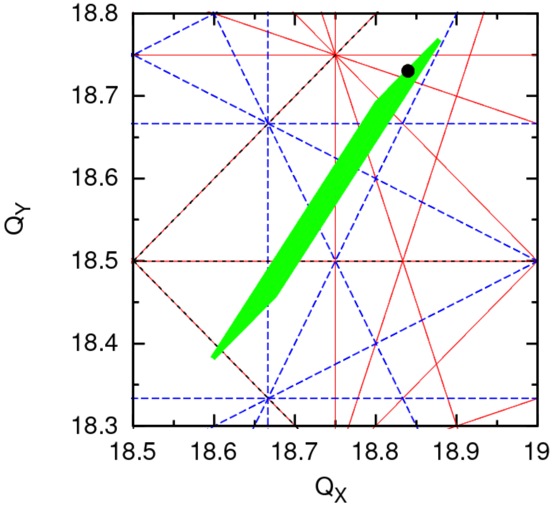


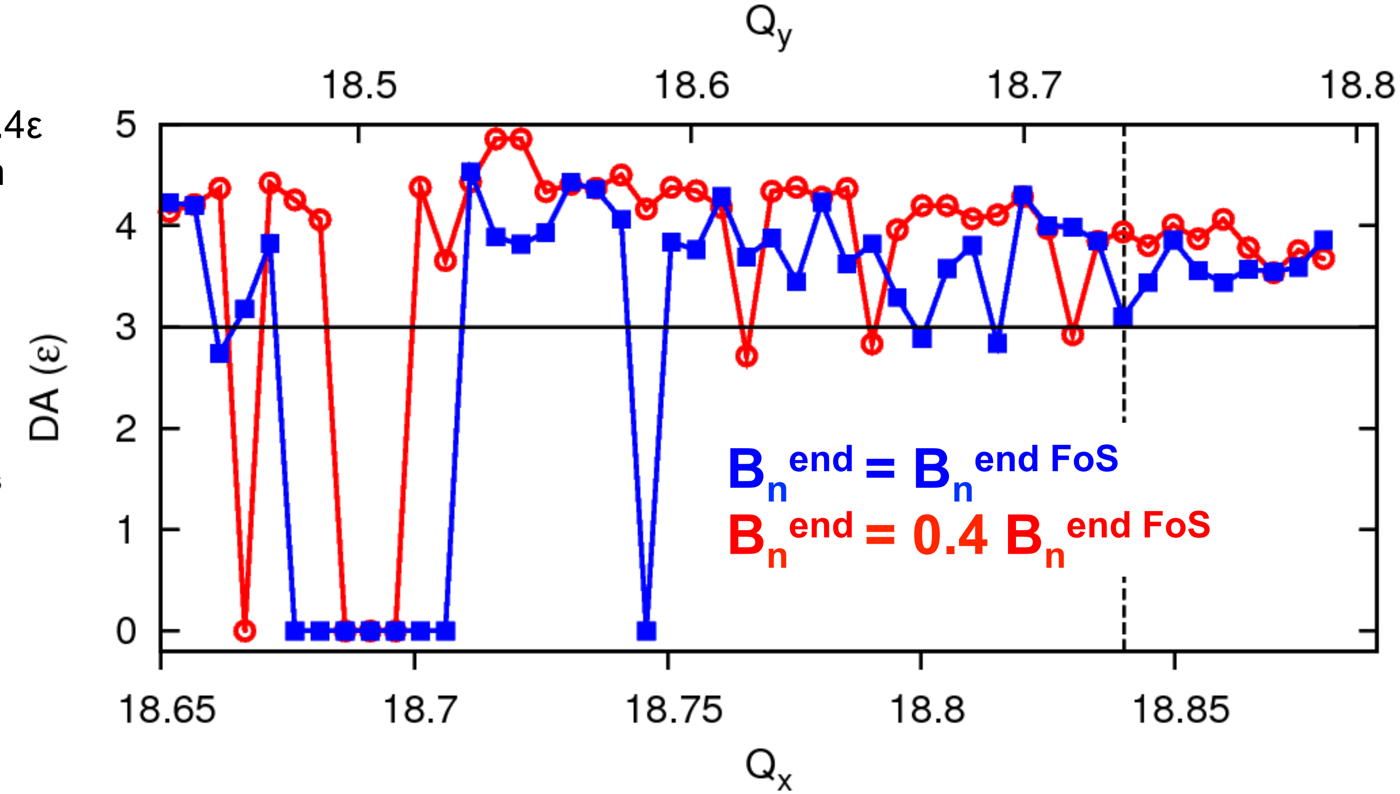
- Dipole Magnets: FoS n≤7; Quadrupoles: Comp. Model
- $\delta B_n = 0.3\ B_n$
- Closed-Orbit: Δx_{rms}=1.5mm, Δy_{rms}=1.0mm
- 10^3−turn scans with MADX, ε=35 mm mrad→2σ
- Tunes, chromaticity compensated
- No Space-Charge, no synchrotron motion

DYNAMIC APERTURE SCANS

Beam **1σ** = 11.8mm (hor)
Measurement area ≈2.4σ→1.4ε
Measurement coil: r=1.7cm







If the magnetic field errors are strong like B_n^{syst} and vary like $B_n^{random} = 0.3\ B_n^{syst}$, strong numerous resonances are excited.

Smaller systematic errors B_n^{syst} (end-block optimization, etc.) or smaller spreads will improve the single-particle stability

RESONANCES, OTHER OPERATIONS

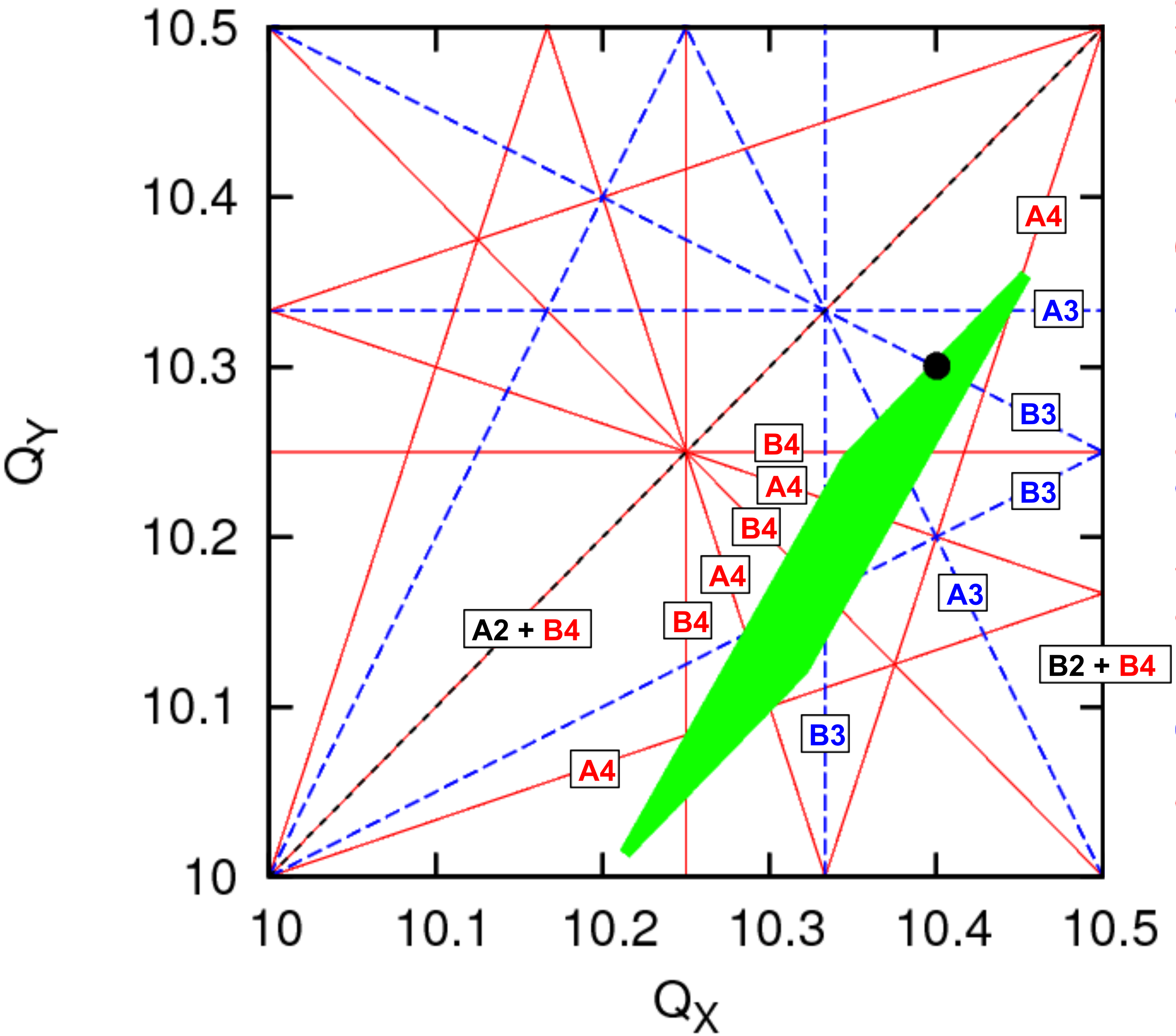
Protons Low γ_t
$Q_{X0} = 10.4$
$Q_{Y0} = 10.3$

B2: normal quadrupole
A2: skew quadrupole
B3: normal sextupole
A3: skew sextupole
B4: normal octupole
A4: skew octupole

╲ coupling sum
╱ coupling difference

Additionally:

- Ions Slow Extraction
  $Q_{X0} = 17.3$, $Q_{Y0} = 17.8$
- Protons High γ_t
  $Q_{X0} = 21.8$, $Q_{Y0} = 17.7$



UPCOMING ACTIVITY

For a reliable assessment of the magnetic field quality,
DA scans and the **beam loss calculations** with space charge are necessary,
for Working Points of different operations.
For this, the random error multipoles δB_n, δA_n are needed
(from measurements or from simulations)

The (B_n,A_n)−measurements of the series magnets are essential:

- will provide the random errors
- will be used for e.g. optimized chromaticity correction, resonance compensation, CO correction
- needed for the commissioning
- will be extensively used in the future 50 operation years

10%−20% of the series magnets are expected to be measured.

The workflow for the series magnetic data is under preparation.
Simulations/Theory development for Beam Loss Studies is under progress.