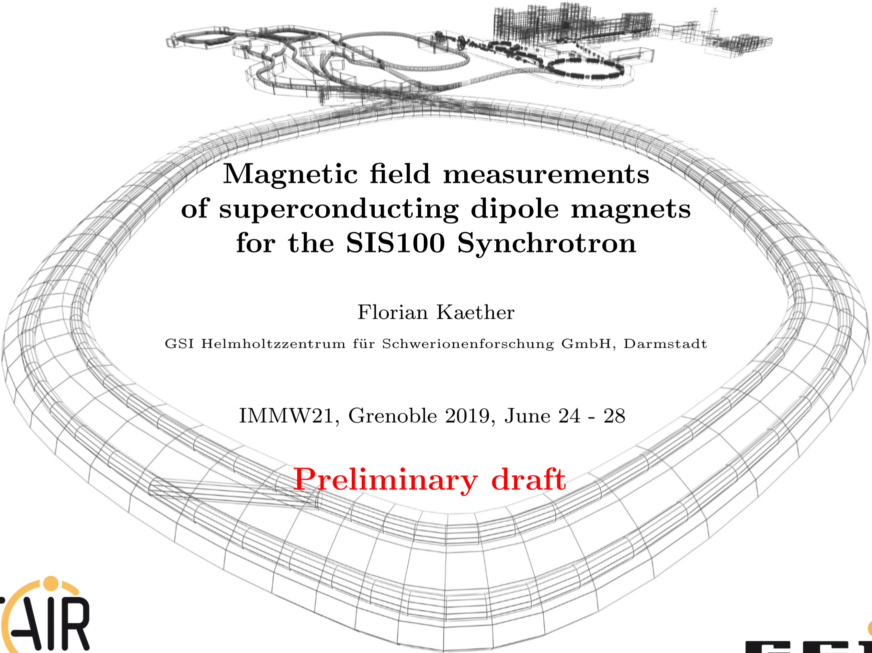

Magnetic field measurements of superconducting dipole magnets for the SIS100 Synchrotron

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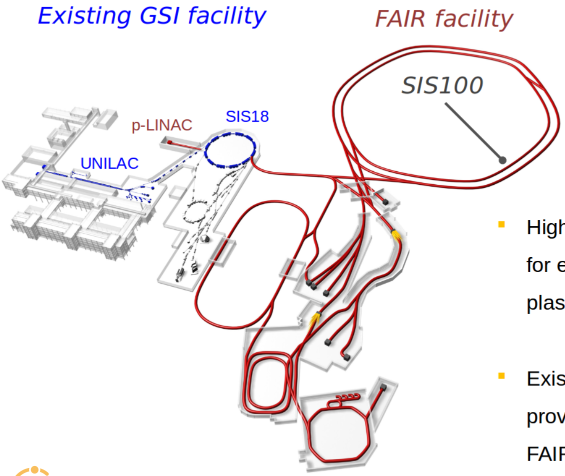
IMMW21, Grenoble 2019, June 24 - 28

Preliminary draft

FAIR = **F**acility for **A**ntiproton an **I**on **R**esearch

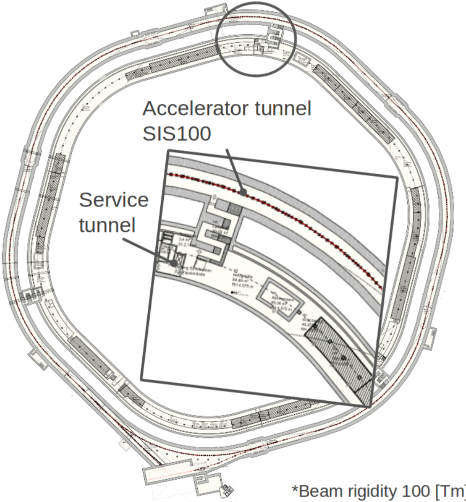


International project

- High intensity ion and antiproton beams for experiments in nuclear, atomic, plasma physics and material science.
- Existing facility UNILAC/SIS18 will provide ion-beam source and injector for FAIR.

Heavy Ion Synchrotron SIS100

SIS100 = Schwerionensynchrotron 100 [Tm] = Heavy ion synchrotron (beam rigidity 100 [Tm]*)



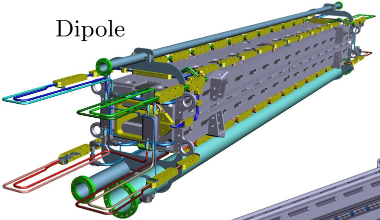
- Hexagonal, circumference 1083.60 m
- Operational modes:
  - Ultra High Vacuum (10^{-11} mbar)
    - Adsorption by cold vacuum chamber (10 - 15K)
    - Superconducting (magnet) accelerator
  - Fast-ramp machine ~0.5 sec. to maximum field

*Beam rigidity 100 [Tm] = Bending dipole field 1.9 [T] × Bending radius 52.632 [m]

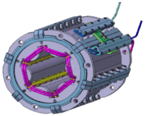
Magnets for SIS100

		Main Dipole	Main Quadrupole	Multipole corrector (nested)			Steerer (nested)	Chromaticity sextupole
	unit			Quadrupole	Skew sextupole	Octupole	Horizontal/ Vertical	Sextupole
Number of Magnets		108	166	12	12	12	83	48
Magnetic field strength	T/m^{n-1}	1.9	27.7	0.75	25	333.3	0.3	175
Effective length	m	3.062	1.3	0.75			0.5	0.5
Usable aperture	mm			150			135/65	135/65
Ramp time to Max.	Sec.	0.5		0.15	0.24	0.24	0.2	0.175

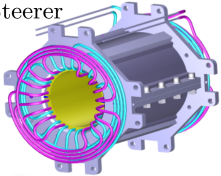
Dipole

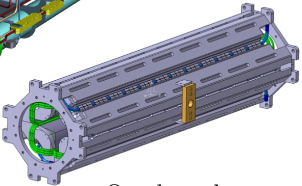


Sextupole

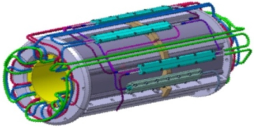


Steerer





Quadrupole

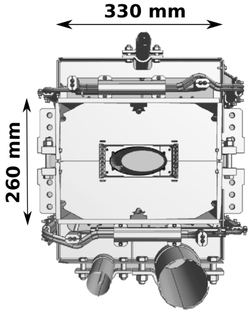


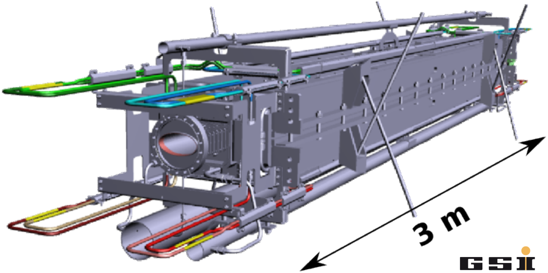
Multipolcorrector

The SIS100 Dipole Magnet design parameters

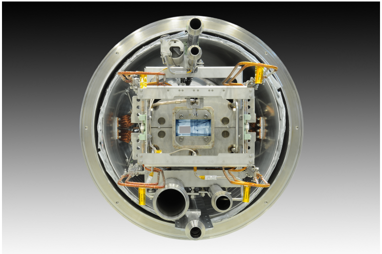
Specifications and beam dynamic requirements:

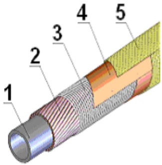
- Iron dominated superconducting (superferric) magnets
- Forced flow two phase helium cooling (4.5 K)
- Maximum magnetic induction
  $B_{max} = 1.9\,\mathrm{T}$
- Maximum ramp rate
  $dB/dt = 4\,\mathrm{T/s}$
- Field homogeneity requirement
  $\Delta B/B = \pm 6 \times 10^{-4}$
- Yoke gap height variations
  $\Delta h = \pm 0.1\,\mathrm{mm}$
- Yoke length
  $L_{\mathrm{Y}} = (3.002 \pm 0.0004)\,\mathrm{m}$
- Effective magnetic length
  $L_{\mathrm{Eff}} = 3.062\,\mathrm{m}$
- Total length (coils) $L_{\mathrm{Tot}} = 3.2\,\mathrm{m}$
- Bending angle $3\frac{1}{3}^{\circ}$
- Radius of curvature $52.632\,\mathrm{m}$





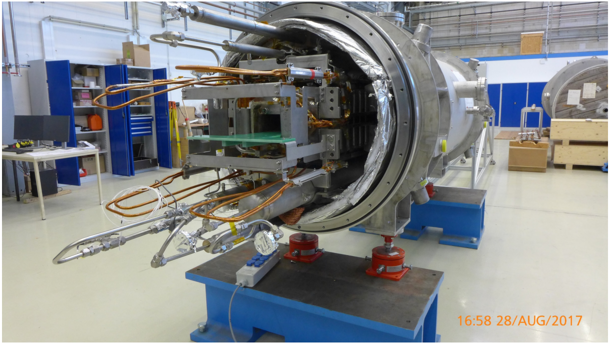
SIS100 Dipole Magnet



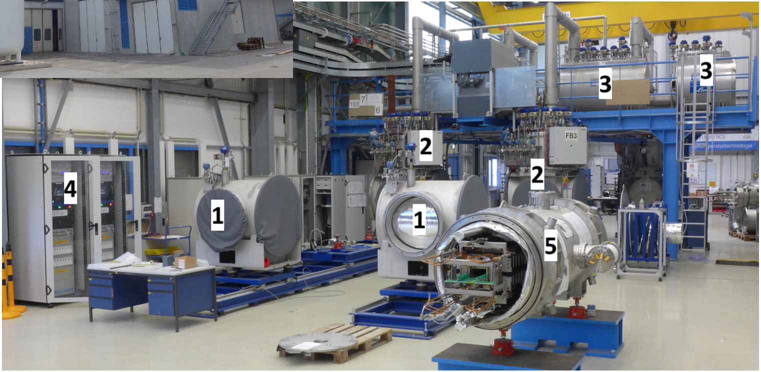


Nuclotron cable:

1 - Cooling tube CuNi
2 - SC wire NbTi
3 - CrNi wire
4 - Kapton tape
5 - Glasfiber tape



1 Endbox
2 Feedboxes
3 Cryo-plant - cooling power of 1.5 kW equivalent
4 Quench detection
5 Dipole magnet



Testing overview

- Yoke geometrie:
  - Aperture height
  - Sag and twist
  - Position
- Process lines
  - Pressure and leaks
  - massflow rate
  - positioning
- Electrical tests
  - High Voltage
  - Continuity (voltage tabs for quench detection)
  - Turn-to-turn Insulation
- Quench detection
- Static heat load and AC-losses

- Magnetic field
  - Integral B-field
  - Harmonics
  - Load line (transfer function)

- For all dipole magnets (110 in total):

→ about 30 parameters to control

→ about 100 steps to follow

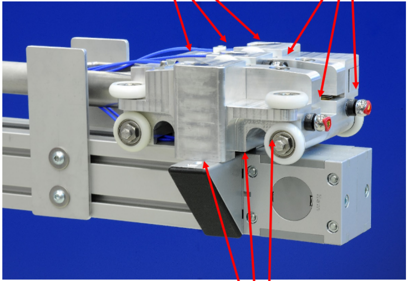
→ duration ∼ 3 weeks

Aperture height measurement system

Aperture Height Measurement of SIS 100 Dipoles
Sensorcarrier with capacitive Sensors und Lasertracker SMR‘s

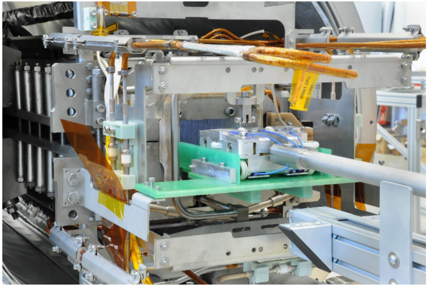
3x upper Sensors

3x Lasertracker SMR‘s



Measurement unit

3x lower Sensors



Measurement unit insertion

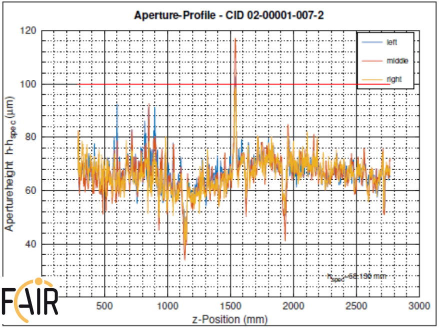
Aperture height measurement results

Height:

Specification: $h_{\text{spec}} = 68.130^{+0.1}_{-0.0}\,\text{mm}$

Measurement errors:

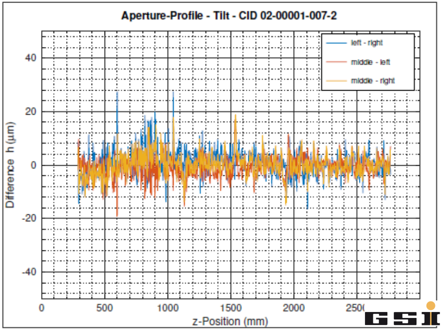
- repeatability: $\pm 3\mu\text{m}$
- absolute: $\pm 15\mu\text{m}$



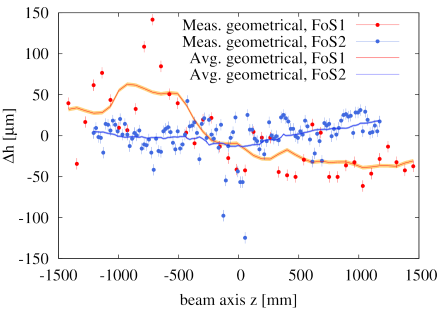
Tilt: no specifications

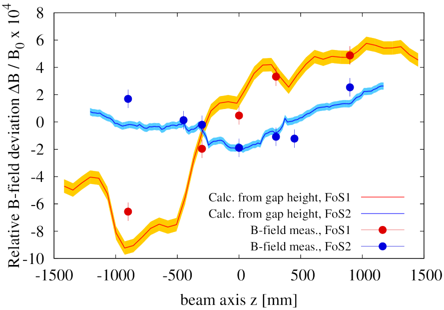
If there is something conspicious it would be a warning.
Maybe there would be correlations with higher harmonics in the magnetic field.

But: no indications up to now !



Dipole



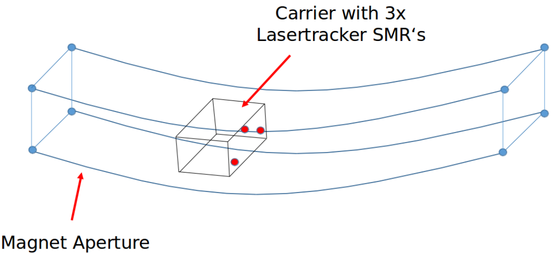


- Magnetic field measured at different positions along the beam axis with rotating coils
- Relative gap height deviations measured with high resolution along the beam axis with capacitive sensors.
- Gap data averaged with respect to rotating coil length of 600 mm.
- Conversion of gap height to field strength using $B = \frac{IN\mu_0}{h}$ (and arbitrary offset correction)

▷ Comparison with B field measurements in good agreement

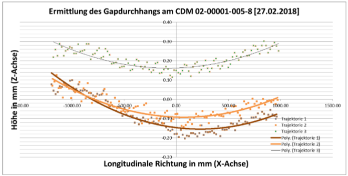
Additional assets

Additional outcome with Lasertracker



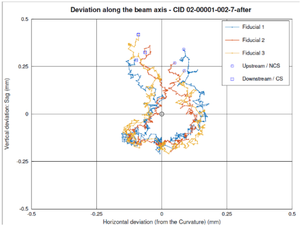
Trajectory can be tracked during Aperture Height Measurement

Sag of Yoke



	Trajektorie 1	Trajektorie 2	Trajektorie 3	Mittelwert
Durchhang	0.30	0.27	0.21	0.26

Torsion of Yoke



Quench training

Specifications:

- nominal current of 13.2 kA has to be reached
  - before 3^{rd} quench in the first cycle
  - before 1^{st} quench from now on
- de-training limited to 5% (compared to previous quench)
- quench current has to stabilize at > 110% at least (14.5 kA).

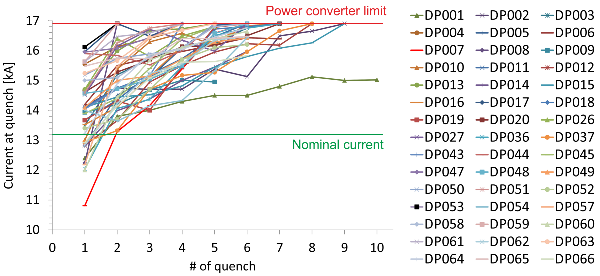
Results:

- nominal current reached at 2nd quench at least
- no significant de-training observed

→ Excellent quench performance!

→ Limit of cable (17.8 kA) nearly reached

→ high stability of coil structure in the yoke



Calibrations

- Measure segment by segment at 300K in a normal conducting magnet
- Magnetic field is known from hall probe and NMR mapping.

→ absolute field strength calibration

→ calibrate gaps in between the coils (needed for magnetic length)

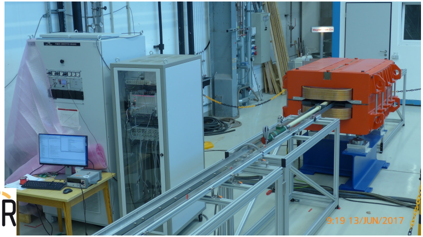
- Compare tilt angles from segment to segment

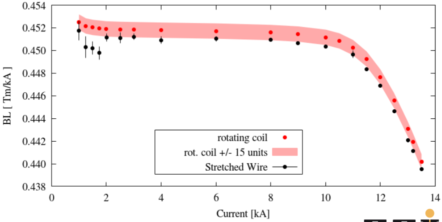
→ apply correction for cold measurements (with small constraints).

- Additional measurement with a stretched wire
  - different lab at GSI
  - different power converter

→ independet determination of the magnetic length

→ confirmation of systematic error estimation of rotating coil results of ±15 units

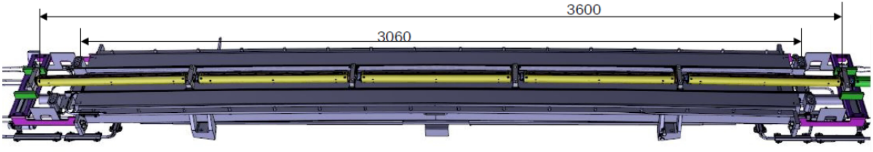


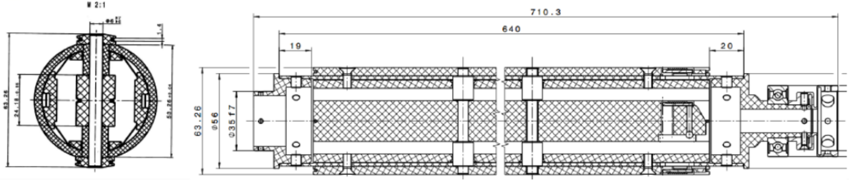


Rotating coils

Mechanical design of the shaft of rotating coilf for the cold measurements

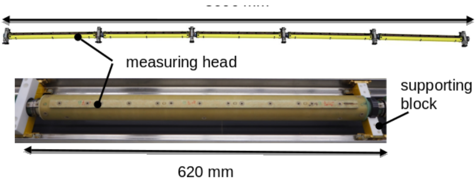
- Shaft length 3.6m - to cover a full magnet length (3.06m) + stray field area
- 5 segments 0.64m – 3 for the central field + 2 for the stray field
- Intermediate space between segments 100 mm
- measuring heads with a dipole compensation (2 coils + 1 „spare“)
- Coil length 60mm, 256 turns, effective surfase 1.67 m2

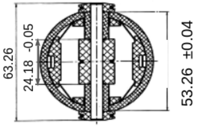




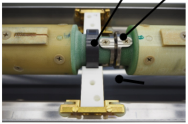
System for magnetic field measurements

- ✓ 5 measuring heads – tangential coils
- ✓ 3 pick up coils per head, 600 mm length
- ✓ effective surface 1.67 m^2
- ✓ Ti-alloy bellows – interconnection between segments and to align the heads along the beam axis
- ✓ SiN ball bearings for rotation motion
- ✓ ceramic supporting blocks for transverse positioning in the gap

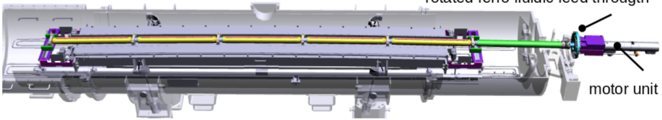




cross section of the measuring head (3 tangentinal coils)



Field measurements in vacuum @ 4.5K



The measuring probe is designed and built in collaboration with CERN

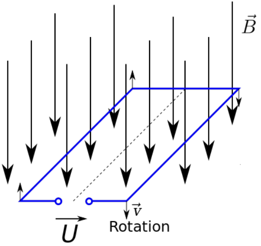
Magnetic flux:

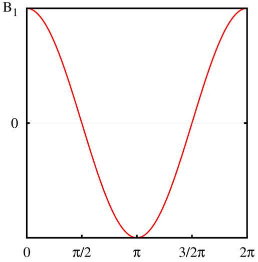
$$\Phi = \int \vec{B}\, dA$$

Faraday's law:

$$U_{\text{Ind}} = -\frac{d\Phi}{dt}$$

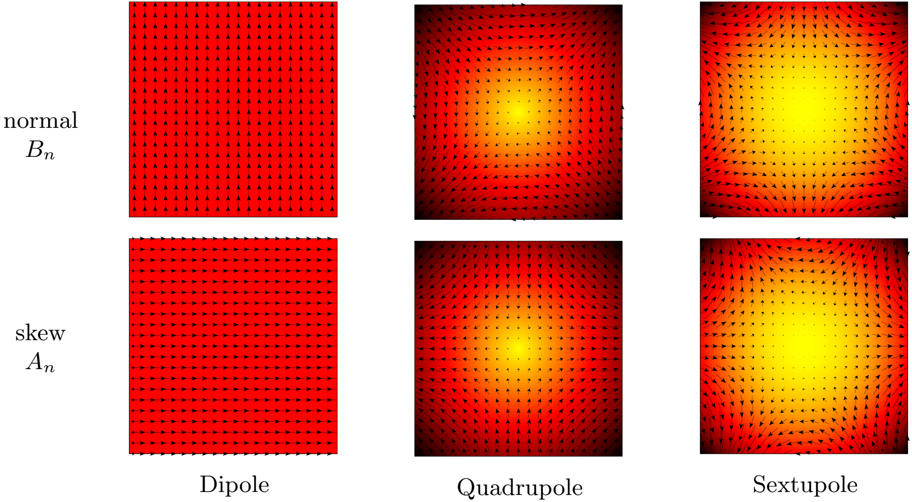
To measure U_{Ind} we have to change either B or A (or both)

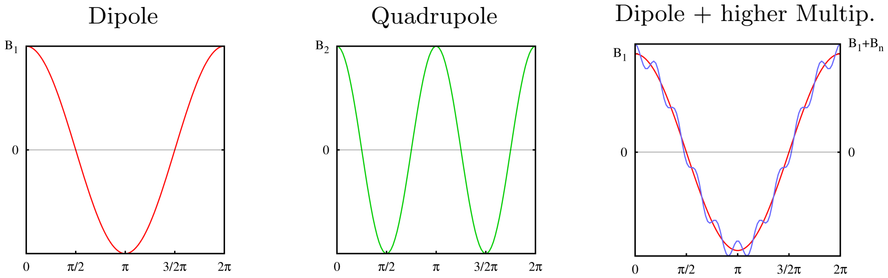




Signal from constant dipole and rotating coil

Multipole expansion

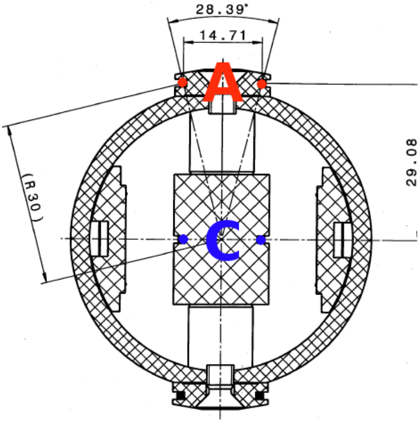




Fourier Transformation of measured signal leads to multipole coefficients of magnetic field:

$$\mathbf{C}_n = \mathrm{FT}(\mathrm{Signal})/\mathbf{K}_n \ , \qquad (\ \mathbf{K}_n\!: \ \text{geometrical sensitivity})$$

$$\mathbf{B}(\mathbf{z}) = \sum_{n=1}^{\infty} \mathbf{C}_n \left(\frac{\mathbf{z}}{R_{\mathrm{ref}}} \right)^{n-1} \ , \quad \mathbf{C}_n = B_n + iA_n$$



Sensitivity:

for dipole field:
$\mathbf{K}_1(\text{CoilA}) = \mathbf{K}_1(\text{CoilC})$

for higher Multipoles:
$\mathbf{K}_{n>1}(\text{CoilC}) = 0$

Compensation method:
subtract Signal(C) from Signal(A)
→ discrimination of dipole and noise
→ precise higher harmonics spectrum

→ use signal A for dipole measurement
→ use signal A-C for higher harmonics

precision $\sim 10^{-5}$

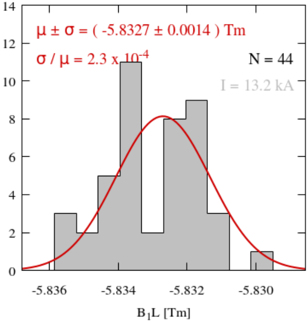
Acceptance criterium for SIS100
(with intergral field $BL = \int B(l)\,dl$):

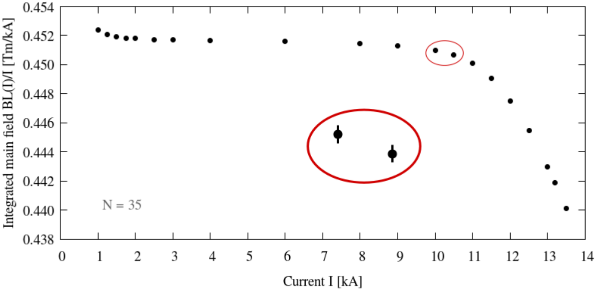
$$\frac{\Delta BL}{BL} \leq 4 \times 10^{-3}$$

Measured 44 Magnets:

$$\frac{\Delta BL}{BL} \leq 2.3 \times 10^{-4}$$

(factor 10 better than requested!)





Systematics from different Shafts and FeedBoxes

The same magnet was measured

- at 3 different feedboxes
- with 2 different shafts

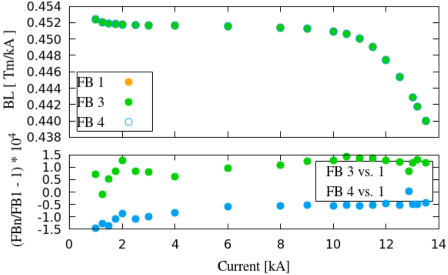
This includes systematics from

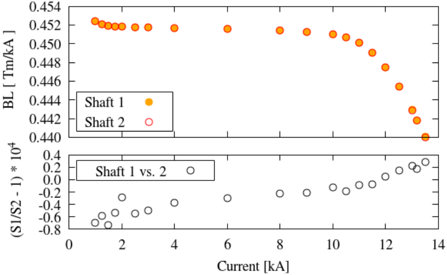
- power supplies
- mechanical installation
- dimensions of rotating coils

→ very good reproducibility

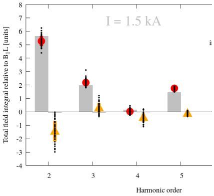
→ very stable system

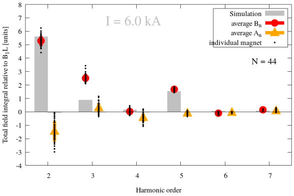
→ relative errors in the range of units (10^{-4}).

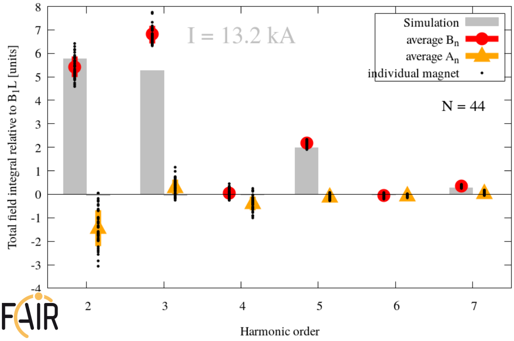




Harmonics







$$\mathbf{B}(\mathbf{z}) = \sum_{n=1}^{\infty} \mathbf{C}_n \left(\frac{\mathbf{z}}{R_{\text{ref}}} \right)^{n-1}$$

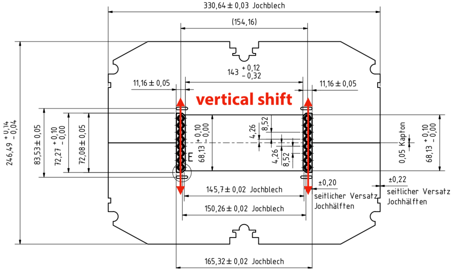
$$\mathbf{C}_n = B_n + iA_n \, , \quad \mathbf{z} = x + iy$$

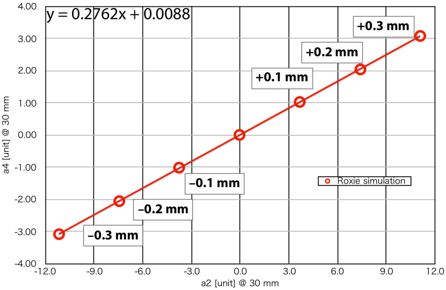
- B_2 (normal quadrupole): from end field (expected from magnetic design)
- B_3, B_5 (normal sextu-/decapole) "allowed" harmonics, same symmetry as dipole, can be corrected in the ring
- all other $B_n \approx 0$
- But not A_2 (skew quadrupole)!

A_2 discussion

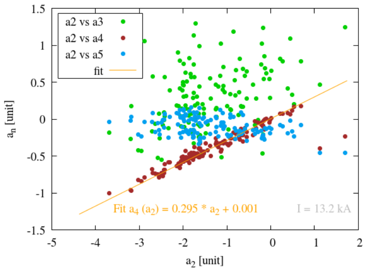
Where is A_2 coming from ?

- Displacement of rotating coil? Ruled out by simulations. No shift or tilt can create A_2.
- A shift of the magnetic coil and/or an asymmetrie in the yoke would cause A_2.
- Confirmation by Roxie2D simulations shows $A_4 \sim A_2$



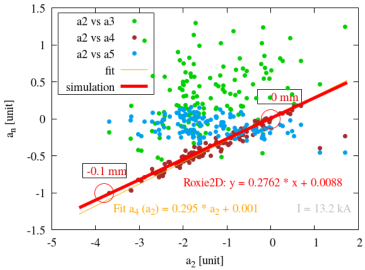


- Measurement results show a linear behaviour $A_4 \sim A_2$.
- Fits perfectly to Roxie2D prediction
- Coil shift / yoke asymmetrie in the order of $\sim 50\,\mu$m.
- production steps were reviewed, but no obvious reasons were found.

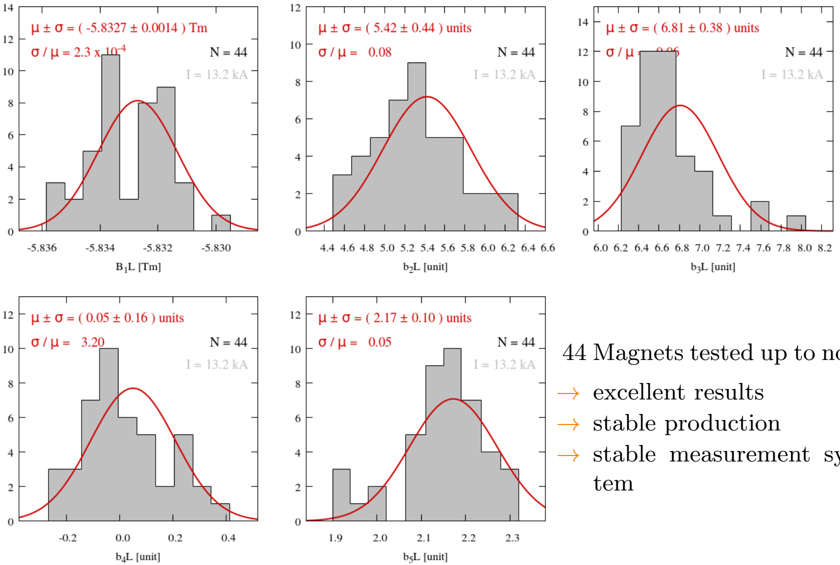


Is A_2 critical ?

$\rightarrow$ No! Uncertainties in the alignment of quadrupole magnets in the ring will cause much bigger A_2.



Statistics



44 Magnets tested up to now

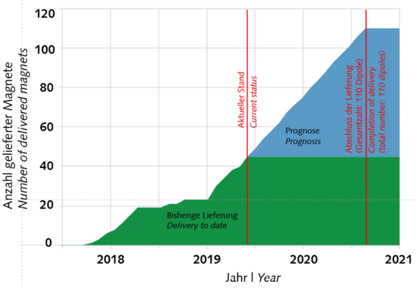
→ excellent results

→ stable production

→ stable measurement system

SIS100 Dipole production

- 110 dipoles in total
- 46 dipoles delivered (current rate 1 per week)
- 44 tested
- excellent magnetic field properties
- excellent yoke geometry
- excellent quench behaviour
- problems with process line positions (solved)
- problems with untight feedthroughs (under discussion)



It's on a good track!

The last but most important slide: the team at GSI

- Survey & Alignment
- Electrical tests
- Quench detection
- Magnetic field measurements
- Software: DAQ & Analysis
- Cryo operator
- power suppy maintenance
- Transport & Installation
- Quality assurance
- Communication with production