Superferric rapidly cycling magnets
Optimized field design and Measurement

P. Schnizer[1], E. Fischer[1], P. Akishin[2], H. Kiesewetter[1], T. Knapp[1], F. Klos[1], R. Kurnyshov[3], T. Mack[1], B. Schnizer[4], P. Shcherbakov[5]

[1]Gesellschaft für Schwerionenforschung, Darmstadt, Germany
[2]Joint Institut for Nuclear Research, Dubna, Moscow Region, Russia
[3]Electroplant, Moscow, Russia
[4]Technische Universität Graz, Austria
[5]Institut for High Energy Physics, Protvino, Moscow Region, Russia

WAMSDO@CERN 19 – 23 May 2008 p.schnizer@gsi.de

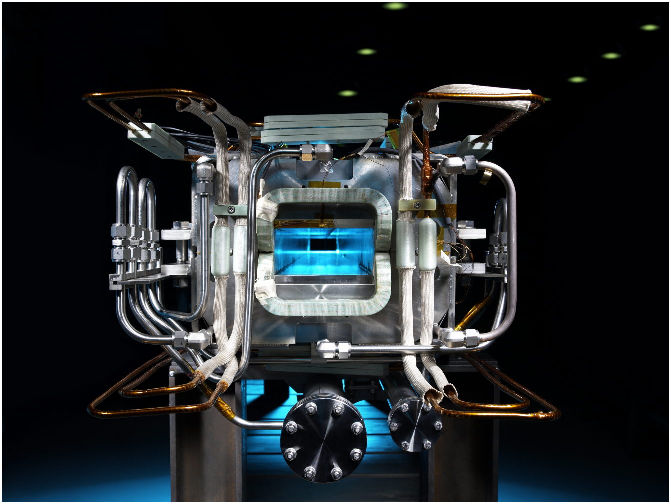
Outline

1. Machine
2. Calculations
    - Field Description
    - DC Calculations
    - Calculations on the ramp
3. Measuring the Field Quality
    - Approach

SIS 100: main parameters

- FAIR @ GSI → 2 synchrotrons with superconducting machines
- SIS 100 → core component
  - Nuclotron "father figure"
  - based on two phase cooled hollow cable
  - 2 T , 4 T / s,
  - 3.5 m long dipoles
  - 1 m long quadrupole in 5 m long SSS
  - elliptic vacuum chamber 115 × 60 mm

SIS 100: Prototype Dipole



Courtesy of Babcock Noell GmbH

Cicrular Multipoles for Elliptic Apertures

Standard field description: Circular Multipoles

$$\mathbf{B}(\mathbf{z}) = B_y + iB_x \; = \sum_{m=0}^{\infty} \mathbf{C_m} \left(\frac{\mathbf{z}}{R_{ref}} \right)^m . \qquad (1)$$

- convergent also outside R_{ref}
- satisfactory field description only for analytical data
- cofficients → FT on data on R_{ref} (FEM, measurement) → thus with artifacts

Multipoles Scale Factors for SIS 100

Aperture width w . . . 115 mm
Aperture height h . . . 60 mm
Coil diameter d . . . 46 mm

$$\left(\frac{w}{h}\right)^n = (\approx 1.9)^n$$

$$\left(\frac{w}{r}\right)^n = (2.5)^n$$

Single rotating coil measurement, single expansion on numerical data → not sufficient

n	w / d	w / h
1	1.00	1.00
3	6.25	3.67
5	39.06	13.50
7	244.14	49.58
9	1525.88	182.13
11	9536.74	669.06
13	59604.64	2457.87

Elliptic Multipoles for Complex Magnetic Field I/II

Field expansion:

$$\mathbf{w} = \eta + i\psi$$

$$\mathbf{B}(\mathbf{w}) = \frac{\mathbf{e_0}}{2} + \sum_{n=1}^{\infty} \mathbf{e}_n \frac{\cosh[n(\eta + i\psi)]}{\cosh(n\eta_0)}$$

$\eta = const\ldots$ hyperbola $\psi = const\ldots$ ellipse

Expansion coefficients:

$$\mathbf{e}_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} \mathbf{B}\left(\mathbf{w} = e\cosh(\eta_0 + i\psi)\right) \times \cos(n\psi)\, d\psi.$$

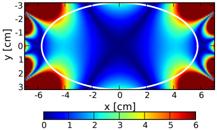
Linear Analytic Transformation to Circular Ones

P. Schnizer, B. Schnizer, P. Akishin, and E. Fischer

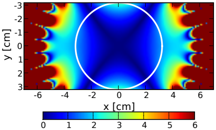
Field representation for elliptic apertures. Technical report, Feb. 2007, Jan. 2008

MT20: Magnetic field analysis for superferric accelerator magnets using elliptic multipoles and its advantages, 3L06

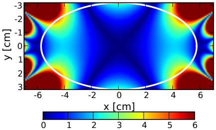
Elliptic Multipoles ⇔ Circular Multipoles



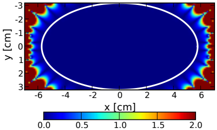
elliptic $\mathcal{C}_e$



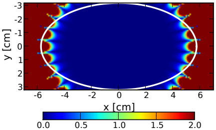
cyclic $\mathcal{C}$



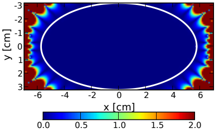
ell. → cyclic in $\mathcal{C}_e$



Δ elliptic $\mathcal{C}_e$



Δ cyclic $\mathcal{C}$



Δ ell. → cyclic in $\mathcal{C}_e$

Illustrated for CSLD at Injection Field ($\approx 0.25\ T$)

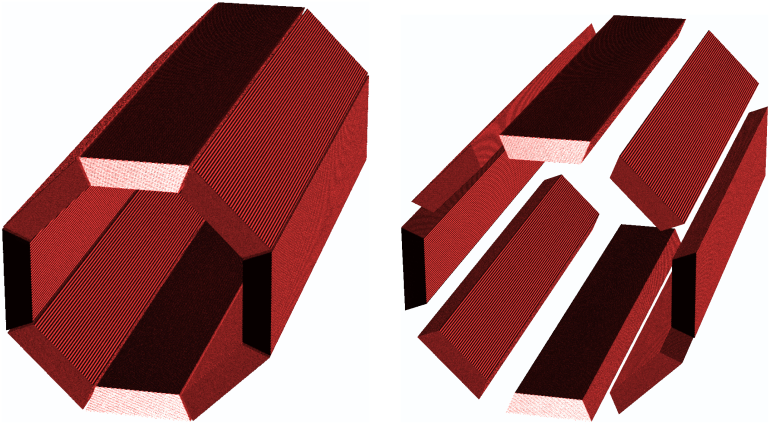
Literature

- P. Schnizer, B. Schnizer, P. Akishin, and E. Fischer.
  Field representation for elliptic apertures.
  Technical report, Gesellschaft für Schwerionenforschung mbH, Planckstraße 1, D-64291 Darmstadt, February 2007.
- P. Schnizer, B. Schnizer, P. Akishin, and E. Fischer.
  Magnetic field analysis for superferric accelerator magnets using elliptic multipoles and its advantages.
  In *The 20th international conference on magnet technology*. IEEE, August 2007.
- P. Schnizer, B. Schnizer, P. Akishin, and E. Fischer.
  Field representation for elliptic apertures.
  Technical report, Gesellschaft für Schwerionenforschung mbH, Planckstraße 1, D-64291 Darmstadt, January 2008.

Static calculations: Challenges

- SIS 100 magnets → superferric → iron dominated
- Nuclotron cable
  - superconducting wires wound around tube
  - small current carrying layer
  - not directly supported by TOSCA 3D
  - → modelling required
- influence of the coil not negibible

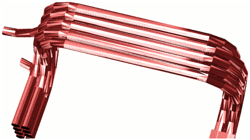
Modelling the Nuclotron Conductor I/II

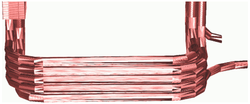


model exploded

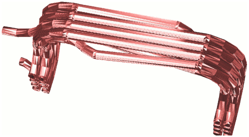
round shape modelled as bricks → many elements → careful selection of longitudinal length

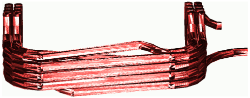
Modelling the Nuclotron Conductor II/II

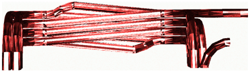

3D BNN


top BNN


bottom BNN

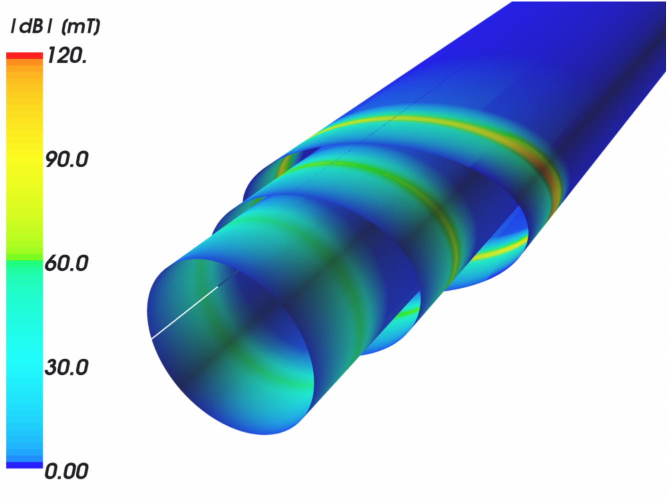

3D JNIR


top JNIR


bottom JNIR

SIS 100 coil ends → embedded in G10 → original interlayer connection too complicated → field change acceptable?

Interlayer connection: Field difference



maximum difference 0.1 T at a small spot; acceptable

Calculation on the ramp

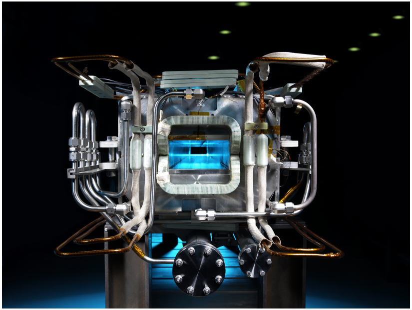
- SIS 100 magnets → nominal ramp rate 4 T / s
- eddy currents
    - in the yoke
    - in the vacuum chamber
    - in the eddy currents

based on R&D presented in:
Cryogenics 2007: E. Fischer, R. Kurnishov, and P. Shcherbakov; Finite element calculations on detailed 3D models for the superferric main magnets of the FAIR SIS100 synchrotron.

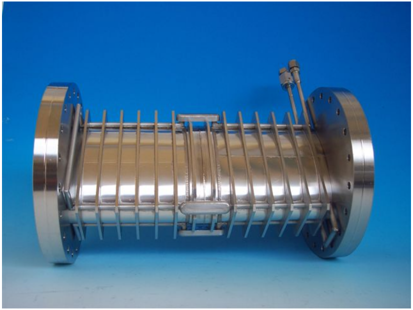
Prototype Magnet: To be tested

magnet

vacuum chamber model consists of: beam pipe ribs, cooling tubes

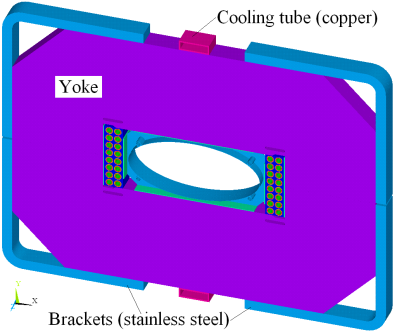


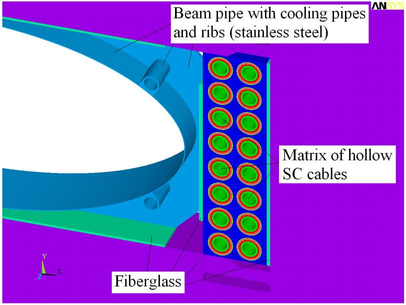
Courtesy of Babcock Noell GmbH



Magnet Design

3D modell of a period in the magnet





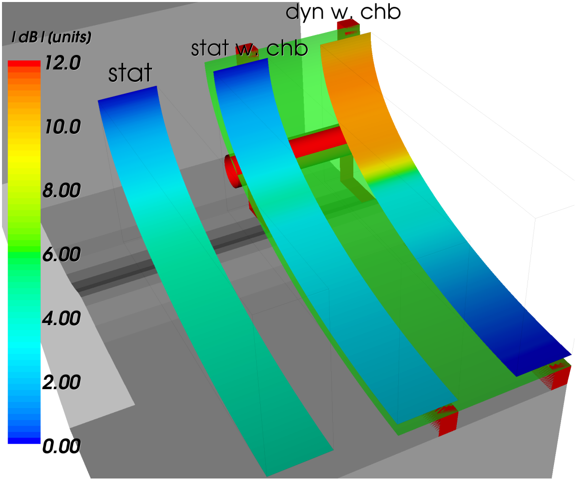
total zoom

EUCAS 2007: E. Fischer, R. Kurnyshov, and P. Shcherbakov; Analysis of Coupled Electromagnetic-Thermal Effects in Superconducting Accelerator Magnets

Method of Calculation and Results

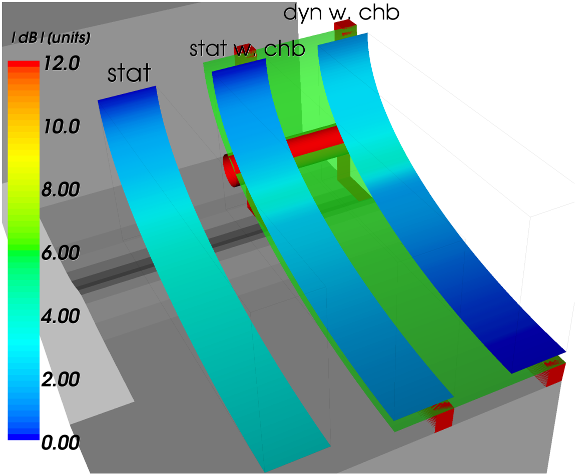
- calculated for triangular cycle (0T → 2T → 0T, 4T/s)
- time points at $\approx 0.25\,T$, $\approx 1.04\,T$, $\approx 1.83\,T$, $\approx 2.00\ T$
- data
  - field on ellipses (maximum errors at the border)
  - circular multipoles (calculated from elliptic ones)

Impact on the field quality



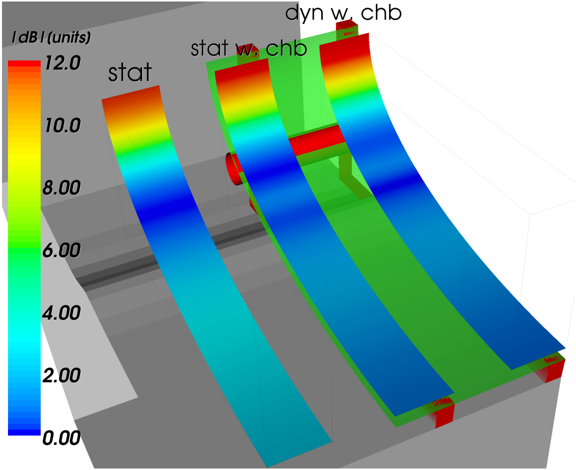
Field *to* 0.248 T (injection) field distortion → static 5 units, dynamic ×3!

Impact on the field quality II/IV



Field *to* 1.04 *T*
$t = 0.25s$
field distortion →
4 units (= 400
ppm)
dynamic *to* higher
variation

Impact on the field quality III/IV

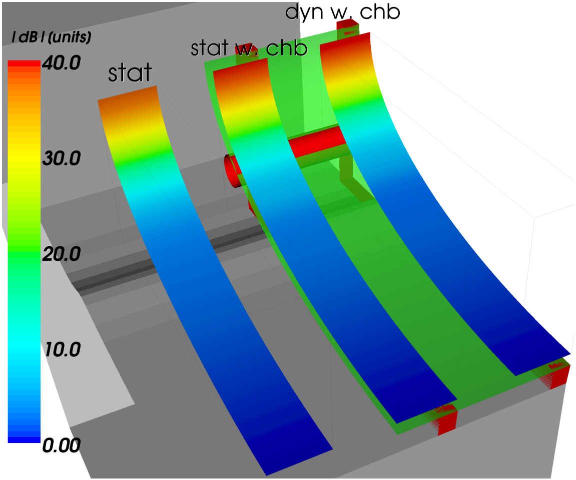


Field *to* $1.832\,T$ saturation → field distortion

dynamic *to* higher variation

dynamic 3×, static 10× higher than injection

Impact on the field quality



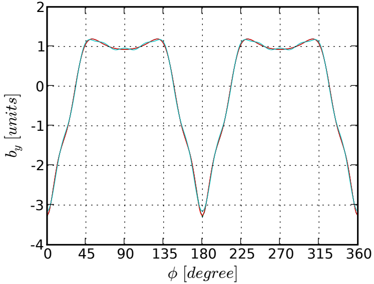
Field *to* 2.00 *T* saturation → field distortion (much larger than at 1.83 T)

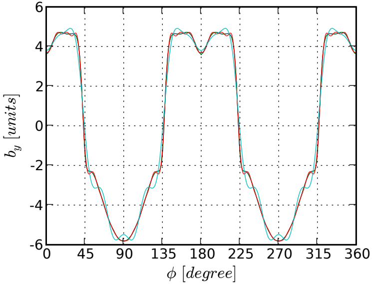
eddy currents *to* not significant

dynamic 3×, static 10× higher than injection

Static to dynamic: Integral over one Period

Deviation of B_y in units once around the ellipse

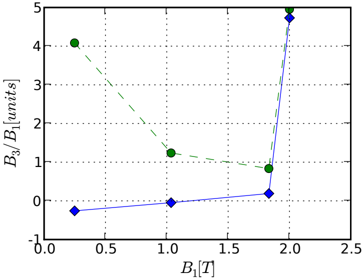




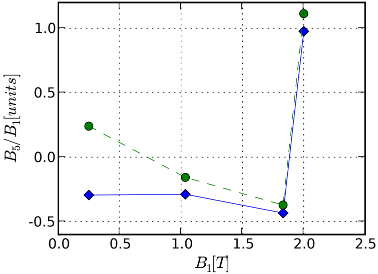
static dynamic with vacuum chamber

at injection: ramp effects factor of 2 - 3!

Expected Multipole Errors I/III



b_3, sextupole $(2^3 = 8)$



b_5, dekapole $(2^3 = 32)$

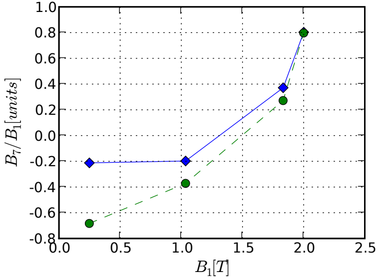
$R_{Ref} = 40\ mm$

blue …static

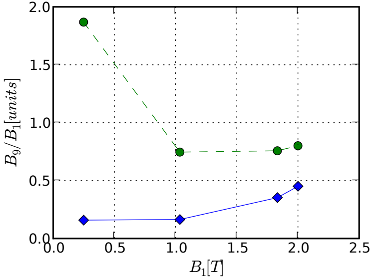
green…on the ramp

sextupole: at injection 10 times larger …

Expected Multipole Errors II/III



b_7, $(2^7 = 128)$



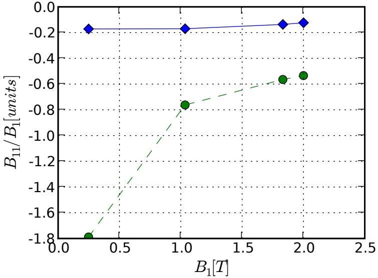
b_9, $(2^7 = 512)$

$R_{Ref} = 40\ mm$

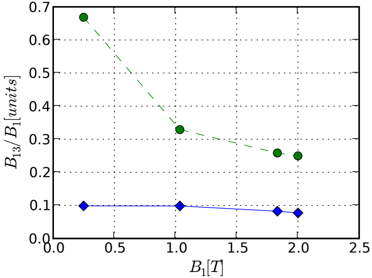
blue ...static

green...on the ramp

Expected Multipole Errors III/III



b_{11}, $(2^{11} = 2048)$



b_{13}, $(2^{13} = 8192)$

$R_{Ref} = 40\ mm$

blue ...static

green...on the ramp

Magnetic Measurement: Accuracy Targets

- integral strength → 250 ppm
- field angle → 0.5 mrad
- field axis (quadrupole) → 0.25 mm
- higher order harmonics → 10ppm

Main Target → strength, angle, axis

Magnetic measurement: field quality

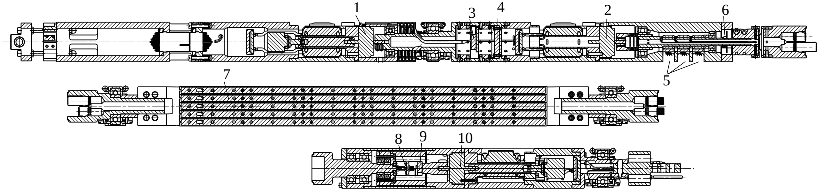
- superferric design: field formed by magnet poles
- deterioriated by the yoke
    - permeability of the iron
    - mechanical artifacts
    - manufacturing tolerances
    - eddy currents
- deterioriated by the vacuum chamber
    - geometry of the vacuum chamber
    - permeability of the steel
    - resistivity of the chamber
- Standard Magnetic Measurement not inside vacuum chamber → field mainly created by yoke
- vacuum chamber distortion → calculated → checked by special measurement

Selected method

- series tests → measurement equipment @ 300 K → anticryostat
- moveable anti-cryostat → covers (nearly) whole ellipse, thus no extrapolation
- rotating coil probe for DC, step by step coil probe on the ramp → same equipment for both magnet operations
- based on “bucking coil probes” → requirements for field homogeneity reduced by $\frac{1}{100}$

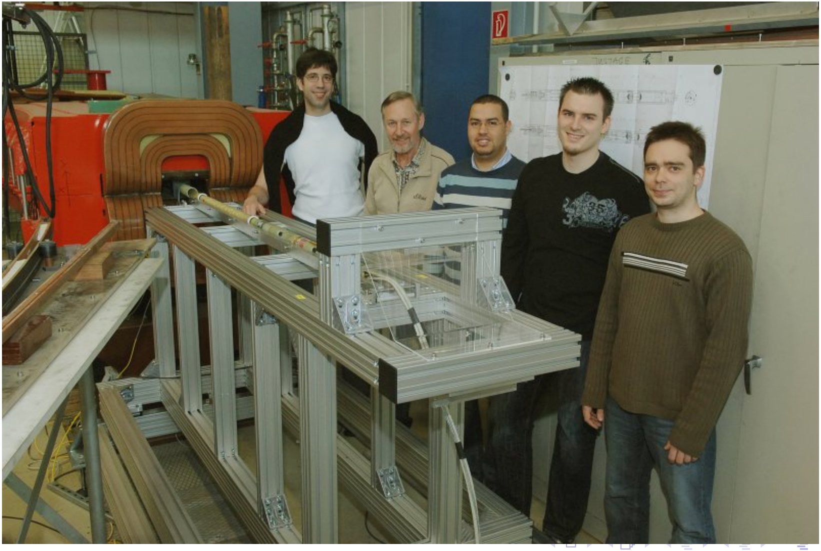
MT20: P. Schnizer et al. : A mole for measuring pulsed superconducting magnets, 4N10

Sketch of the Mole



1 levelling piezo motor 2 coil rotation piezo motor 3, 4 inclinometers 5 slip rings 6 angular encoder with 512 ticks, 7 coil probes 8 angular encoder with 7500 counts 9 its inclinometer and 10 levelling motor

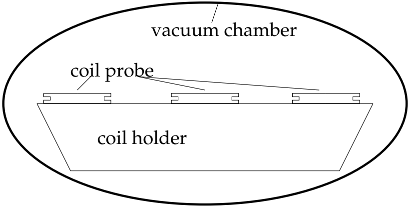
The mole I/II



The mole

II/II

Vacuum chamber artifacts: special measurement



- Vacuum chamber → elliptic vacuum chamber
- coil probes on a common support placed laterally separate
- allow to compare calculations to measurements

Conclusion

- SIS 100 Dipoles: first prototype produced
- DC and ramp field quality calculated
- Vacuum chamber adds considerably to the field distortion
- Standard Magnetic Measurement not inside vacuum chamber → field mainly created by yoke
- vacuum chamber distortion → calculated → checked by special measurement