Measuring of the SIS100 Dipole Magnets

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Outlook

- Introduction
  - requirements for SIS100 bending magnets
  - magnet design
- Magnetic field measurements for SIS100 sc-magnets
  - used convention for a field description
  - field parameters of interest
  - measuring methods and systems
- Magnetic field measurements for SIS100 FoS Dipole
- Magnetic field measurements for SIS100 series Dipole

Introduction: Requirements for SIS100 bending magnets

Radioactive beam program:

$5 \cdot 10^{11}$ U^{28+} ions per pulse,

acceleration to 2.7 Gev/u

Antiproton production:

$2.5 \cdot 10^{13}$ protons per pulse,

acceleration to 29 GeV

Bmax = 1.9 T, field err. B_n/B_m $6 \cdot 10^{-4}$

dB/dt = 4 T/s , cycle frequency ~ 1 Hz

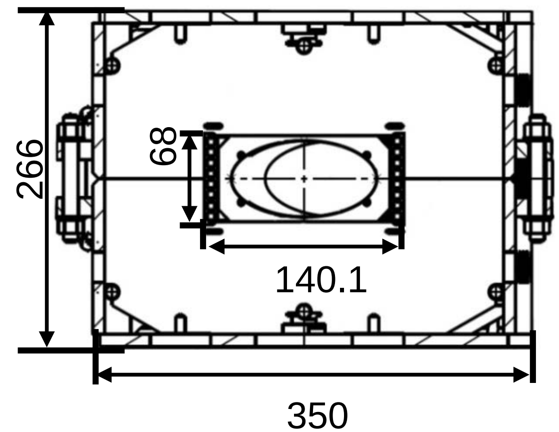
vacuum pressure ~ 10^{-12} mbar

Magnet design

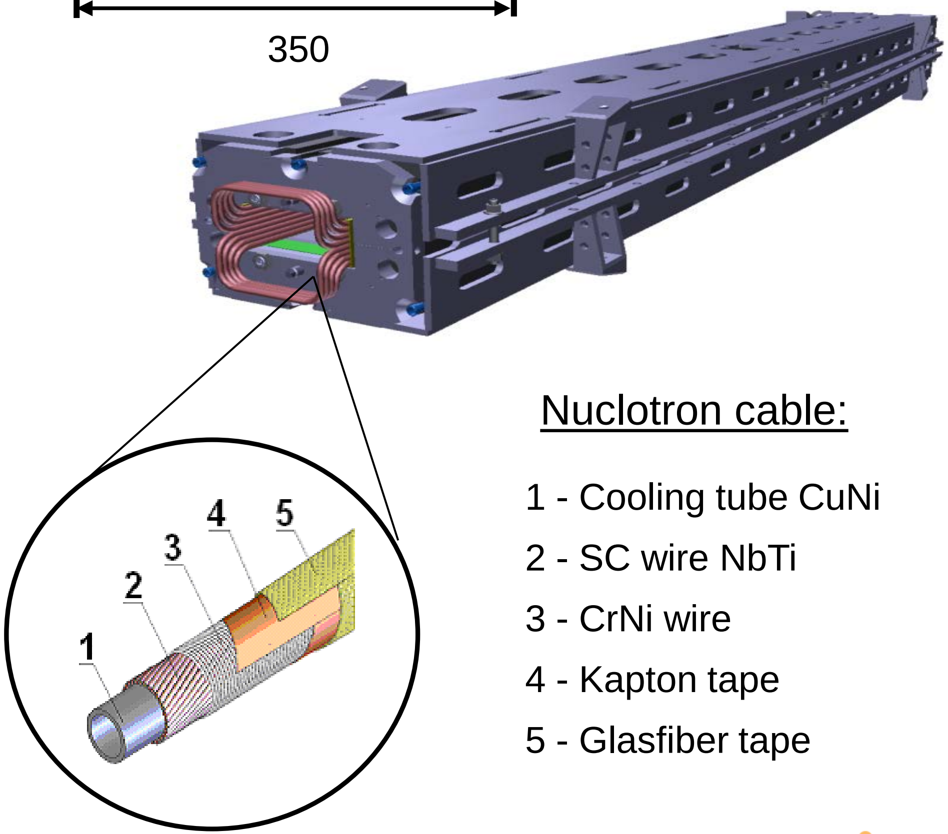
- iron dominated (super-ferric) magnets,
- superconducting coil (Nuclotron cable)
- cooling by two phase Helium @ 4.5 K
- cold vacuum chamber @ 15 K for a cryo pumping

Introduction: Design for SIS100 main Dipole

- ✓ Super-ferric window-frame, sector magnet
- ✓ superconducting (sc) coil
- ✓ Nuclotron type cable



Effective length L_{eff}	m	3.062
Usable aperture	mm x mm	60 x 120
Bending angle	°	3 1/3
Bending radius	m	52.632
B_{min}	T	0.228
$\mathbf{B_{max}}$	T	1.9
$\Delta B/B_{main}$ x10^4	units	< ± 6
dB/dt	T/s	4



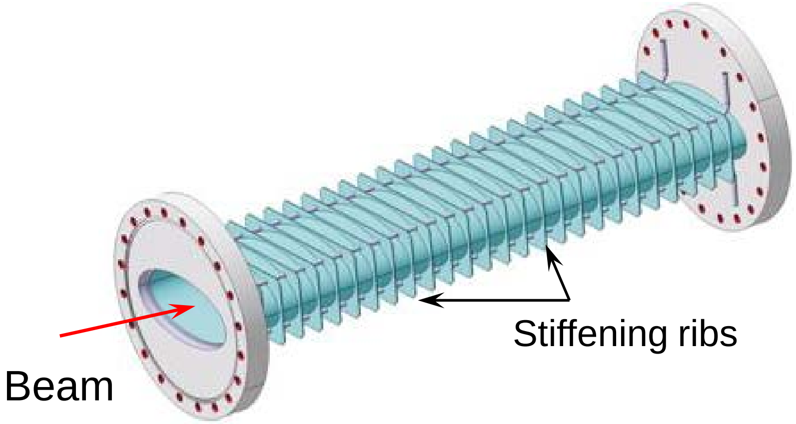
Nuclotron cable:

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

Introduction: Beam Pipe for the SIS100

Design and requirements

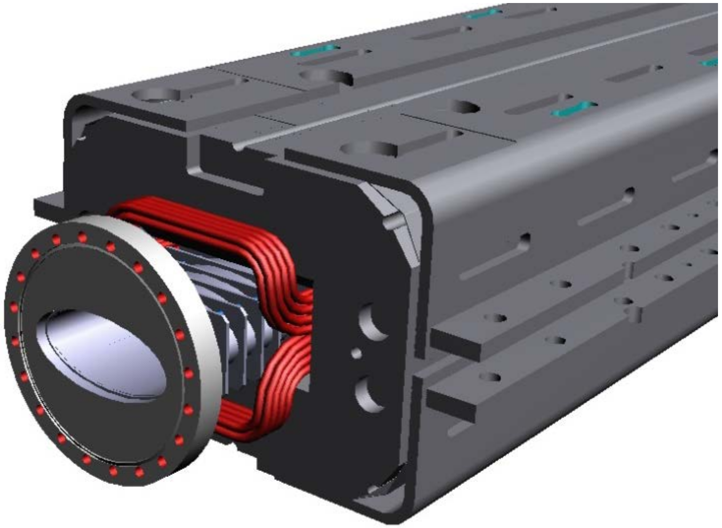
- ✓ elliptical cross section
- ✓ Wall thickness 0.3 mm → eddy currents reduction
- ✓ mechanical support against implosion (Stiffening ribs)
- ✓ cooling of the beam pipe



U^{28+} beam → dyn. Vacuum ~ 10^{-12} mbar

⇩

Beam Pipe as a cryopump T_{max} < 15 K



- ✓ reliable cooling with forced 2 phase ^{4}He @ 4.5K
- ✓ minimum impact on the magnetic field quality in the beam area

B_{min}	T	0.228
B_{max}	T	1.9
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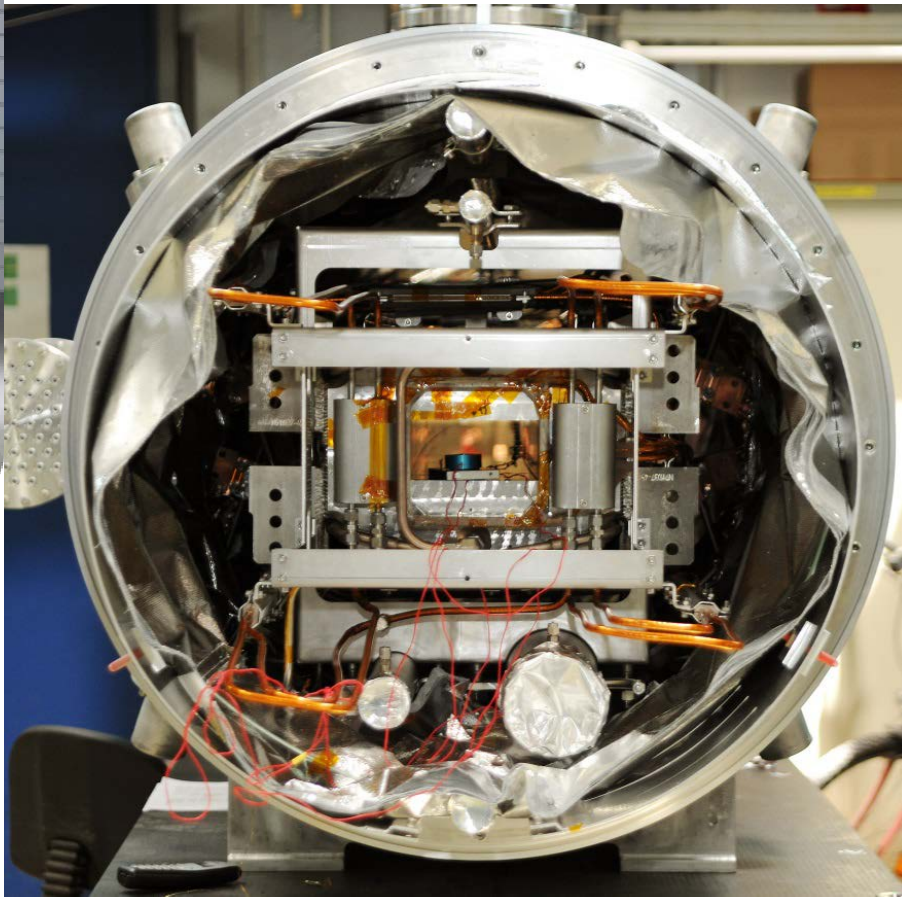

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    - requirements for SIS100 bending magnets
    - magnet design
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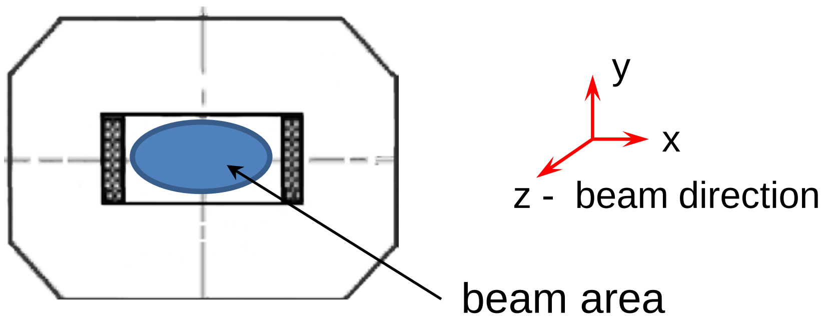
Magnetic field measurements: used convention for a field description

Standart field description: Circular Multipoles

$\vec{B}(\vec{r}) = (B_x, B_y, B_z)$ B_z constant



$$B(\mathbf{z}) = B_y + iB_x = \sum_{n=0}^{\infty} [B_n + iA_n] \left(\frac{\mathbf{z}}{R_{ref}} \right)^n$$

$$\mathbf{z} = y + ix = re^{\theta}$$

$$x = r\cos\theta, \qquad y = r\sin\theta$$

$$0 \le r \le \infty \qquad -\pi \le \theta \le \pi$$

B_n - normal multipole, A_n - „skew“ multipole

R_{ref} = 50 – 70% of the magnet aperture

$$b_n = \frac{B_n}{B_m} \qquad a_n = \frac{A_n}{B_m}$$

m – Index of the main field component

m = 0	dipole	bending
m = 1	quadrupole	focusing
m = 2	sextupole	dispersion

Elliptic Multipoles

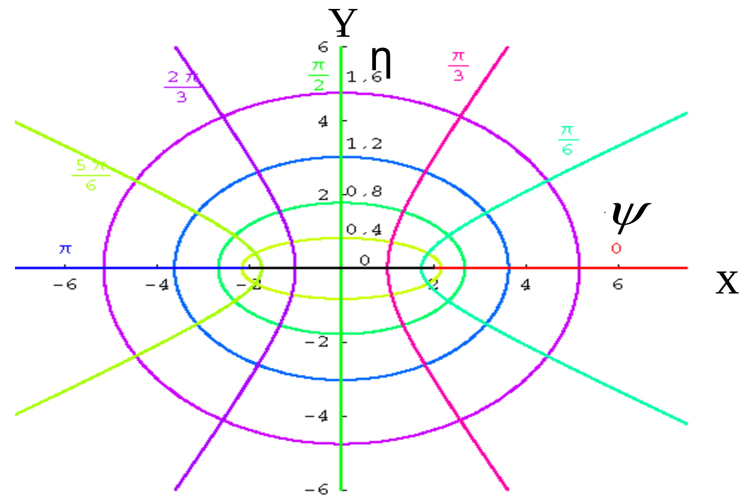
$$B(z) = \sum_{n=0}^{\infty} E_n \frac{\cosh[n(\eta + i\psi)]}{\cosh(n\eta_0)}$$

$$x = e\ \cosh\eta\ \cos\psi, \qquad 0 \leq\ \eta \leq \eta_0\ < \infty$$

$$y = e \sinh\eta\ \sin\psi, \qquad -\pi \leq 0 \leq \pi$$

$$z = x + iy = e \cosh(\eta + i\psi)\,, \qquad \eta_0 = \tanh^{-1}(ba)$$

- ✓ represent the field in the whole aperture of SIS 100
- ✓ give a concise error propagation for rotating coil measurements in elliptic aperture
- ✓ calculate circular multipoles within the ellipse



$$C_n(e/R_{ref})^n = \sum_{k=0}^{M} (E_k/\cosh(k\eta_0))t_{kn}$$

► **see also:** P.Schnizer et al. "Theory and Application of Plane Elliptic multipoles for Static Magnetic Fields", NIMA 607(3):505-516, 2009

Magnetic field measurements: Parameters of interest

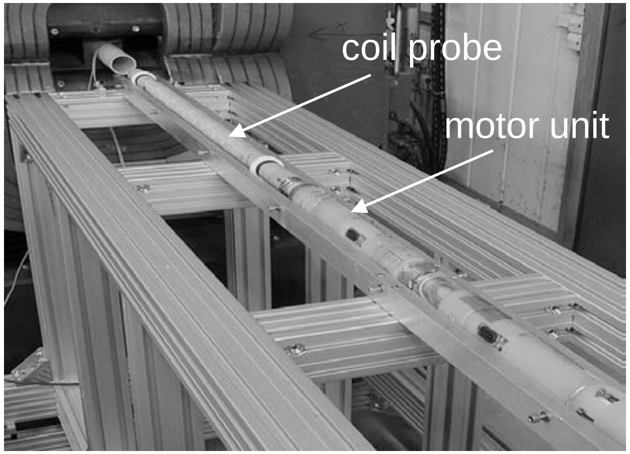
1. New curve, Load line (B_0 vs. I), → QA verification of magnet model, machine operation
   - Rotating coil probe
2. Field homogeneity (rel. harmonics) → machine operation
   - Rotating coil probe
   - Mapper with a hall probe

   (check of the reproduced field quality at the magnet ends) → QA verification of the magnet model
3. Integral field Length → machine operation and tuning
   - Single Stretched Wire
   - Shaft of rotating coil
4. Impact of the vacuum chamber on the field quality → machine operation and tuning
   - stationary coil probe array on a holder (check for test pieces)

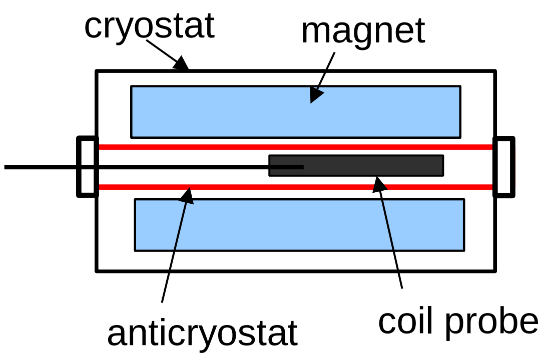
Magnetic field measurements: Using methods

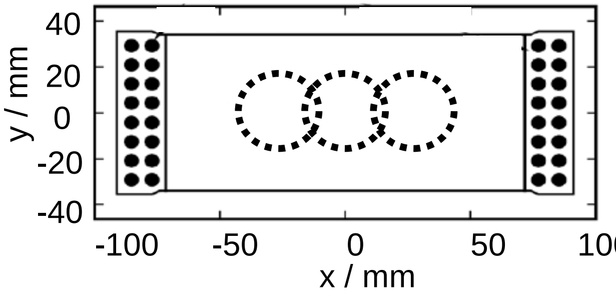
Combining rotating coil probe measurements:

- ✓ main field strength
- ✓ field homogeneity (high order harmonics)



- field measured without a beam pipe
- anticryostat R_{out} = 32mm, R_{in} = 23.45mm
- rotating coil probe R_{ref} = 17mm, l = 600mm,
- coil probe with dipole compensation windings
- measurements at the three lateral positions
- measurements for 5 longitudinal positions



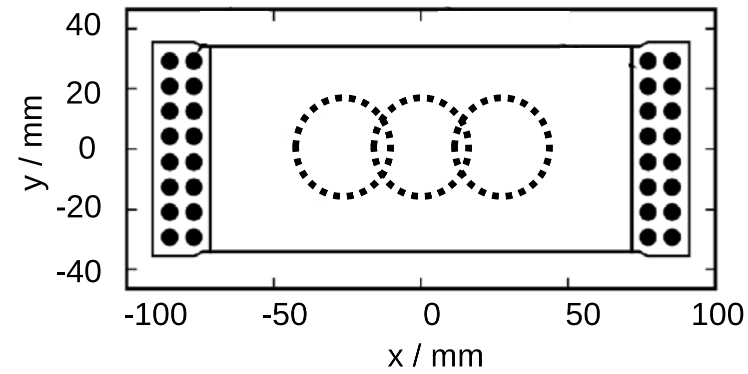


Combining rotating coil probe measurements

- ✓ data reconstruction for the reference ellipse

  a = 45 mm, *b* = 17 mm

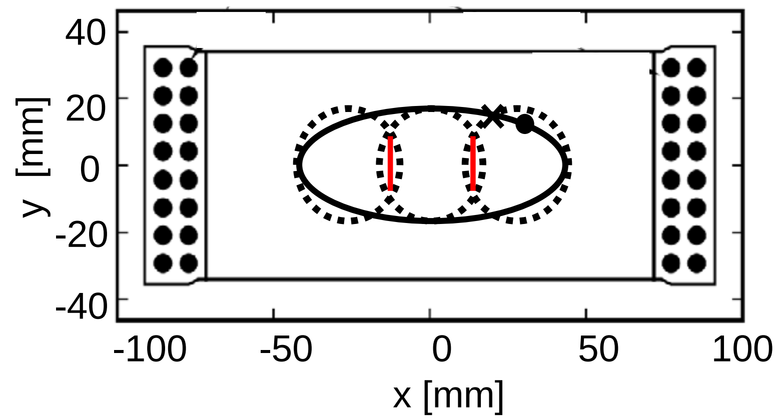
$$B_i(z) = \lambda \sum_{n=0}^{M} C_n^c \left(\frac{z}{R_{ref}} \right)^n + (1-\lambda) \sum_{n=0}^{M} C_n^{l,r} \left(\frac{z - x_n}{R_{ref}} \right)^n$$



$C_n^{l,r}$ - measured multipoles for the left and right circles

C_n^c - measured multipoles for the central circles

λ - weight function



$$\lambda(p) = 3p^2 - 2p^3 \quad \lambda(p_0) = 0, \; \lambda(p_1) = 1, \; \lambda(p_0, p_1) = 0$$

$$p = \begin{cases} 0, & \psi < p_0 \\ \dfrac{2\psi - \pi}{2p_0 - \pi}, & p_0 \le \psi \le \pi \end{cases}$$

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Combining rotating coil probe measurements

Measurement results for a SIS100 prototype dipole (S2LD)

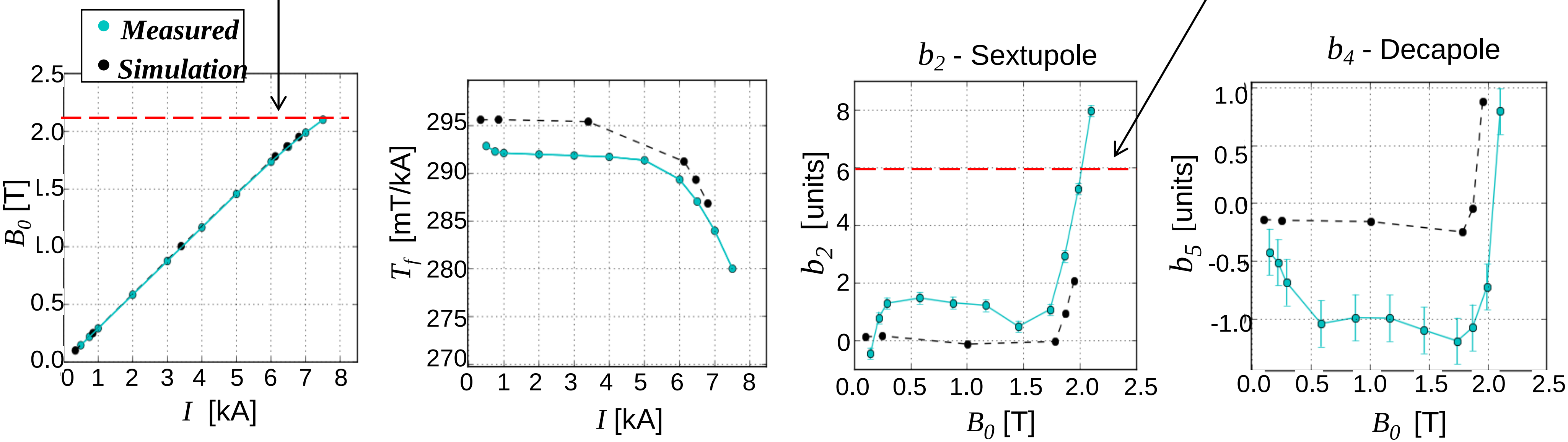
I = 7.5 kA per turn

B_0 = 2.1 T – nominal dipole field

$$T_f = \frac{B_m}{I}, \quad m = 1 \qquad b_n = \frac{B_n}{B_1} \cdot 10^4 \text{ units}$$

$b_n < 6$ units

limitation for SIS100 main magnets



Simulation: 3D Model of the SIS100 prototype dipole (straight magnet with a double layer coil) Vector Fields Opera®,

Measuring: rotating coil probe inside an anticryostat,

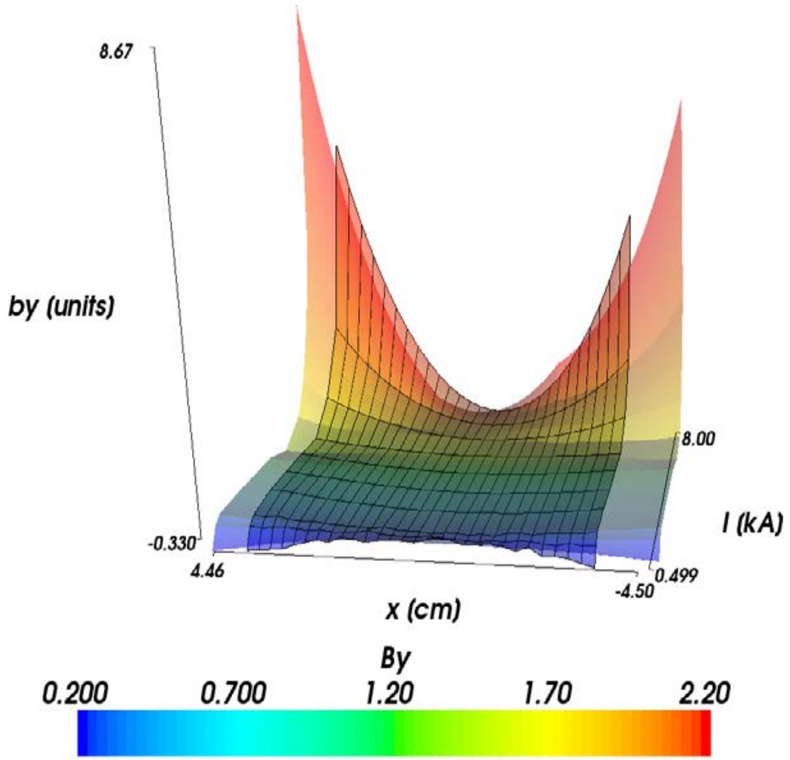
measurement err. for a main field ± 5 units

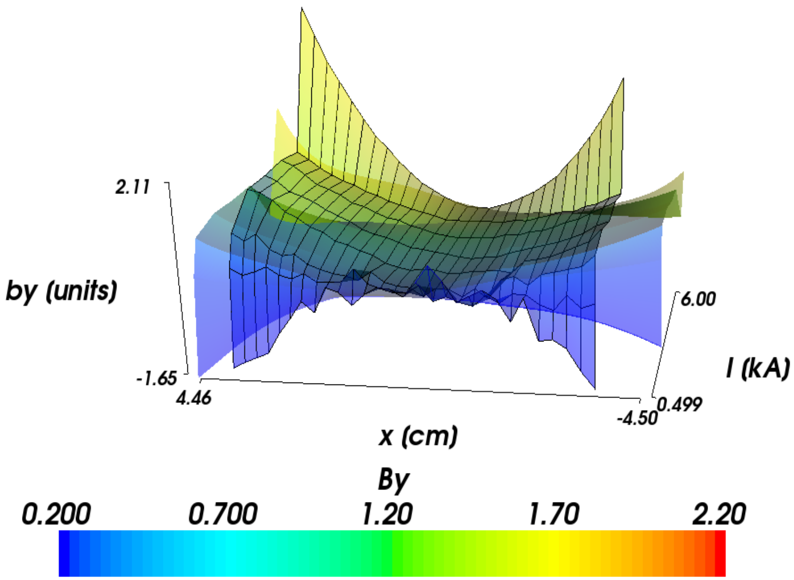
measurement err. for a b_n ± 0.2 units

Magnetic field measurements: Using methods

Mapper with a hall probe → Check of the reproduced field quality at the magnet ends

Measurement results for a SIS100 prototype dipole (S2LD)





Field deviation in an area +/- 45 mm less than 2 units up to 1.75 T

Coil probe (center) agree well with Hall Probes @ (~1m)

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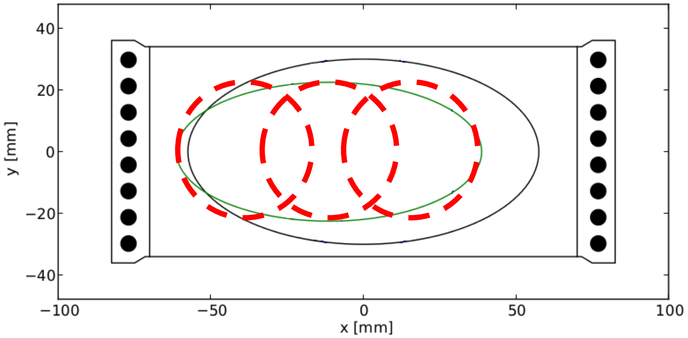
Magnetic field measurements for FoS Dipole

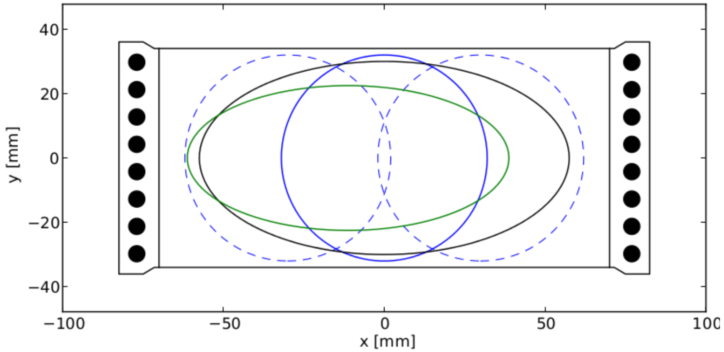
Field measurements without a beam pipe

measurements coverage

1. rotating coil probe inside an anticryostat → (∫Bdl, field quality)
   - ✓ anticryostat R_{out} = 32mm, R_{in} = 23.45mm
   - ✓ rotating coil probe R_{ref} = 17mm, l = 600mm
   - ✓ measurement over the overall magnet length



2. „cold" rotating coil (CERN), mechanical adaptation GSI → (field quality@ magnet end, finalization for end block design)
   - ✓ R_{ref} = 31 mm, l = 1200 mm
   - ✓ measurement at one magnet end



solid black: magnet aperture, usable beam aperture

blue cold coil, (dashed – relocated positions)

green area covered by measurements with a coil probe in the anticryostat

Magnetic field measurements for FoS Dipole

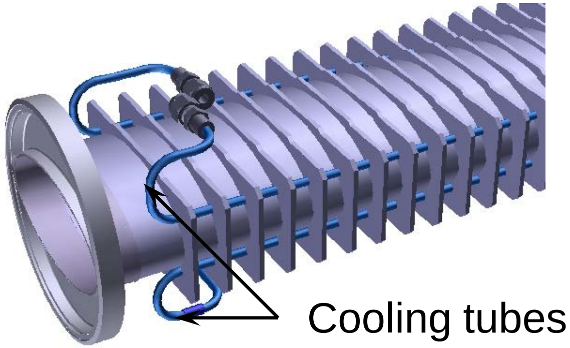
Field measurements without a beam pipe

3. Mapper with a Hall probe →(field quality@ magnet end, finalization for end block design)
   - ✓ magnet end parts

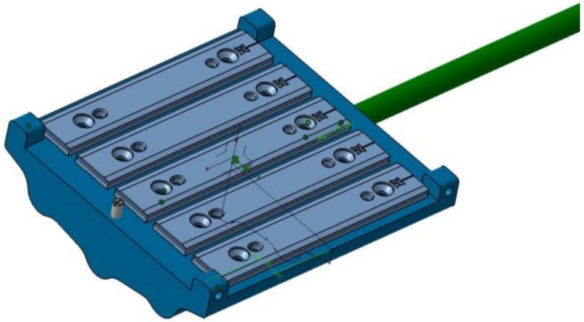
4. Single Stretched Wire → (∫Bdl after correction straight measurement line vs. curved beam trajectory)

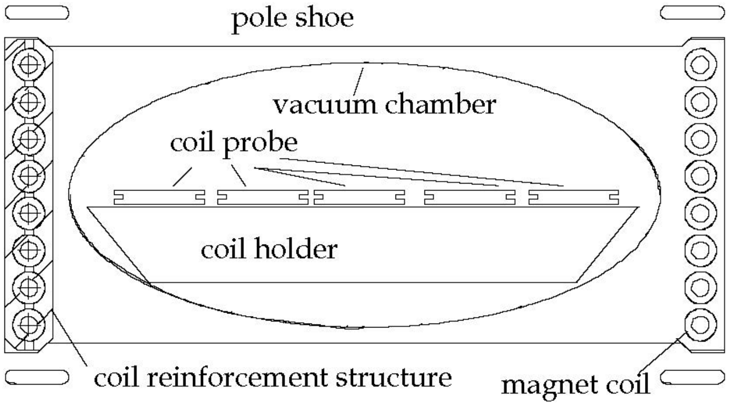
Magnetic field measurements: Using methods

Field measurements inside a beam pipe



- ✓ stationary coil probe array on a holder (check for test pieces)
- ✓ short samples of the beam pipe
- ✓ measurements on the ramp in the SIS18 reference dipole (nc)
- ✓ measurements on the ramp in the SIS100 FoS Dipole (sc)





Magnetic field measurements for FoS Dipole

	Value	Meas. Techn.	Application / user
Load line	B_0	Rotating coil in anticryostat	QA verification of magnet models
Field quality (transverse restricted area without beam pipe)	b_2	Rotating coil in anticryostat	MD/BD: $\int b_2 dl$ optimisation $\rightarrow$ milling an optimised end block design
Field quality (full aperture without beam pipe)	$c_2, ..., c_n$	Cold rotating coil , manual displacement (thermal cycle)	QA magnet design; BD: dynamic aperture calculation
Effective field length (static, dynamic)	$\int Bdl$	Single stretched wire	QA: Yoke length variation MD: iron quality, magnet end chamfering SV: current pre-setting, eddy current compensation BD: closed orbit distortion, tune error (dynamic during acceleration)
Eddy currents	$\Delta B(x_i)$	5 stationary coils	BD: distortion during acceleration

SV – Set-Value generation, BD – beam dynamics, QA – quality assurance

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Magnetic field measurements for SIS100 series Dipole

	Value	Meas. Techn.	Application / user
Effective field length (static)	∫Bdl	Shaft of cold rotating coils	QA: Yoke length variation SV: current pre-setting BD: closed orbit distortion, magnet sorting, tune error
Field quality (transverse restricted area, without a beam pipe)	b_2	Shaft of cold rotating coils	BD: random Δb_2, magnet sorting (higher harmonics with low precision)
Field quality (full aperture without a beam pipe)	c_2 , ..., c_n	Cold rotating coil , manual displacement (thermal cycle)	BD: variation of harmonics in the series, dynamic aperture and resonance excitation

SV – Set-Value generation, BD – beam dynamics, QA – quality assurance

Thank you for your attention