The SIS100 Superconducting Magnets

Anna Mierau

Workshop
Beam physics for FAIR 2012

May 10 – 11, 2012
Hotel Haus Schönblick

1. Overview of superconducting beam guiding magnets of the SIS100
    - Requirements to the magnets
    - Types of the beam guide magnets of the SIS100
2. SIS100 dipole magnets
    - Magnet design
    - Studies of the operation characteristics
        - FEM simulations
        - Measurement result
3. Conclusion

Overview: Key operation parameters of the SIS100

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

operation with U^{28+}

vacuum pressure ~ 10^{-12} mbar

cold vacuum chamber @ 15 K
for the cryo pumping

Principles of the magnet design

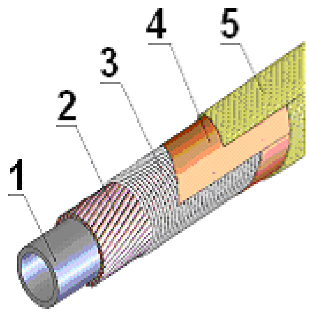
iron dominated (super-ferric) magnets,

superconducting coil,

Nuclotron cable,

cooling by two phase Helium @ 4.5 K

Nuclotron cable:

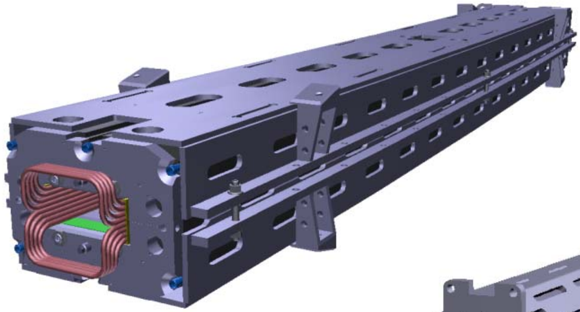


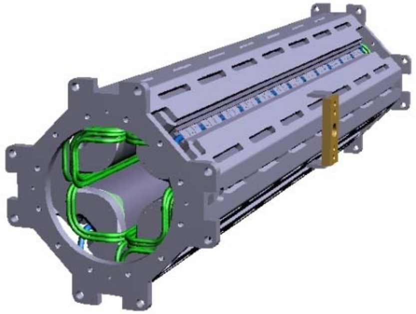
1 - Cooling tube CuNi
2 - SC wire NbTi
3 - CrNi wire
4 - Kapton tape
5 - Glasfiber tape

Image source: [1]

Overview: Beam guide magnets for SIS100

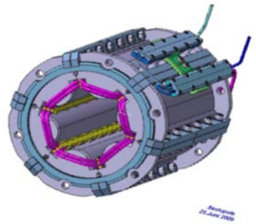
Dipole magnets to bend the beam



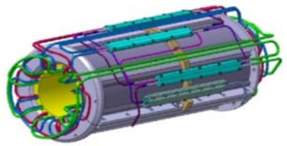


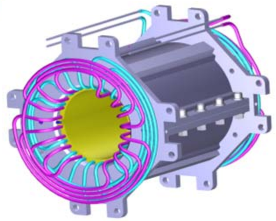
Quadrupol magnets to focus the beam

Chromaticity sextupole
to correct chromatic aberration of particals



Multipole corrector magnets





Steering magnets for the minor corrections of the beam

Overview: Beam guide magnets for SIS100

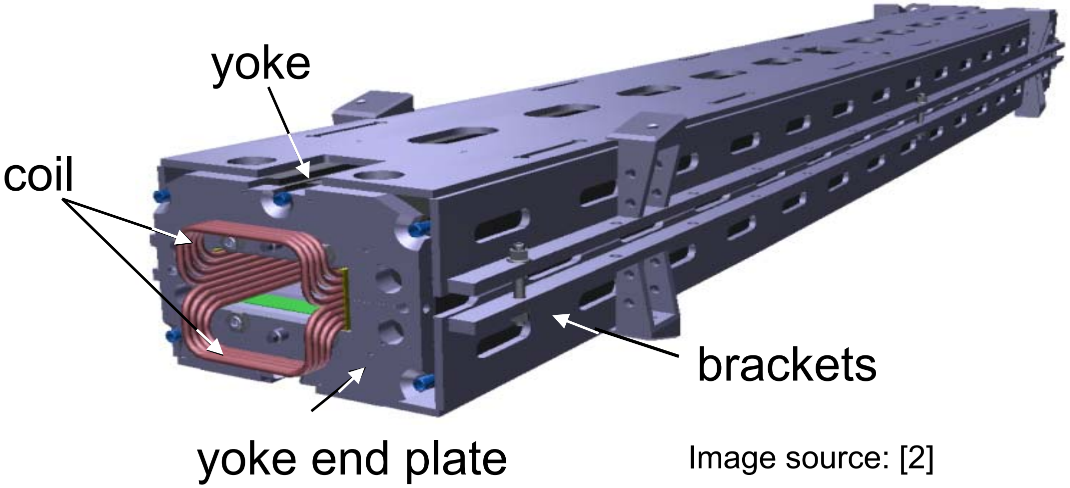
SIS100 dipole magnets

Super-ferric window-frame

curved

superconducting (sc) coil

Nuclotron type cable



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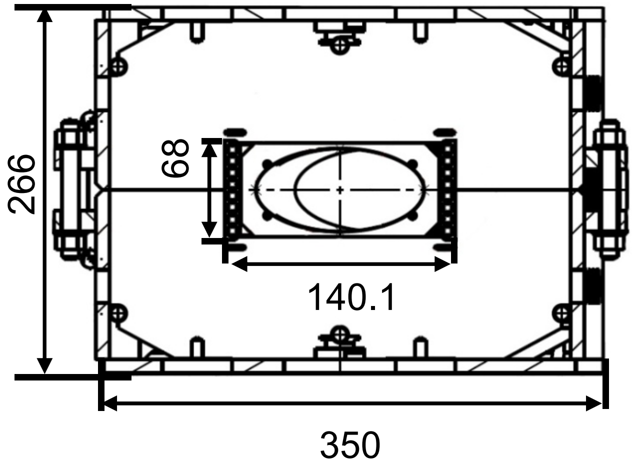


Image source: [2]

Number of magnets		108+1
Bmin	T	0.228
Bmax	T	1.9
Effective length, L_{eff}	m	3.062
Bending angle	mrad	58.18
Bending radius	m	52.632

Introduction: Beam guide magnets for SIS100

SIS100 Quadrupole magnets

Super-ferric

superconducting (sc) coil

Nuclotron type cable

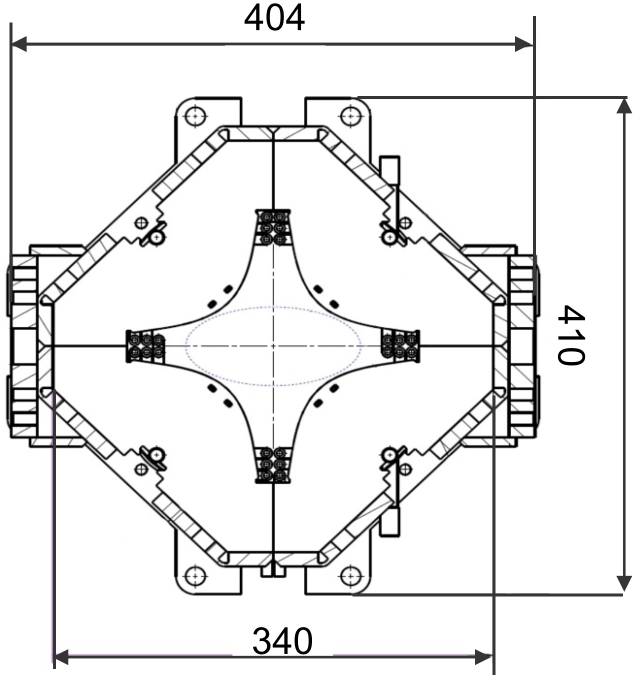


Image source: [3]

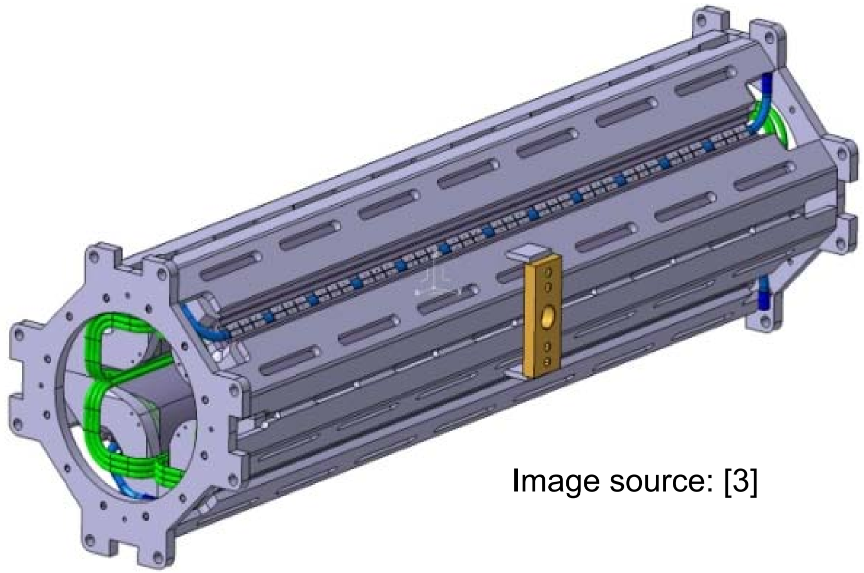


Image source: [3]

Number of magnets		168+3
Max. field gradient	T/m	27
Min. field gradient	T/m	3.24
Effective field length, L_{eff}	m	1.3
Pole radius	m	0.05
Max. ramp rate	(T/m) /s	57

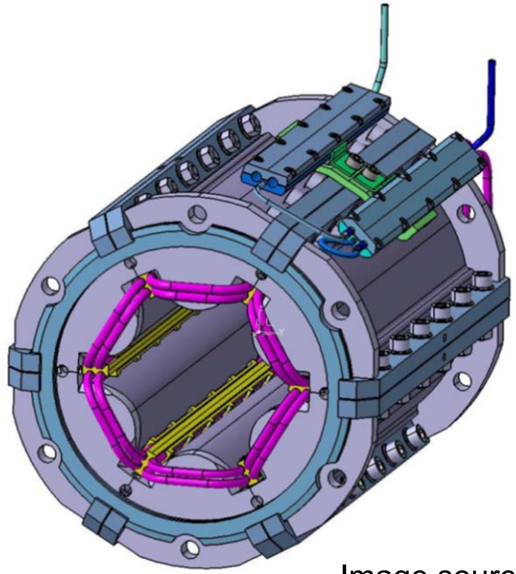
Overview: Beam guide magnets for SIS100

SIS100 Cromaticity sextupole

Super-ferric

superconducting (sc) coil

Nuclotron type cable with insulated sc wires



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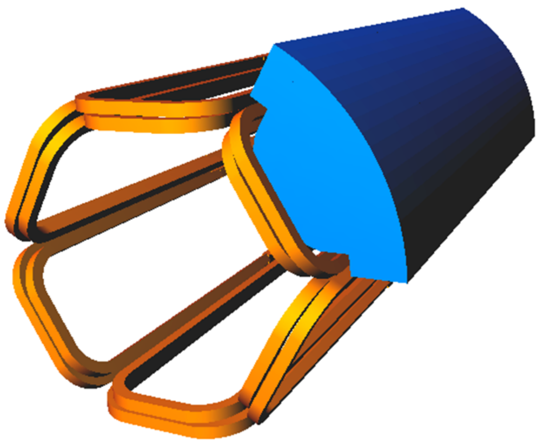

Image source: Dr. Kei Sugita, GSI, SMS-group

Number of magnets		48
Max. strength	T/m^2	175
Effective field length, L_{eff}	m	0.5
Max. ramp rate	(T/m^2) /s	2000

► **see also:** FAIR Technical Design Report SIS100, 2008.

Introduction: Beam guide magnets for SIS100

SIS100 Multipole Corrector Magnets

Cos Θ - magnet

Quadrupole, sextupole and octupole nested

Nuclotron type cable with insulated sc wires

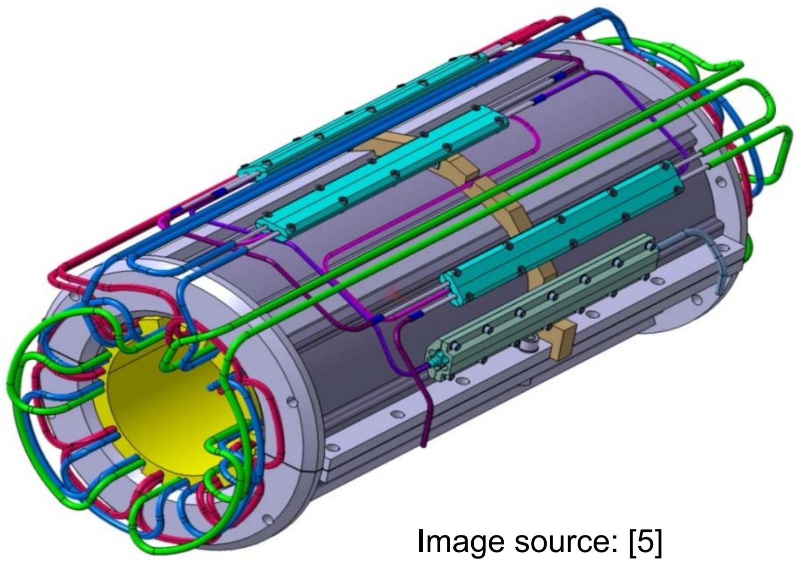

Image source: [5]

Error Compensation Quadrupole Magnets		
Number of magnets		12
Max. gradient	T/m	0.75
Effective field length, L_{eff}	m	0.75
Max. ramp rate	(T/m) /s	5

Error Compensation Sextupole Magnets		
Number of magnets		12
Max. strength B_3	T/m^2	25
Effective field length, L_{eff}	m	0.75
Max. ramp rate	(T/m^2) /s	210

Error Compensation Octupole Magnets		
Number of magnets		12
Max. strength B_4	T/m^3	334
Effective field length, L_{eff}	m	0.75
Max. ramp rate	(T/m^3) /s	8500

► **see also:** FAIR Technical Design Report SIS100, 2008.

Overview: Beam guide magnets for SIS100

SIS100 Steering Magnets

Horizontal/vertical dipole combined magnet

Nuclotron type cable

Number of magnets		84
Max. Field	T	0.3
Effective field length, L_{eff}	m	0.5
Max. ramp rate	T/s	1.5

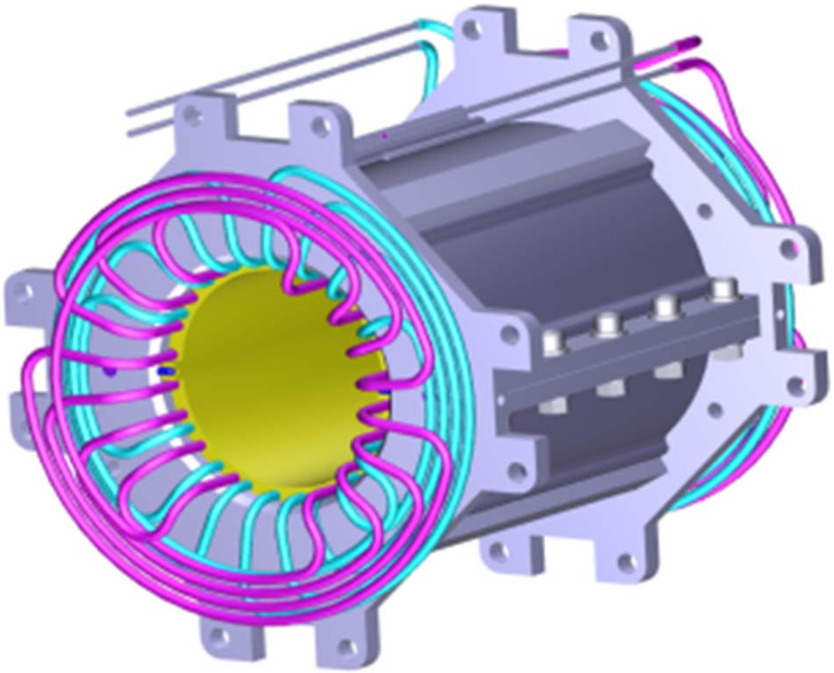

Image source: Dr. Kei Sugita, GSI, SMS-group

► **see also:** FAIR Technical Design Report SIS100, 2008.

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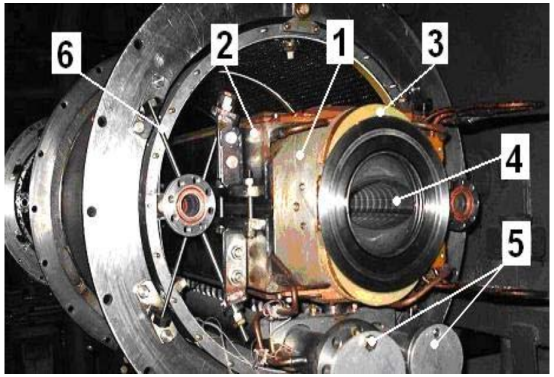
SIS100 Dipole Magnets: Magnet design

Requirements

- ✓Bmax = 1.9 T
- ✓field homogeneity $6 \cdot 10^{-4}$
- ✓dB/dt = 4 T/s
- ✓fast ramping ~ 1 Hz

Nuclotron dipole as a starting point

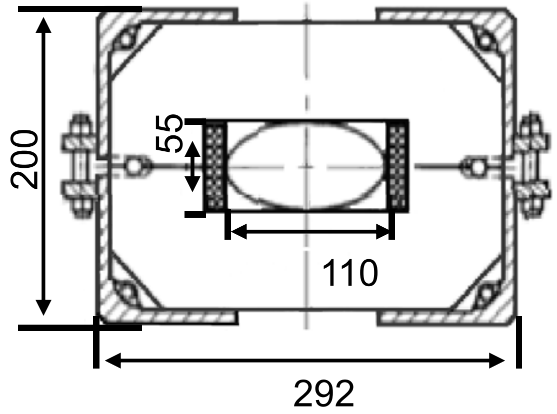


Nuclotron dipole inside cryostat:

1 - yoke end plate, 2 - brackets, 3 - coil end loop, 4 - beam pipe, 5 - helium headers, 6 – suspension. Image source: [7]

Design of the Nuclotron dipole

super-ferric, window-frame



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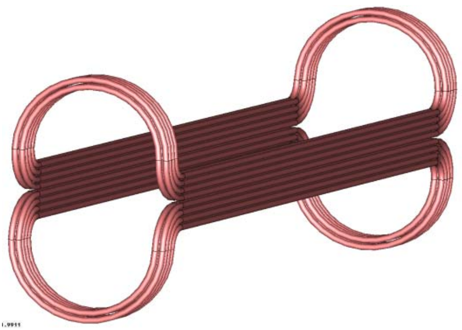
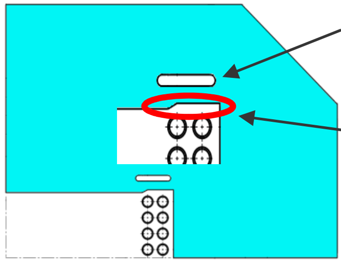


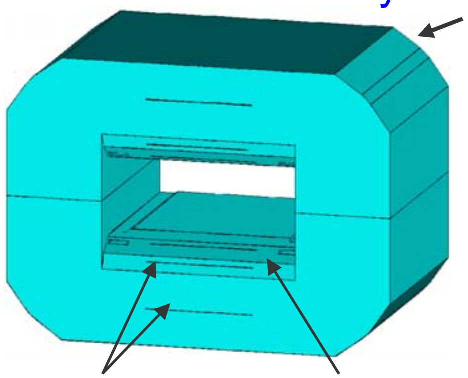
saddle-coil
built of the Nuclotron type cable

SIS100 Dipole Magnets: Design modification



Improvement of the field quality:

- enlarged aperture
  from 110×55 mm to 140.1×68 mm
- additional slits and negative shims

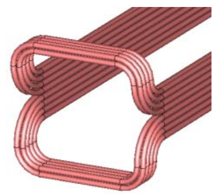


Reduction of AC losses:

- Rogowski-profile for the yoke end parts
- thin cuts in lamination at the yoke ends
- reshaped coil head
- stainless steel for the supporting structure
  (magnet end plates and brakets)

coil head

Nuclotron dipole



SIS100 dipole

Introduction: Models of the SIS100 dipole

Build and tested precursor models of the SIS100 dipole						final design
	unit	Nuclotron	**S2LD** BNG	**S2LD JINR**	C2LD BINP	CSLD series magnet
B_{max}	[T]	1.98	2.1	1.9	1.9	1.9
$L_{effective}$	[m]	1.426	2.756	3.062	3.062	3.062
Estimated L_{yoke}	[m]	1.370	2.731	3.002	3.002	3.002
Bending angle	[deg]	3.75	3.33	3.33	3.33	3.33
Radius of curvature	[m]	22.5	47.368	52.632	52.632	52.632
Usable aperture (h x v)	[mm]	110 x 55	130 x 60	120 x 60	113 x 58	115 x 60

SIS100 Dipole Magnets: Vacuum Chamber

Requirements:

- ✓ elliptical cross section
- ✓ vacuum pressure ~ 10^{-12} mbar

⇩

- ✓ T_{max} < 15 K (to act as a cryopump)

⇩

has to be cooled

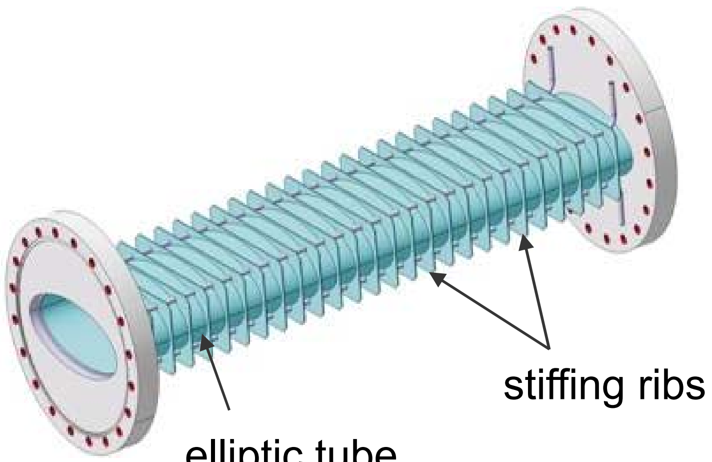


Image source: [9]

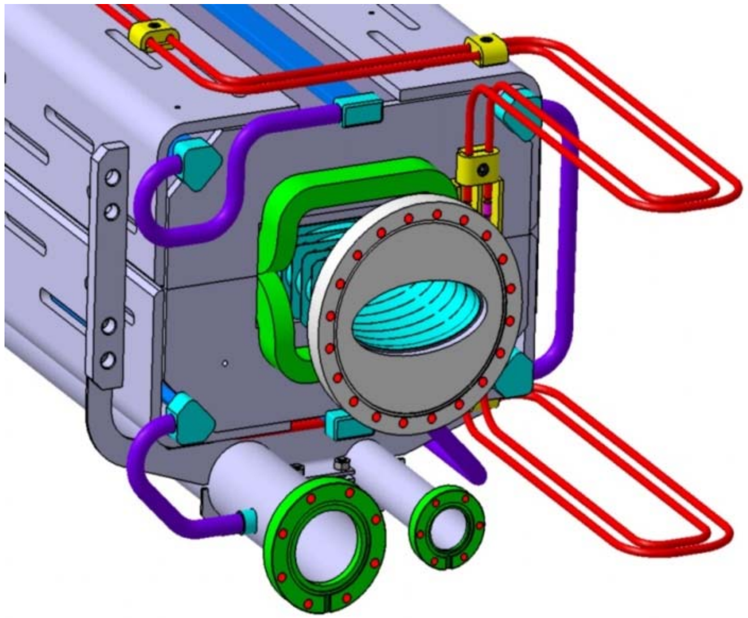


Image source: [8]

Design:

- ✓ wall thickness: 0.3 mm (minimize AC-losses!)
- ✓ strengthening of chamber by ribs

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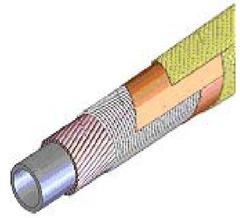
SIS100 Dipole Magnets: FEM Simulations

Challenges in field simulations:

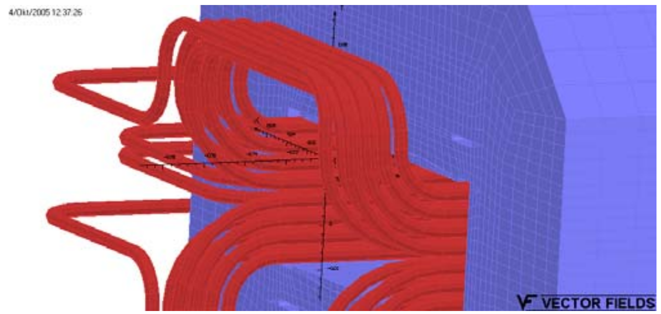


Ø = 7 mm

- representation of the Nuclotron cable
  - ✓ to be studied:

    impact of the cable representations
    on the field distributions in the beam area

- representation of the coil head
  - ✓ coil head has to be proper modelled



- magnet field calculation

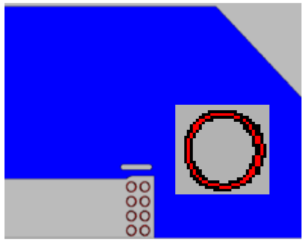
  with a precision better than 100 ppm
  - ✓ analysis of the accuracy of field calculations

SIS100 Dipole Magnets: FEM Simulations

Cable representation in 2D and 3D Models

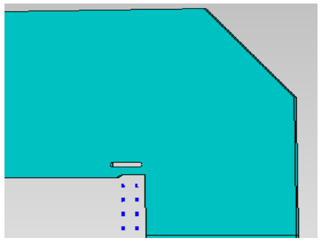
2D Modelling

Vector Fields Opera®

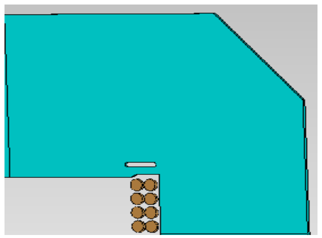


hollow cable

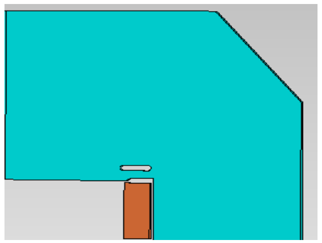
CST EM STUDIO™



infinite thin cable

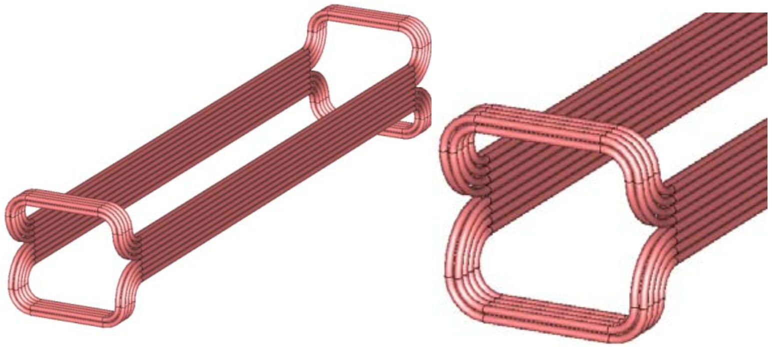


cylindrical cable

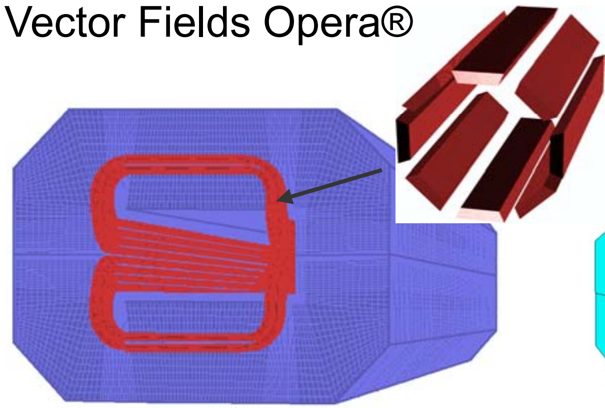


rectangular cable

3D Modelling

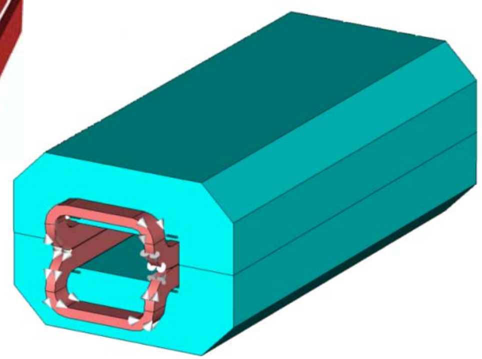


Vector Fields Opera®



hollow cable

CST EM STUDIO™



rectangular cable

SIS100 Dipole Magnets: Field description in the aperture

Standart field description: Circular Multipoles

$$B(z)=B_y+iB_x=\sum_{n=1}^{\infty} C_n\left(\frac{z}{R_{ref}}\right)^{(n-1)}$$

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

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

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

Elliptic Multipoles

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

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

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

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

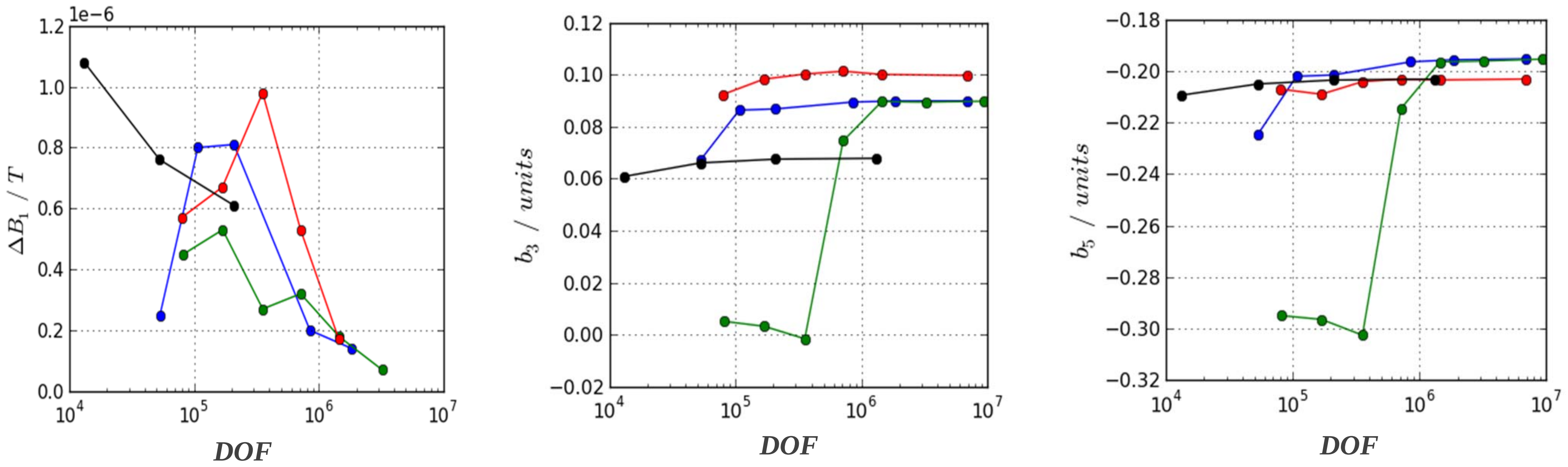
- represent the field in the whole aperture of SIS 100.
- give a concise error propagation for rotating coil measurements in elliptic aperture.
- calculate circular multipoles within the ellipse.

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

SIS100 Dipole Magnets: FEM Simulations

Impact of the coil representation on the field distribution in the beam area

Results of the 2D simulations



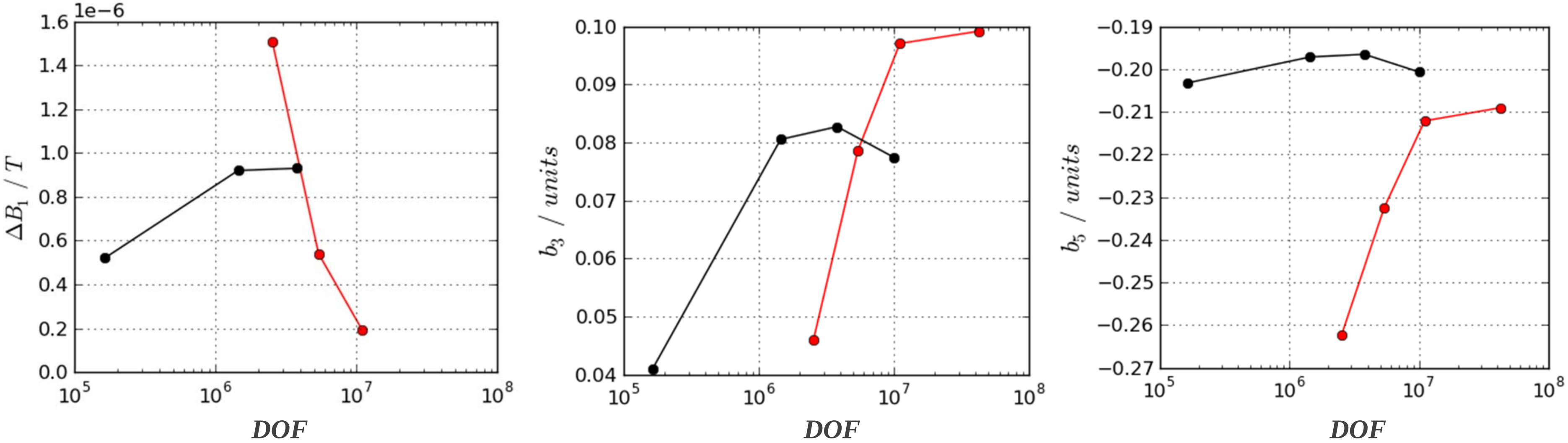
Absolute deviation of the main field from the reference value and the relative sextupole and decapole components of the field versus DOF which were used for the field simulations.

Cable type: • infinite thin, • cylindrical, • rectangular, • hollow

SIS100 Dipole Magnets: FEM Simulations

Impact of the coil representation on the field distribution in the beam area

Results of the 3D simulations

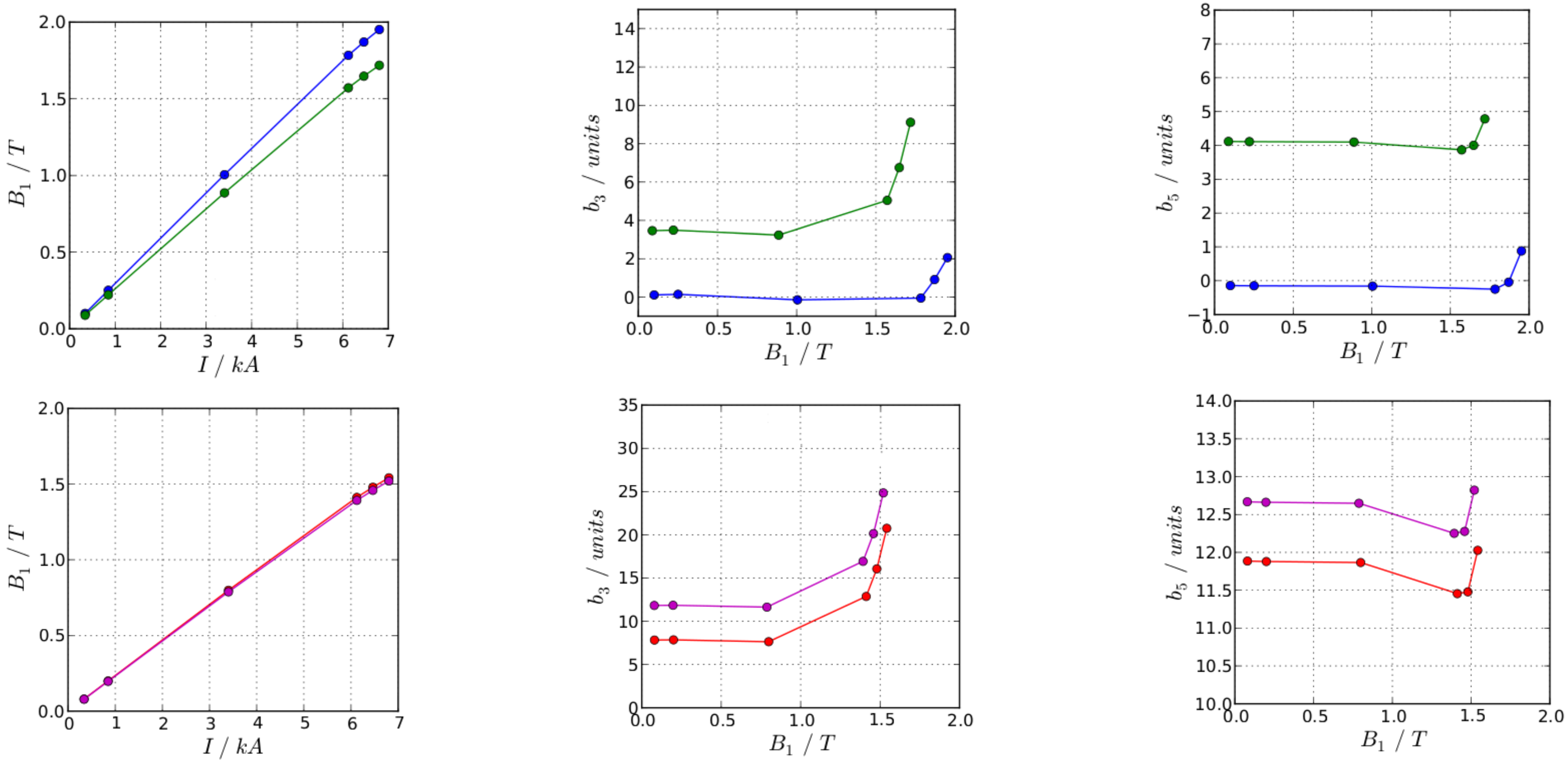


Absolute deviation of the main field from the reference value and the relative sextupole and decapole components of the field versus DOF which were used for the field simulations.

Cable type: • rectangular, • hollow

SIS100 Dipole Magnets: FEM Simulations

Results of the 3D simulation for the S2LD (straight magnet with a two layer sc-coil)



Load line and the relative sextupole and decapole components of the field for the different parts of the magnet. Blue for a central part of the magnet, green – total magnet length, red connection side, magenta – non connection side of the magnet.

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SIS100 dipole magnets: Measurement results for S2LD

First full size prototype dipole magnet

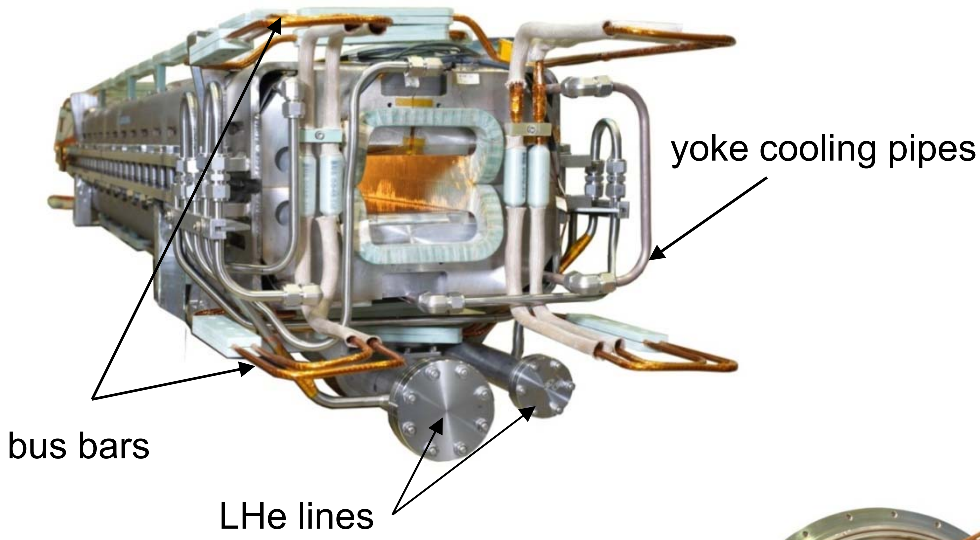
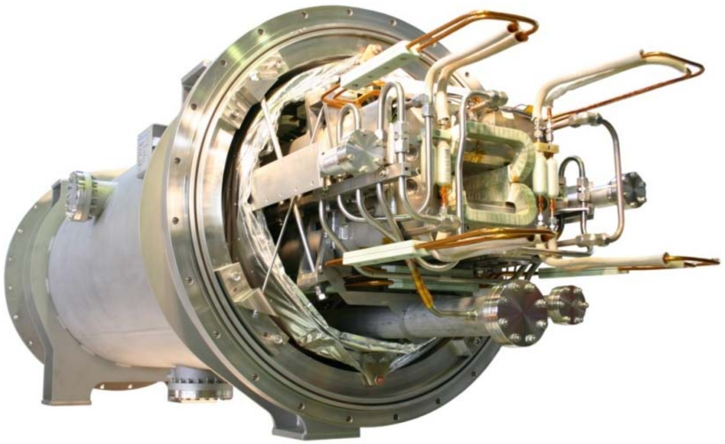
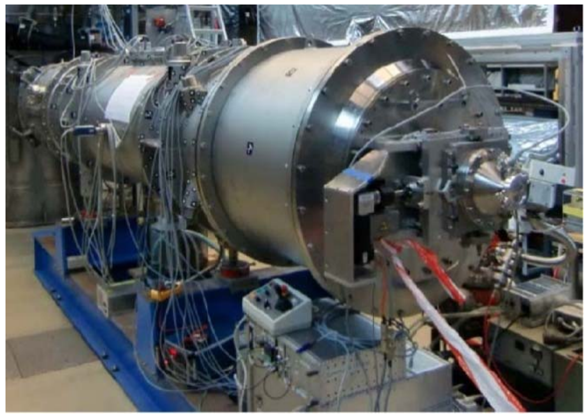


Image source: [10]

General parameters		
mechanical length	m	2.73
usable apertur	mm	130 x 60
Bending angle	mrad	58.18
B_{max}	T	2.1
nominal ramp rate (dB/dt)	T/s	4

► **see also:** G. Sikler et al. "Manufacturing of the first Full Size Model of a SIS100 Dipole Magnet", WAMSDO 2008, 19-23 May, CERN, Geneva; and PAC´09: MO6PFP065, TH5PFP057





SIS100 dipole magnets: Measurement results for S2LD

Field measurement

- rotating coil probe system
- dipole compensation windings
- measurements at the different lateral positions
- data reconstruction for the reference ellipce

  a = 4.5 cm, b = 1.7 cm

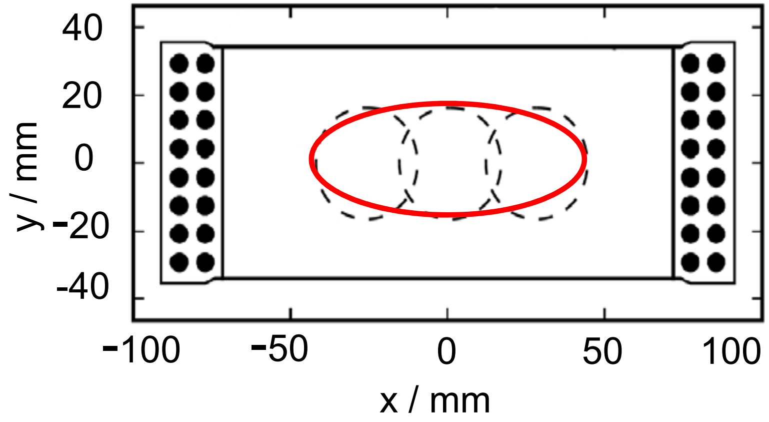


Image source: [11]

$$B_i(z)=\lambda \sum_{m=0}^{M_m} C_m^c \left(\frac{z}{R_m}\right)^{(m-1)} + (1-\lambda)\sum_{m=0}^{M_m} C_m^{l,r}\left(\frac{z-x_m}{R_m}\right)^{(m-1)}$$

$C_m^{l,r}$ - measured multipols for the left and right circles

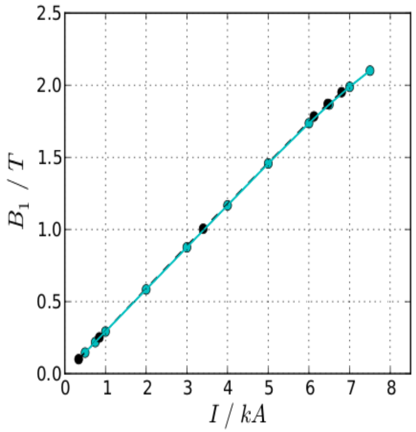
C_m^c - measured multipols for the central circles

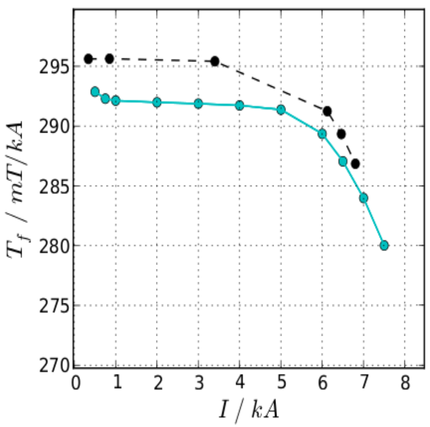
λ - weight function

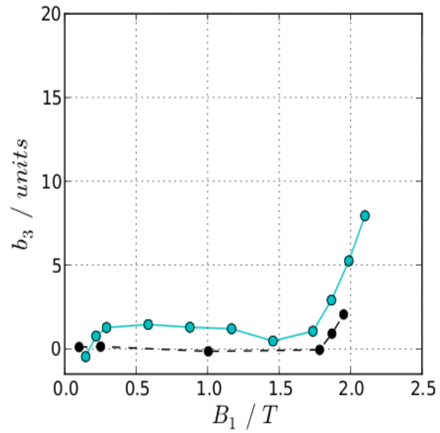
► **see also:** P.Schnizer et al. "Theory and Application of Plane Elliptic multipoles for Static Magnetic Fields", NIMA 607(3):505-516, 2009

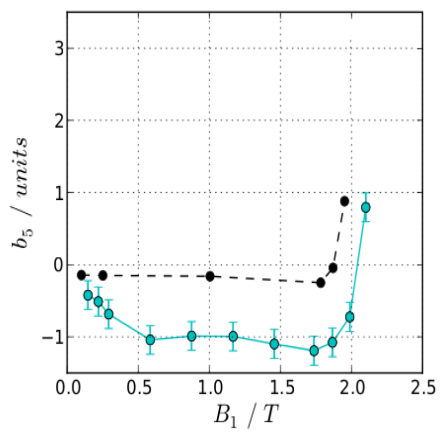
SIS100 dipole magnets: Measurement results for S2LD

Evaluation of the field quality in the gap









Measured and calculated data for the load line and the relative sextupole and decapole components of the field in the central part the magnet.

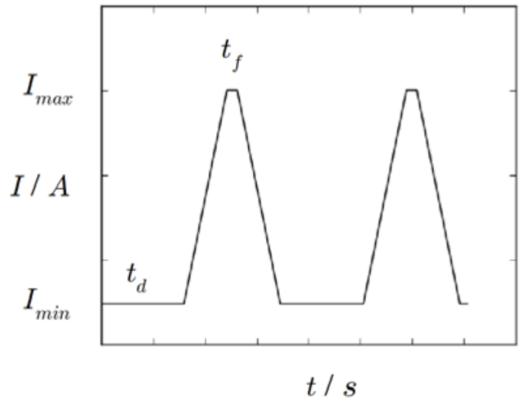
Cyan – measured data
black – calculated from the simulation

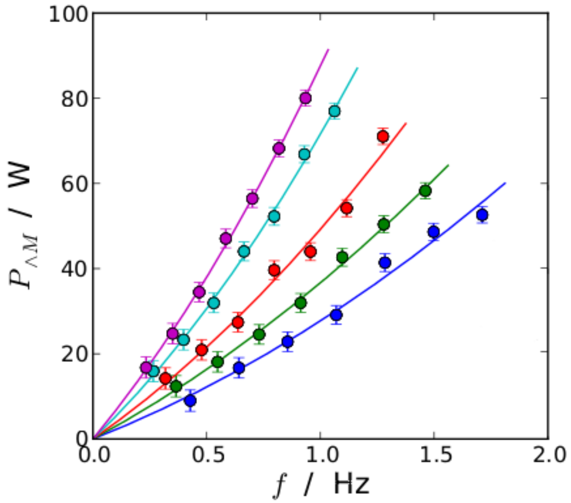
SIS100 dipole magnets: Measurement results for S2LD

AC losses

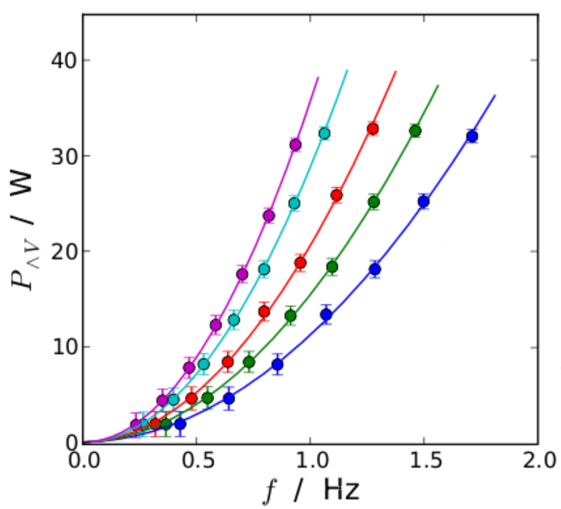
Two methods:

- calorimetric (meas. error 2 W)
- electrical (meas. error 1 W)





▲ average dynamic heat loss in the magnet

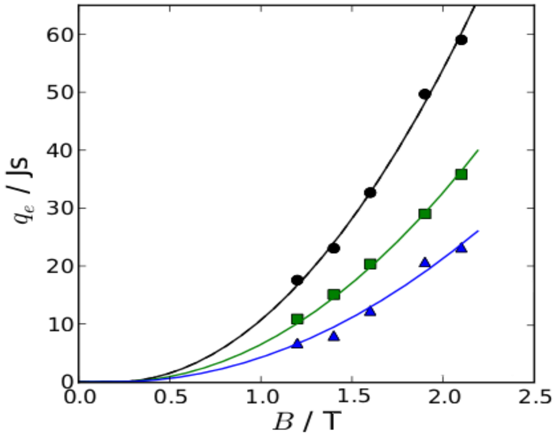


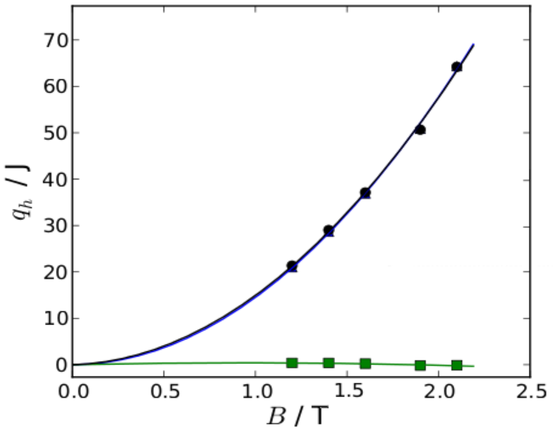
▲ average dynamic heat loss in the vacuum chamber

B_{max} = 1.2 [T]
B_{max} = 1.4 [T]
B_{max} = 1.6 [T]
B_{max} = 1.9 [T]
B_{max} = 2.1 [T]

dB/dt = 0.5 → 4 [T/s]

SIS100 dipole magnets: Measurement results for S2LD





▲ - **magnet**

■ - **vacuum chamber**

• - **assembly (magnet + VC)**

AC losses - Data parametrisation

$$P_\wedge = q_h(B_{max}) f + q_e(B_{max}) f^2 \quad f = 1/\tau_\wedge$$

$$q_h = h_a\, B_{max} + h_b\, B_{max}^2$$

$$q_e = \begin{cases} 0 & B_{max} < B_{th} \\ e_a\,(B_{max} - B_{th})^2 & B_{max} \geq B_{th} \end{cases}$$

Component	h_a	h_b	e_a	B_{th}
Magnet	0.2	14.31	6.57	0.2
VC	0.9	-0.47	10.09	0.2
Assembly	1.09	13.84	16.66	0.2

SIS100 dipole magnets: Measurement results for S2LD

Estimated and measured losses for the FAIR cycles

t – total magnet, ***vc*** - vacuum chamber, ***m*** - magnet

cycle	B_{max} [T]	t_f [s]	f_c [Hz]	P'_{vc} [W]	P'_m [W]	P_{vc} [W]	P_m [W]
1	1.2	0.1	0.71	15.57	24.9		
2a	1.2	0.1	0.71	15.67	24.9	10.99	18.13
2b	0.5	0.1	1.0	4.19	4.66		
2c	2.0	0.1	0.55	19.62	41.68		
3a	1.2	1.3	0.38	8.44	13.41	5.85	12.71
3b	0.5	1.0	0.53	2.22	2.46		
3c	2.0	1.7	0.29	10.39	22.07	8.34	23.21
4	2.0	0.1	0.2	7.06	15.01	5.69	15.94
/\	2.1	0	1.05	37.19	78.98		

results agree well with calculations
(ANSYS, extrapolation from short model magnet measurements)

Conclusion

- The main operating parameters of the S2LD were studied

- Two code packages (CST EM STUDIOTM® and Vector Fields Opera®) were used to calculate the field for static operations.

- The used codes allow predicting the fields with reliable accuracy.

- Models with a simplified representation of the cable can be used for the preliminary estimation of the field quality in the beam area.

- The calculated results are of good quality and in agreement with the measurements for the regions reachable by presently available equipment.

- The losses were analysed and a two variables model (B_{max} and f) built, allowing predicting the required cooling power for any arbitrary cycle with sufficient accuracy.

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Thank you for your attention