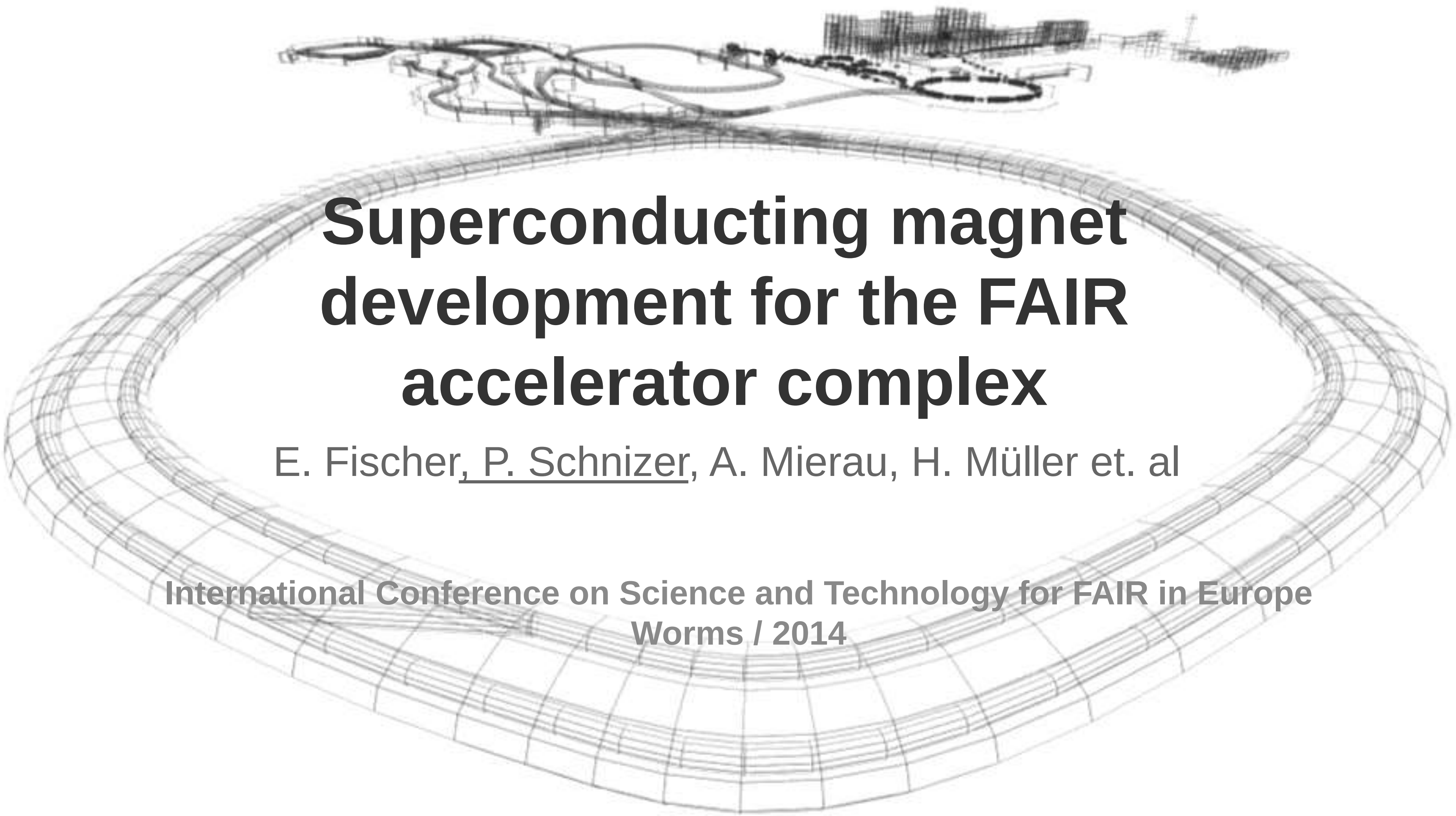
GSI Helmholtzzentrum für Schwerionenforschung GmbH



Superconducting magnet development for the FAIR accelerator complex

E. Fischer, P. Schnizer, A. Mierau, H. Müller et. al

International Conference on Science and Technology for FAIR in Europe
Worms / 2014

Outline

- Introduction
- SuperFRS
- SIS100
  - Dipoles
  - Quadrupole Modules
- SIS300
- Preparing for Series Magnet Testing

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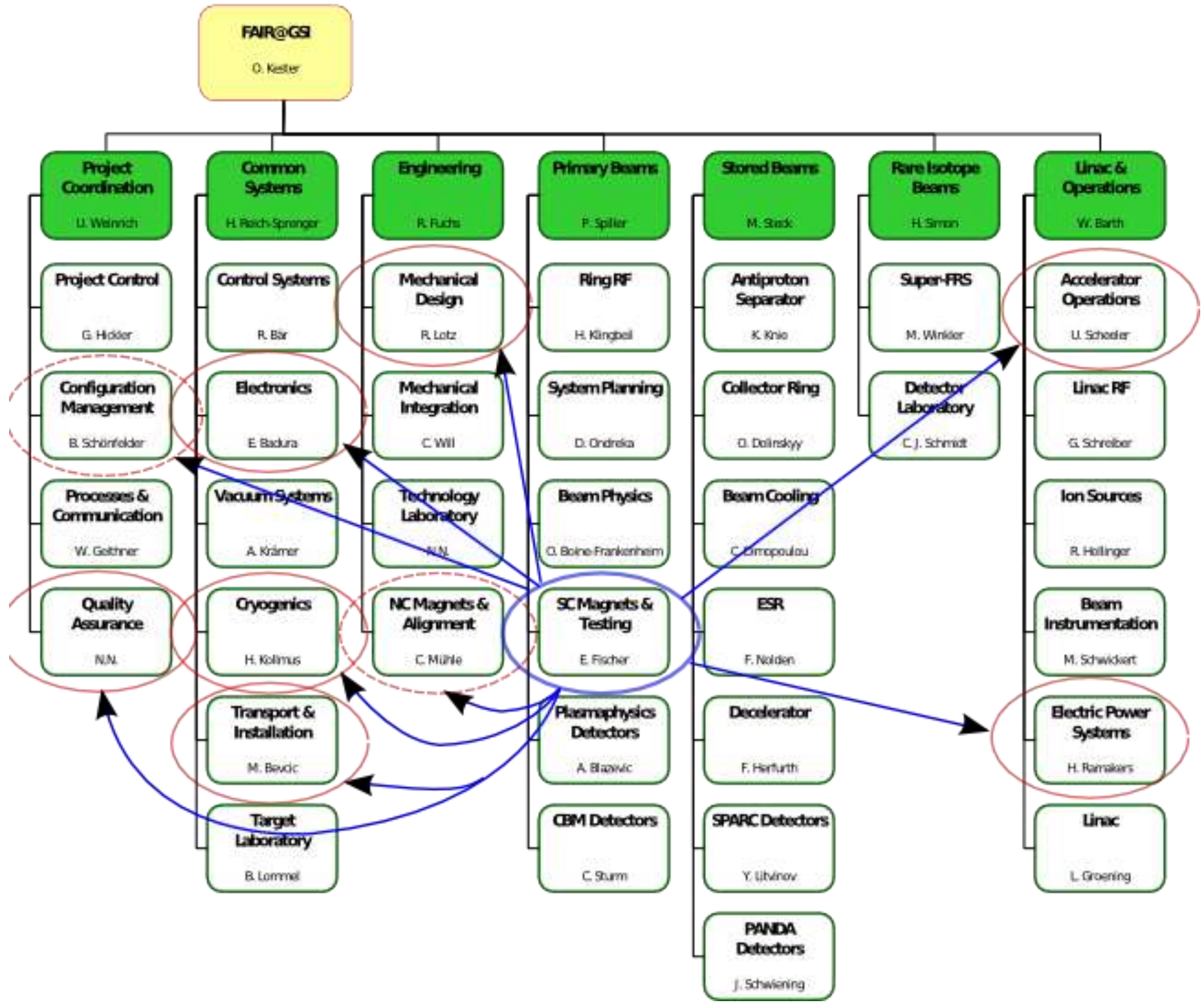
Magnet Production and Testing

Magnet Production and Test

Supported by many groups within GSI



Magnet Production and Testing

- The results presented today were achieved within a short time scale.
- Dirk Acker, Vitalij Bezkorovaynyy, Alexander Bleile, Peter Borisch, Holger Brand, Antonio Coronato, Eric Floch, Walter Freisleben, Anke Gottsmann, Florian Henkel, Franz Klos, Thomas Knapp, Kerstin Knappmeier, Boris Körber, Henning Kummerfeldt, Thomas Mack, Ron Mändel, Sven Meyer, Vassili Maroussov, Fahrid Marzouki, Thorsten Miertsch, Henning Raach, Claus Schroeder, Gerd Schulz, Andrzej Stafiniak, Kei Sugita, Piotr Szwangruber, Vasileios Velonas, Detlef Theuerkauf, Franz Walter, Mischa Weipert, Harald Weiss, Horst Welcker
- together with the ones not even mentioned!

Magnet Production and Test

International Collaborations

Magnet Production

- JINR / Dubna Russia: SIS100 Quadrupole Modules
- CEA/Scalay, France: SuperFRS Dipoles, Design, Technical Support Follow up
- VECC/Kolkata, India SuperFRS: energy buncher magnets

Magnet Testing

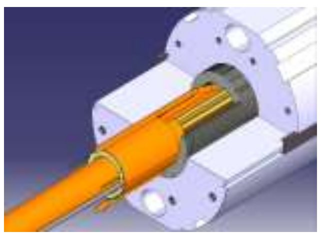
- JINR/Dubna Russia: SIS100 Quadrupole Units
- CERN/Geneva Switzerland: SuperFRS Magnets
  Measurement device development

- new ones on the horizon (and productive!)
  - INFN/ Genua, Milano Italy, SIS300:superconducting dipoles
  - IHEP/Protvino, Russia SIS300:superconducting quadrupoles

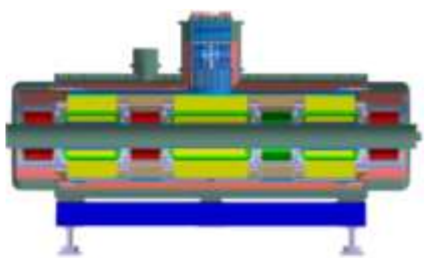
Talk‘s Content: keeping particles on track

particle guiding devices

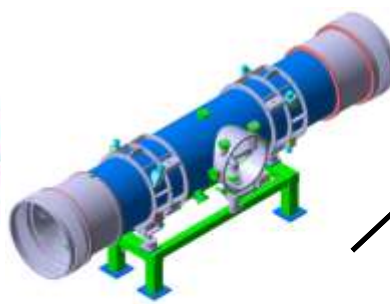
SIS300

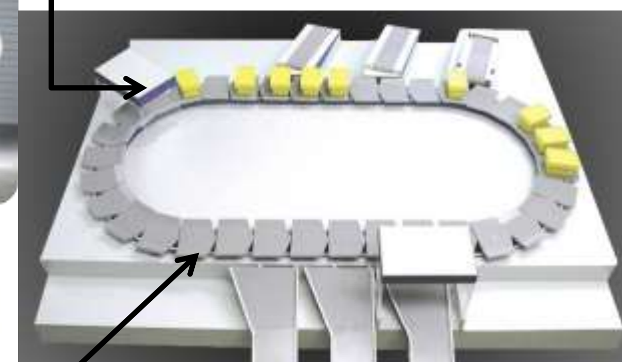


SuperFRS



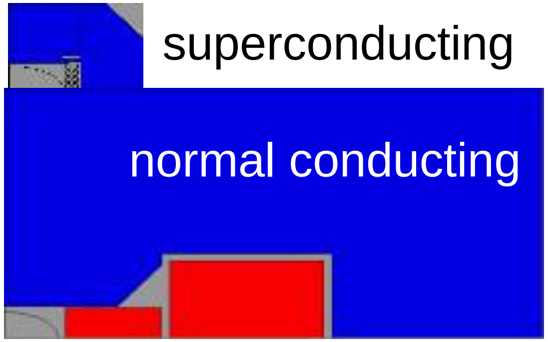
SIS100





a parcel sorting plant
Source: designprojekt-dd.de

Talk‘s Content: keeping particles on track



SIS100: dipole

but why superconducting?

- make it small
  - → higher field: e.g. SIS300: 4.5 T magnets
  - smaller coil
  - smaller size
- make it achievable
  - environement → e.g. SIS100, high current U^{28+} beams → 10^{-12} vacuum chamber as cryopumps
  - SuperFRS quadrupoles: 2.3 T pole dip field
- make it economic
  - todays‘ medical cyclotrons: swtiching to superconductivity
    - smaller building size
    - availability → # of systems
  - SuperFRS dipoles: 1.6 T, huge energy comsumption

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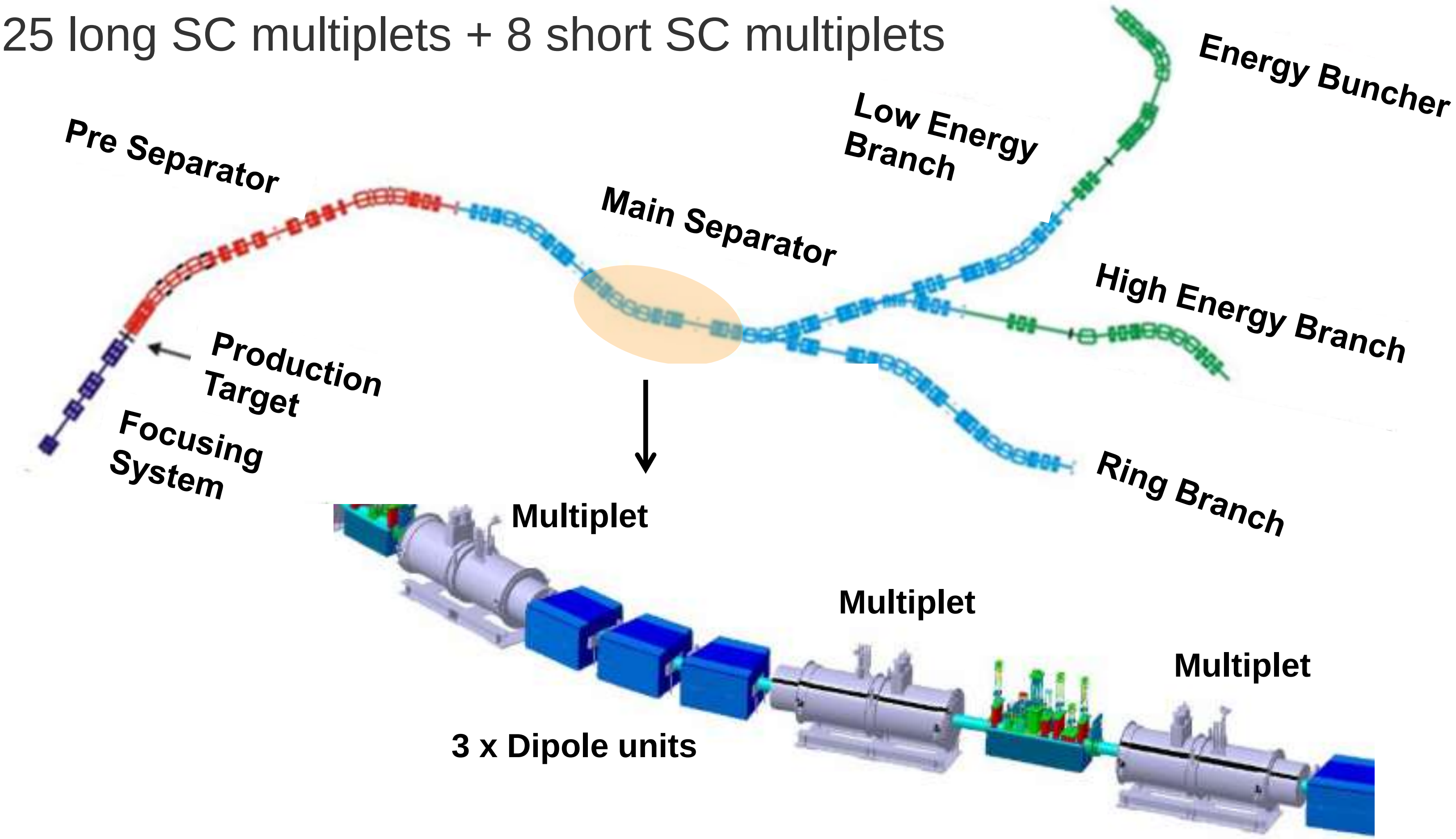
Status of the SuperFRS Magnets

- 24 superconducting (SC) dipole magnets
- 25 long SC multiplets + 8 short SC multiplets



Super Fragment Separator

Status of the SuperFRS Magnets

Prototype made by FAIR China Group

Inst. of Electrical Engineering, Beijing: conceptual design

Inst. of Plasma Physics, Hefei: cryostat and coil

Inst. of Modern Physics, Lanzhou: yoke and tests

Status of the SuperFRS Magnets

SC Dipoles

- 21 superferric dipoles
  - design finalised by CEA / Saclay
  - FAIR will open tendering soon

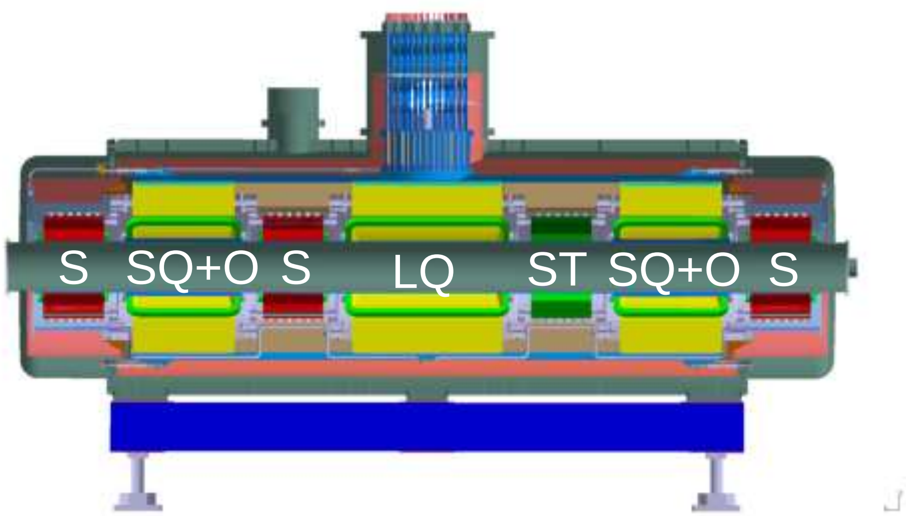
- 3 energy buncher magnets
  - design conducted by VECC / Kolkata

Status of the Super-FRS Magnets

SC Multiplets

- 25 long multiplets + 8 short multiplets
- Cold, laminated iron yoke (> 40 tons)
- Common helium bath (~ 1200 liter helium)
- 1 pair of current leads per magnet
- max. current < 300 A for all magnets

- 380 mm aperture
- 2.3 T pole dip field
- electrical stored energy ~ MJ



- ~ 7 m long, > 60 tons
- 1 x long quadrupol (LQ)
- 2 x short quadrupol (SQ) equipped with octupol (O) coil
- 3 x sextupole (S)
- 1 x steering dipole (ST)

longest multiplet system

tender running

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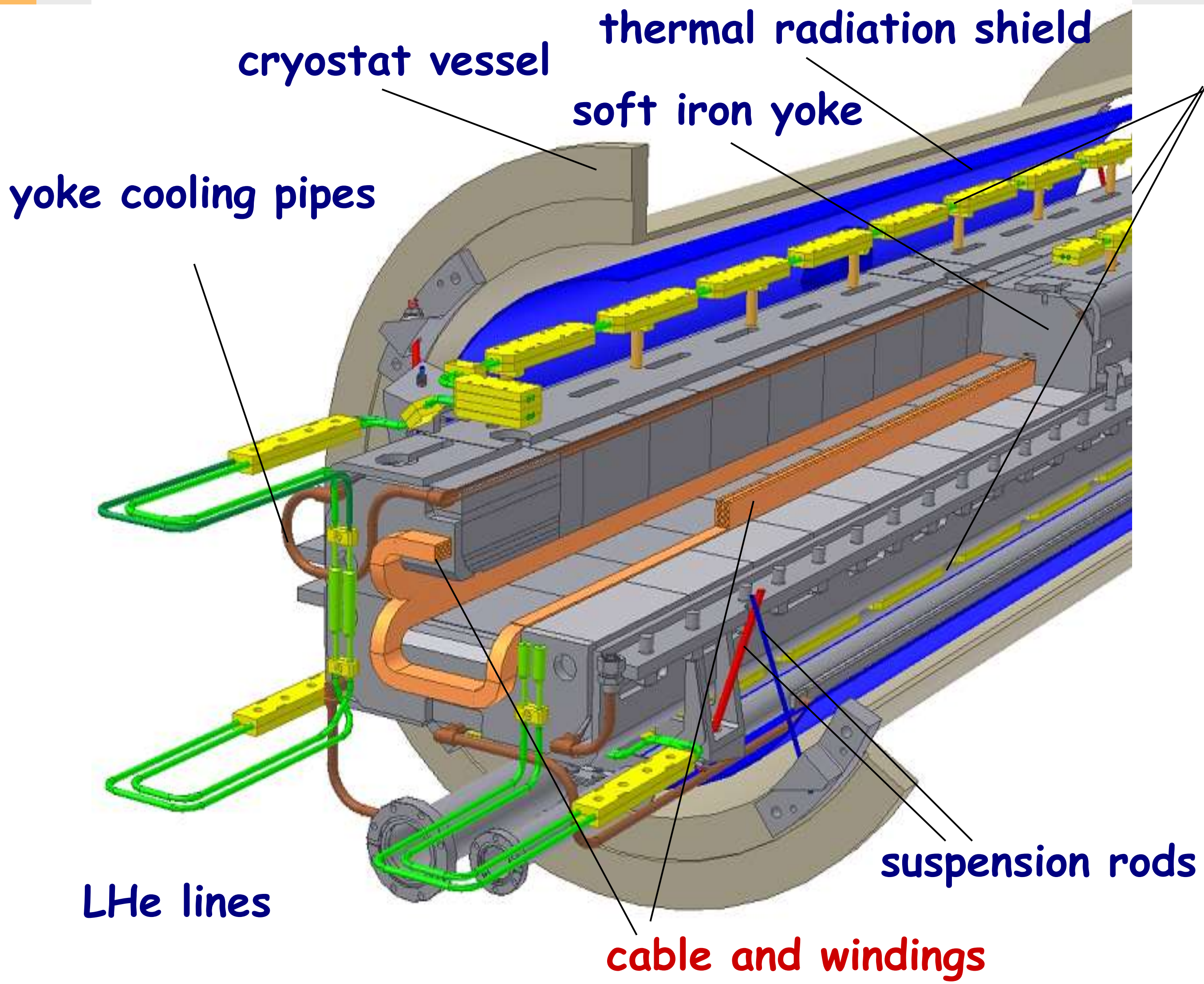
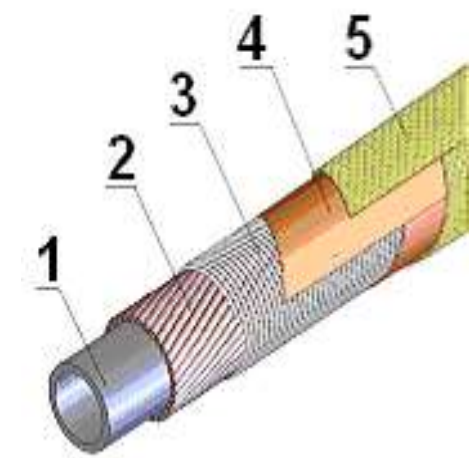
SIS100 Main Magnets: Dipole Design



<u>Nuclotron cable:</u>

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



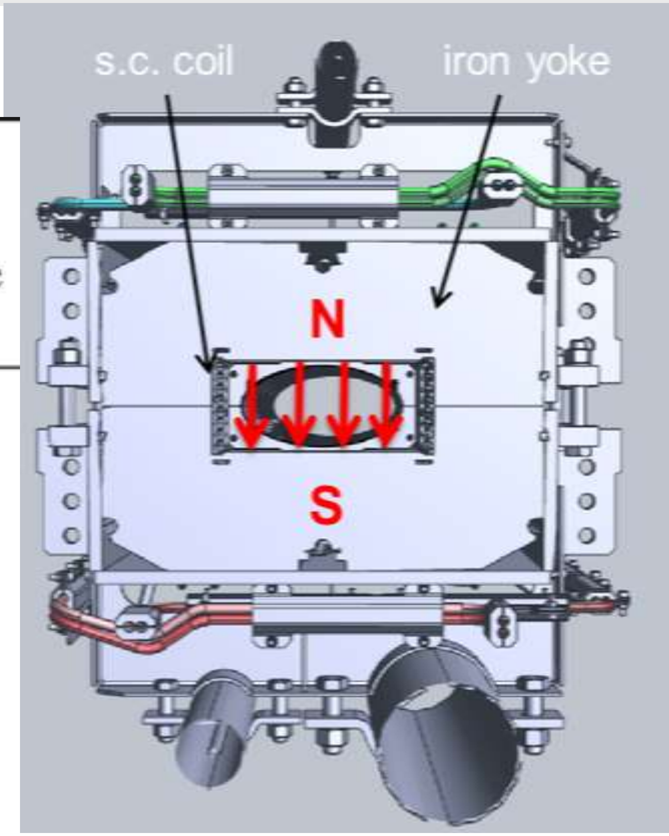
helium within cable, continous cooling stream

SIS100 Main Magnets: Fast ramped

Parameters of the SIS100 Dipole

number of magnets	108 + 1 reference magnet
design	window-frame, laminated cold iron yoke, lamination thickness 1mm, one layer with 8 turns

number of magnets	108 + 1	
max. field B_{max}	1.9	T
min. field B_{min}	0.23	T
bending angle	3 1/3	Deg.
orbit curvature radius, R	52.632	m
effective magnetic length, L	3.062	m
good field region	$115 \cdot 60$	mm^2
field quality target	600	ppm
current at max. field	13093	A
inductance	0.55	mH
ramp rate	4	T/s



other components:

- 168 quadrupole magnets
- 144 corrector magnets
- cold vacuum chamber
- cryo-collimators

SIS100 Dipole: Manufacturing

Cable Production

► analog to the prototype dipole,
but curved coil and yoke,
new cable dimensions

Coil Winding → Assembly of Cold Mass → Mounting into Cryostat → Factory Acceptance Test

Yoke Stacking

Cryostat

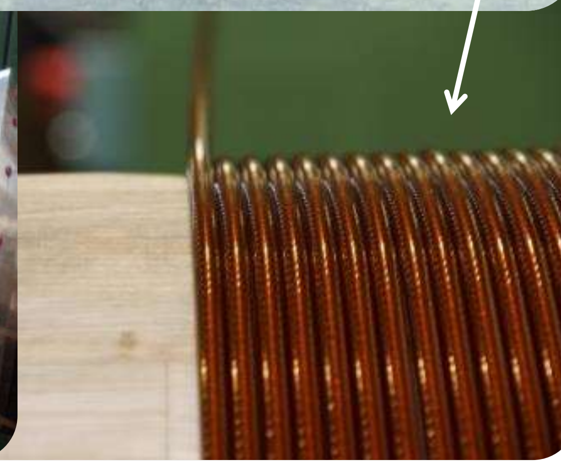
Thermal Shield

SIS100 Dipole: Cable production

► Demand of cable per dipole: 62 m (coil) + 52 m (busbars)

► Cable produced for 1 dummy coil with copper strands

► In total 265 m of SC Nuclotron type cable produced



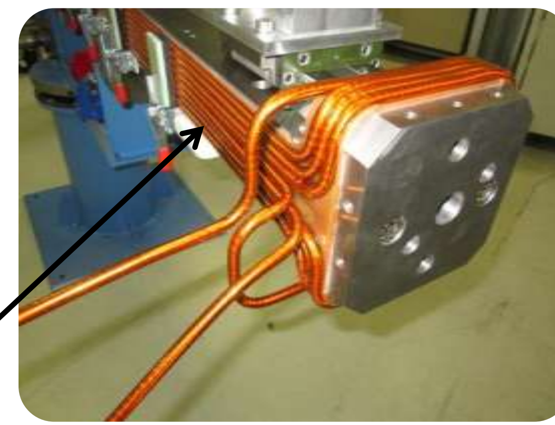
$\upsilon_{Spinner}$ = 705 rpm

v_{Cable} = 0.35 m/min

cable bobbin

SIS100 Dipole: Coil winding

Winding tool developed for curved single layer FoS coil,
same concept as for Prototype coil



Superconducting cable sustains 15 kA (diameter: 9 mm)

all coil windings

SIS100 Dipole: Coil fabrication

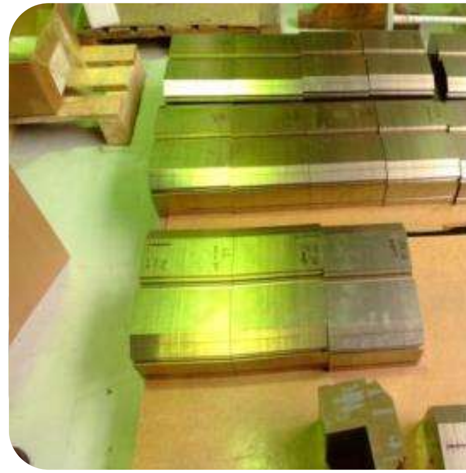
coil windings
in G11
reinforcement
structure

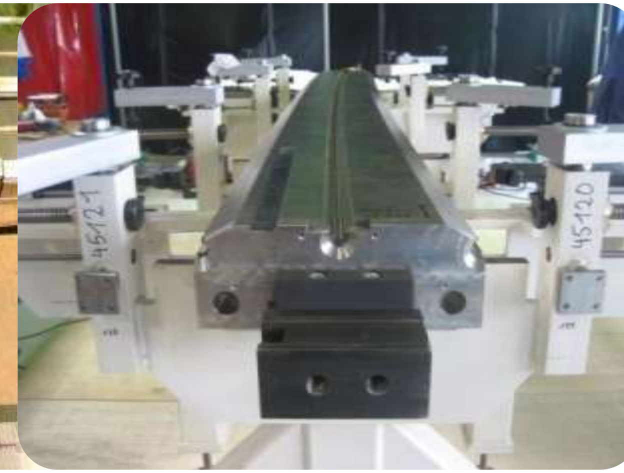
in press

t ~ 3.5 h
T ~ 150 °C

SIS100 Dipole: the yoke

Lamination: M600-100A, 1mm,
Stabolit 70 coating



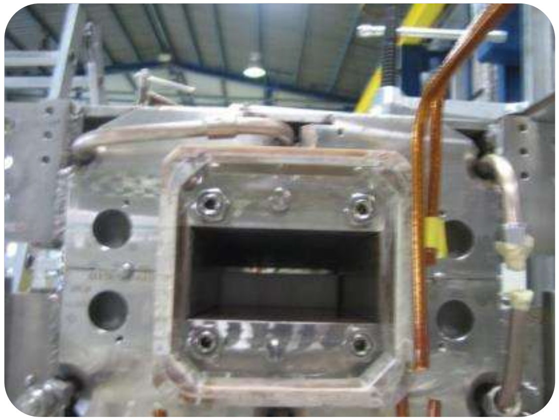


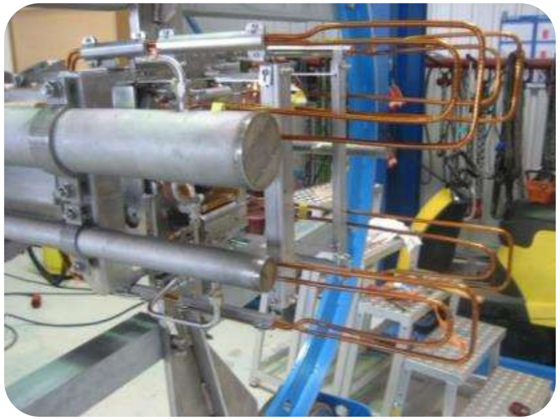
Yoke Manufacturing:

1. **Stack 200 mm curved packages, filling factor ≥ 98%**
2. **Glue packages in oven**
3. **Place packages on girder**
4. **Adjust filling factor**
5. **Insert cooling tubes**
6. **Weld side and top covering sheets**

SIS100 Dipole: Assembling the cold mass

- Assembly of coil and half yokes on rotating device
- Installation of:
  - Busbars
  - Potential breakers
  - Instrumentation
  - Helium supply-lines

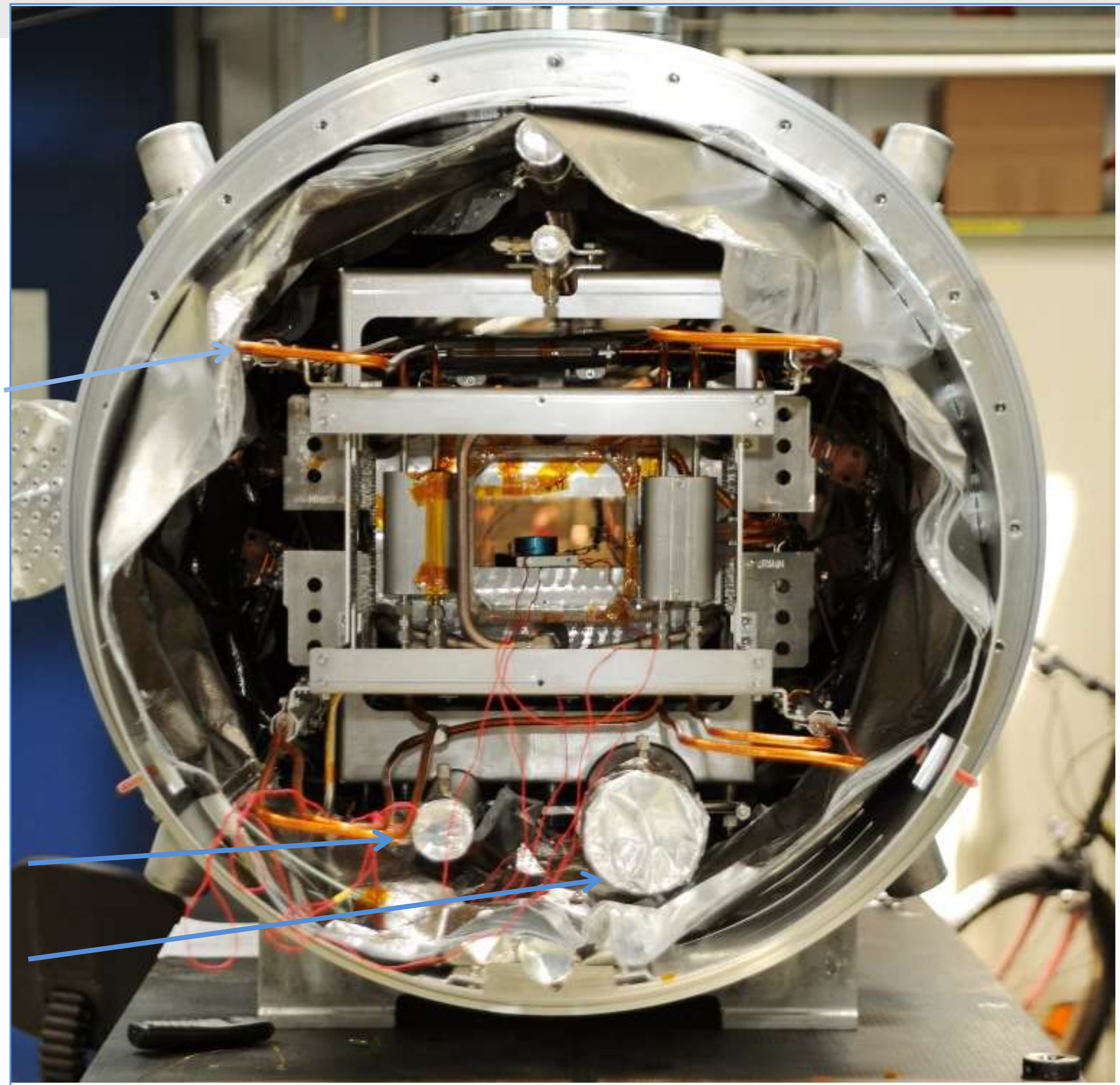




SIS100 Dipole: Ready for testing

looking into aperture

bus bars



helium
headers

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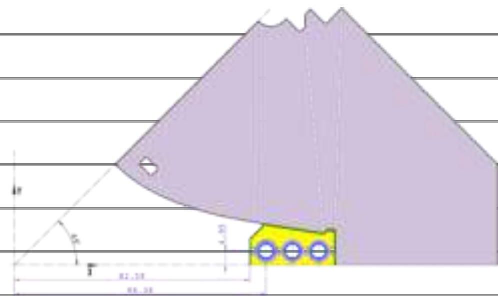
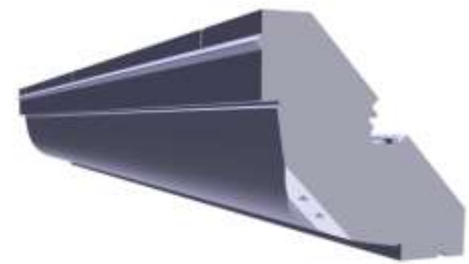
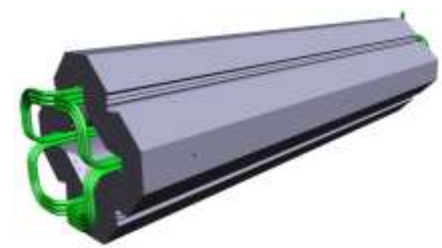
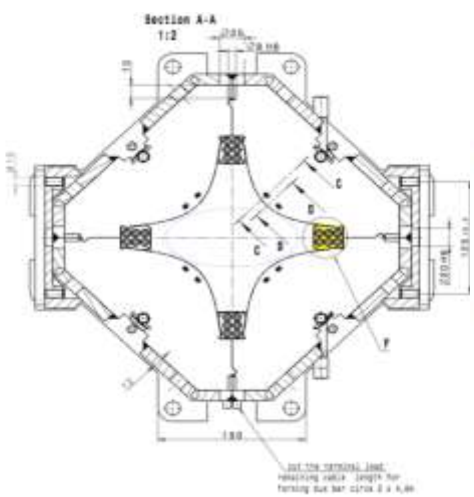
SIS100 QP Modules: Quadrupole Design

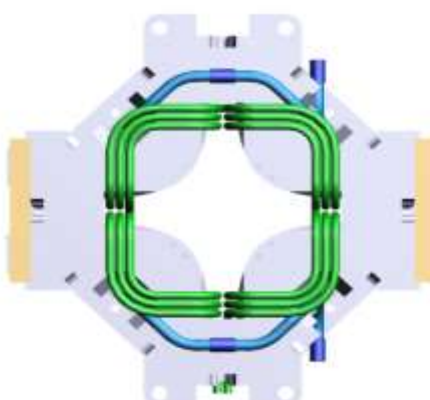
Parameter	Units	Value
Number of magnets		166+3
Design		Superferric
Maximum magnetic induction B_2	T/m	27
Effective magnetic length L_{eff}	m	1.3
Ramp rate dB/dt	(T/m)/s	57
Field quality		$\pm 6 \times 10^{-4}$
Good field region	mm^2	135×65
Overall magnet length (coil ends)	m	1.33











SIS100 QP Modules: Corrector Magnets

	Multipole			Steerer		Chrom.
Num. of Mag.	12			84		48
	Quad.	Sext.	Oct.	H	V	
Cable length [m]	12	14	17	13	12	13
Num. of wires	10	22	19	28	28	20
Current [A]	249	245	251	260	268	255
Max. field [T]	0.5			0.5		1.2
dB/dt [T/s]	2.1			2.5		6.8

- Common cooling system: 2 phase helium forced flow,
- Nuclotron type cable: Effective cooling
- Low current < 300A: Minimize heat load from current leads.

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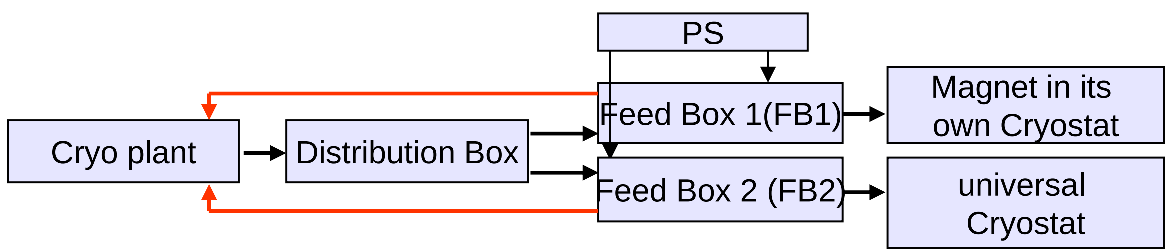
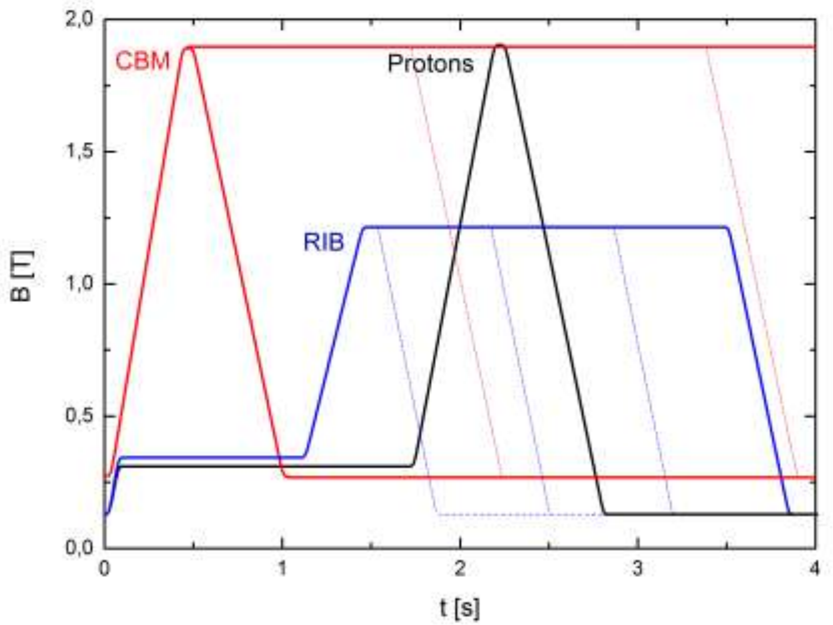
SIS100 Dipole: Ready for testing

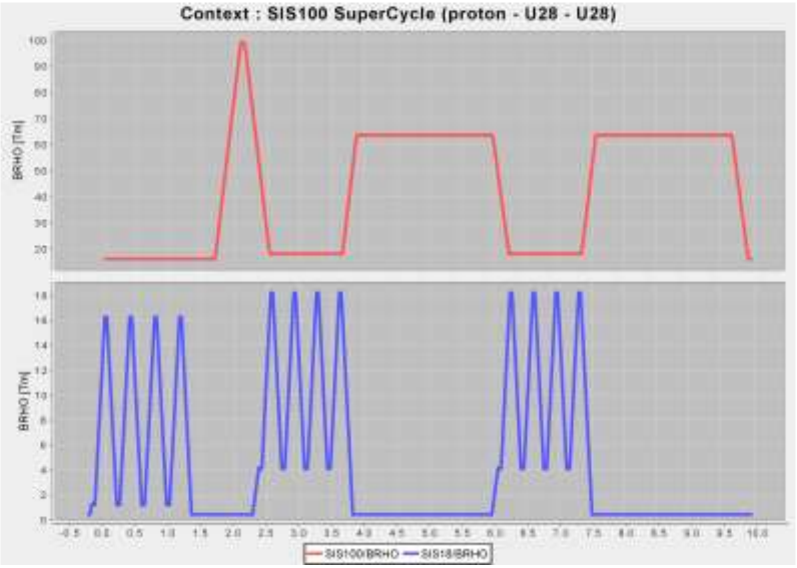
Photo: G. Otto

@ the GSI Prototype Test Facility



SIS100 operation modes



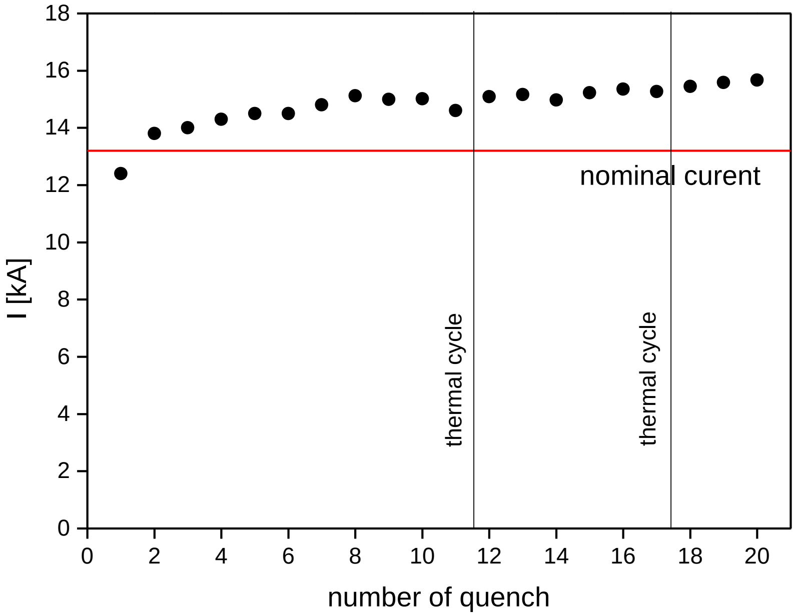


Cycle	B_{max} [T]	B_{min} [T]	t_f [s]	t_c [s]
CBM	1.9	0.27	0.1	1...10
Protons	1.9	0.13	1.7	2.83
RIB	1.2	0.13	3.0	3.88
/\	1.9	0	0	0.95

- four injections from SIS18
- acceleration: ramp up at 4 T/s
- extraction (slow or fast)
- ramp down at 4 T/s

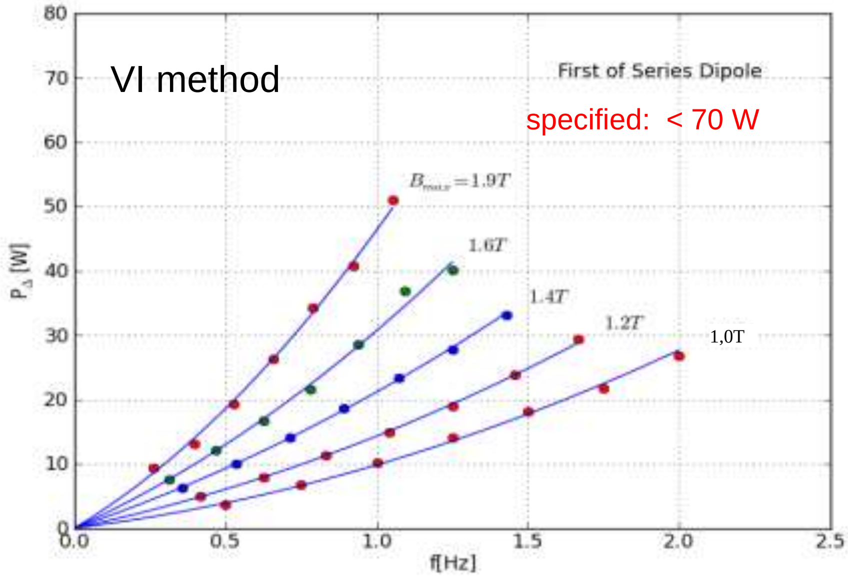
SIS100 Dipole: quench performance and AC losses

electrical powering



- nominal current reached after the first quench
- no de-training after thermal cycling

ac losses



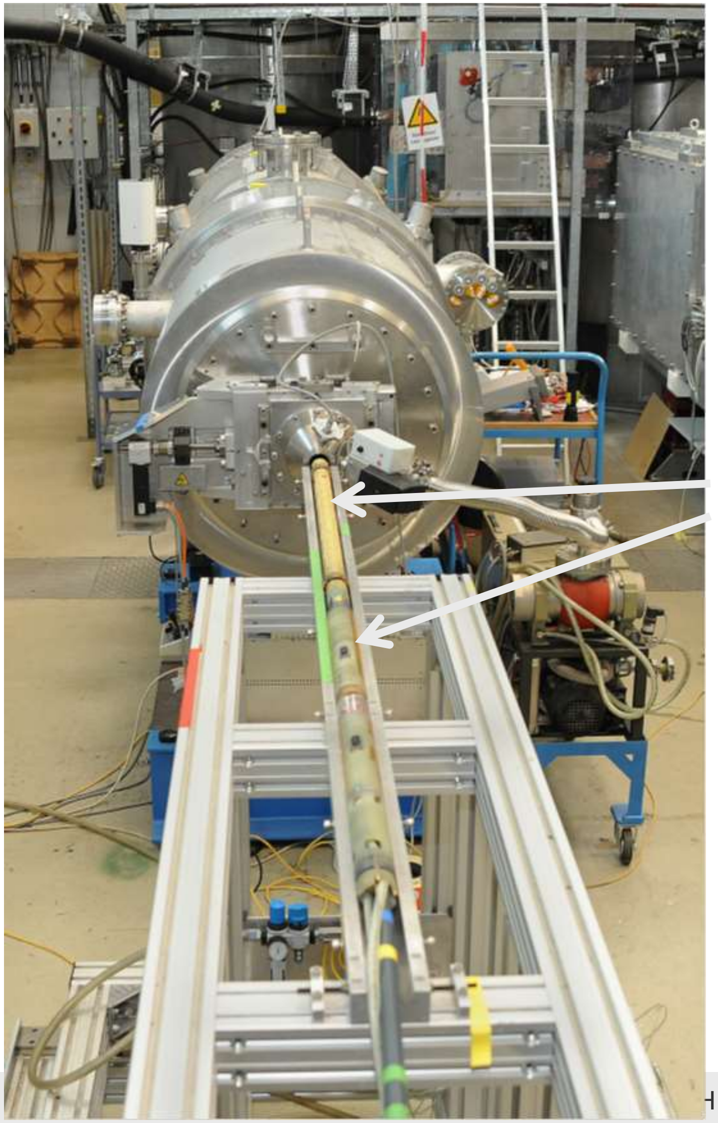
$$P_\Lambda = q_h(B_{max}) \cdot f + q_e(B_{max}) \cdot f^2$$

$q_h = 4.2 \pm 0.5$ J „hysteresis“

$q_e = 6.0 \pm 0.2$ J·s „eddy currents“

SIS100 Dipole: measuring the magnetic field

mole: warm rotating coils

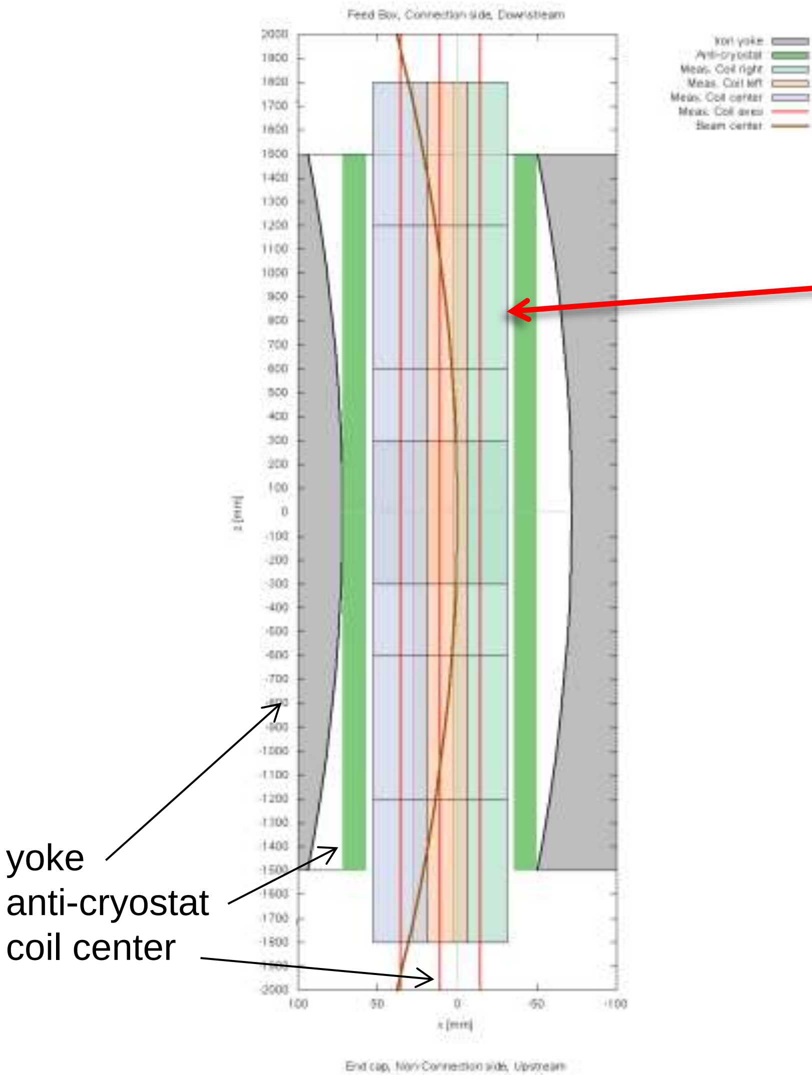


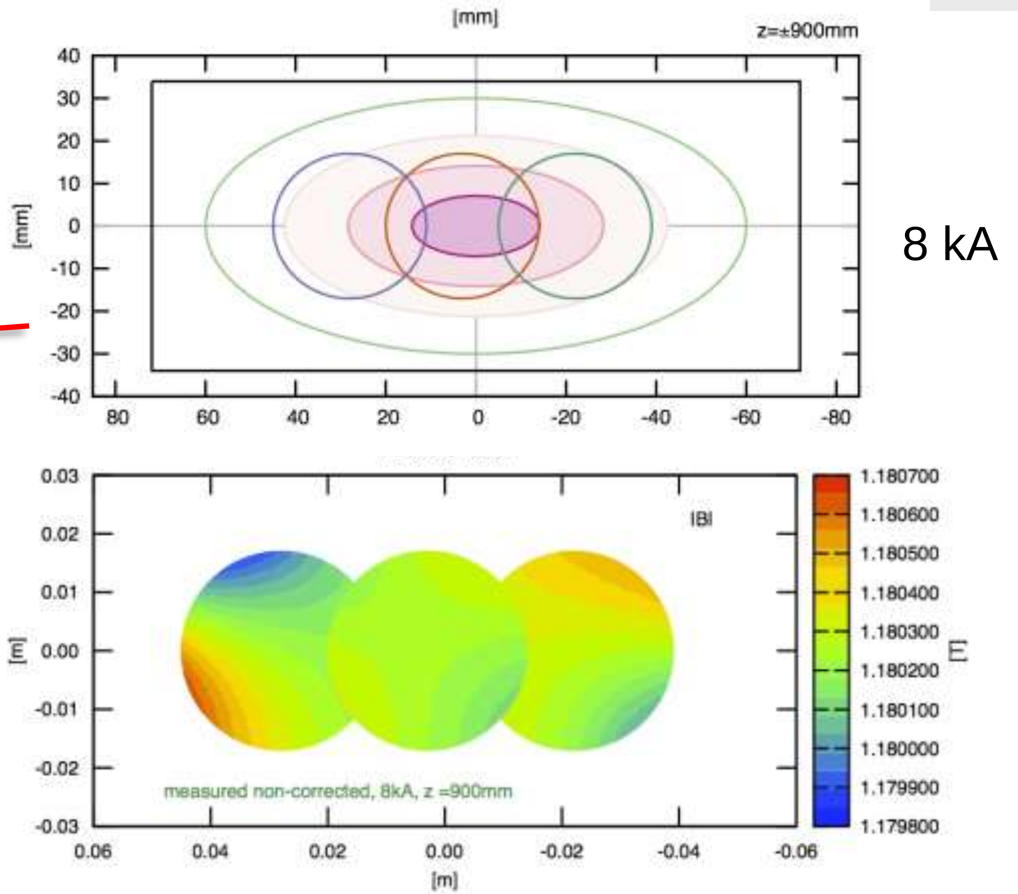
coil unit
motor unit

hall probe on mapper

cold rotating coils (in vacuum)

SIS100 Dipole: measuring with overlapping rotating coil probes



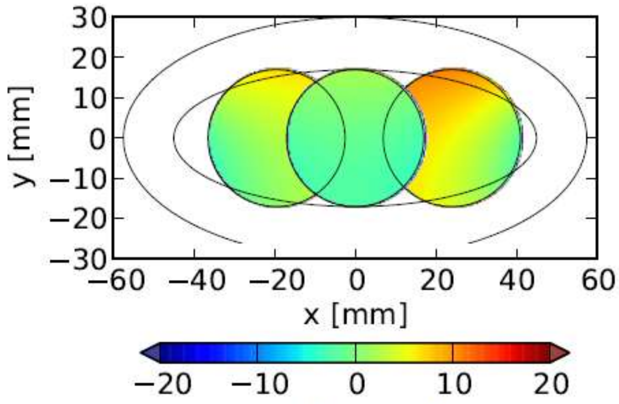


three channels:

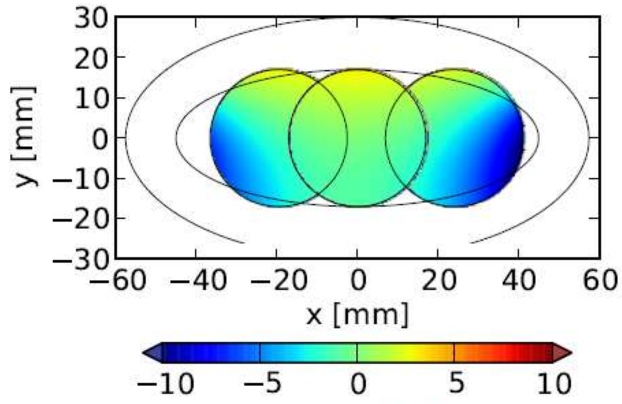
- adjustment due to continuity
- calculation of field components on large scale

SIS100 Dipole: measuring with overlapping rotating coil probes

B_y field for 1.9 T, @ z = -900 mm



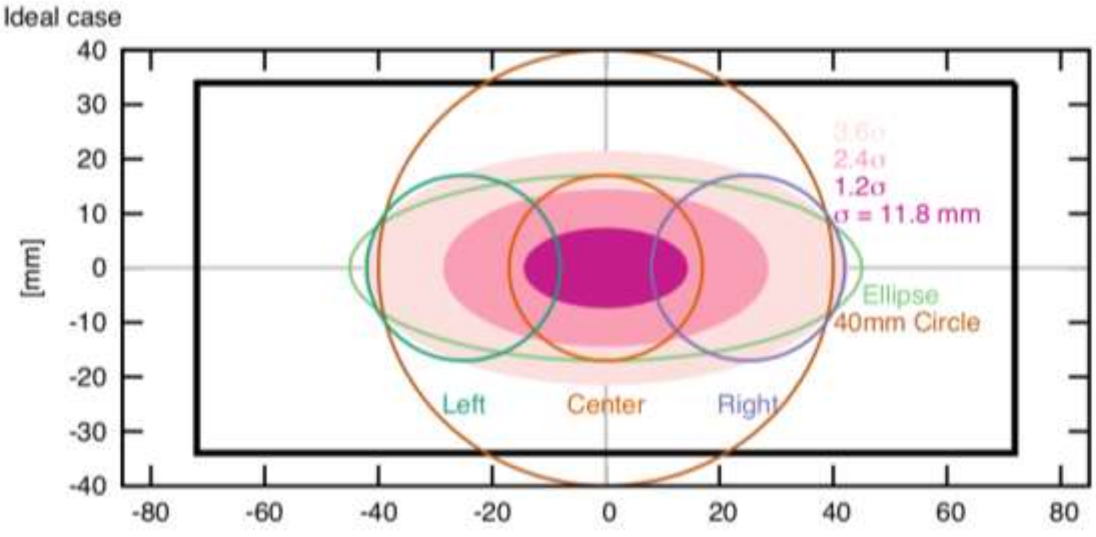
original



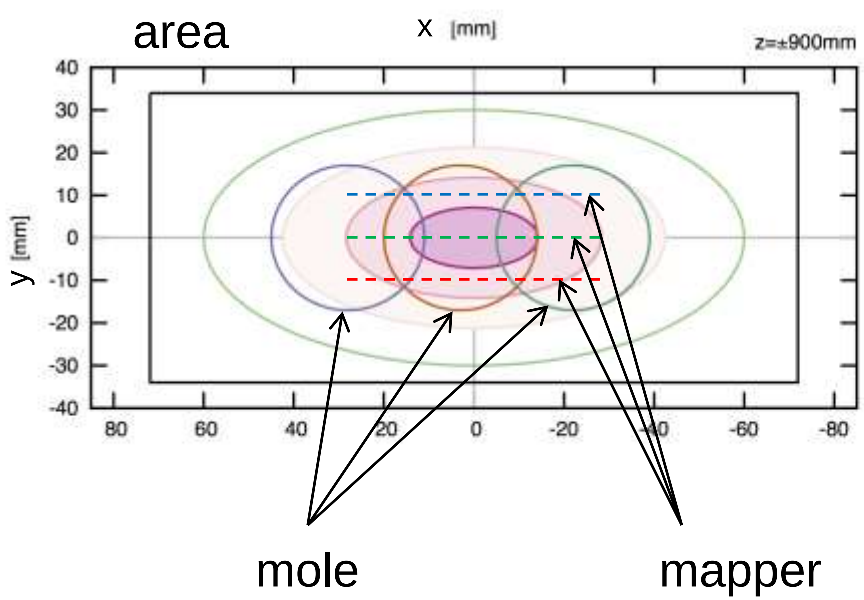
corrected data

left: the field “jumps” between the coils

right: field “continuous”



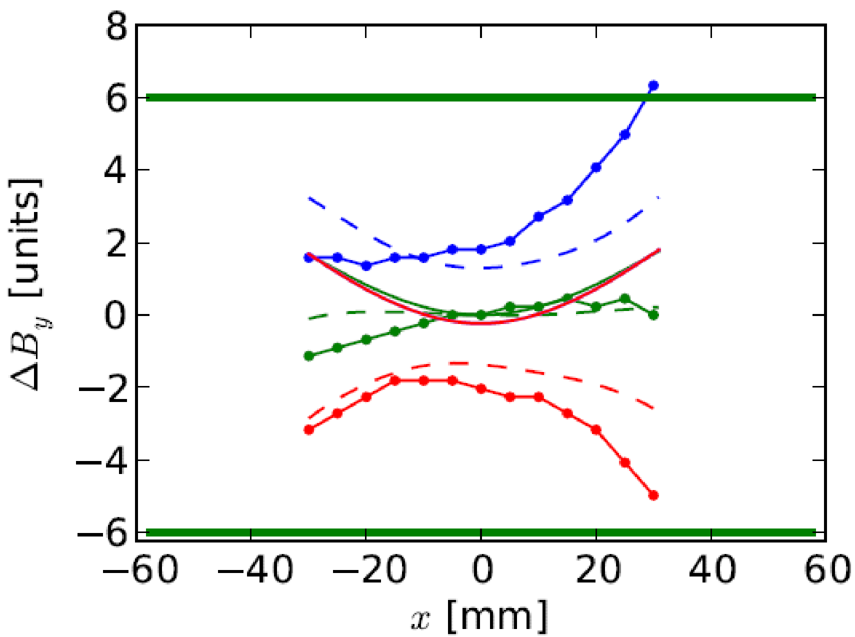
SIS100 Dipole: comparing hall probes to rotating coils



warm mole:
- small measurement area
- positioning errors (anti-cryostat)

- mapper: plane area
- mole: integration

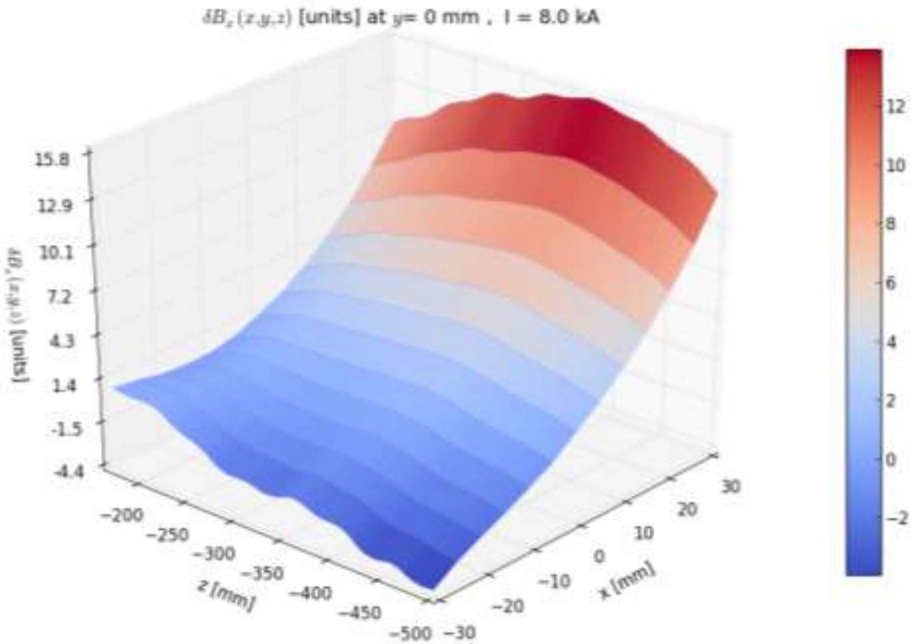
results:

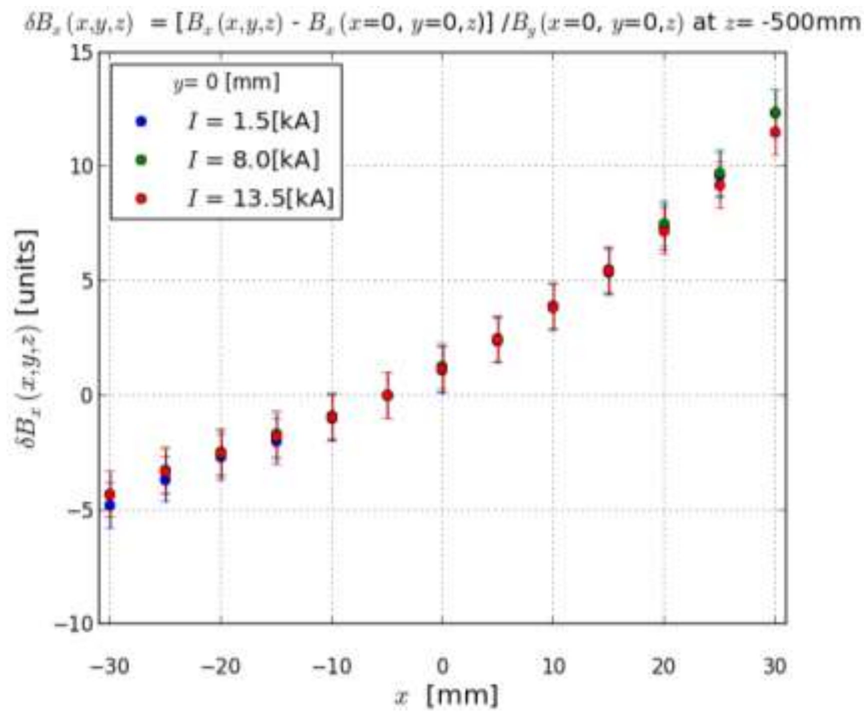


(b) centre

dashed: mole
dotted: mapper
solid: calculated

SIS100 Dipole: unallowed B_x-component



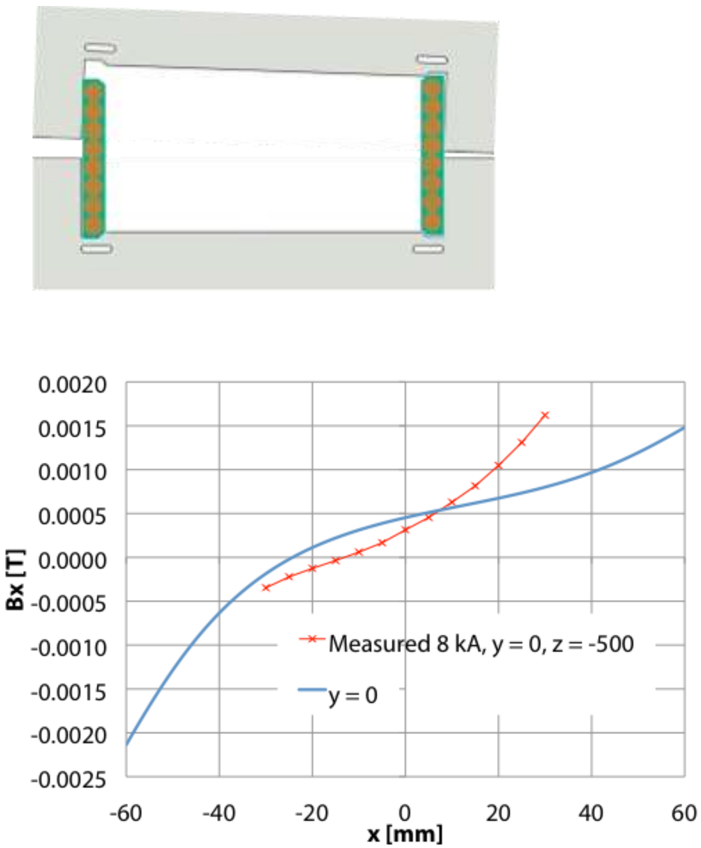


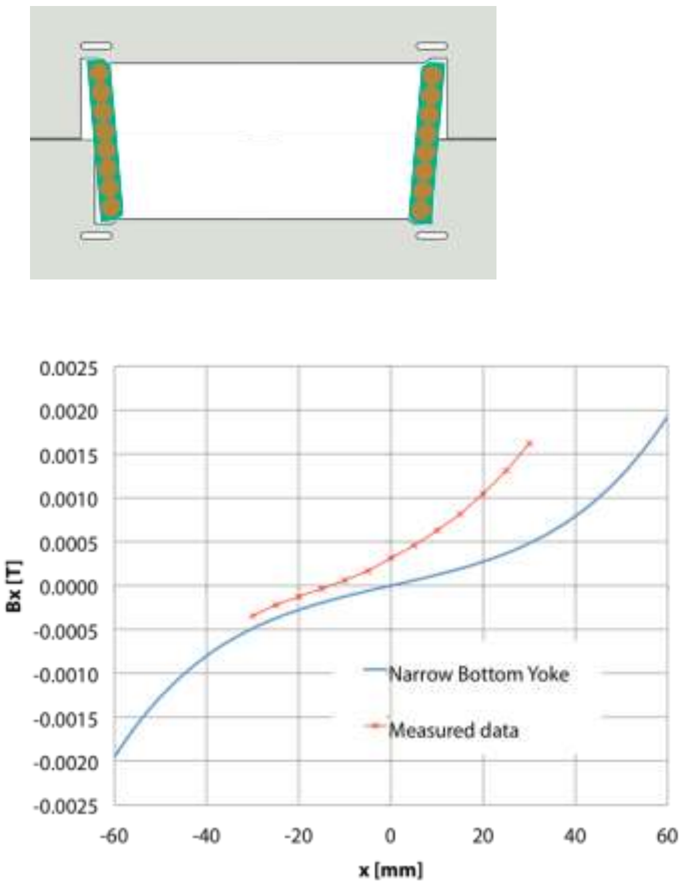
change of x-component by > 15 units across gap

SIS100 Dipole: main error candidates

a) opening: +0.33 mm (1 mrad rotation)

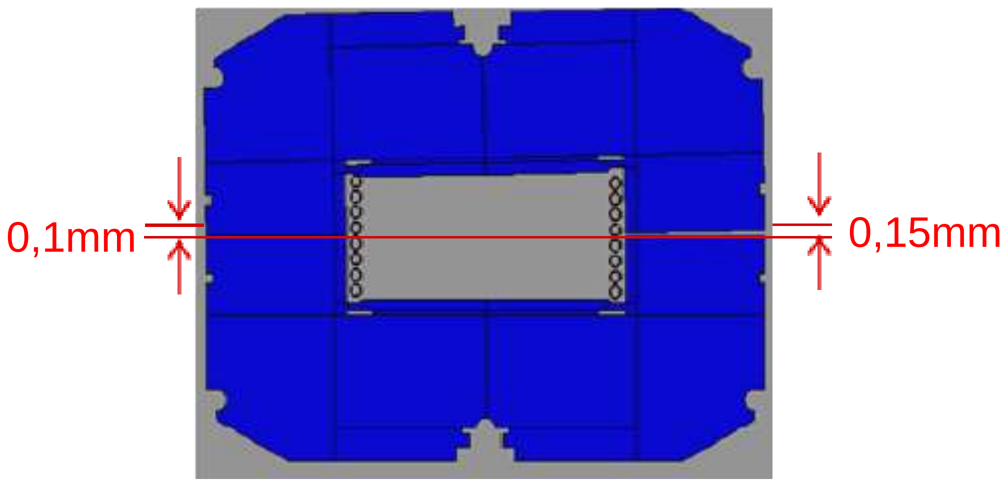
b) 1 mm narrow width at bottom yoke

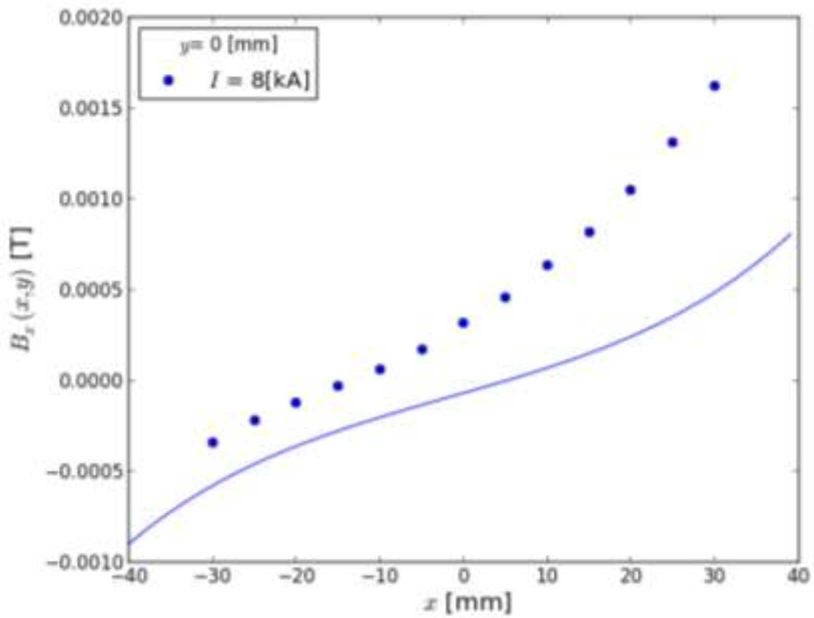




both cases can explain B_x

SIS100 Dipole: main error candidates: combination





- Gap width for a top yoke = d + 0,6mm
- gap width for a bottom yoke = d – 0,6mm
- slits on the left and right side correspond to the geometrical measurements

SIS100 Dipole: next steps towards series production

mechanical measurements

to be measured precisely:

- parallelity of pole surfaces
- horizontal displacement
- ‚height' of lamella
- ...

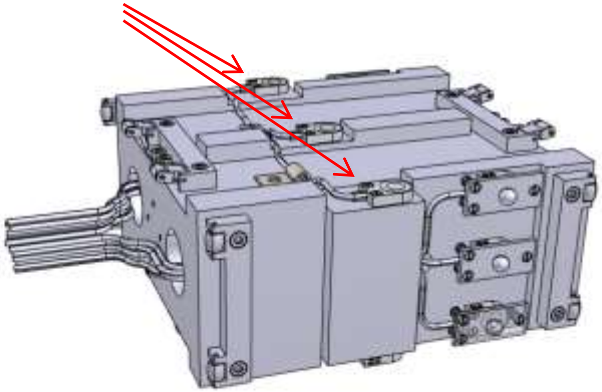
important steps:

- **measurement with cold coil (currently)**
- measurement of geometry (warm)
- preparation for cold geometrical measurements

new tools under development

@ 300 K: mechanical gauge

@ 4 K: capacitive sensors



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SIS300 Magnets: Dipole

DISCORAP Project:

- ✓ **Development of new low loss conductor**
- ✓ **Production and successfull test of a short full size curved prototype**

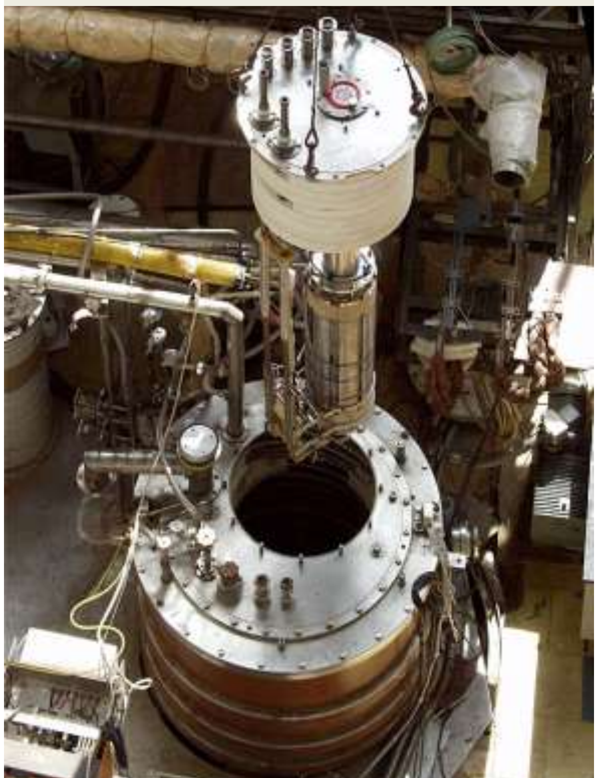
2nd prototype collared coil will be built in frame of European CRISP project

Measurements and Analysis of the SIS-300 Dipole Prototype During the Functional Test at LASA, M. Sorbi, P. Fabbricatore et al.
Applied Superconductivity, IEEE Transactions on , vol.24, no.3, pp.1,5, June 2014

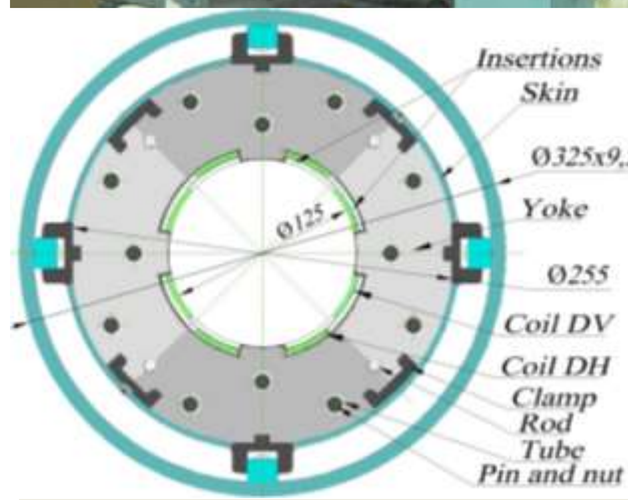
SIS300 Magnets: QP and Corrector Prototypes

- ✓ two quadrupole magnets built (different cables) →
- ✓ successfully tested

Quadrupole Prototype built and tested by IHEP



Parameter	Value
Central gradient, T/m	45
Rate of central gradient, (T/m)/s	10
Operating current, kA	6.26
Maximum magnetic field on coil, T	3.51
Temperature margin, K	1.5
Stored energy, kJ	38
Inductance, mH	2
Number of turn in coil (one layer)	80
Inner diameter of coil, mm	125
Thickness of collars, mm	22
Thickness of iron yoke, mm	52
Effective length, m	1



Steering Dipole Prototype built and tested by IHEP

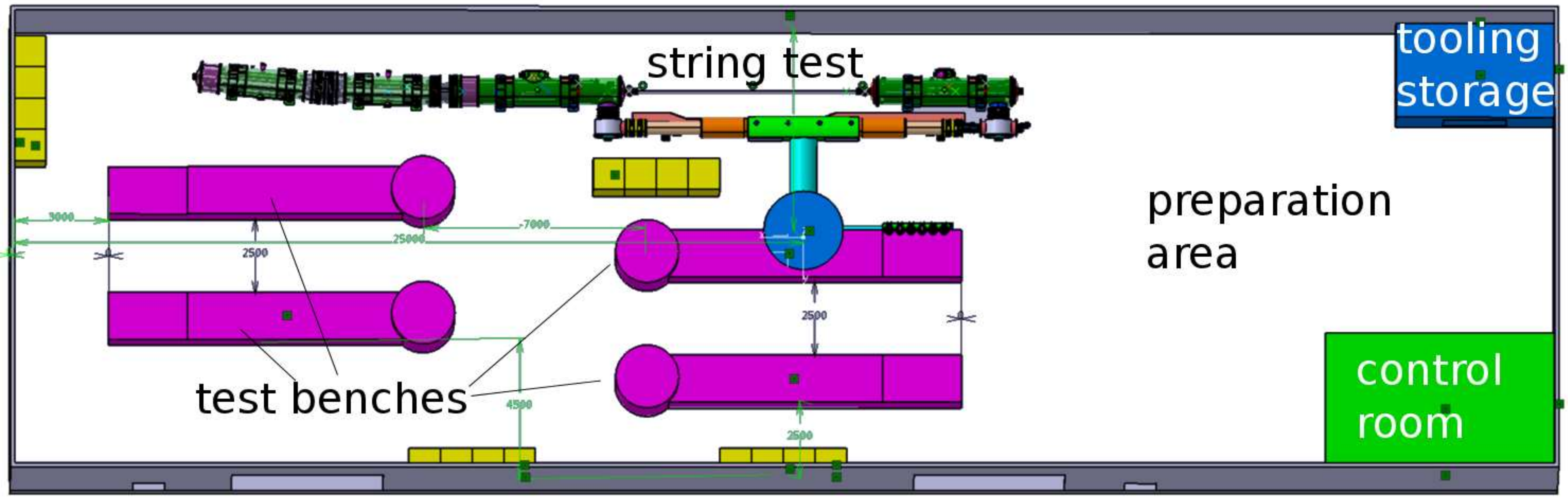
S-. Kozub,.; et al "SIS 300 Fast-Cycling Superconducting Quadrupole Prototype," *IEEE T. Appl. Supercon.* , vol.22, no.3, pp.4001104,4001104, June 2012

Outline

- Introduction
- SuperFRS
- SIS100
  - Dipoles
  - Quadrupole Modules
- SIS300
- Preparing for Series Testing

SIS100 Dipole: Series Testing

Series test facility @ GSI currently build up

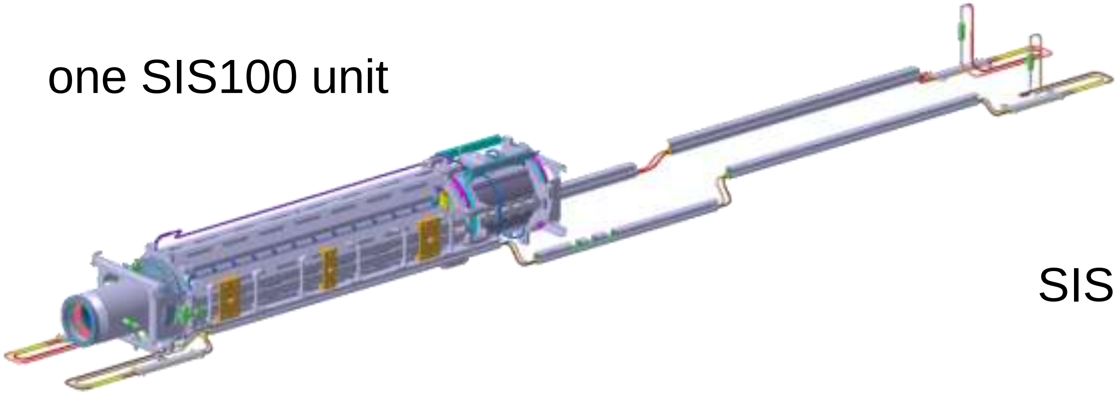


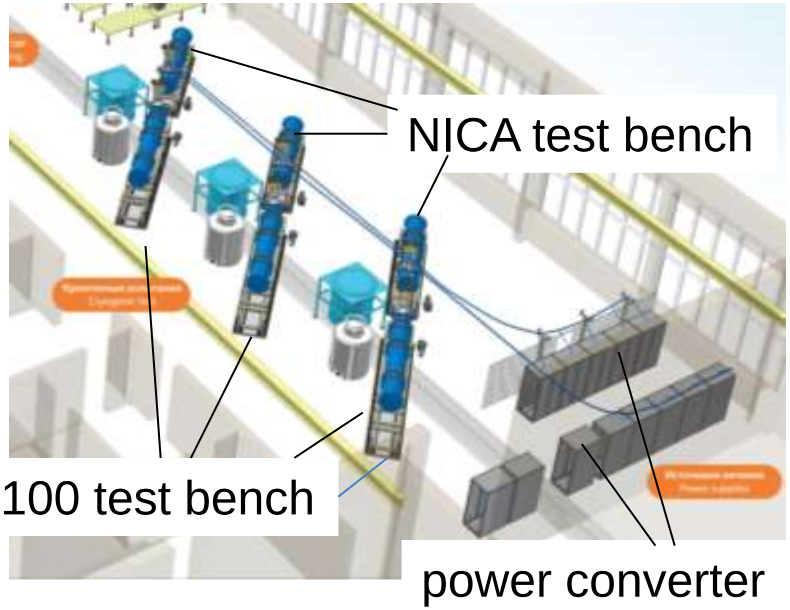
- Operation start: target Q2 / 2015
- Building finished
- Cryoinfrastructure finalised
- Power Converters / Current leads beginng Q1/2015

Testing SIS100 Quadrupoles: Units Testing @ JINR

- Common Test facility: NICA & FAIR
- share of:
  - infrastructure (power converters, cryo-supply)
  - test benches
  - measurement systems:
  - magnetic field
  - thermodynamic parameters

one SIS100 unit





SIS100 Quadrupoles @JINR

Production and Testing of the QP-Units at JINR

GSI-JINR Collaboration for SIS100

Conclusions

- The SIS100 FoS Dipole testing started in 2013-11
- The SIS100 Quadrupole and Corrector Magnets will be manufactured and tested at JINR, with the first units are ready for testing in 2015

- SuperFRS magnets being tendered: first prototypes begining 2016

- Testing prepared:
  - SIS100 Dipoles + SIS100 String @ GSI
  - SIS100 Quadrupole Units @ JINR
  - SuperFRS Magnets @ CERN

- Outlook
  - SIS300 prototype magnets being built and tested

Thank you for your attention !

WEB Cam at the FAIR site

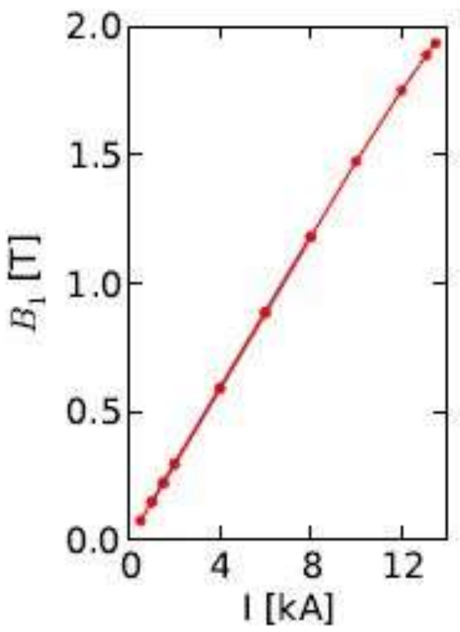
http://www.fair-center.eu

FAIR Site & Buildings

Magnetic Field Properties

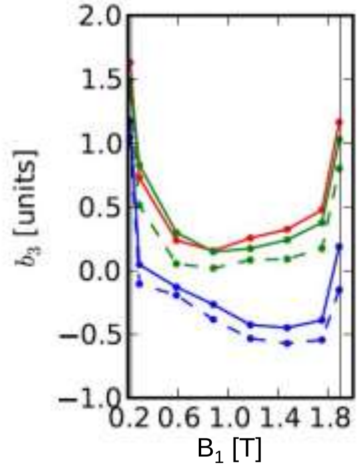
field measurement data (mole)

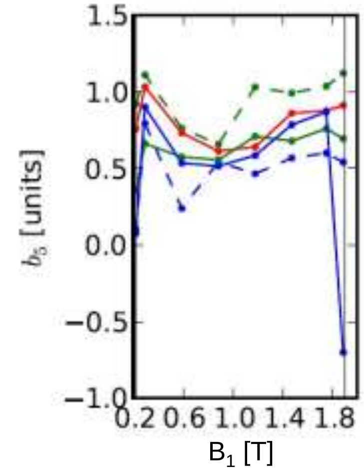
main field:



(a) load line

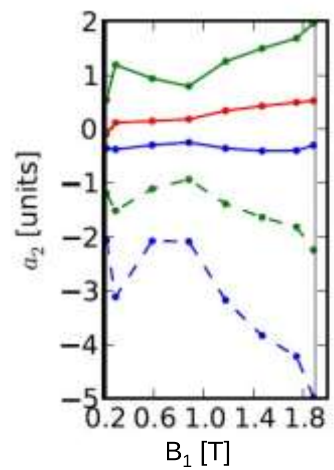
allowed harmonics:

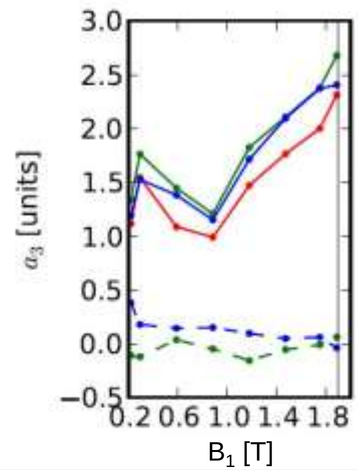




- z = 0
- z = ±300 mm
- z = ±900 mm

skew harmonics:



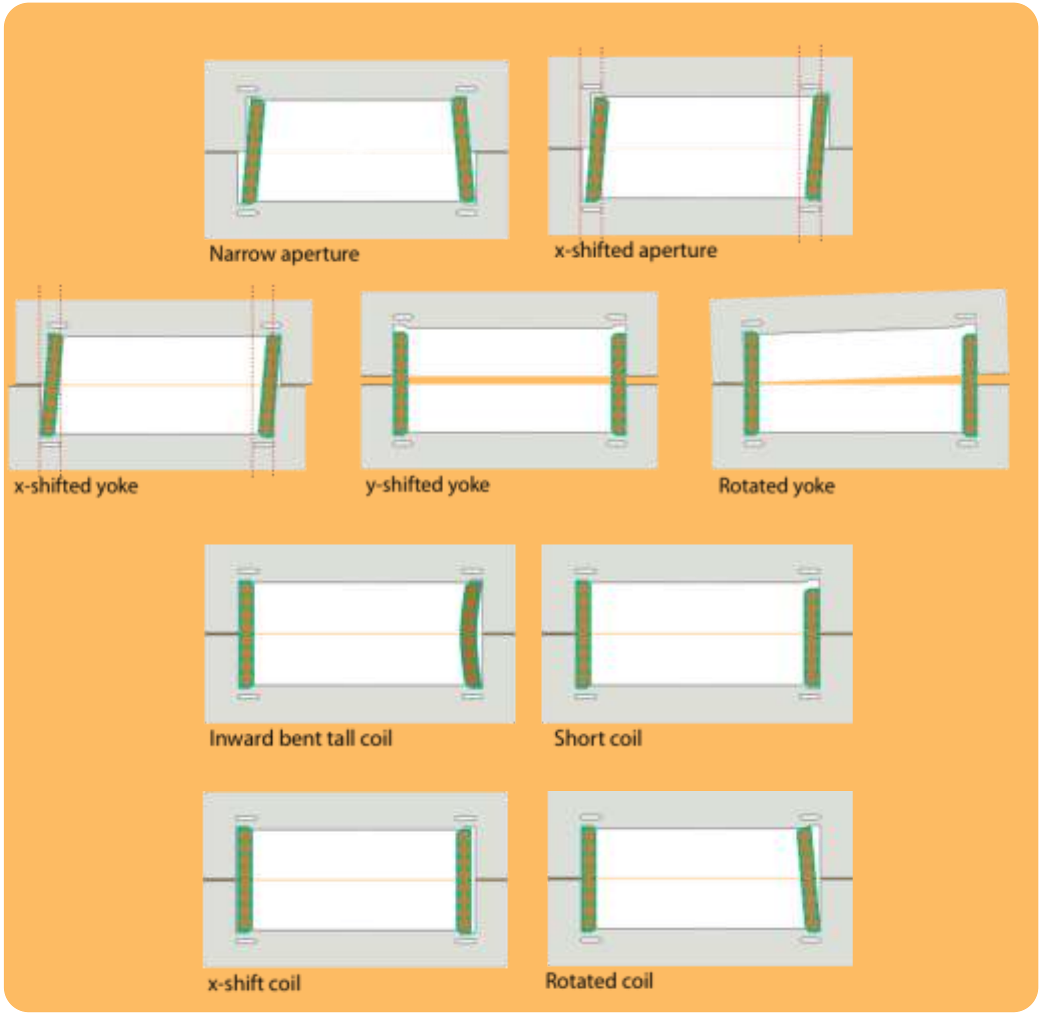


R_{ref} = 40 mm

Next steps toward Series Production

error analysis

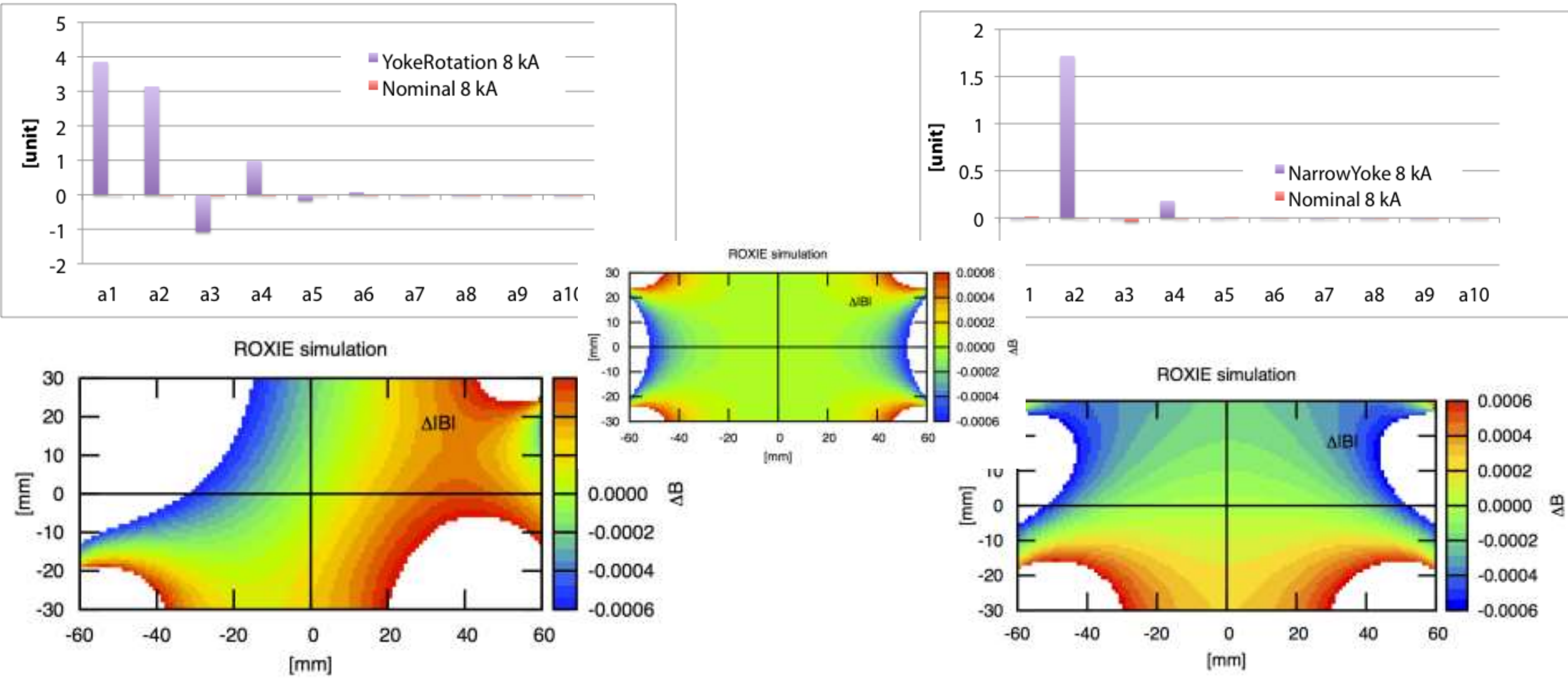
possible errors (machining & alignment)



Next steps toward Series Production

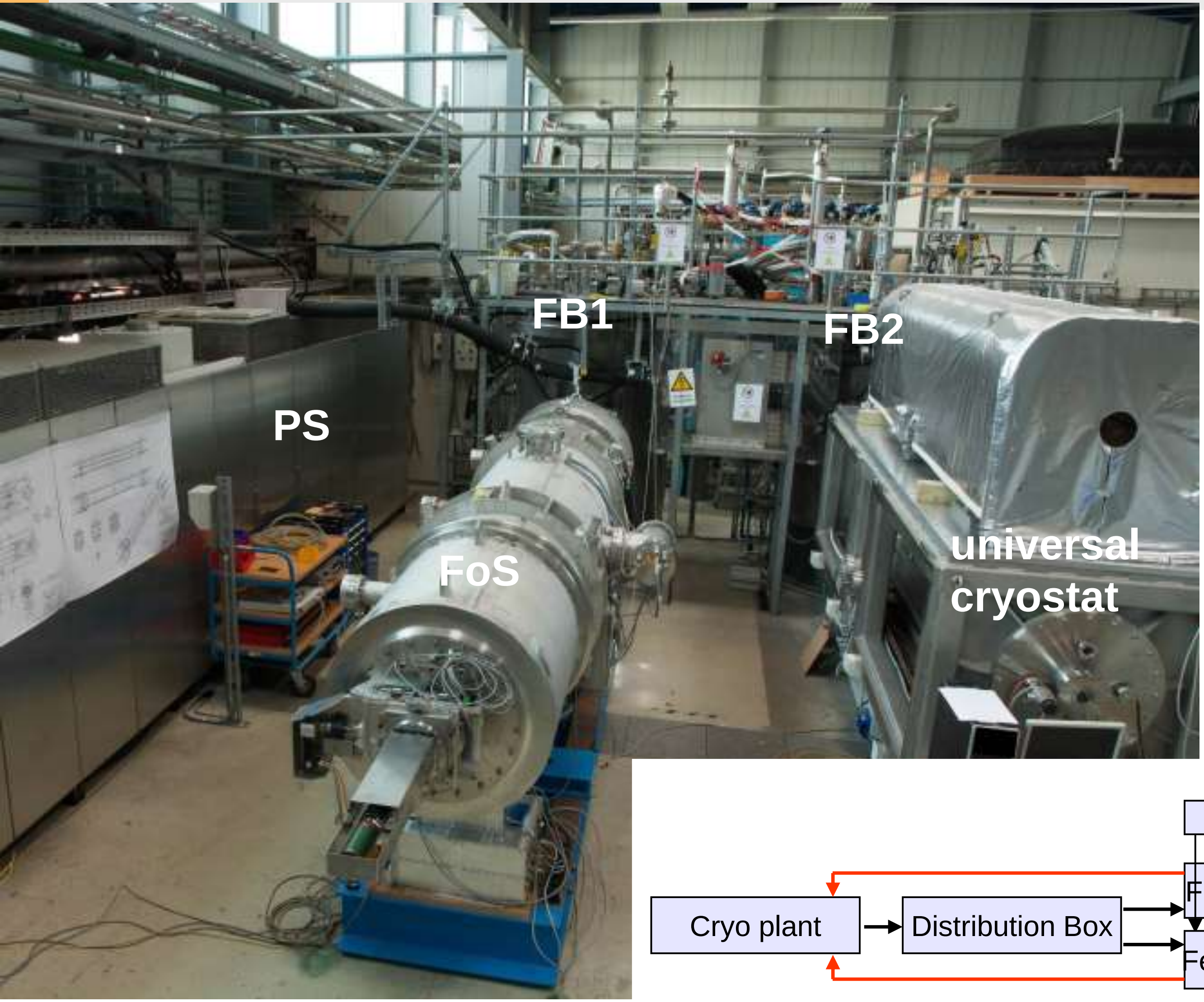
main error candidates

a) opening: +0.33 mm (1 mrad rotation) b) 1 mm narrow width at bottom yoke



measurement of multipole coefficients will tell us more

SIS100 Dipole: Ready for testing



@ the GSI Prototype Test Facility