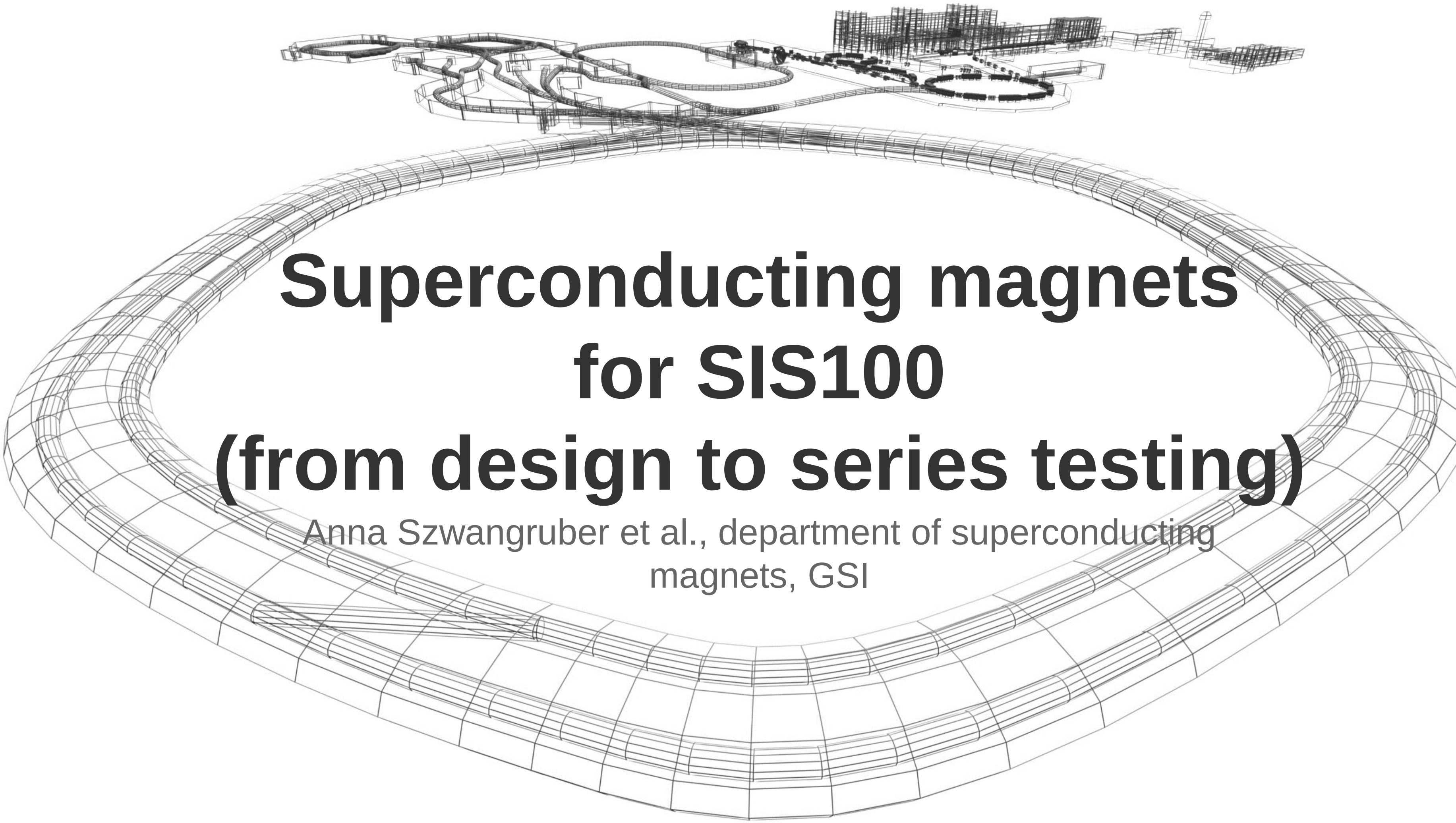


Superconducting magnets for SIS100 (from design to series testing)

Anna Szwangruber et al., department of superconducting magnets, GSI

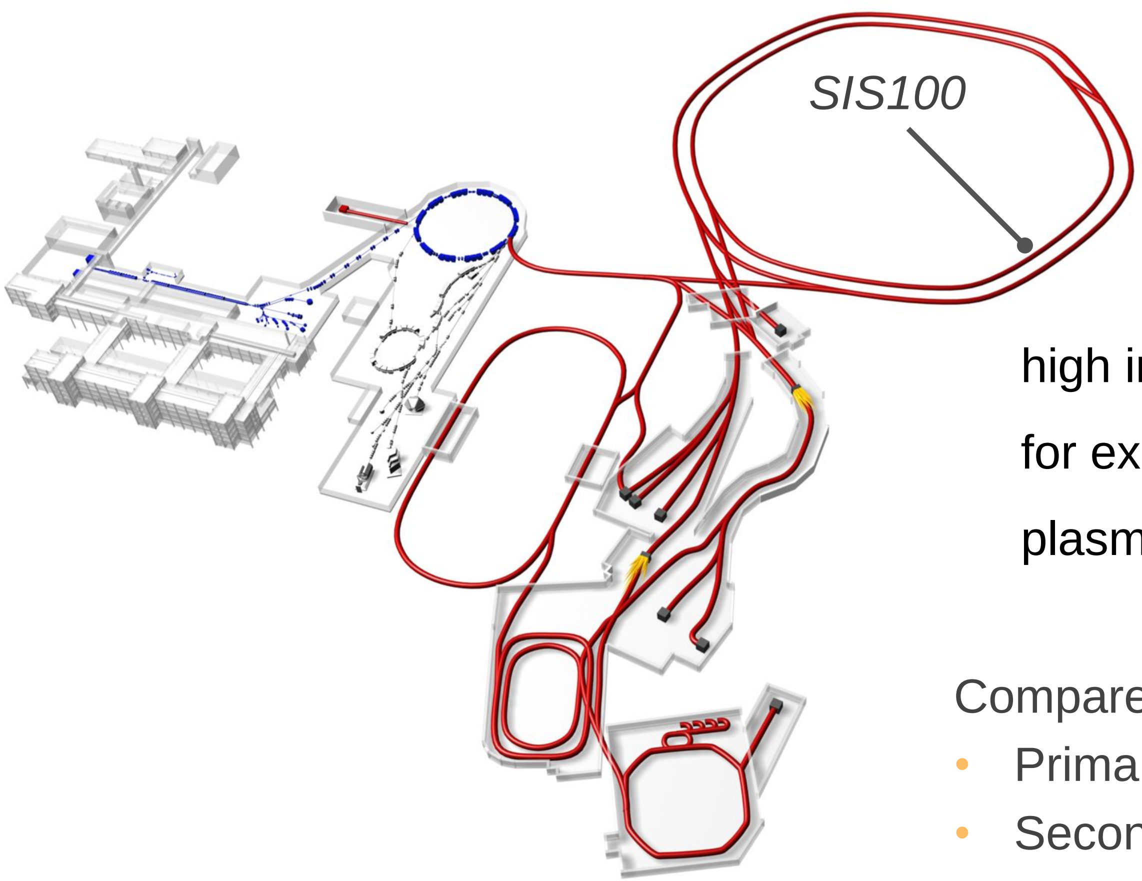
Achievements which will be presented in this talk were only possible with a long term highly professional contribution of the colleagues from SCM, ENG-NCM, CRY, ENG, EPS, VAC, QA, BB, TRI, MEWE, collaboration and business partners of GSI.

Outline

- Introduction
- SC magnets for SIS100
  - why sc technology?
  - magnet design
    - main magnets
    - corrector magnets
- SIS100 dipole magnets
  - development
  - lessons learned from prototypes
  - series production
- Testing of series dipole magnets
  - Testing strategy
  - GSI test facilities
  - Main measurement systems
  - The team for dipole testing
  - Test results
- Next activities at test facilities for sc magnets
- Summary

Facility for Antiproton and Ion Research

Existing GSI facility *FAIR facility*



International project

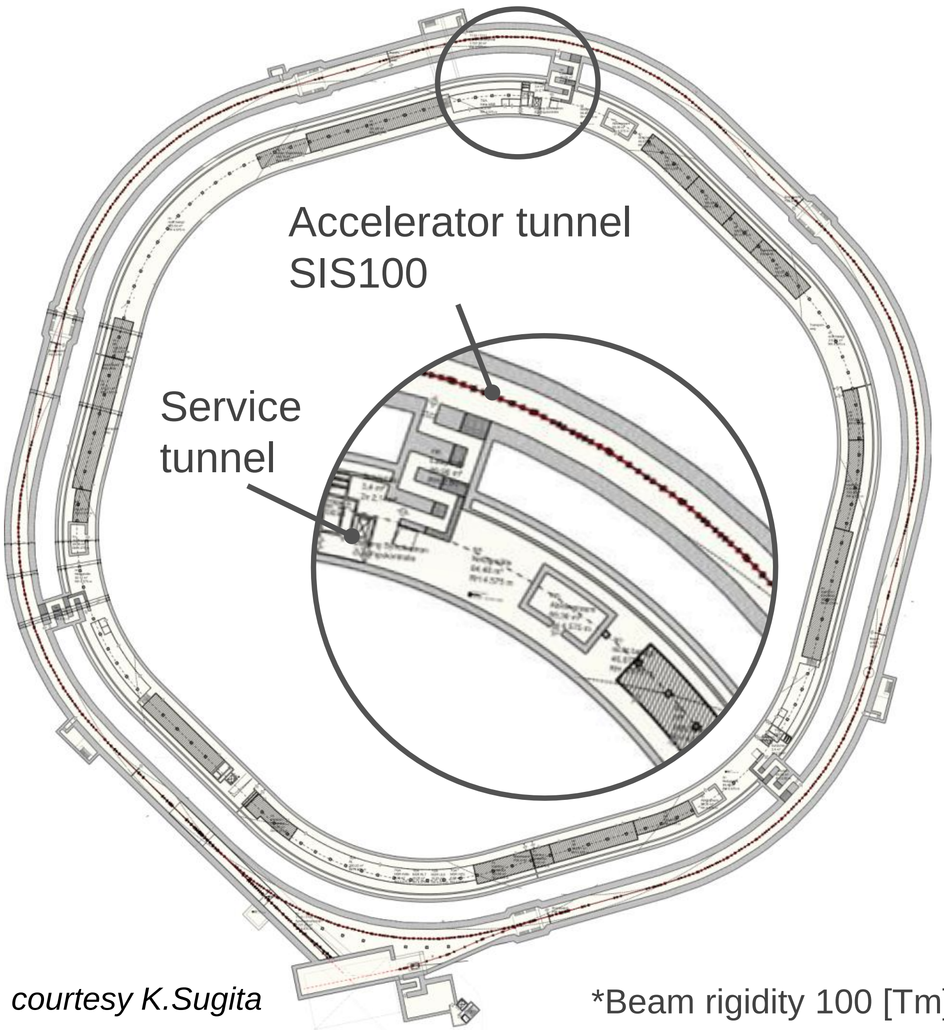
high intensity ion and antiproton beams for experiments in nuclear, atomic, plasma physics and material science

Compare to the existing GSI facility

- Primary beam intensities: ×**100**
- Secondary beam intensities: ×**10000**
- Primary beam energies: ×**10**
- Antiproton production

Heavy Ion Synchrotron SIS100

SIS100 = **S**chwer**i**onen**s**ynchrotron 100 [Tm] = Heavy ion synchrotron (beam rigidity*) 100 [Tm]



Hexagonal, circumference 1083.60 m

Superconducting (magnet) accelerator

Fast-ramp Machine

~0.5 sec. to maximum field.

courtesy K.Sugita

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

SC Magnets for SIS100 – Why SC Technology?

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

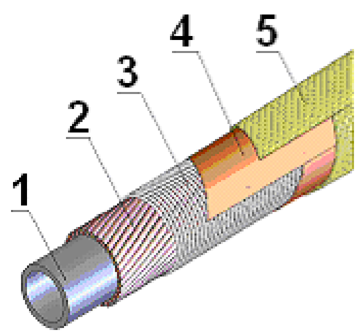
for the cryo pumping

Principles of the magnet design

- iron dominated (super-ferric) magnets
- superconducting (sc) coil
- Nuclotron cable
- cooling by two phase Helium @ 4.5 K
- low AC losses magnets

(to remove 1W @ 4.5K 300W @ 300K are needed)

Nuclotron cable:



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

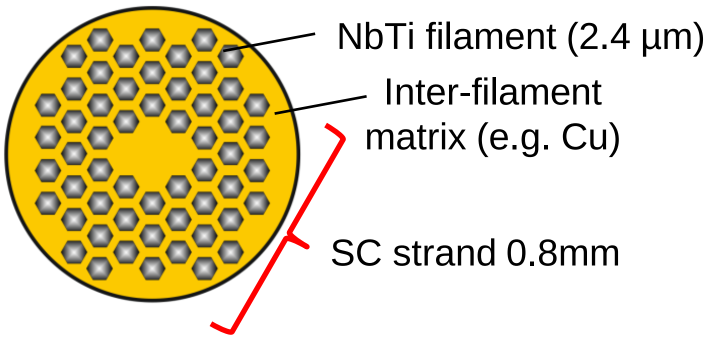
SC Magnets for SIS100 – Why SC Technology?

Normal Conducting (NC)	Superconducting (SC)
• B_{dipole} only 1.9 T... typical regime for NC magnets • AC operation (1 Hz) → AC losses in the magnetic yoke and in Cu windings • Lower construction cost but higher operation cost • Ultra high vacuum (UHV) 10^{-7}…10^{-12} mbar → Cryo adsorption pumping → beam chamber at 10-15 K → **sophisticated cryostat and cryoplant required for the beam chamber** • Access to the magnet parts and instrumentation → easy maintenance • **Large cross-section → large machine size**	• No DC losses but we aim for AC operation anyway... • Higher construction cost but lower operation cost • **Ultra high vacuum 10^{-7}…10^{-12} mbar → Cryo adsorption pumping → beam chamber at 10-15 K → no problem since we anyway need LHe for SC coils** • Required cooling and quench detection/magnet protection systems • Difficult access to the magnet parts → magnet is immersed into a cryostat • **Low cross-section → compact machine size**

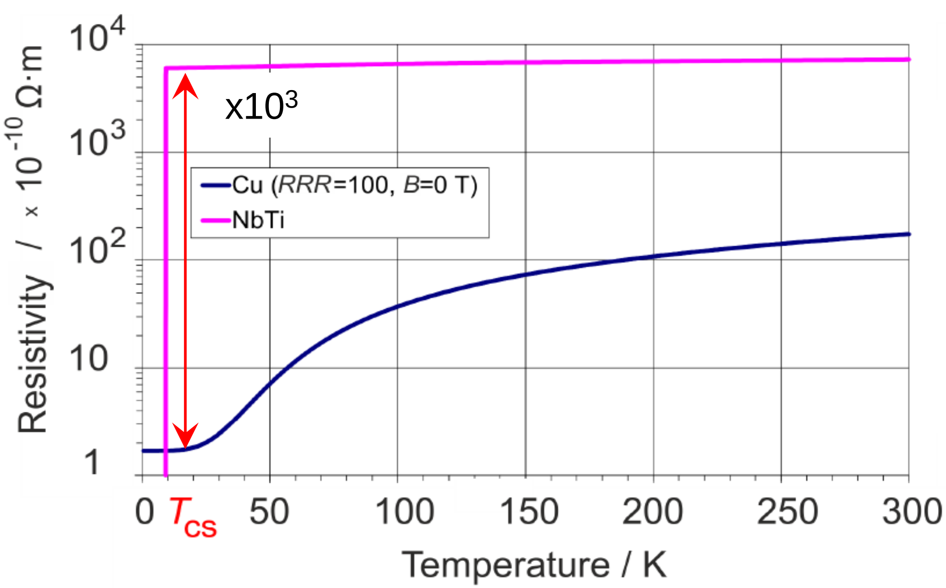
SIS100 is SC because of UHV requirements

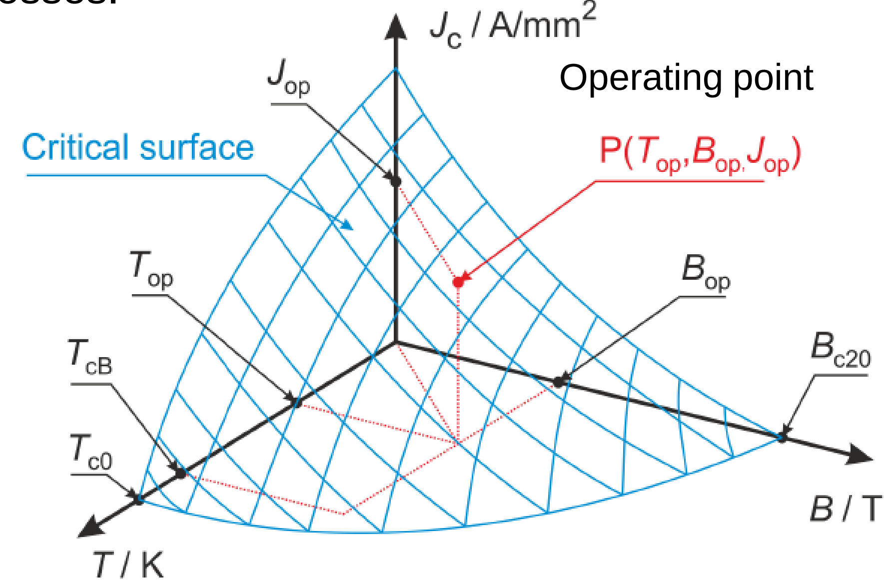
Superconducting Magnets and Quench

Conductor: **NbTi** – “work horse” for superconductivity (LTS type II, alloy); T_{c0}=9.2 K, B_{c20}=14.5 T.



Quench – sudden transition from the superconducting state to normal conducting (resistive) state.
Origin: conductor movement (friction), poor cooling, beam losses.





“P” below the critical surface → **SC**
“P” beyond the critical surface → **NC**

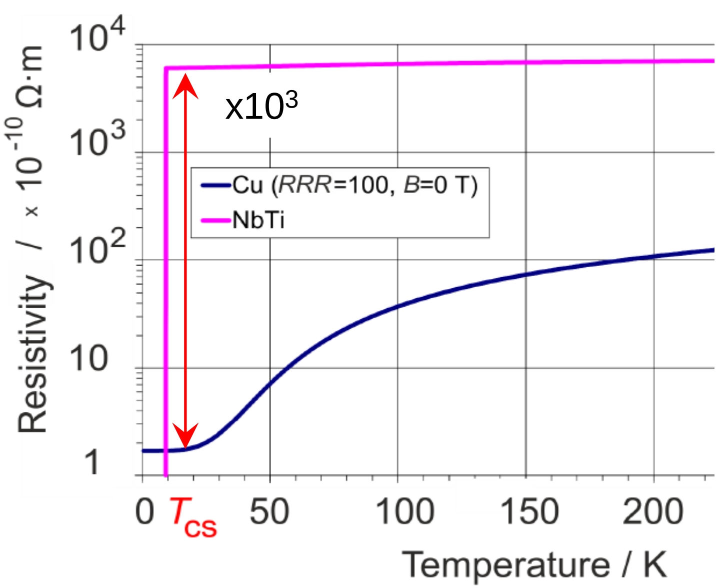
Superconducting Magnets and Quench

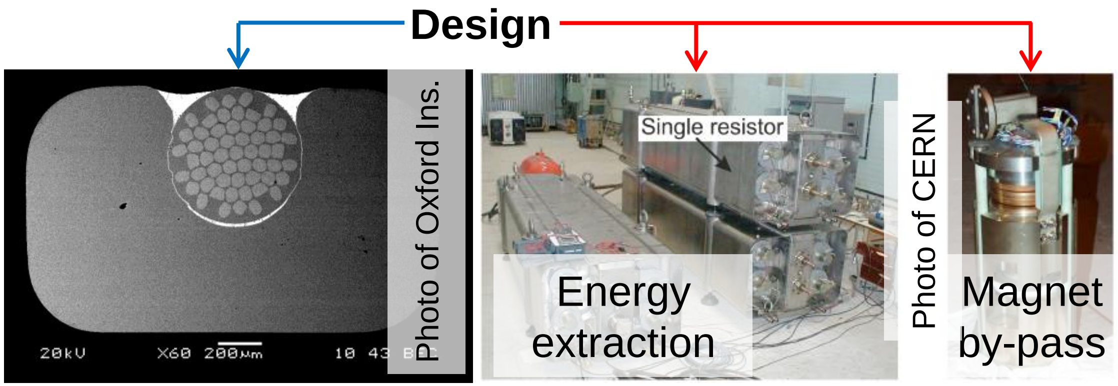
A quench is a natural phenomenon! Therefore it shall be taken into account in the machine design as a **normal operating** condition.

Is a quench dangerous?

SC NbTi → 1000–3000 [A /mm^2] at 4 K and 5 T

Cu → 2 (el. installations) – 20 (extreme cooling) [A /mm^2]



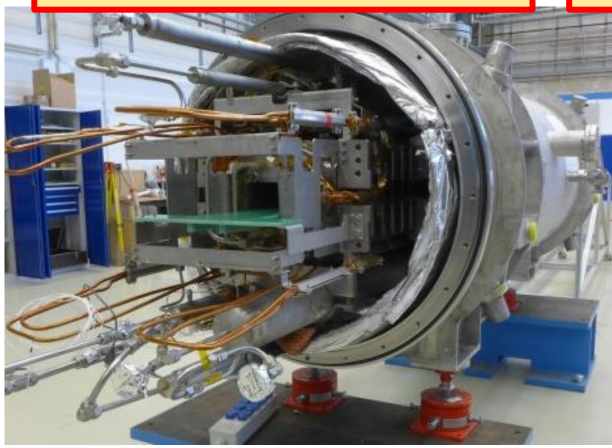


Self-protecting magnet

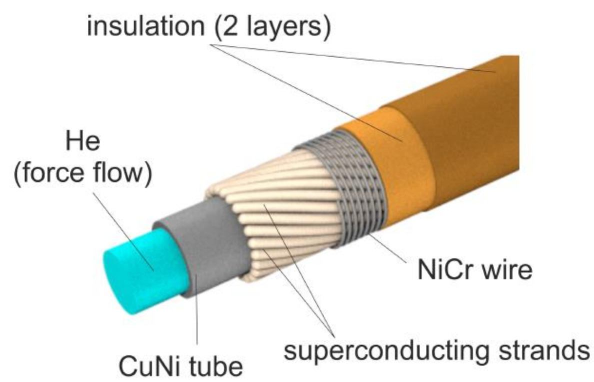
Magnet protection & quench detection

SIS100 Dipole Magnet: Low AC Loss SC Cable

SIS100 dipole prototype



Low AC-loss cable (CuMn matrix)

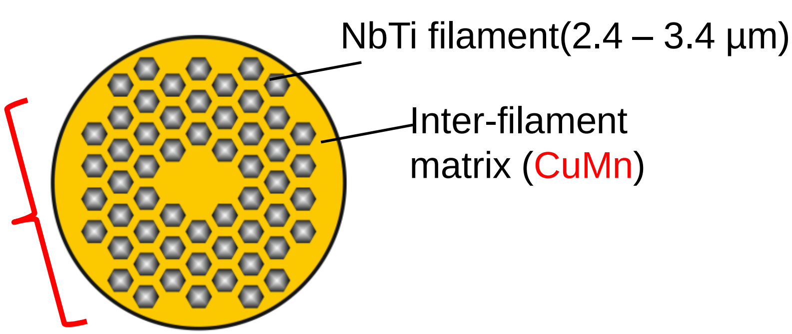


histeresis loss in NbTi

$$P_{\mathrm{h}} \propto d_{\mathrm{f}}, \qquad P_{\mathrm{ifc}} \propto \frac{t_{\mathrm{pf}}^2}{\varrho_{\mathrm{IF}}}$$

inter-filament loss: eddy currents through the matrix

SC strand 0.8mm

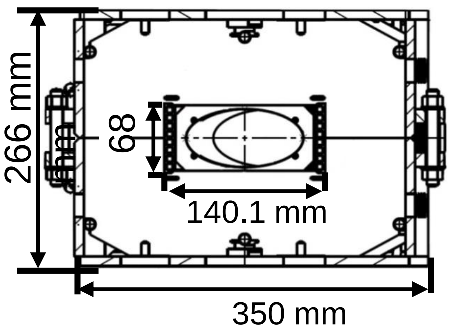


Quench back effect is not expected!
If a single magnet quenches, other magnets will not quench due to high d*i*/d*t* at current extraction
(very low probability).

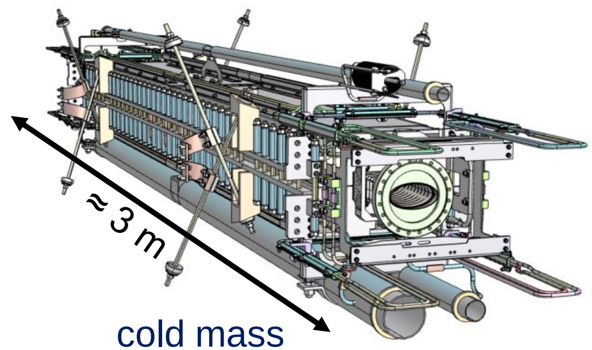
Superconducting Magnets for SIS100

Main Dipole Magnets

- super-ferric 1.9T
- window frame,
  curved magnet R 52.632 m
- Nuclotron-type cable
- fast ramped 4T/s
- cooling with 2 phase He
- 108 Magnets

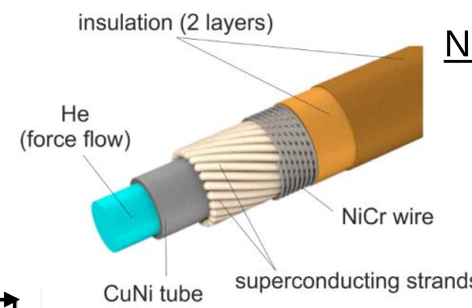


yoke cross section



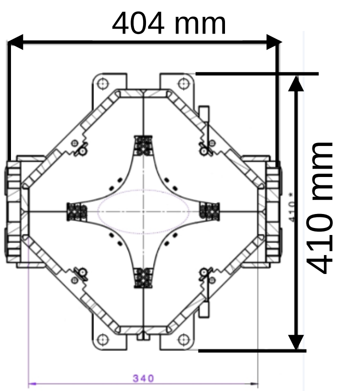
cold mass
with beam chamber

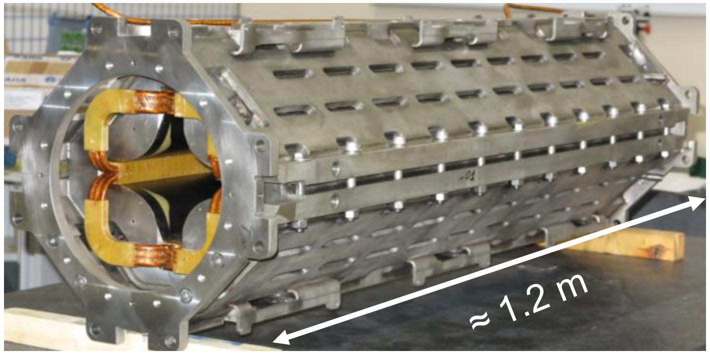
Nuclotron cable:



Main Quadrupole Magnets

- super-ferric, 27.7 T/m
- Nuclotron cable
- cooling with 2 phase He
- 166 Magnets

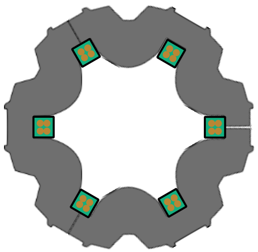


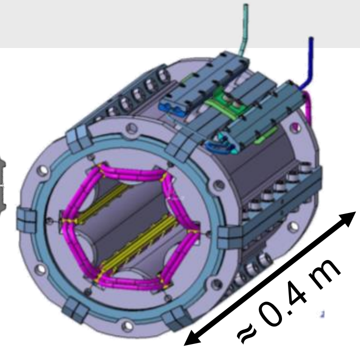


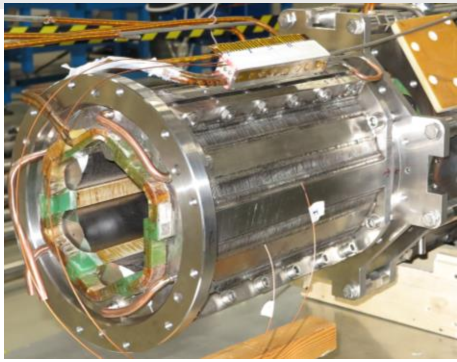
Superconducting Magnets for SIS100

Chromaticity sextupole:

- Super-Ferric 232 T/m^2
- Nuclotron cable with insulated strands
- 42 Magnets



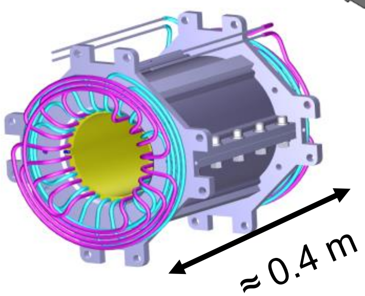


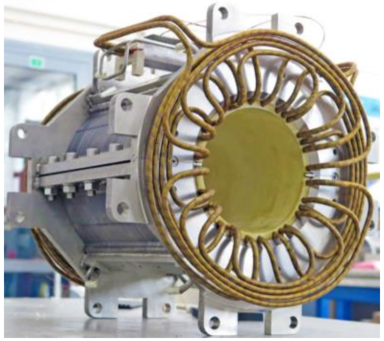


photos courtesy JINR

Steering magnet:

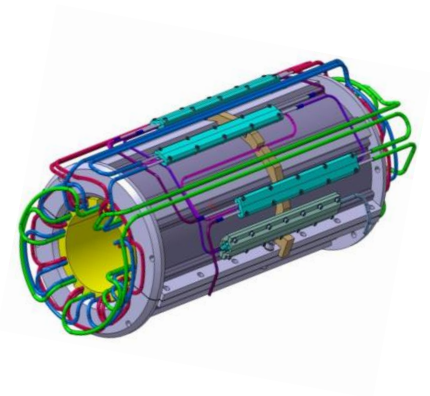
- Cos-Θ
- Nuclotron cable
  with insulated strands
- Nested (horizontal and vertical correction)
- 83 Magnets



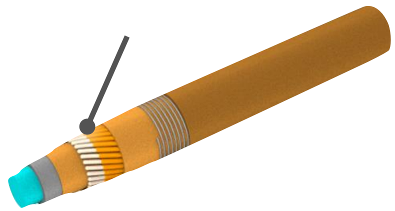


Multipole corrector magnet:

- Cos-Θ
- Nuclotron cable
  with insulated strands
- Nested (B2, A3, B4) correction
- 12 Magnets



Insulated Sc. strands connected in series



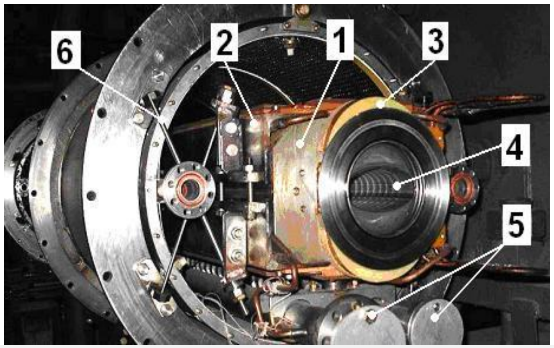
250A × 27 Strands = 6.75kA

Superconducting Magnets for SIS100

	Unit	Main Dipole	Main Quadrupole	Chromaticity sextupole	Steerer (nested h/v)		Multipole correctors (nested)		
							Quadrupole b2	Sext. (skew) a3	Octupole b4
Design		super-ferric	super-ferric	super-ferric	cosθ		cosθ	cosθ	cosθ
Number of Magnets		108	166	42	83		12	12	12
Magnetic field strength	T/m^{n-1}	1.9	27.77	232	0.372	0.366	0.91	31.8	446
Effective length	m	3.062	1.264	0.383	0.403	0.410	0.62	0.59	0.56
Usable aperture	mm	133x65	133x65	135x65	135x65		133x65		
Ramp time to Max.	sec.	0.5	0.5	0.175	0.2		0.175		

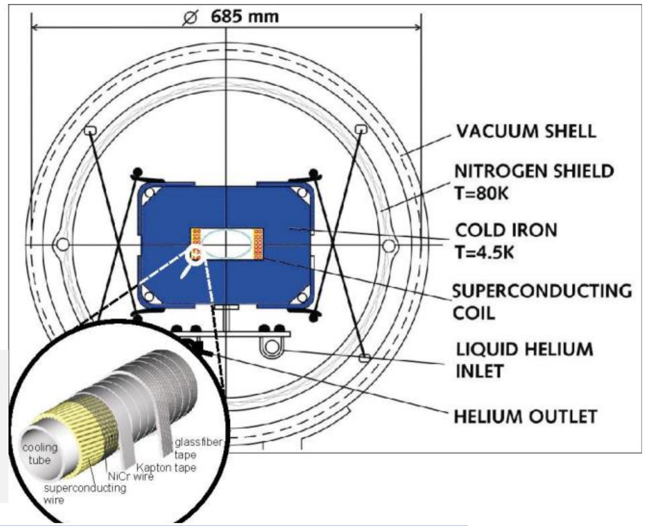
415 sc magnets of different type are needed for the magnetic system of SIS100
411 + 4 (inj. / extr. quadrupoles)

SC magnets for Nuclotron synchrotron - starting point for SIS100 magnets



Nuclotron dipole inside cryostat:

1 - yoke end plate, 2 – brackets, 3 - coil end loop,
4 - beam pipe, 5 - helium headers 6 - suspension



Nuclotron quadrupole inside cryostat

- Nominal gradient: 34 T/m
- Ramp rate: 68 T/m·s

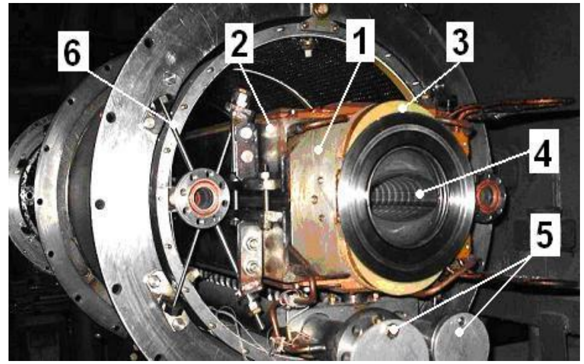
Main parameters		
		Super ferric, window-frame, 2 layer coil with 8 turns per pole
Effective length L_{eff}	m	1.426
Usable aperture	mm x mm	55 x 110
Bending angle	deg.	3.75
Bending radius	m	22.5
Nominal Field	T	1.9 @ 6kA
Ramp rate	T/s	4

Nuclotron-Synchrotron 160 SC magnets (dipoles and quadrupoles) for magnetic system

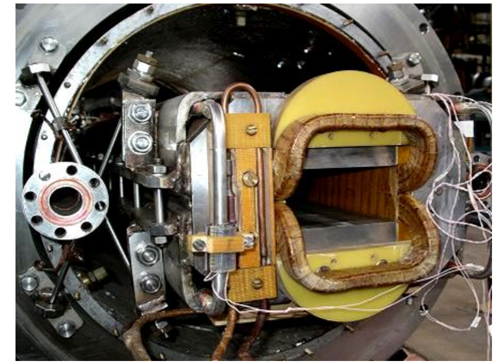
SIS100 Dipole Magnets: Development

2001 - start of the R&D program

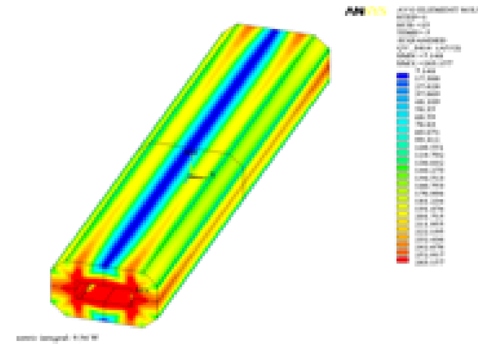
2001 – 2005 multiphysics FEM simulations (2D, 3D) and tests on the short models (> 20 different short magnet models were constructed and tested)



Nuclotron dipole

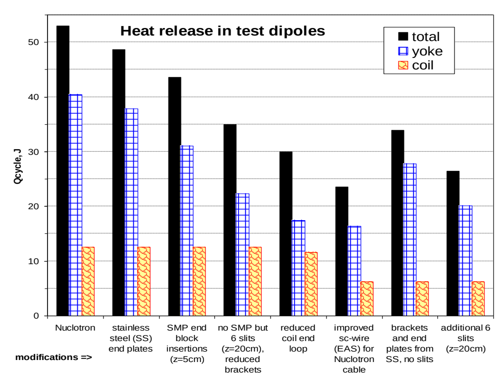


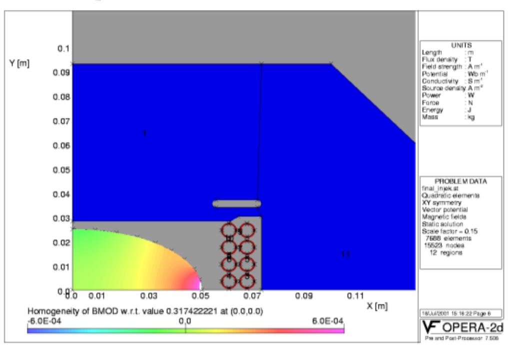
short model - 4KDP6a



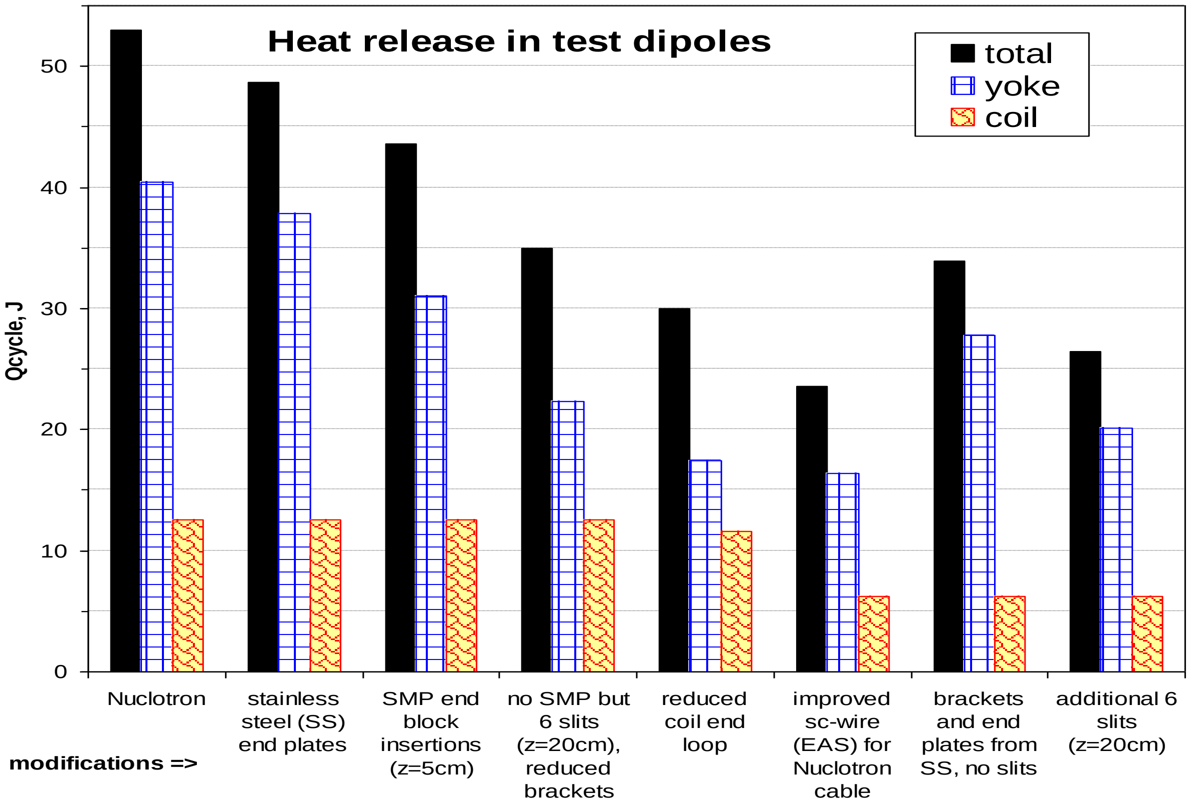
Goals of the design optimizations on short models and FEM:

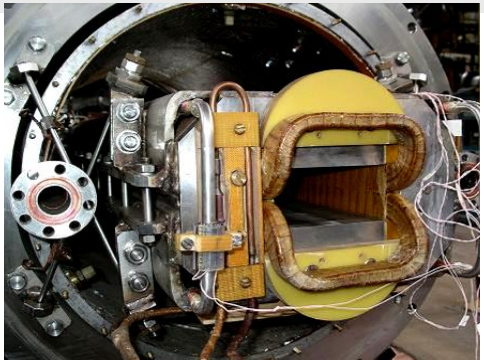
- reduction of the AC losses,
- improvement of the field homogeneity by optimizing the lamination geometry
- precise positioning of the sc-cable
- mechanical stability of the coil ($\geq 2 \cdot 10^8$ cycles)





SIS100 Dipole Magnets: Development





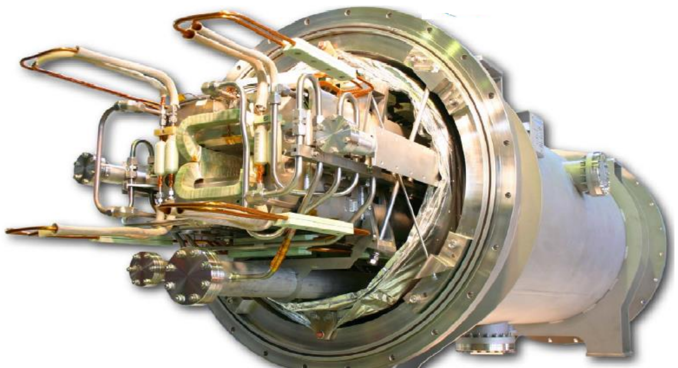
Optimised design for SIS100 magnets:

- brackets, end plates made from SS
- laser cut lamination slits
- optimized lamination geometry
- minimized coil ends
- new coil package structure
- new sc wire with higher current density and lower losses

courtesy E.Fischer

SIS100 Dipole Magnets: Development

Full size models

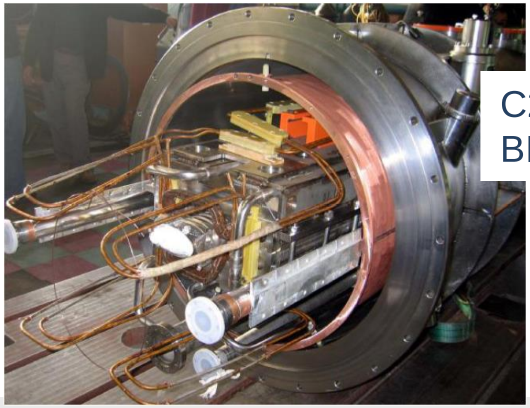


S2LD – production
Babcock Noell GmbH

<u>Objectives:</u>

- practical evaluation of the magnetic, cryogenic, mechanical properties of the magnets
- evaluation of the different manufacturing technologies:
  - cable production (dry/wet)
  - coil winding,
  - precise positioning of the cable
  - long term mechanical stabilisation of the coil
- impact of the steel properties AC losses and field properties

S2LD – production JINR Dubna



C2LD – production
BINP, Nowosibirsk

Photos courtesy BNG, JINR, BINP

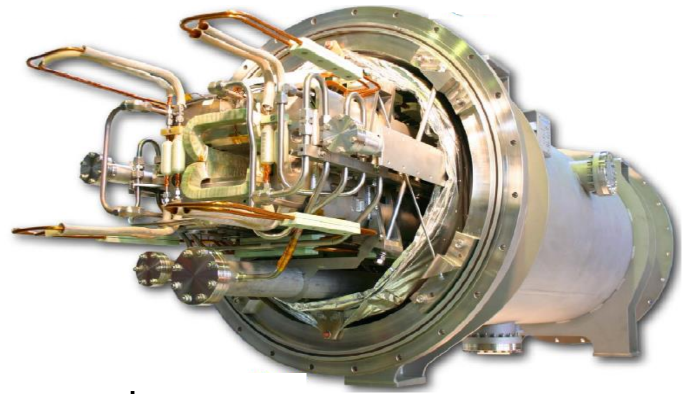
SIS100 Dipole Magnets: Development

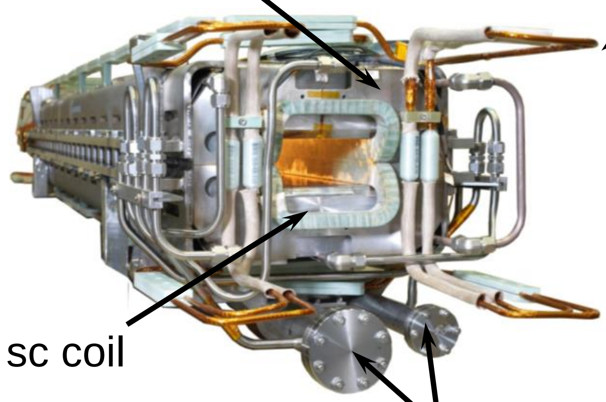
First full size prototype for SIS100 dipole – S2LD

produced by Babcock Noell GmbH

tested @ GSI Dec. 2008 – Nov.2009 (6 test runs)

Design		Window-frame, straight laminated cold iron yoke, lamination thickness 1mm, two layer coil with 16 turns, **steel M700-100**
Effective magnetic length L	m	2.76
Useable aperture	mm	130 * 60
Bending angle	deg	3 1/3
Bending radius	m	47.36
Bmin	T	0.253
Bmax	T	2.1
Current at max. field	A	7500
Ramp rate	T/s	4





Photos courtesy: Babcock Noell GmbH.

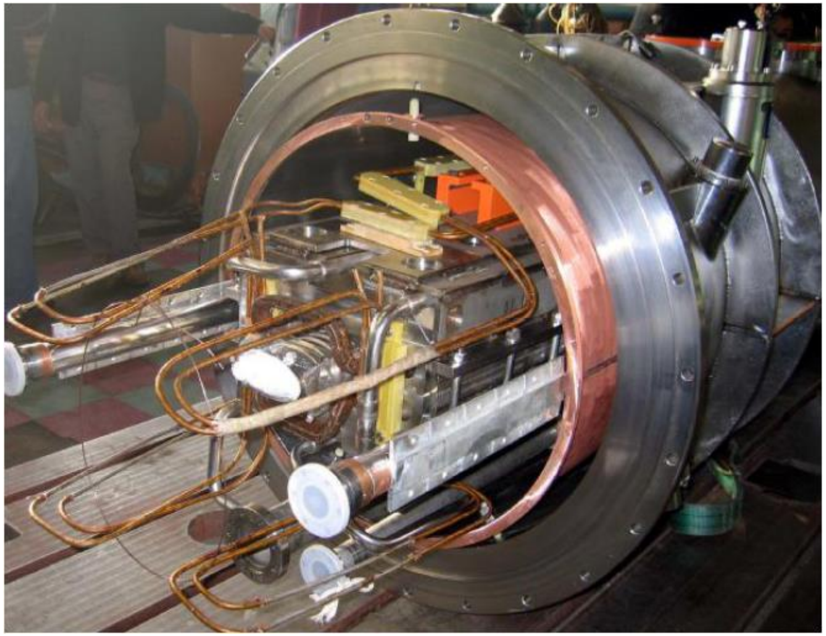
SIS100 Dipole Magnets: Development

Second full size prototype for SIS100 dipole – C2LD

produced by BINP (Nowosibirsk)

tested @ Dez.2009 – Nov 2011 (11 test runs)

Design		Window-frame, curved laminated cold iron yoke, lamination thickness 1mm, two layer coil with 16 turns, **steel ET3414 (anisotr.)**
Effective magnetic length L	m	3.062
Useable aperture	mm	113 * 58
Bending angle	deg	3 1/3
Bending radius	m	52.632
Bmin	T	0.253
Bmax	T	1.9
Current at max. field	A	6500
Ramp rate	T/s	4

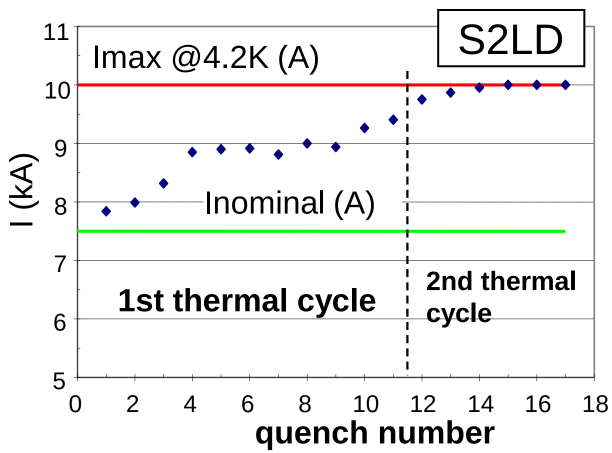


curved magnet:

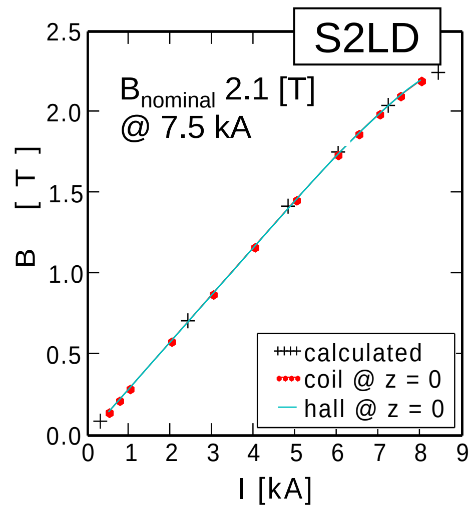
- reduces the magnet aperture width

Test Results for Full Size Dipole Models

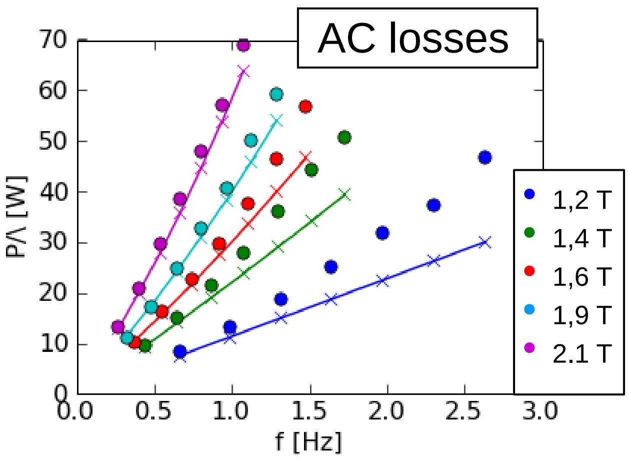
Magnet training

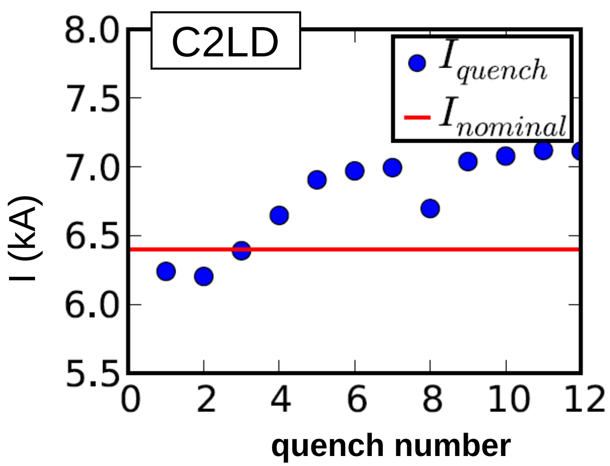


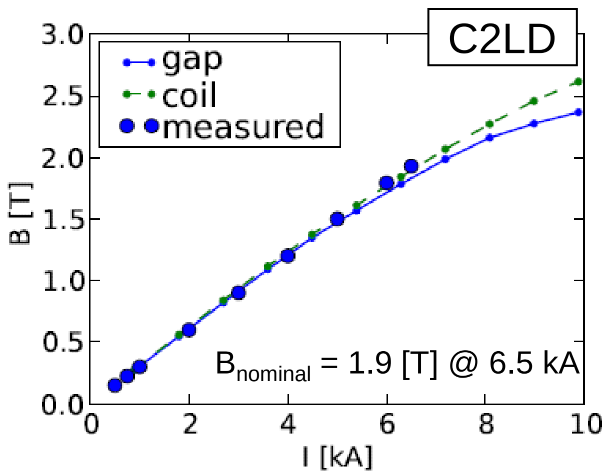
Load line



AC loss as measured for the C2LD (circle) versus the loss obtained for the S2LD magnet (x)

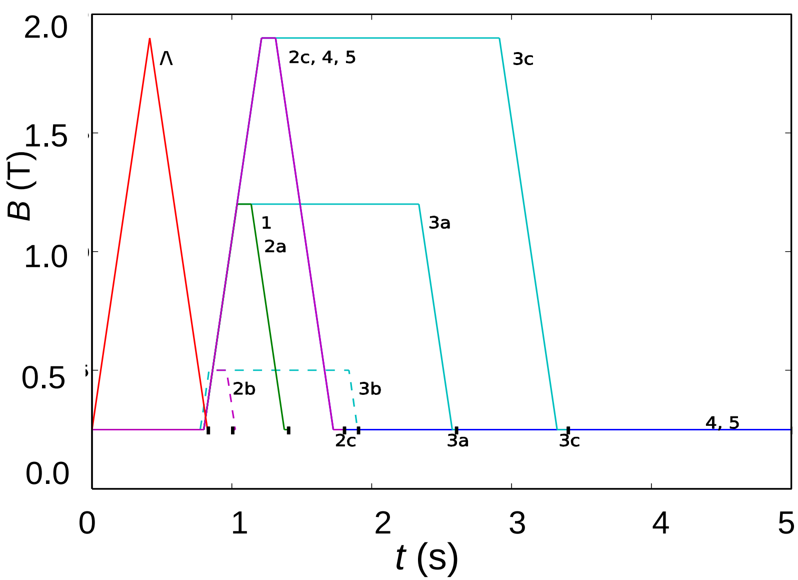


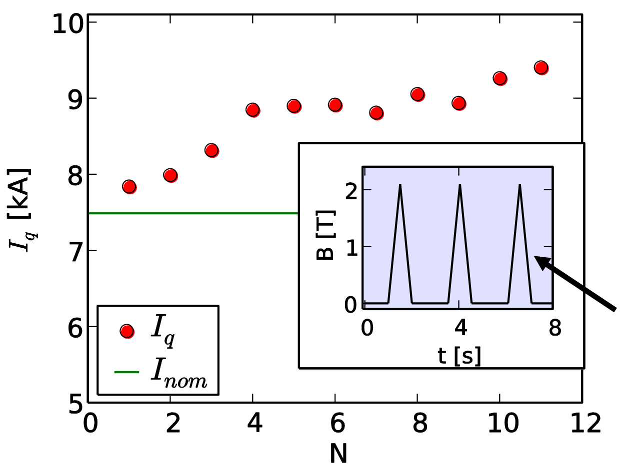




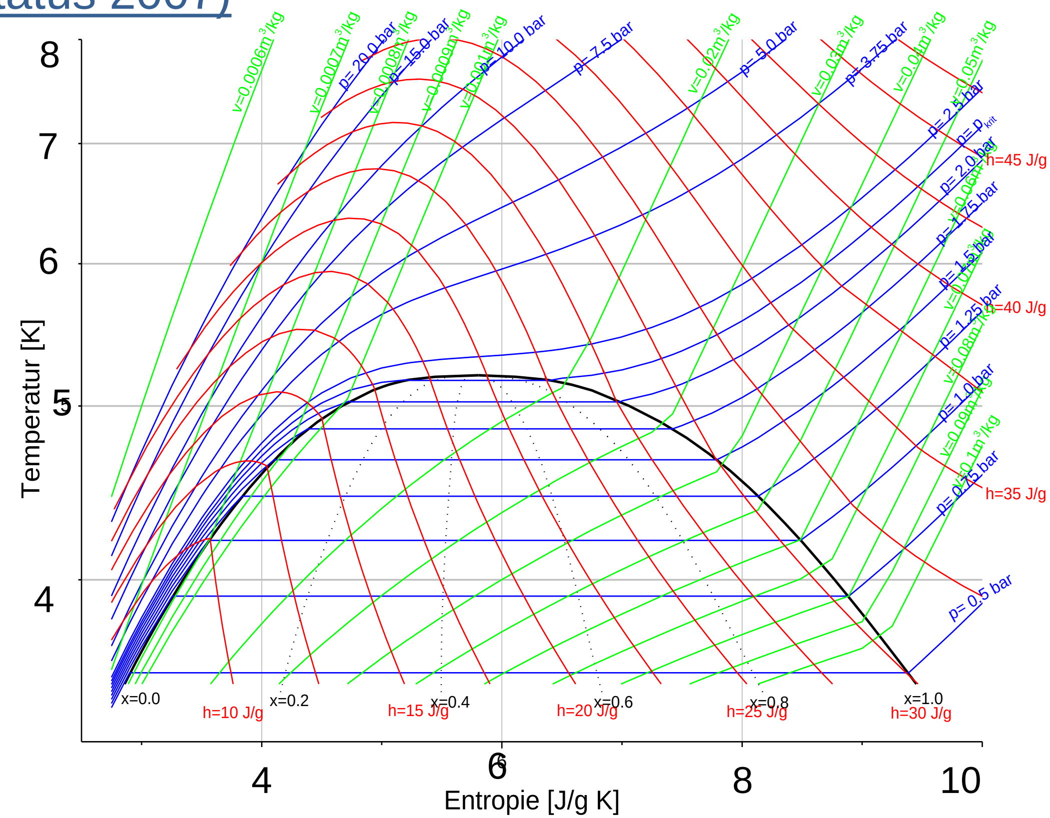
Test Results for Full Size Dipole Models

Main operation cycles for SIS100 (status 2007)



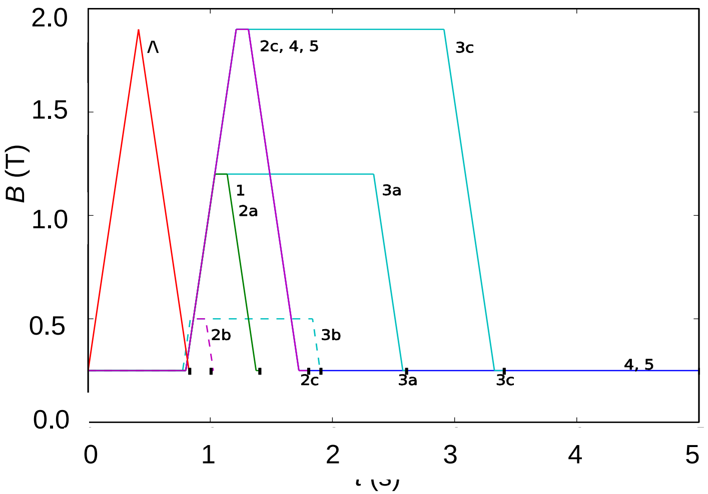


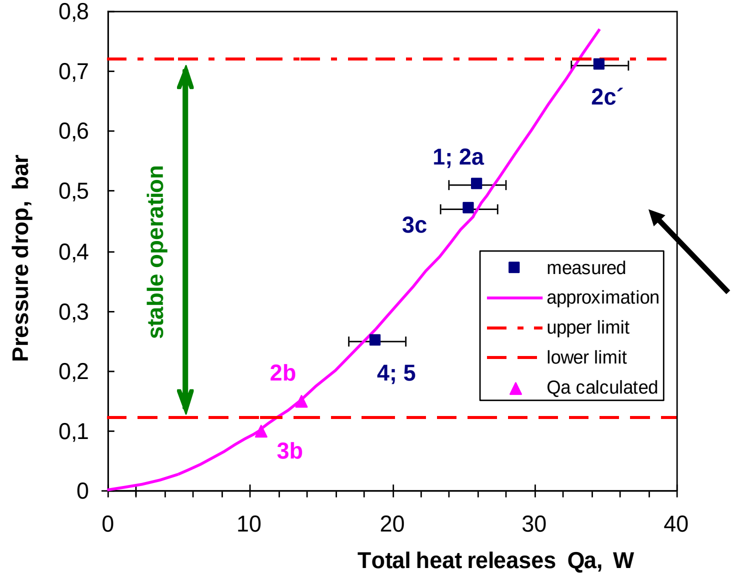
the strongest cycle mode of the magnet continuously tested at S2LD during one week and up to now for $2 \cdot 10^6$ cycles.



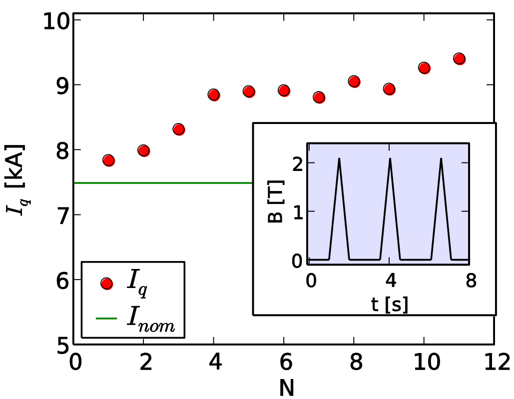
T – S phase diagrams for He^4

Test Results for Full Size Dipole Models

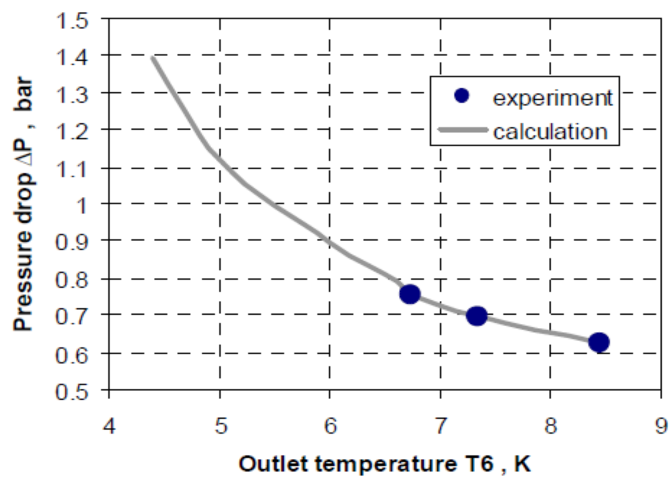




Straight dipole: Cryogenic stability range evaluation from an analytical model dipole for double layer coil



strongest cycle mode achieved for S2LD



Dependence of the cooling circuit pressure drop from the yoke outlet temperature calculated for equivalent dipole model for a stable triangular cycle

& measured for S2LD, C2LD

Conclusions for the Final Dipole Design

- ➢ The test results achieved at S2LD and C2LD confirm R&D results and calculations for AC loss and magnetic field quality
- ➢ Both the calculation (analytical) and measurements of the hydraulic resistance showed that with the 2 layer coil design the new SIS100 cycles are not feasible
- ➢ The hydraulic resistance of the double layer coil limits the cycling rate of SIS100!
- ➢ The comprehensive test of these models gave important information required to optimize the final design and to specify the pre-series magnets.
- ➢ The redesign of an optimized curved dipole with a single layer coil can fulfill the updated operation requirements of the FAIR SIS100 accelerator.

Redesign of the coil to satisfy the operation parameters:

- ✓ new cable design (with lower hydraulic resistance)
- ✓ shorter coil length - 4 turns per pole instead of 8

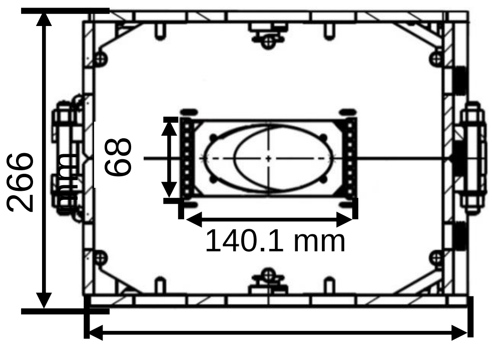
  → 13.1 kA higher nominal current instead of 7.5 kA

- ✓ CSLD (curved single layer dipole)

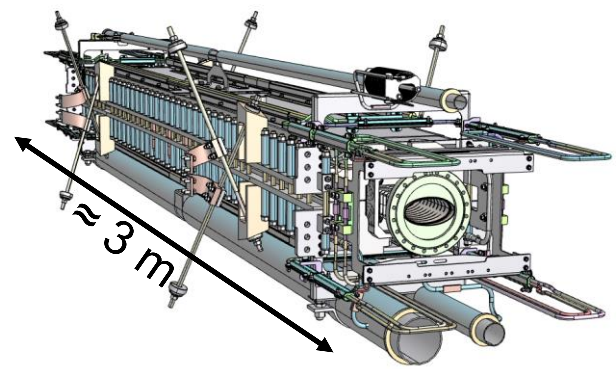
First of Series (FoS) Dipole for SIS100

Final design

- super ferric
- window frame
- sc coil - 4 turns per pole
- low AC loss Nuclotron-type cable (CuMn inter-filament matrix)
- cooling with 2-phase He



magnet cross section

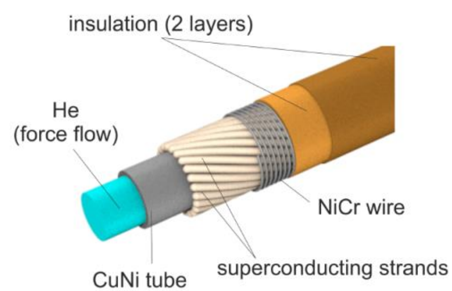


cold mass with beam chamber

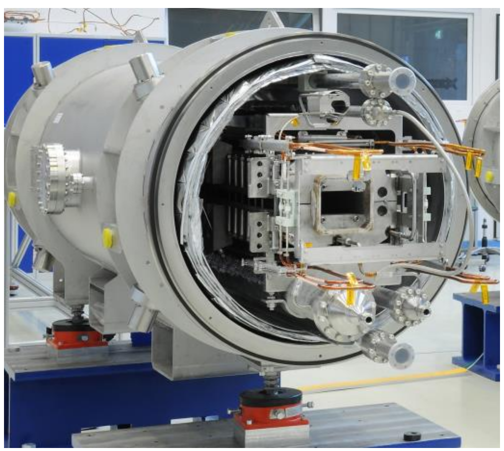
Main design parameter

Number of magnets in SIS100		108 + 1
Effective length L_{eff}	m	3.062
Usable aperture	mm x mm	60 x 120
Bending angle	deg.	1 1/3
Bending radius	m	52.632
Nominal Field	T	1.9
Field homogeneity $\Delta B/B_{main}$ x10^4	units	< ± 6
Ramp rate	T/s	4 @1Hz

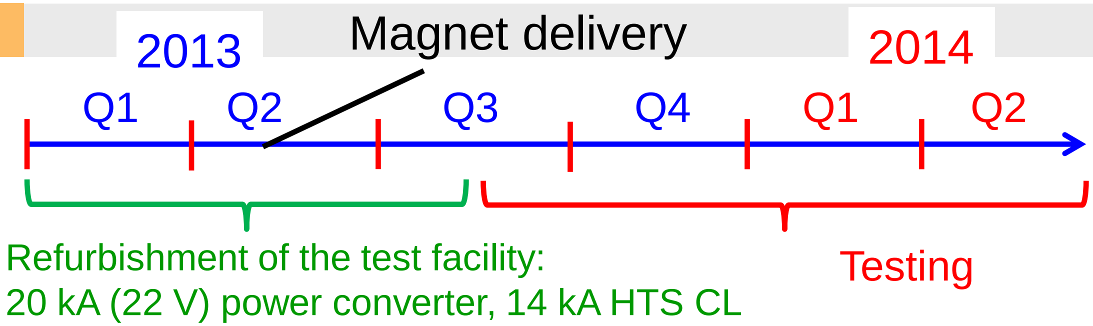
Nuclotron cable:

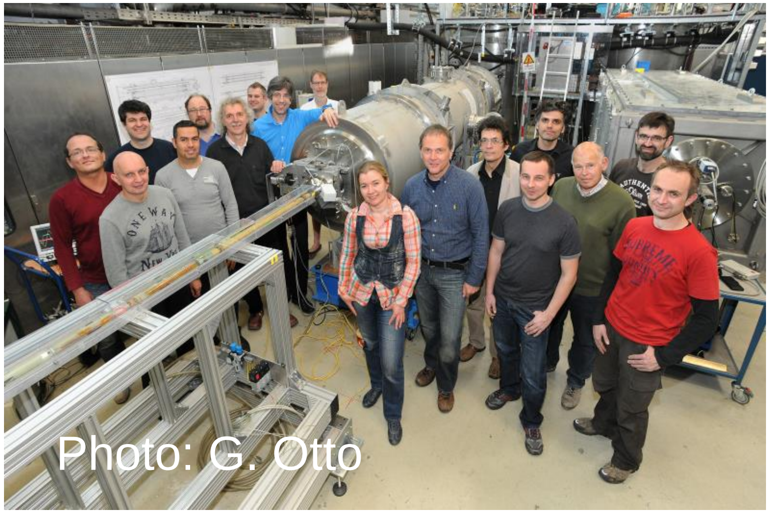


1 – CuNi Cooling tube
2 – NbTi SC wire
3 - CrNi wire
4 - Kapton tape
5 - Glasfiber tape


cryo-dipole module

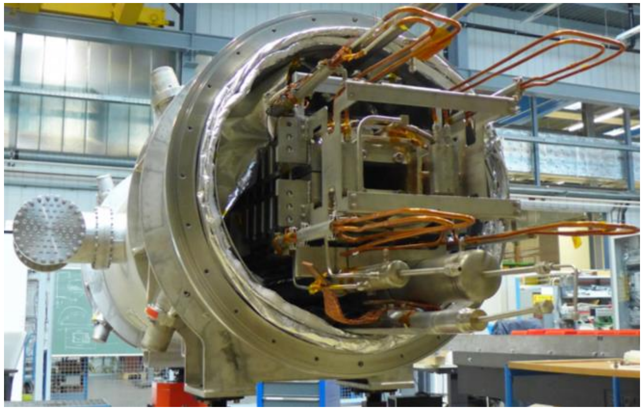
First of Series (FoS) Dipole for SIS100





Testing program:

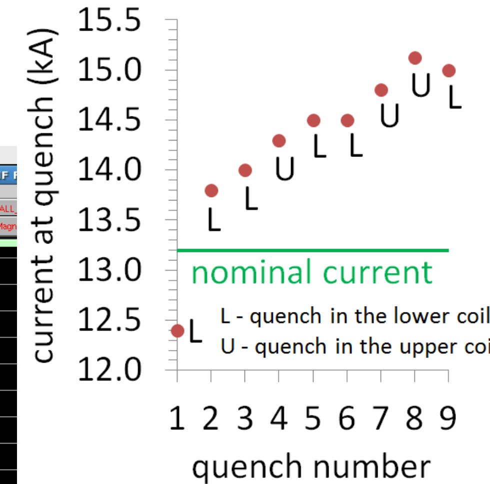
- Alignment
- Pressure drop and flow rate tests for all He-lines
  $\rightarrow$ hydraulic adjustment
- Leak- and vacuum tests for a vacuum vessel
- Electrical tests for HV and LV circuits
  (HV-, capacitor discharge, continuity tests)
- Magnet training
- Field measurement
  - new curve - to obtain better accuracy for the field simulations
  - load line and field homogeneity (DC& AC-operation - for beam dynamic requirements
  - end profile optimization – to improve the integral field quality (b_3)
- AC-losses – to estimate dissipated heat load
  $\rightarrow$ required cooling power for the SIS100



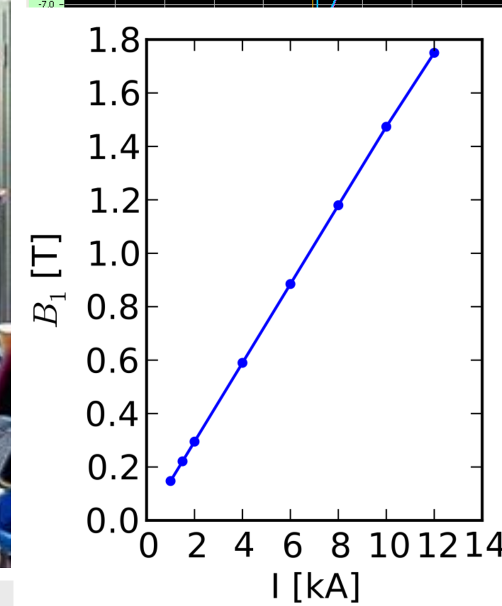
Testing of the SIS100 FoS Dipole

Lucky Friday the 13th (Dec. 2013)

- the first powering at cold
- virgin curve measured
- 2nd quench above nominal current
- magnet trained up to 15 kA (CL limit)



Actual first training quench (12.4 kA)

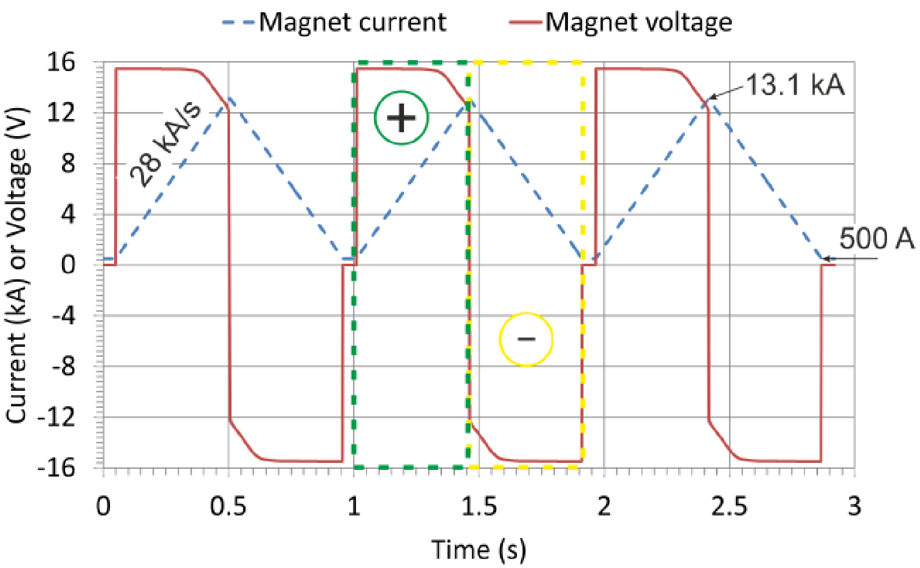


Virgin curve
- the first magnetization of the yoke

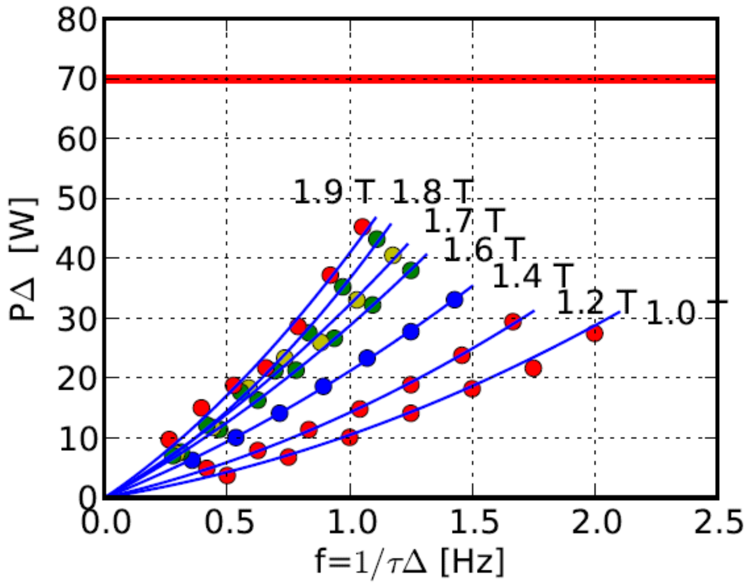
FoS Dipoles: AC Loss Measurement

V-I Method:

- we measure the energy absorbed by the magnet and returned to the power converter over a single powering cycle
- the tiny difference in the energy is associated with AC losses
- the measurement requires a high precision DVM for the voltage acquisition which also gives the trigger for the synchronized current acquisition



$$E = \underbrace{\int V(t) \cdot I(t) \cdot dt}_{cycle}$$



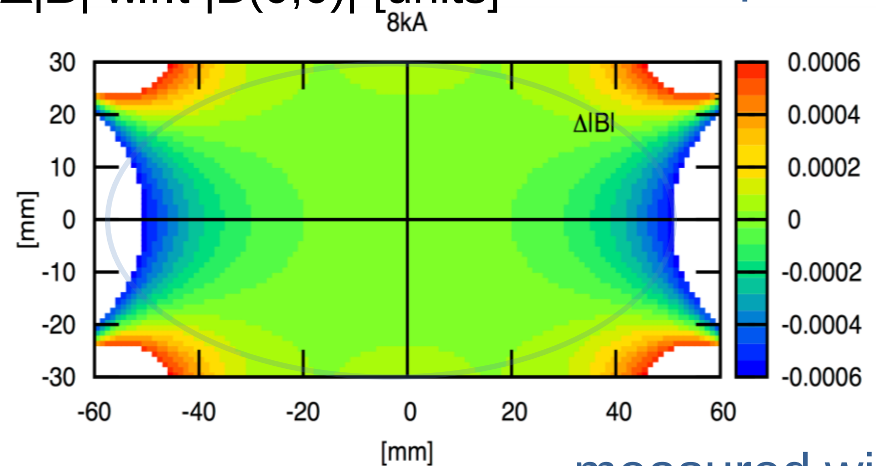
The AC loss for various operation cycles (various cycling rates). The maximum field is given at the end of the line.

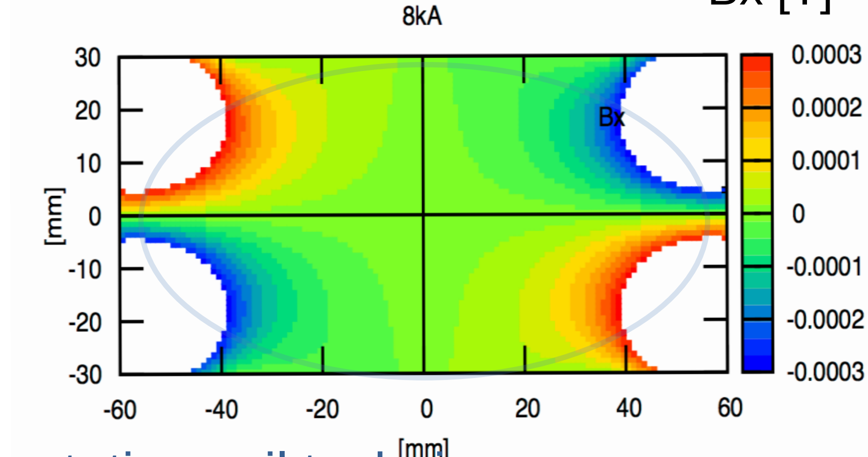
FoS Dipole: Magnetic Field Issues

Δ|**B**| w.r.t |B(0,0)| [units]

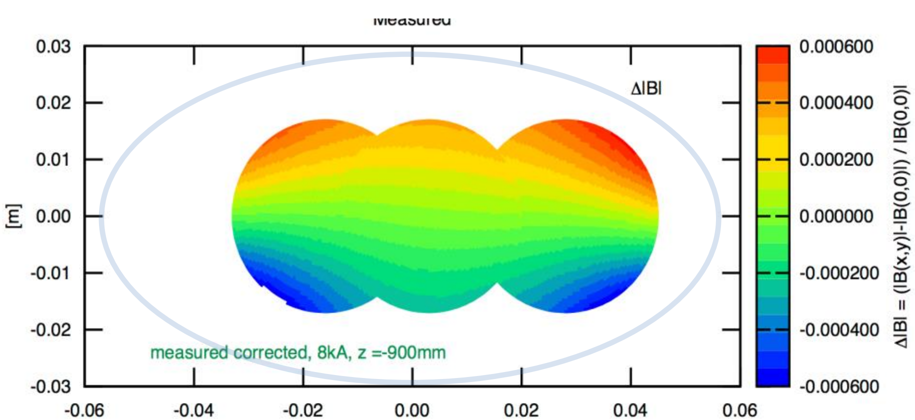
expected field distribution

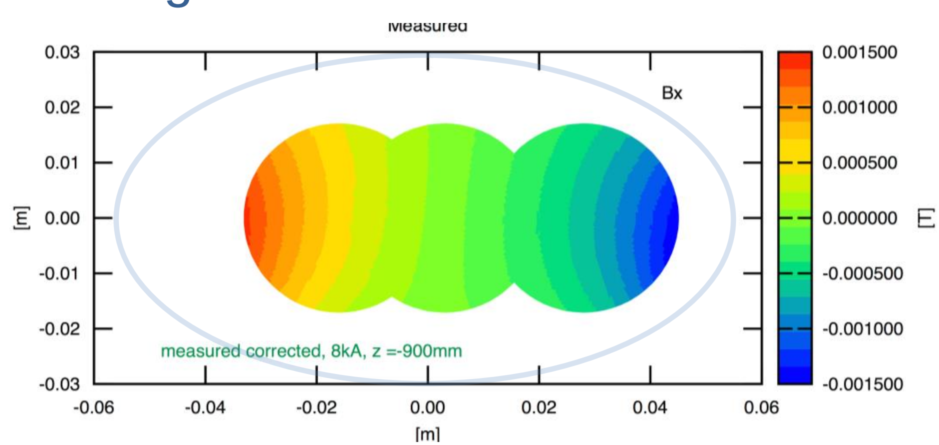
Bx [T]





measured with rotating coil technic





Δ|**B**| colored ±6unit = 0.0006 w.r.t |B(0,0)|

Bx colored ±0.0003T (top), ±0.0015T (bottom)

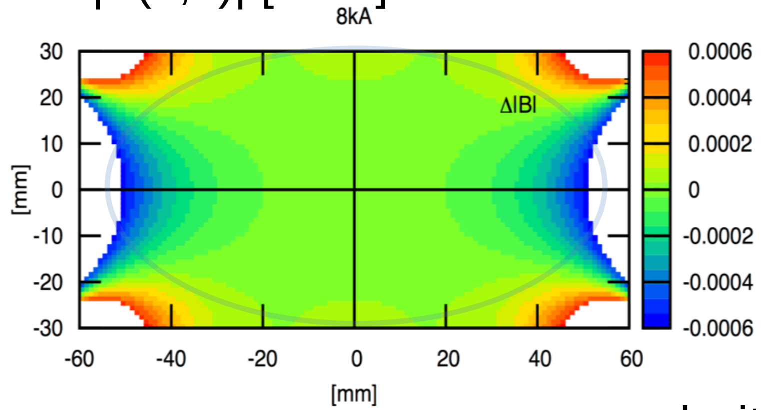
courtesy K.Sugita

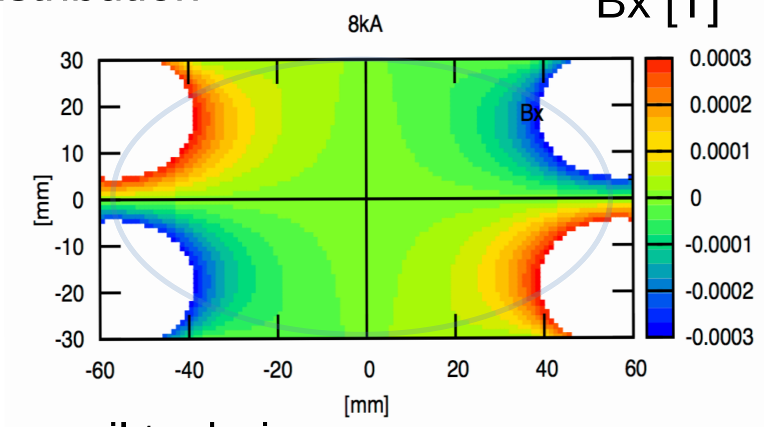
FoS Dipole: Magnetic Field Issues

Δ|**B**| w.r.t |B(0,0)| [units]

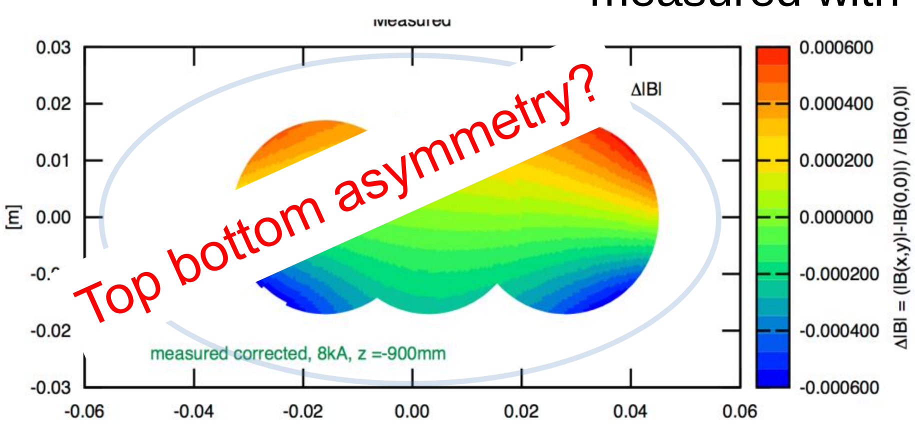
expected field distribution

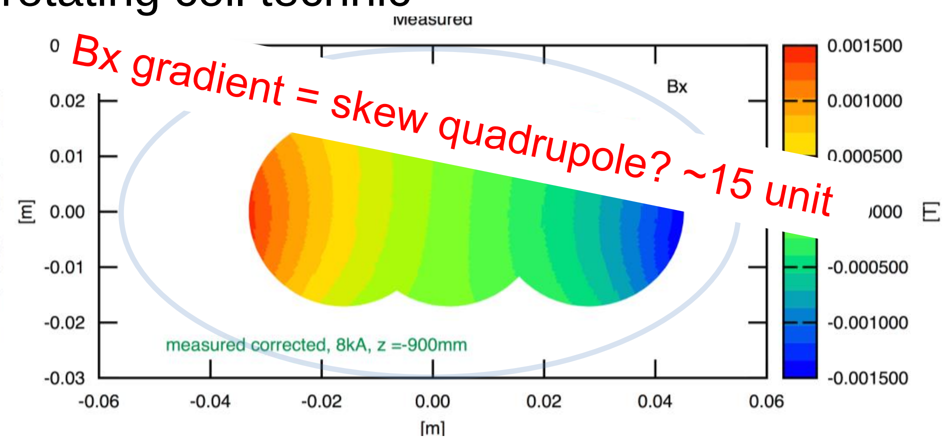
Bx [T]





measured with rotating coil technic



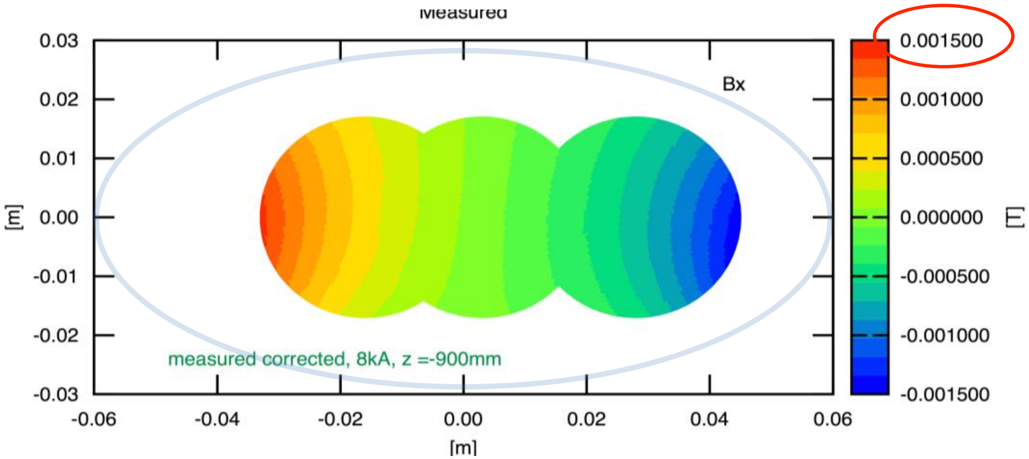


What could be the reason? Measurement error?

Not really easy to produce such an error but let us crosscheck with another technique

FoS Dipole: Magnetic Field Issues

measured with rotating coil technic



Bx gradient = skew quadrupole ~15 units proved by Hall probe measurement

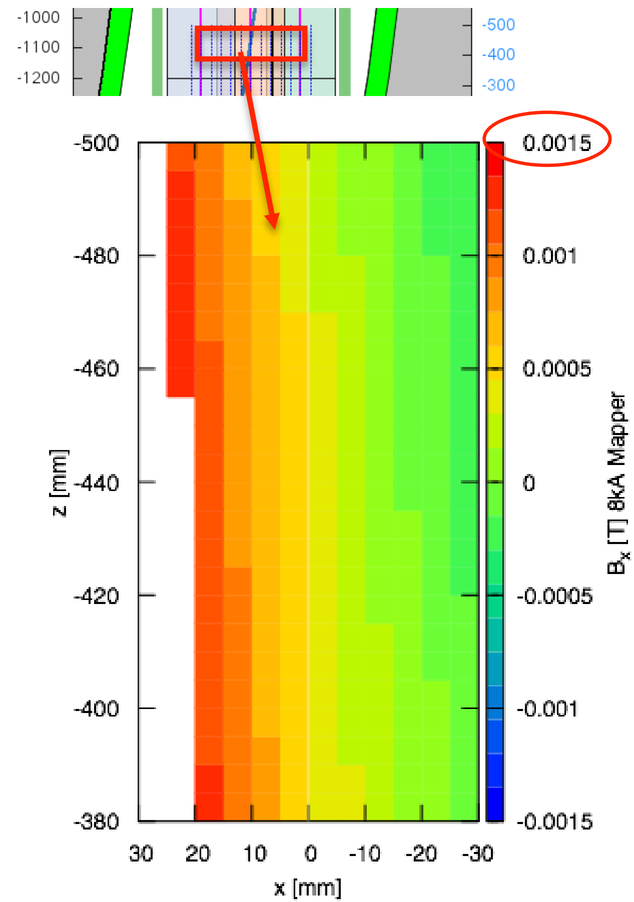
How can we explain unexpected field error?

Is it a manufacturing error? Which one?

The contractor built the magnet according to the drawings.

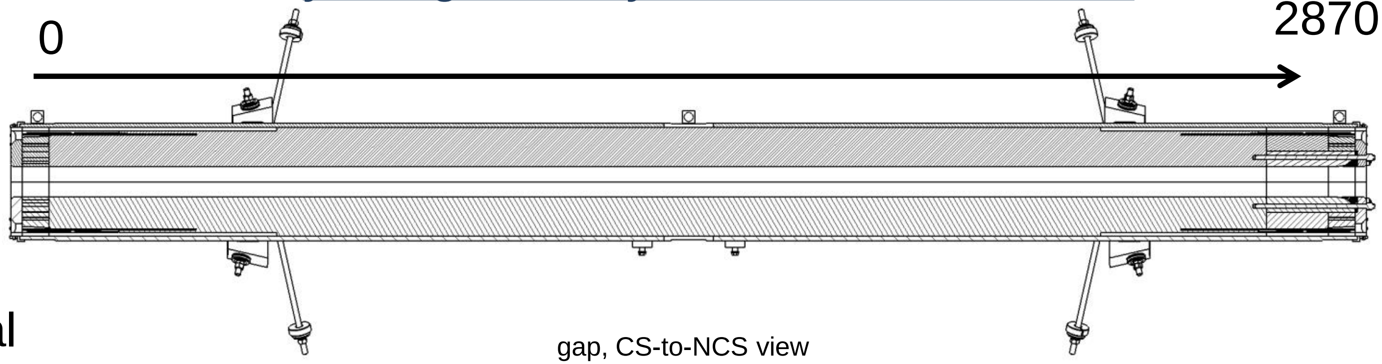
To demonstrate, that the observed field distortion is caused by the production, one needs to precisely measure the geometrical parameters (gap height, width)

Hall probe measurement Bx in the 2D field region



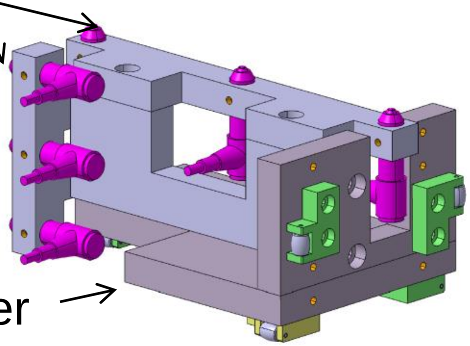
FoS Dipole: Magnetic Field Issues

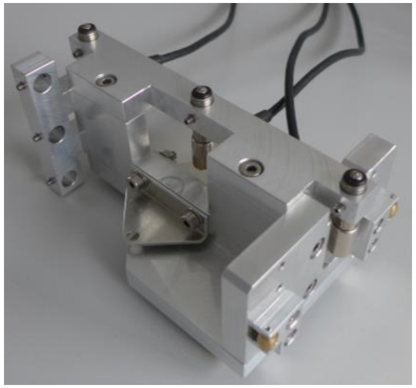
yoke geometry: measurement tools



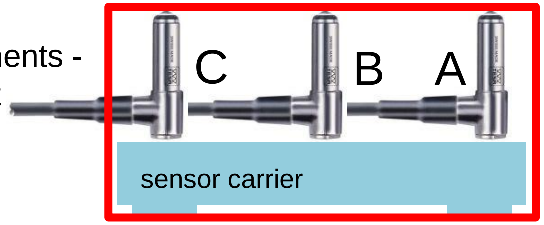
mechanical sensors

carrier

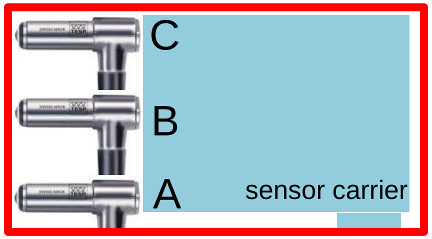




vertical measurements - gap height



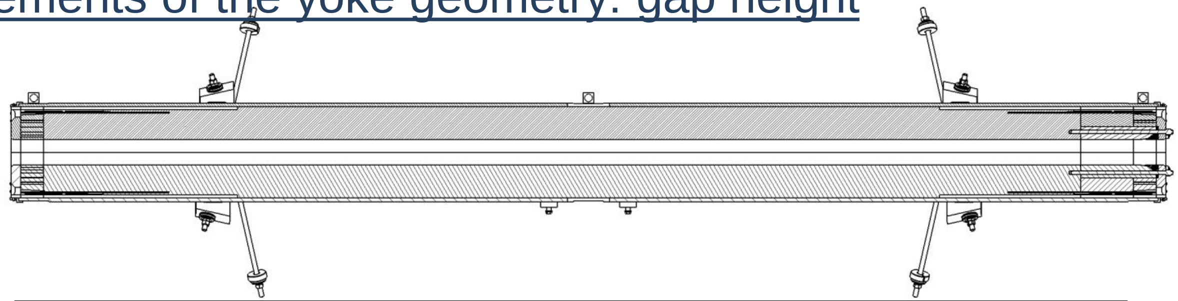
horizontal measurements – gap width

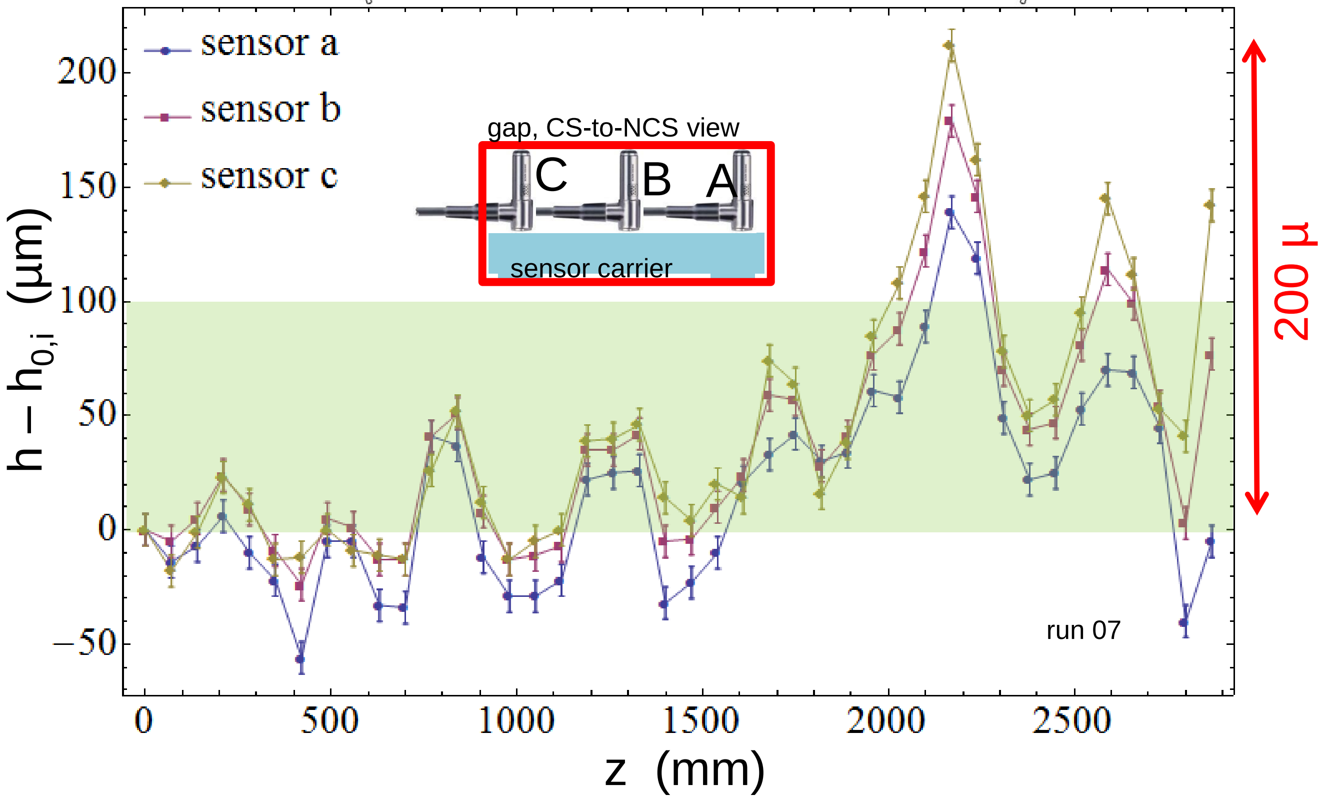


courtesy C.Roux

FoS Dipole: Magnetic Field Issues

Measurements of the yoke geometry: gap height





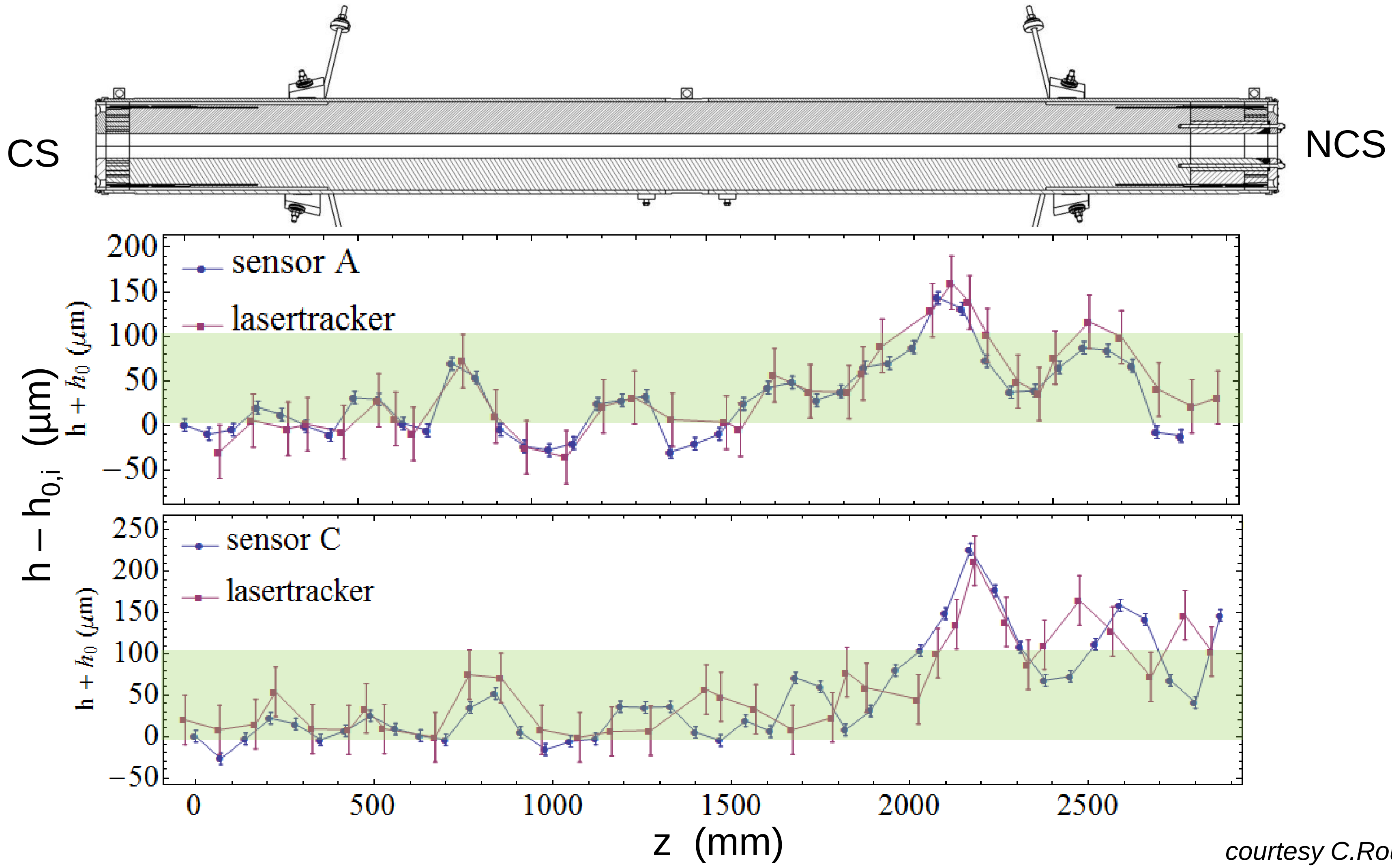
Spec. 2.2.11: gap tolerance (+100/- 0)µ

specified tolerance

courtesy C.Roux

FoS Dipole: Magnetic Field Issues

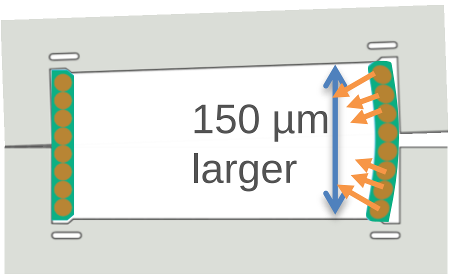
yoke geometry: comparison of measurement techniques



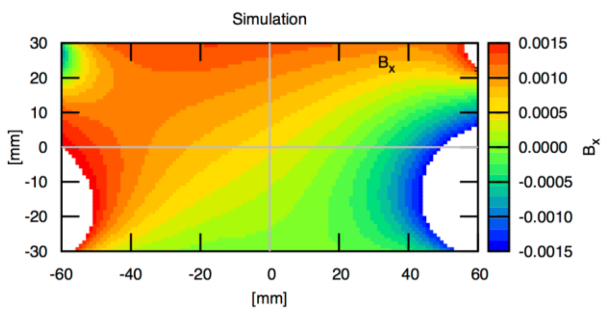
courtesy C.Roux

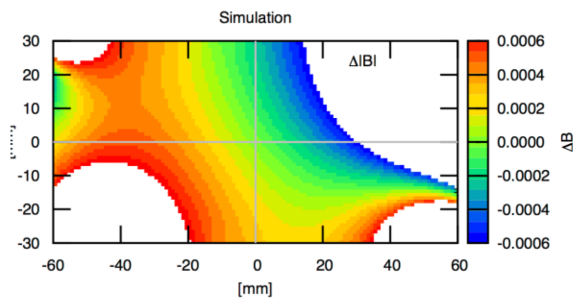
FoS Dipole: Magnetic Field Issues

FEM studies - model based on the geometrical measurements



This can explain Bx,
but not |B| top-bottom asymmetry





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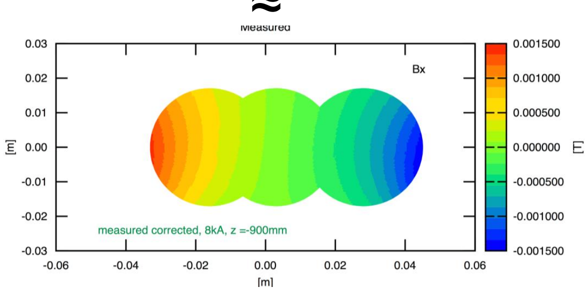
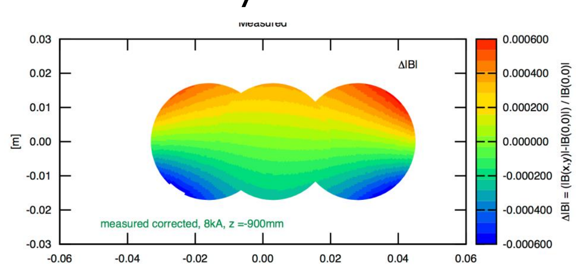
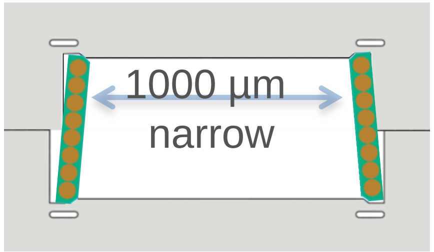
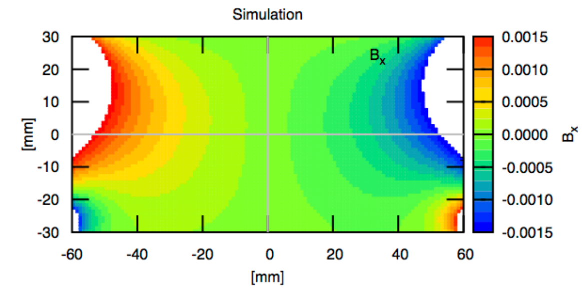
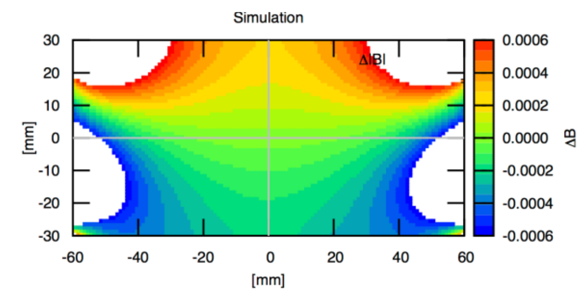




cf.







Such huge deviation was not observed
→Combination of manufacturing errors

courtesy K.Sugita

FoS Dipole: Magnetic Field Issues

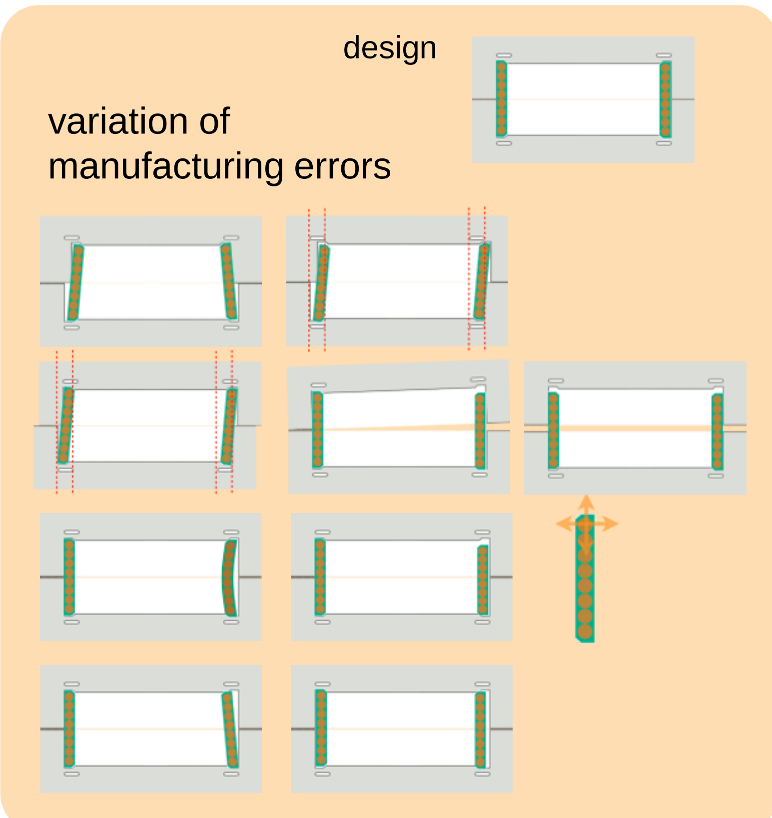
field-error simulations: starting point

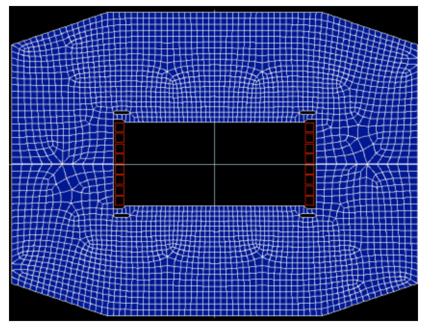
courtesy K.Sugita

Input:

analysis of production drawing/procedure

analysis of magnetic field measurement results





Simulations
Roxie2D

We have simulated a number of possible magnet assembly errors. However we couldn't reproduce the observed field distortion completely.

SIS100 Dipole Magnets: Production

Q/2 2014 – Q1/ 2015 - survey on alternative manufacturing technics
analysis of possible manufacturing errors

Q2- Q3/2015 – manufacturing of the new yoke and magnet reassembly

lamination stamped to final geometry

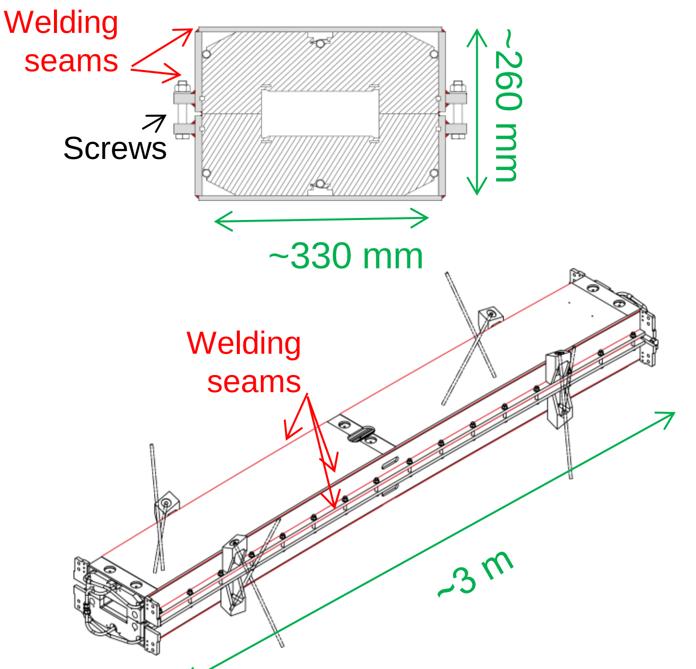
- no further machining

laser welding

- low heat input
- low tension
- automated

removal of gap between yoke halves

- coil clamped in elastic range



courtesy C.Roux

+ > 130 further changes in fabrication and quality issues for series dipoles

October/2015 – reassembled magnet delivered to GSI for testing

SIS100 Dipole Magnets: Production

FoS 2 – FoS dipole assembled with a new yoke and reused coil

Testing at GSI - October/2015 – Q1/2016

lamination stamped to final geometry

- no further machining

laser welding

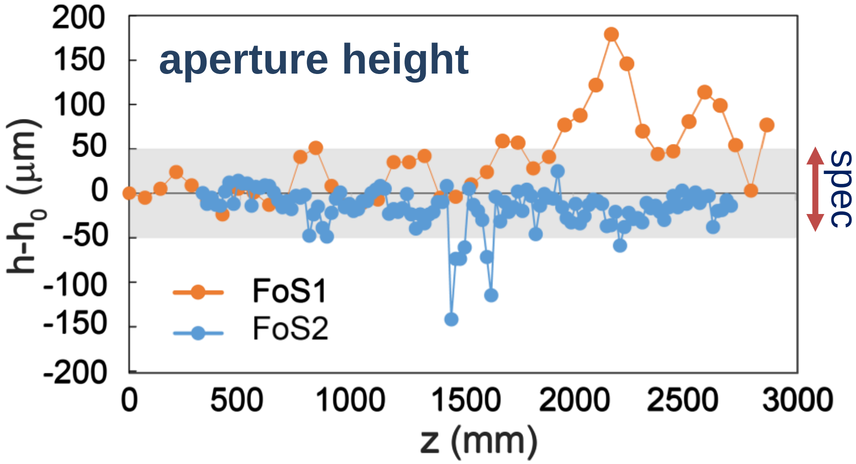
- low heat input
- low tension
- automated

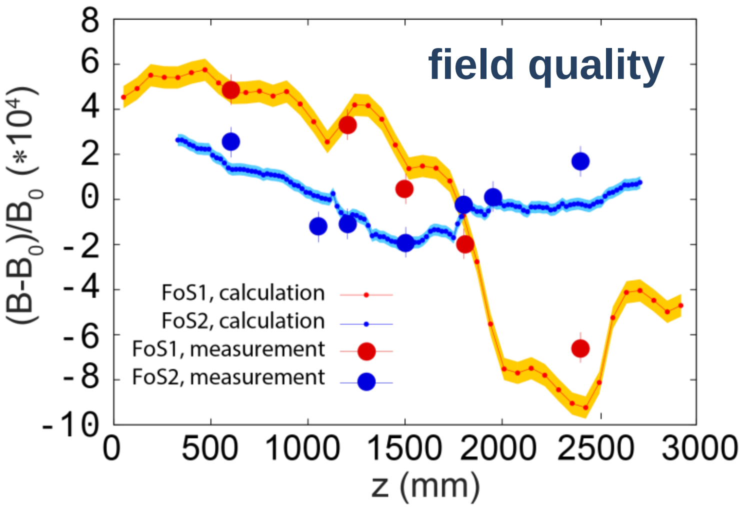
removal of gap between yoke halves

- coil clamped in elastic range

successful

08/2016 Release of series production





SIS100 Dipole Magnets: Testing Strategy

At the contractor site:

- Quality inspections at different production steps

(e.g. yoke geometry for half yokes before and after welding, after assembly with the coil)

- Functionality tests @ 300K
  - ✓ components of assembly
  - ✓ assembled magnet
- Factory Acceptance Test (FAT)
  - ✓ measurement protocols
  - ✓ quality certificate (summary of single tests)

At the GSI site:

- Standard Test Program for 100% of magnets:
  - ✓ documents control
  - ✓ quality controls
  - ✓ functionality tests @ 300K (after delivery, after cold tests)
  - ✓ functionality tests @ 4.5K

    including magnetic field measurements (DC, AC mode)
- Advanced Test Program for 10% of magnets
  - ✓ magnetic field measurements in the enlarged area

Site Acceptance Test (SAT): Scope

quality assurance (including safety)

- yoke geometry
  - ✓ aperture height (precise)
  - ✓ sag and twist
  - ✓ positioning
- process lines
  - ✓ pressure and leak,
  - ✓ massflow rate
  - ✓ positioning
- instrumentation check
- electrical integrity
  - ✓ HV
  - ✓ continuity
  - ✓ turn-to-turn isolation
- quench performance
- static heat load and AC losses

machine control

- integral B-field
- harmonics
- load line

about 30 parameters

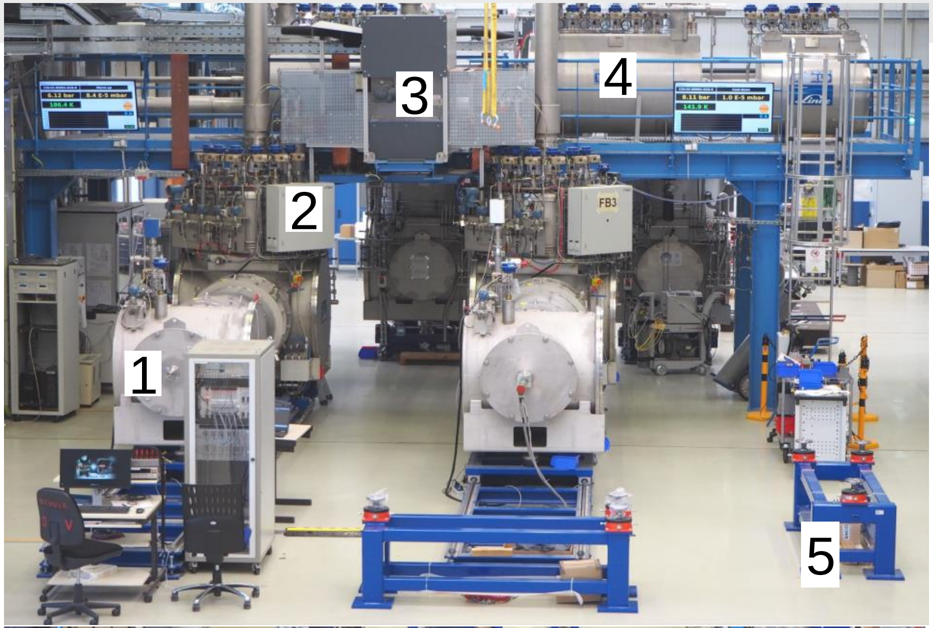
about 110 steps

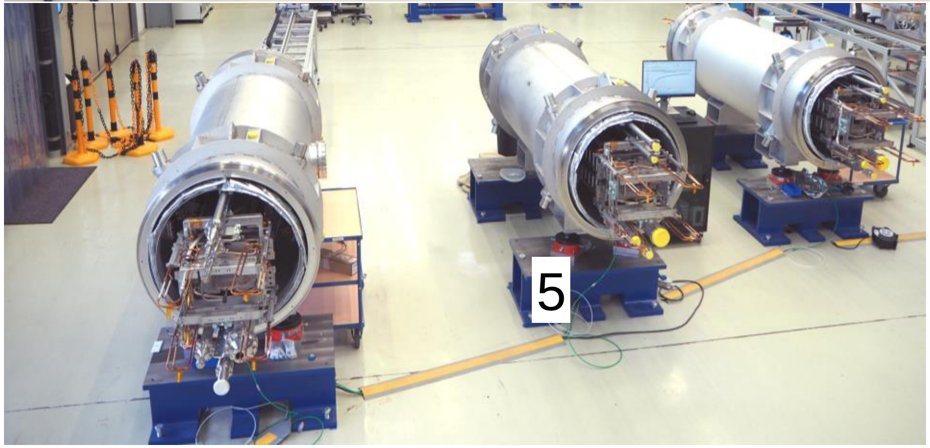
Duration ~ 3 weeks per magnet

GSI Test Facilities for SIS100 Magnets

Series Test Facility (STF)

- ✓ Refurbishment of the SH2-SH3, installation of the test benches – 2013 - 2015
- ✓ Cryo-plant 1.5 kW – commissioned Q2/2015
- ✓ power converters 2 x 20 kA (66 V) – commissioned Q1 & Q3/2016
- ✓ 14 kA DC HTS Current Leads (CL) – commissioning Q3/2015 – Q1/2017
- ✓ QD / Magnet protection system
- ✓ 687m^2 total area
- ✓ 4 test benches for cold tests
- ✓ 6 preparation benches
- ✓ calibration chain for MF-probe





Test benches for superconducting magnets: 1-end box, 2 - feed box, 3 - distribution box, 4 - power switch, 5 - preparation bench

GSI Test Facilities for SIS100 Magnets

Series Test Facility (STF)

- ✓ Cryo-plant 1.5 kW – commissioned Q2/2015
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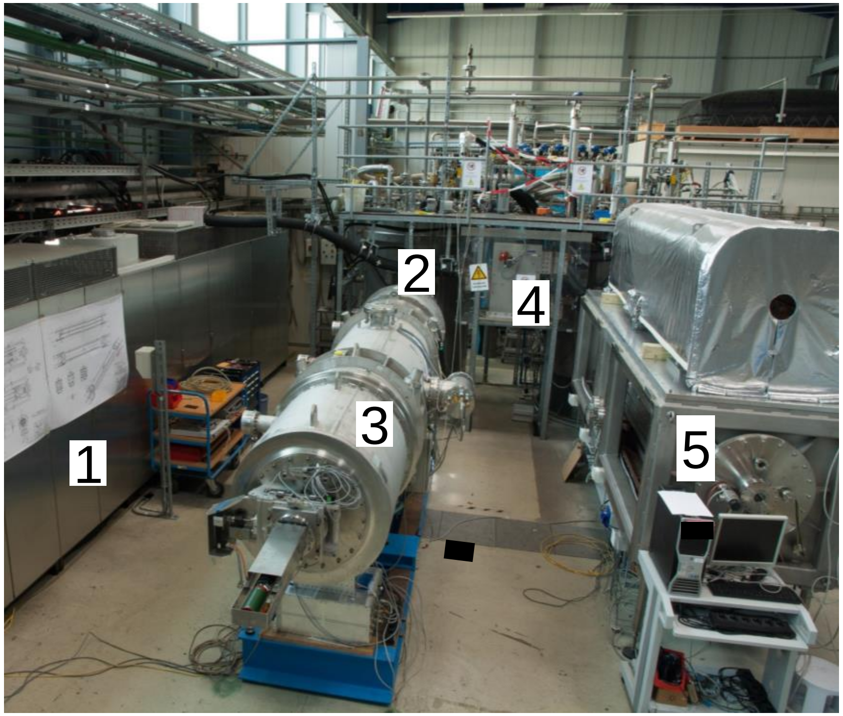
- ✓ 6 preparation benches
- ✓ calibration chain for MF-probe

Test benches for superconducting magnets: 1-end box, 2 - feed box, 3 - distribution box, 4 - power switch, 5 - preparation bench

GSI Test Facilities for SIS100 Magnets

Prototype Test Facility

- ✓ Cryo-plant 0,6 kW – commissioned 2007
- ✓ power converters 20 kA (66 V) – commissioned Q3/2013
- ✓ 14 kA DC HTS Current Leads (CL) – commissioning Q3/2013, Q4/2014
- ✓ QD / Magnet protection system
- ✓ 150 m^2 total area
- ✓ 1 test benches for cold tests SIS100 dipole
- ✓ 1 universal cryostat



1 - power converter, 2 - feed box for testing of SIS100 magnets, 3 - First of series dipole for SIS100, 4 – power switch, 5 Universal cryostat for cryogenic tests of small components.

GSI Test Facilities: Testing Capabilities

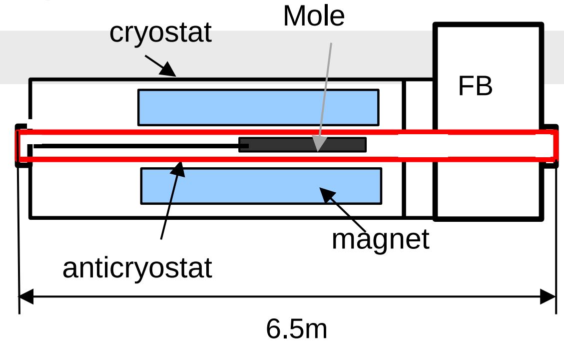
Series Test Facility

- ✓ SIS100 series dipole -100%
- ✓ SIS100 string test
- ✓ 14kA HTS CL for SIS100 (11 pairs)
- ✓ Cryo Components for SIS100 (Bypass Line, FoS Current Lead and Feed Box)
- ✓ UHV components (FoS vacuum camber for SIS100 dipole, FoS cryosorbtion pumps)

Prototype Test Facility

- ✓ Local current leads (250A HTS) for SIS100 corrector magnets
- ✓ small cryo components (cryo-catcher) 14kA HTS CL for SIS100 (11 pairs)

Magnetic Field Measurements: Used Methods

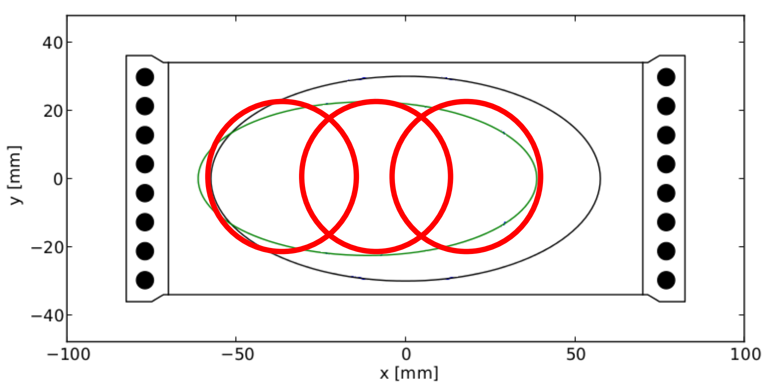


Combining rotating coil probe measurements:

Warm rotating coil probe – the „Mole“

- rotating coil probe with dipole compensation

  R_{ref} = 17mm, L= 600mm,
- operate in anticryostat R_{out} = 32mm, R_{in} = 23.45mm, L = 6.5m
- measurements at 3 lateral positions
- measurements for 5 longitudinal positions



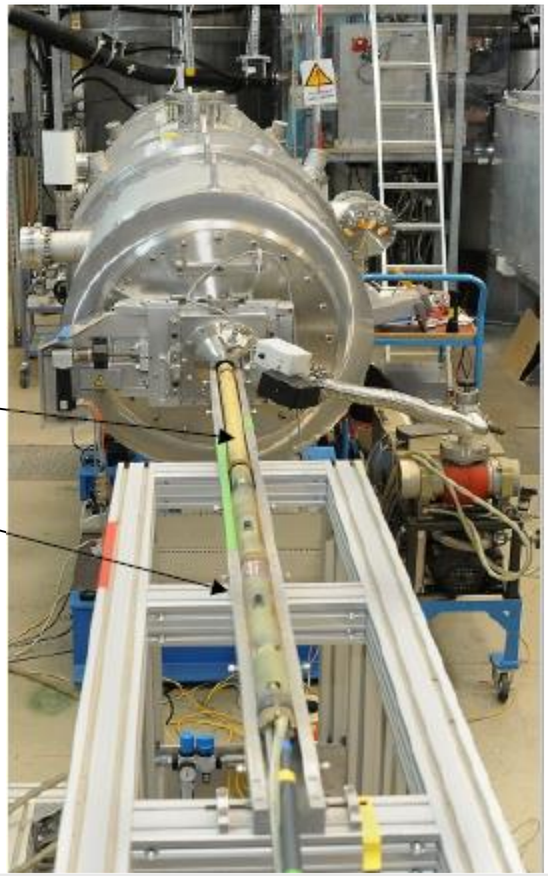
solid black: usable beam aperture

red area covered by Mole for a single lateral position

green area covered by measurements with the Mole in the anticryostat

coil probe

motor unit

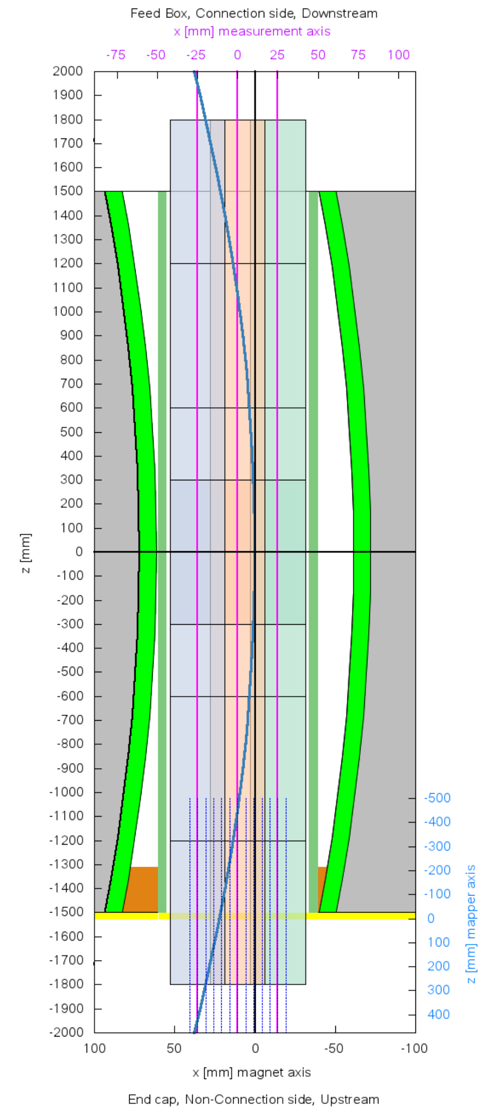


Magnetic Field Measurements: Used Methods

<u>Challenges of the Mole system:</u>

- Precise positioning of the anticryostat in the magnet with respect to XY plain
- Precise positioning of the coil probe respect to the beam axis
- The field can not be measured directly on the beam axis with the existing probe. Recalculation of the field on the beam axis is difficult since the real position of the probe with respect to the x-axis is not known -> not systematic error -> not clear error propagation for reconstructed field
- only small area inside the magnet gap can be covered
- complicated installation and alignment procedure for anticryostat

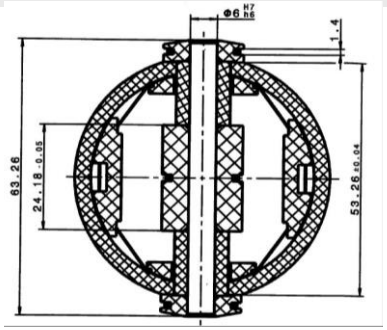
Therefore a new system with appropriate measurement precision, larger coverage (xy plane) and simpler handling is needed for qualifying the series dipole magnets!

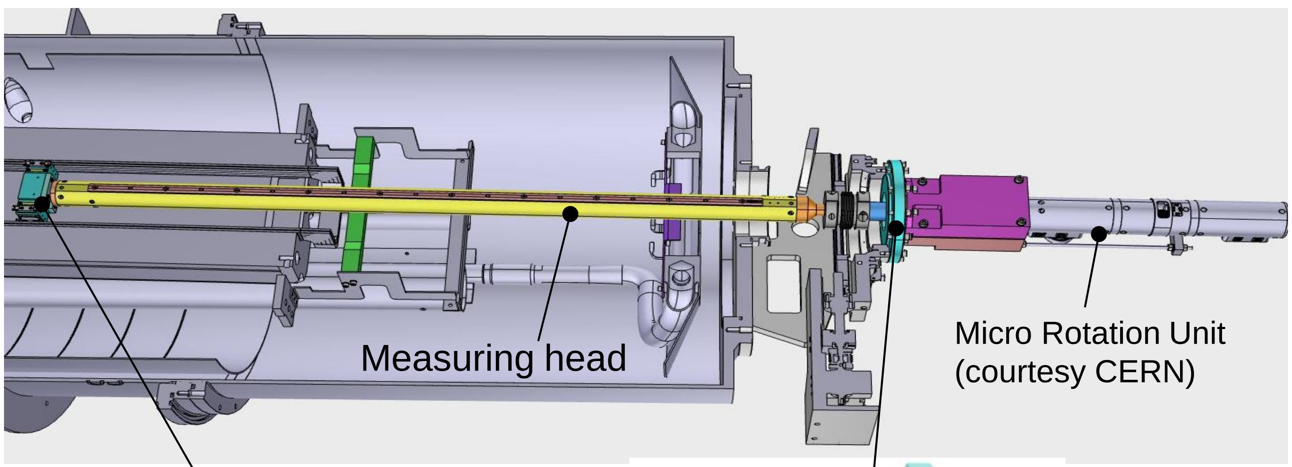


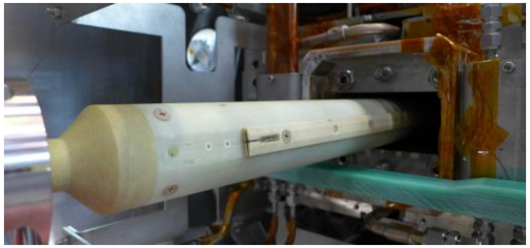
New Measurement Systems for Qualifying SIS100 Series Dipoles

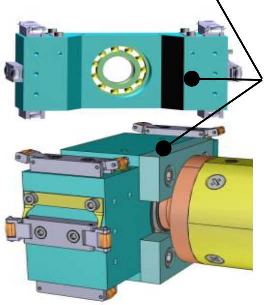
Field measurements @ 4.5K in vacuum

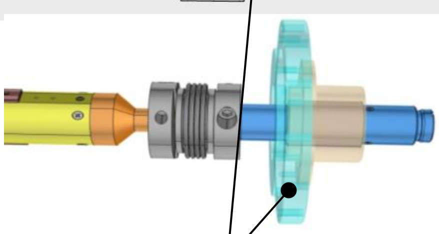
Mechanical adaptation of the CERN rotating coil probe R30/L1200mm (tangential coils) for the field measurements in vacuum @ 4.5K

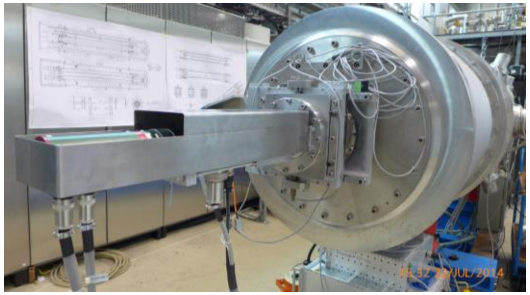












Start of development - Oct. 2013

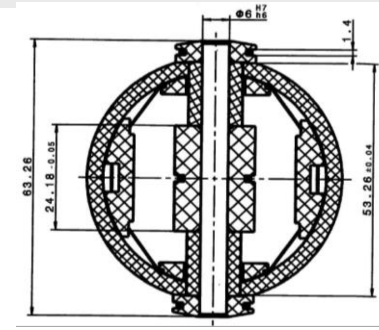
First measurements in FoSD Jul. 2014

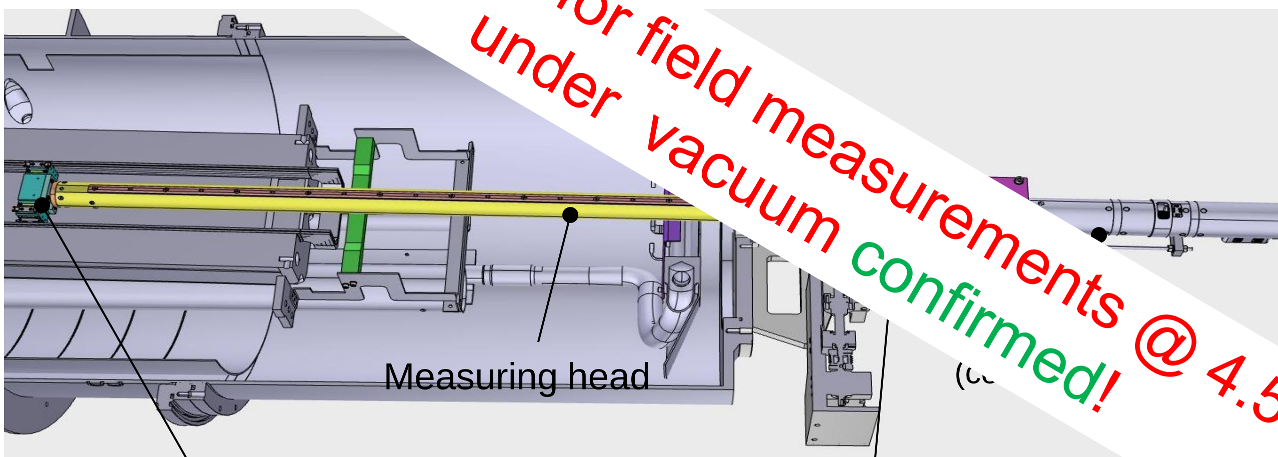
New Measurement Systems for Qualifying SIS100 Series Dipoles

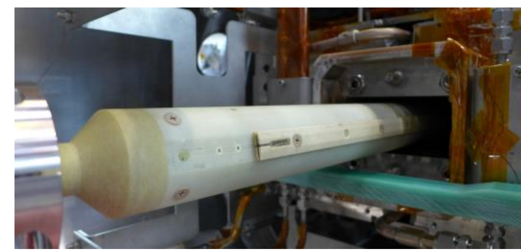
Field measurements @ 4.5K in vacuum

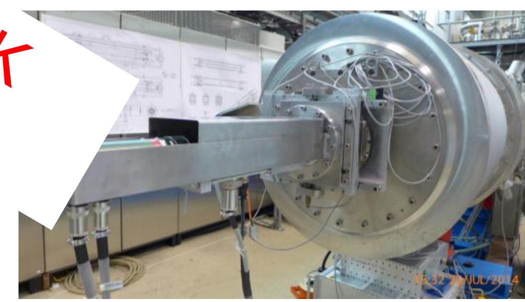
Mechanica… …n of the CERN rotating coil probe R30/L1200mm
(tangenti… …ld measurements in vacuum @ 4.5K

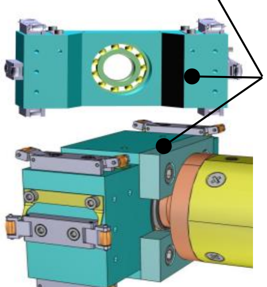
Concept for field measurements @ 4.5K under vacuum confirmed!

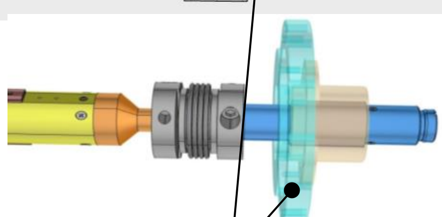












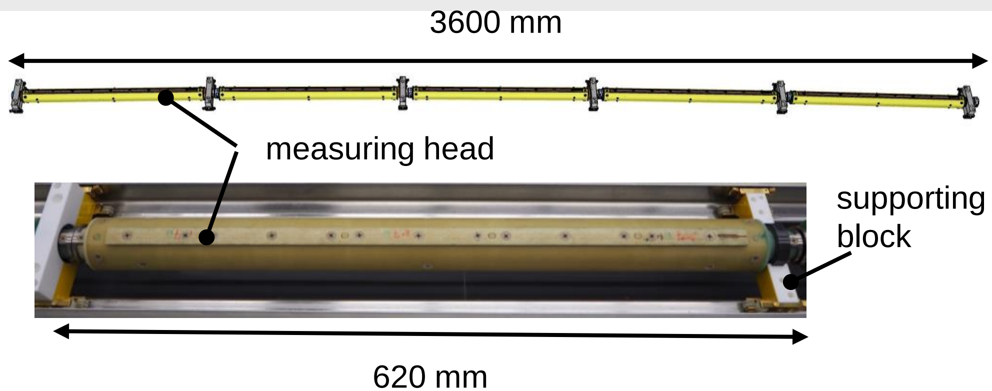
Start of development - Oct. 2013

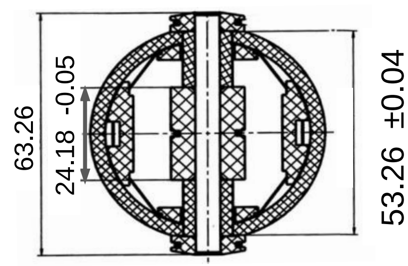
First measurements in FoSD Jul. 2014

New System for Magnetic Field Measurements

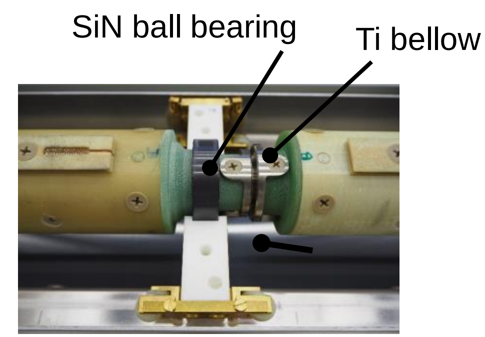
System for magnetic field measurements

- ✓ 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

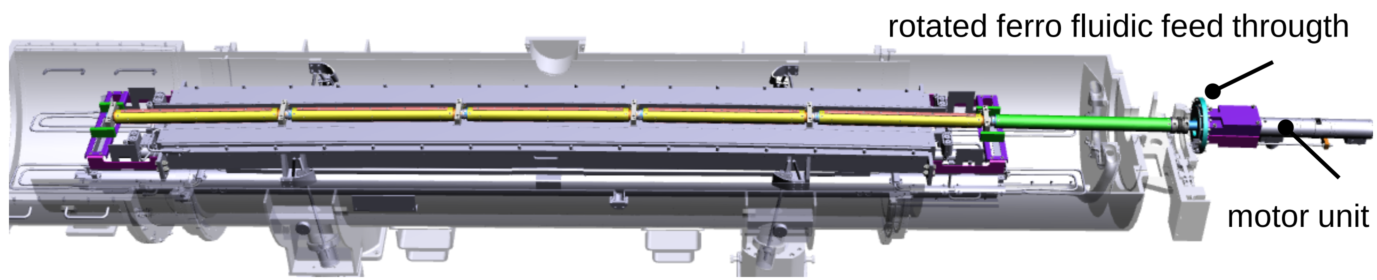




cross section of the measuring head (3 tangentinal coils)



Field measurements in vacuum @ 4.5K

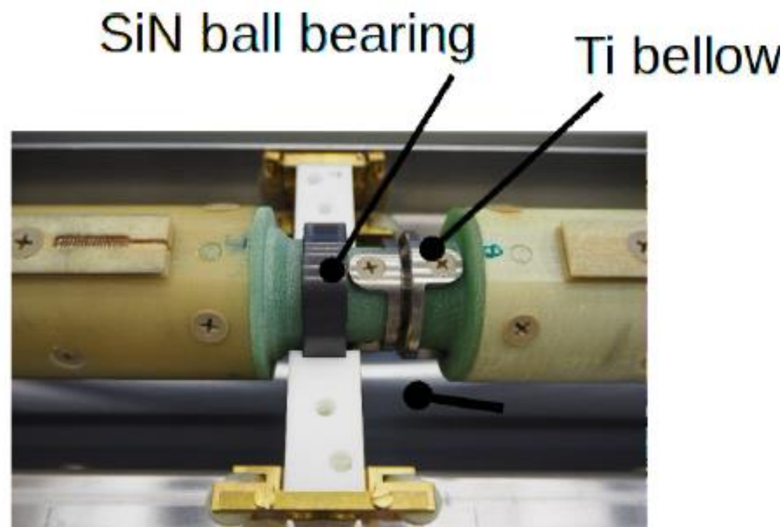


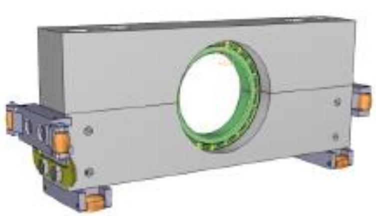
The measuring probe is designed and built in collaboration with CERN

New System for Magnetic Field Measurements

Mechanical challenges

- all material should be non-magnetic
- thermal expansion
- Ceramic Si_3N_4 ball bearings
  - moving at 4.5 K (no grease or oil)
  - → many different types tested
- Ti-alloy bellows
  - shaped for eddy-current reduction
- Ceramic holder with small wheels for installation
  - two parts for easier maintenance
- Peek screws (nylon didn't work)

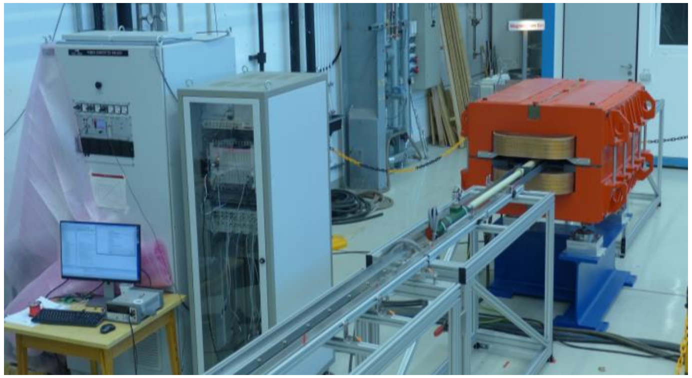




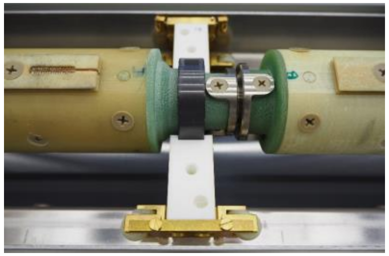
courtesy F. Kaether (SCM)

New Measurement Systems for Qualifying SIS100 Series Dipoles

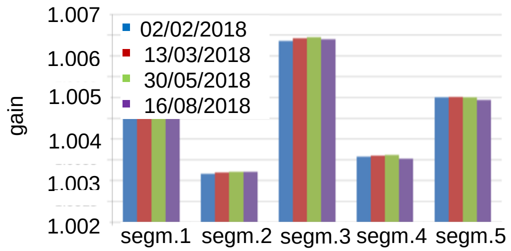
Calibration of the magnetic field measuring probe

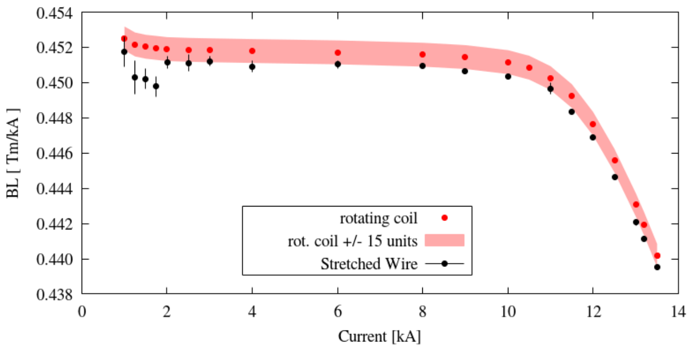


- ✓ calibration @ 300K in NC dipole
- ✓ surface calibration –> precise measurement B_1,$\int Bdl$
- ✓ angular displacement of the head relative to the reference one, i.e., the middle segment –> direction B_1, higher order harmonics
- ✓ lengths of the interconnection areas between the segments –> precise measurement $\int Bdl$



does the warm calibration work for the cold measurements?

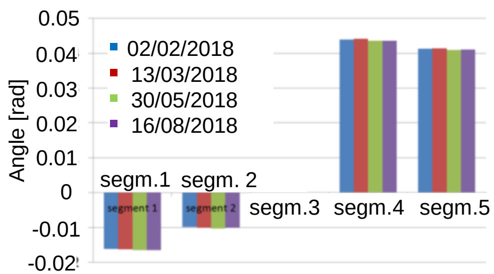




yes, it works and is precise enough for qualifying of the SIS100 dipoles.

Required precision < 4×10^{-3}

mechanic of the MF-probe is not affected by thermal cycles. The calibration stays stable



New Measurement Systems for Qualifying SIS100 Series Dipoles

System for high precision gap height measurement V2

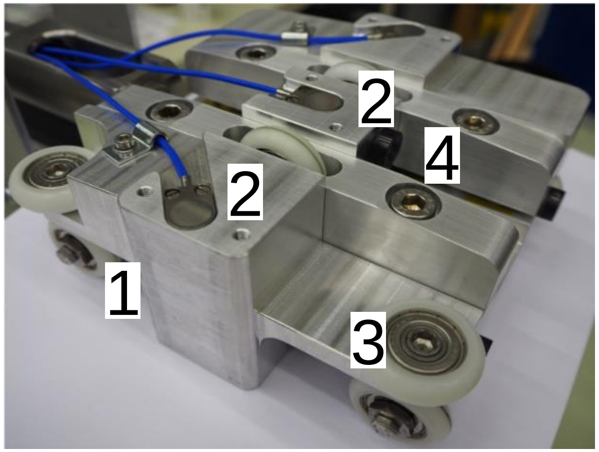
- ✓ 6 capacitive sensors CSH1,2FL(20)-CRm 4,0 from Micro - Epsilon GmbH& Co.KG
- ✓ linear encoder WDS-100-P 115-CR from Micro-Epsilon GmbH& Co for reproducible positioning of the carriage along the magnet

absolute precision 15µm

relative precision < ± 3µm

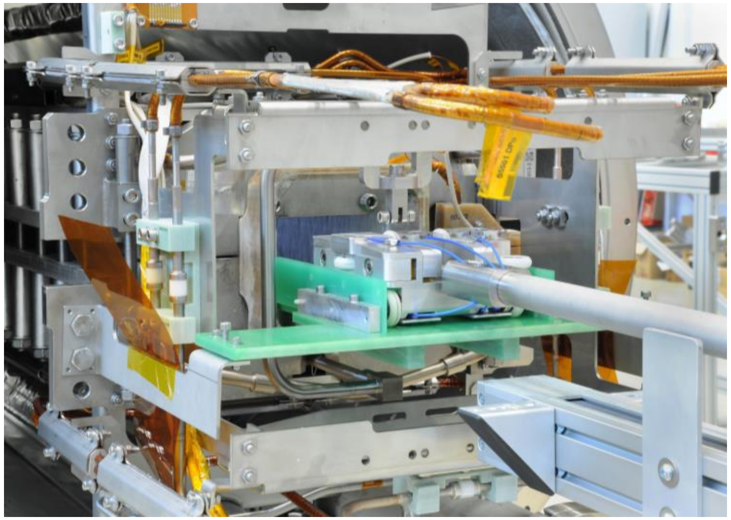
} @ 300K

In combination with a laser tracker, the system provides data regarding the yoke’s sag and twist.



1 carriage, 2 capacitive sensors, 3 wheels,

4 holder for spherically mounted retroreflectors.



The Team for SIS100 Dipole Testing

design, physics, evaluation, et al.

+ W. Freisleben, M. Al Ghanem, A. Zaghloul, H. Bouillot, V. Velonas, K. Knappmeier, A. Junge, T. Ziglasch

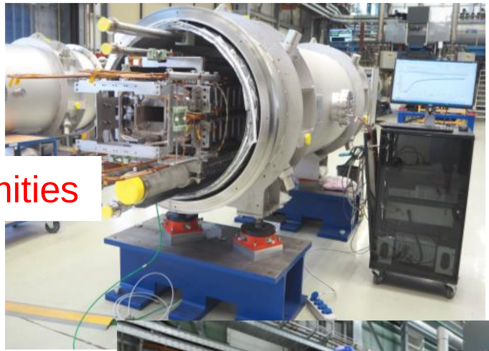
- survey & alignment
- electrical integrity
- field measurement
- quench detection
- cryo operators
- DAQ, control and analysis
- transport & installation
- quality assurance
- Communication with production
- test coordinators

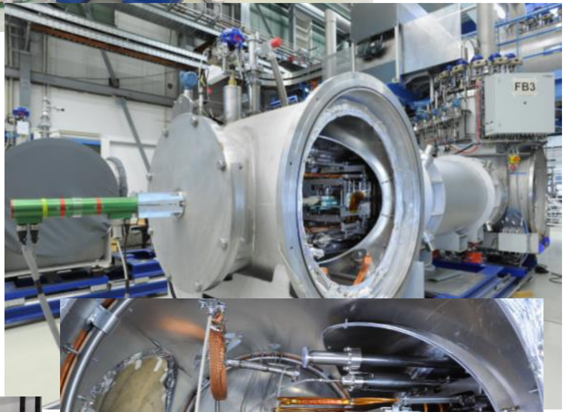
GSI departments

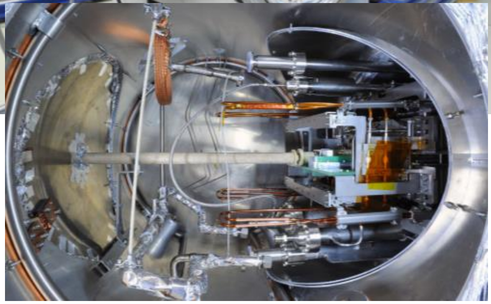
SCM, QA, TRI, CRY, EN-MG, EPS, VAC, BB, RHV
Support on demand – MEWE, KB, ENG

Site Acceptance Test (SAT): Sequence

- Reception
  - ✓ visual inspection
  - ✓ document check
- SAT @300 K (incoming) 5 days to 4 weeks if non-conformities
  - ✓ geometry
  - ✓ instrumentation
  - ✓ electrical insulation
  - ✓ pressure and leaks, massflow rate
- Mounting on the test bench 2 - 3 days
  - ✓ Installation of the MF-probe
  - ✓ electrical integrity magnet+current leads
  - ✓ pumping - 24 h
  - ✓ cool down – 76 - 90h
- SAT @ 4.5K 3 - 4 days
  - ✓ electrical integrity and insulation
  - ✓ magnet training
  - ✓ inductance
  - ✓ magnetic field
  - ✓ static and AC losses
- warming up and dismounting 4 - 5 days
- SAT @ 300K (outgoing) - 2 days







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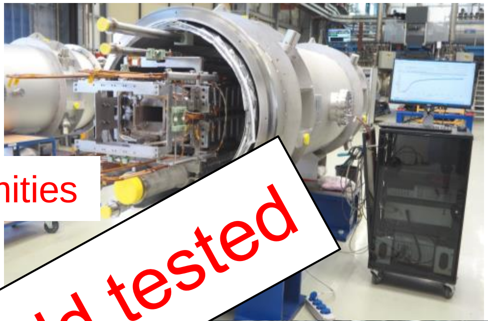
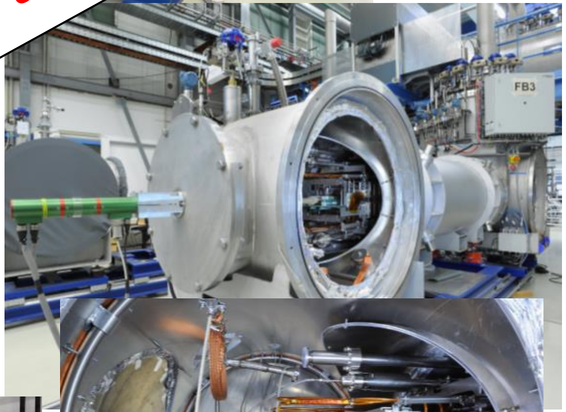
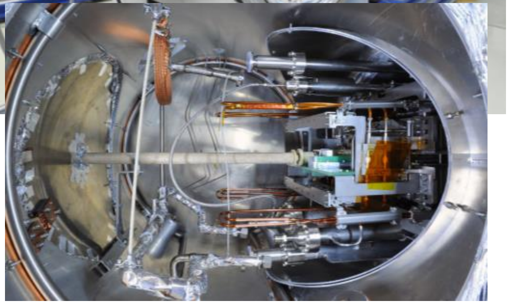
  - ✓ g
  - ✓ ce
  - ✓ gnetic field
  - ✓ static and AC losses
- warming up and dismounting 4 - 5 days
- SAT @ 300K (outgoing) - 2 days

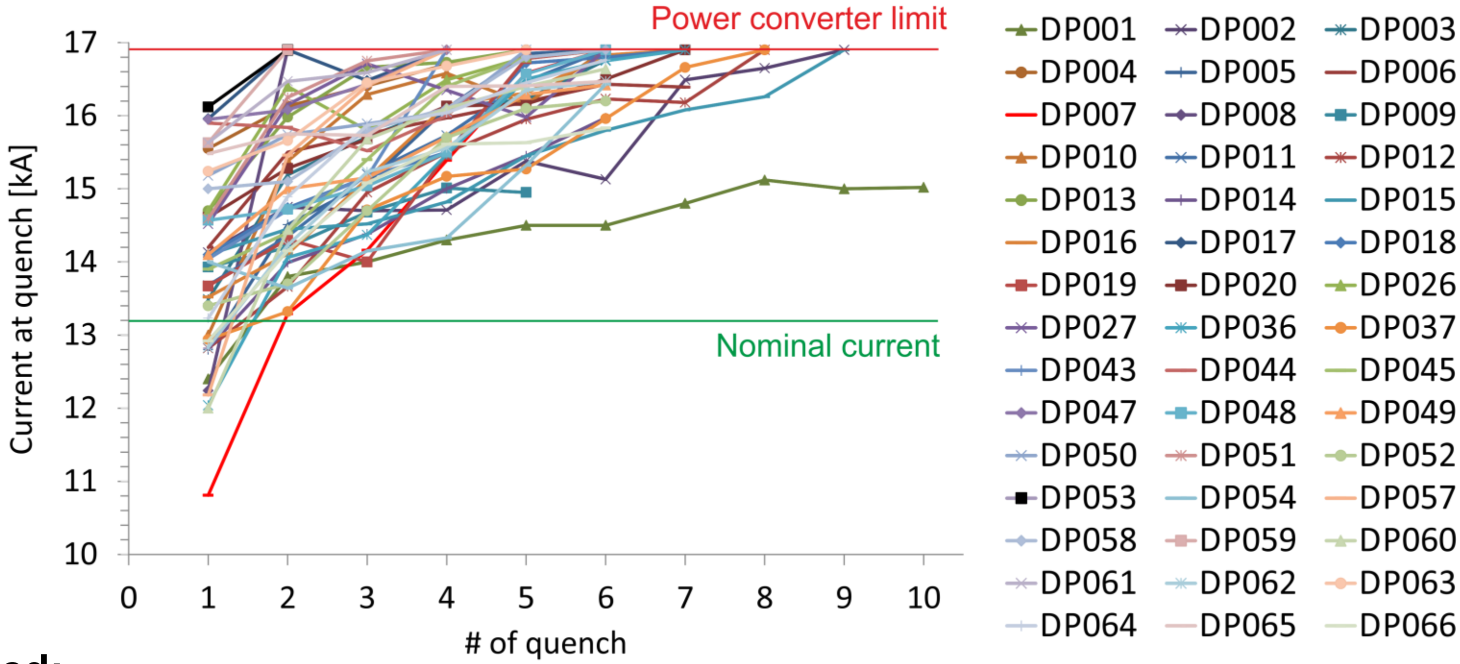
47 out of 110 magnets have been cold tested







SIS100 Series Dipole Magnets: Training



45 magnets tested @ **cold**

Specified:

- nominal current (nc) to be reached:
  - at 3rd quench in first cycle
  - at 1st quench in further
- de-training limited to 5 % of nc (compared to previous quench)
- quench current has to stabilize at 110 % of nc at least (14.5 kA)

Outstanding quench performance!

✓ nom. current reached at 2nd quench at least

✓ no significant de-training observed

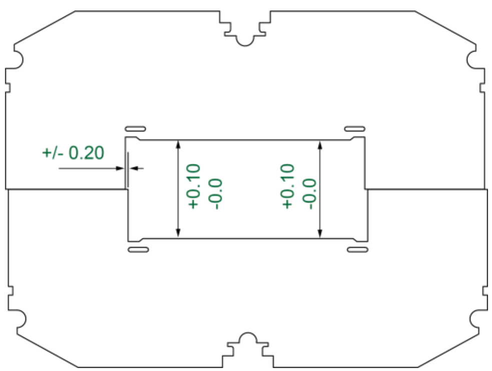
Training close to the short sample limit of the cable (17.8 kA)

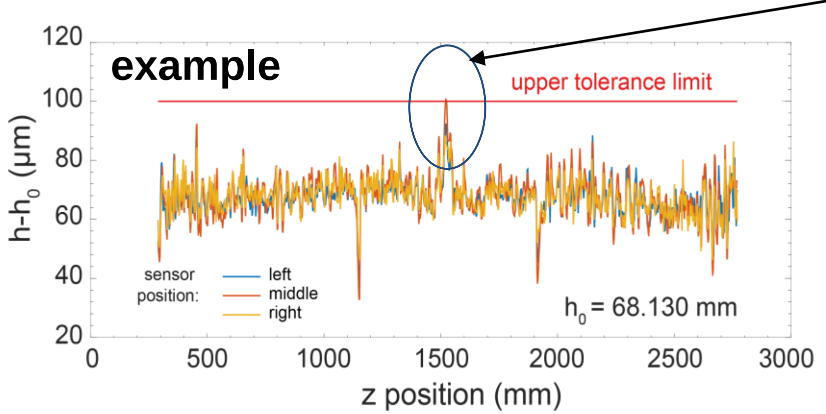
→ high stability of the coil structure in the yoke.

Test Results for SIS100 Series Dipoles

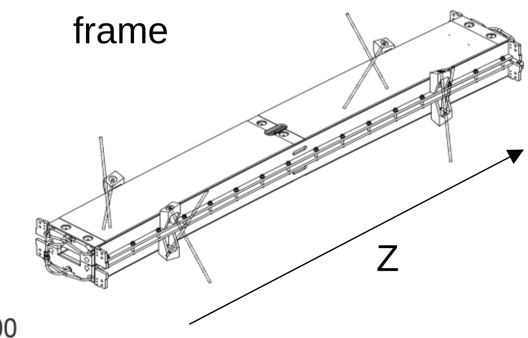
Gap geometry

required:





spot welding of lamination to outer frame

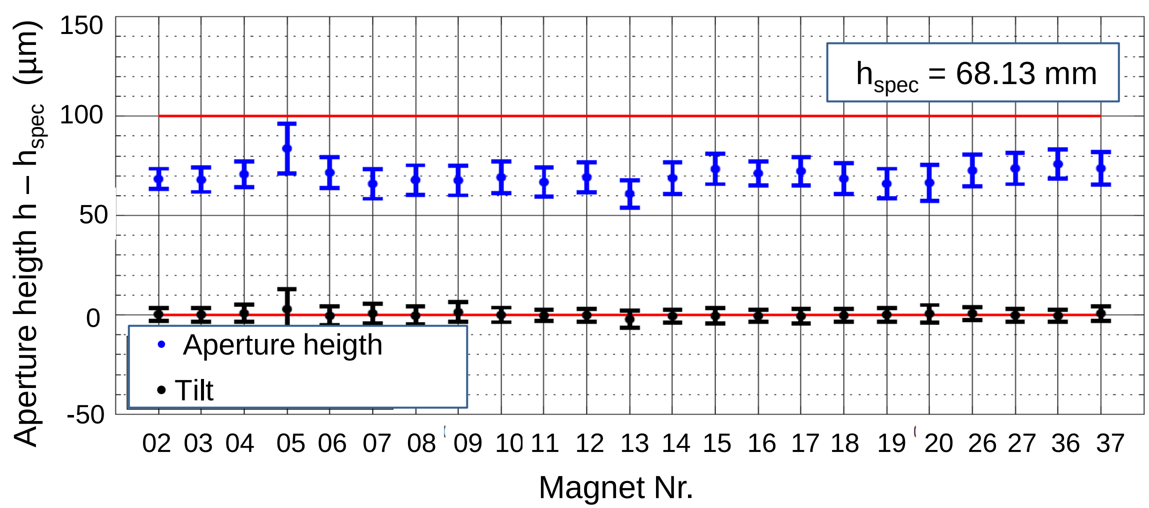


aperture height (→BL)

- well within specification on average for each magnet
- very good reproducibility

tilt (→ a_n, b_n)

- negligible



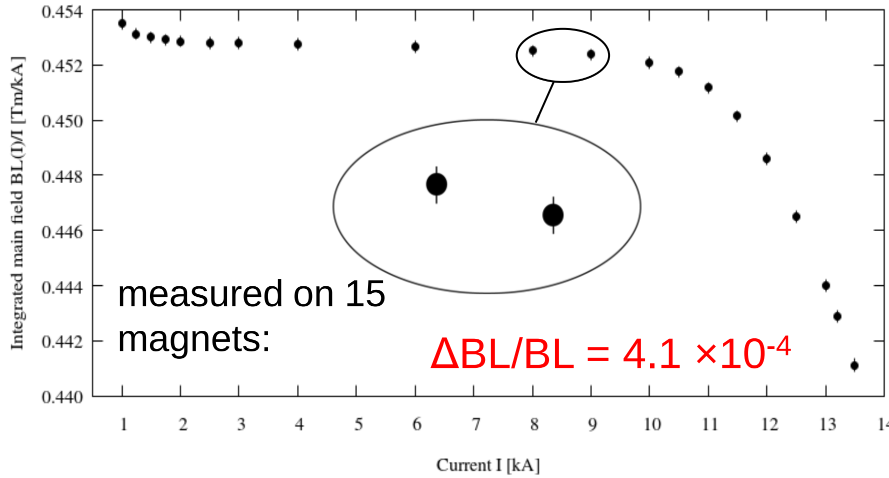
Test Results for SIS100 Series Dipoles

Integral Field

acceptance criteria for SIS100:

$\Delta BL / BL \leq 4 \times 10^{-3}$ with $BL = \int B(l)dl$

measured on 15 magnets: ΔBL/BL = 4.1 ×10^{-4}



Field homogeneity

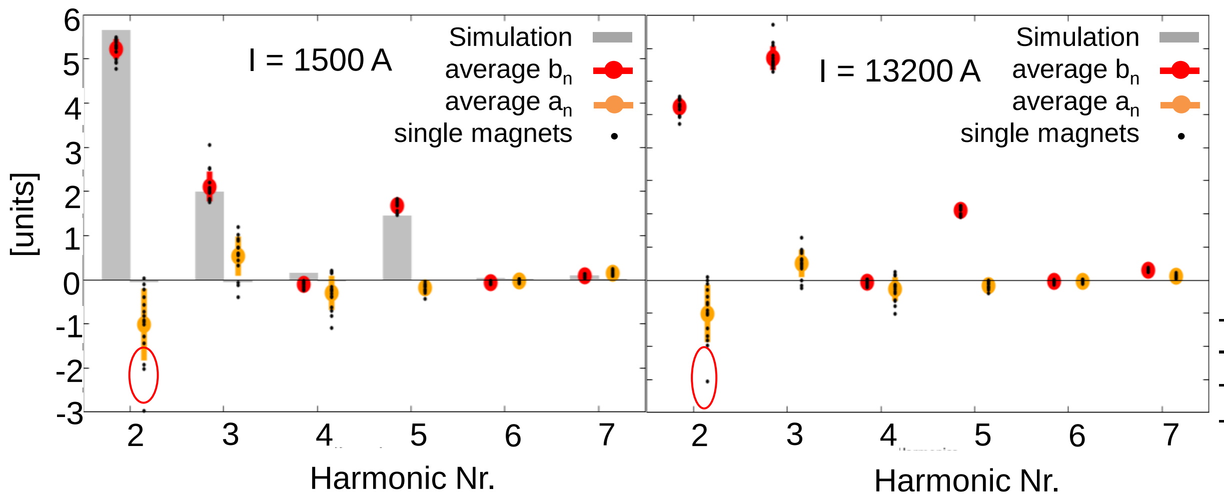
acceptance criteria:

$\sum_n C_n / B_1$ < ± 6 units @ R_{ref}= 30mm

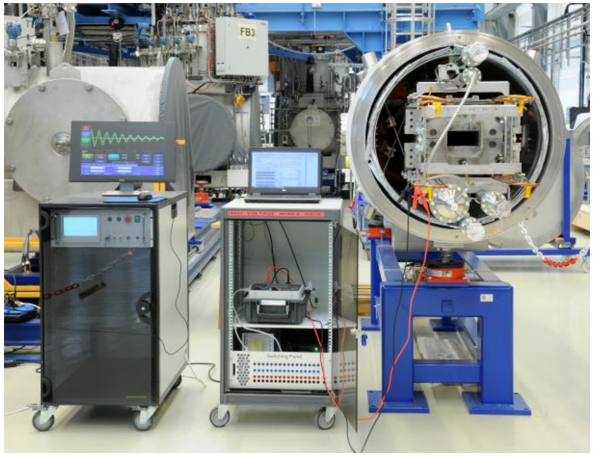
$$\boldsymbol{B}(z = x + iy) = \sum_n \boldsymbol{C_n} \left(\frac{z}{R_{\mathrm{ref}}}\right)^{n-1} \quad \text{with} \quad \boldsymbol{C_n} = B_n + iA_n$$

measured on 15 magnets:

- ✓ magnet data acceptable for synchrotron operation
- ✓ good agreement with expectation except:
  - b_3 systematic → correctable
  - a_2 under investigation
- ✓ high reproducibility (except …)



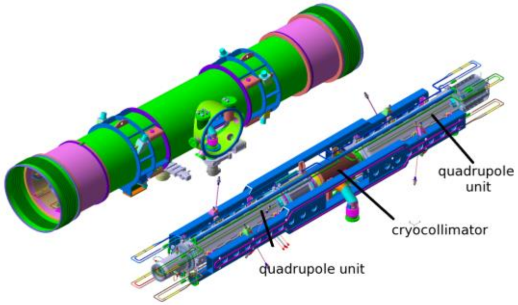
Next Activities at Test Facilities for SC Magnets



SAT for SIS100 Dipole ~29th Sept. 2017 – Mai. 2020

delivery rate - 1 magnet per week starting from the 5th one (approximately. from Dec.2017).

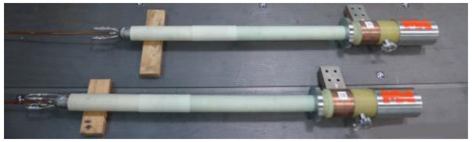
SAT for FoS Quadrupole Module (Typ 2.5) for SIS100 ~ Q3/2019



String Test

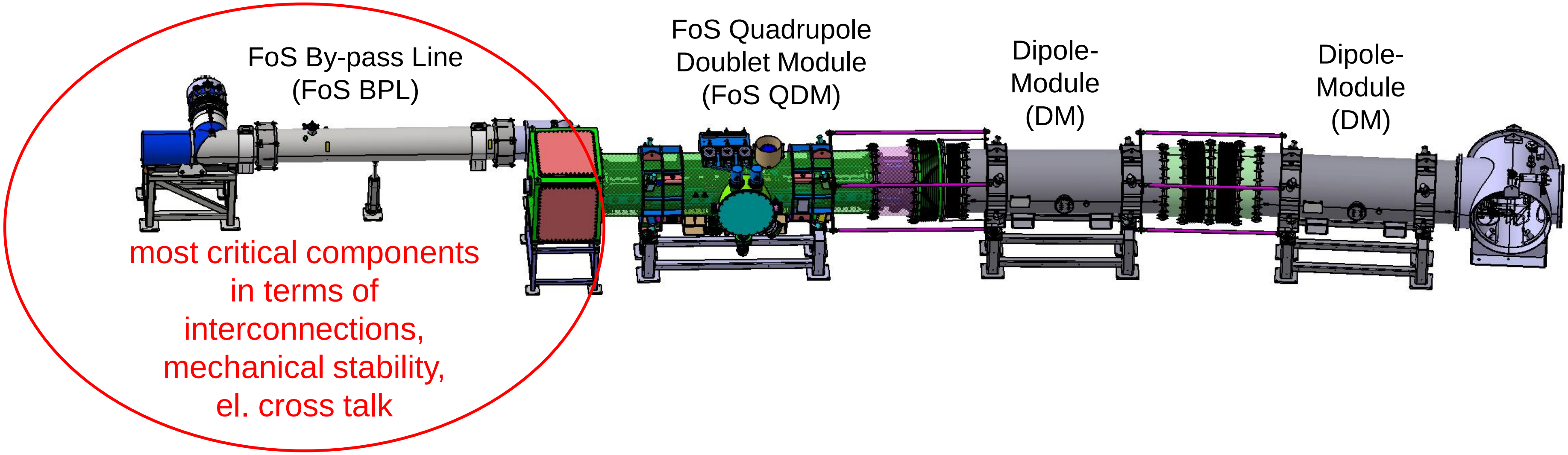
- from Q1 2020 to Q4 2020

Other testing activities



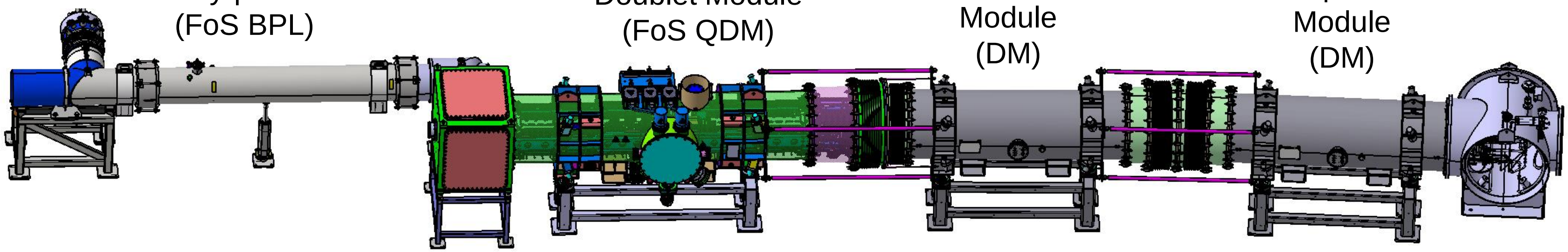
- 13 pairs of the Main Current Leads (14kA DC HTS) for SIS100 ~ March 2016 – Sept. 2019
- FoS BPL (long unit)
- Feed-, End- and Current Lead Boxes for SIS100 of one type
- FoS VC for the SIS100 dipole
- LCL for SIS 100
- Cryocatcher
- CL (FoS) for Super-FRS

SIS100 String Test



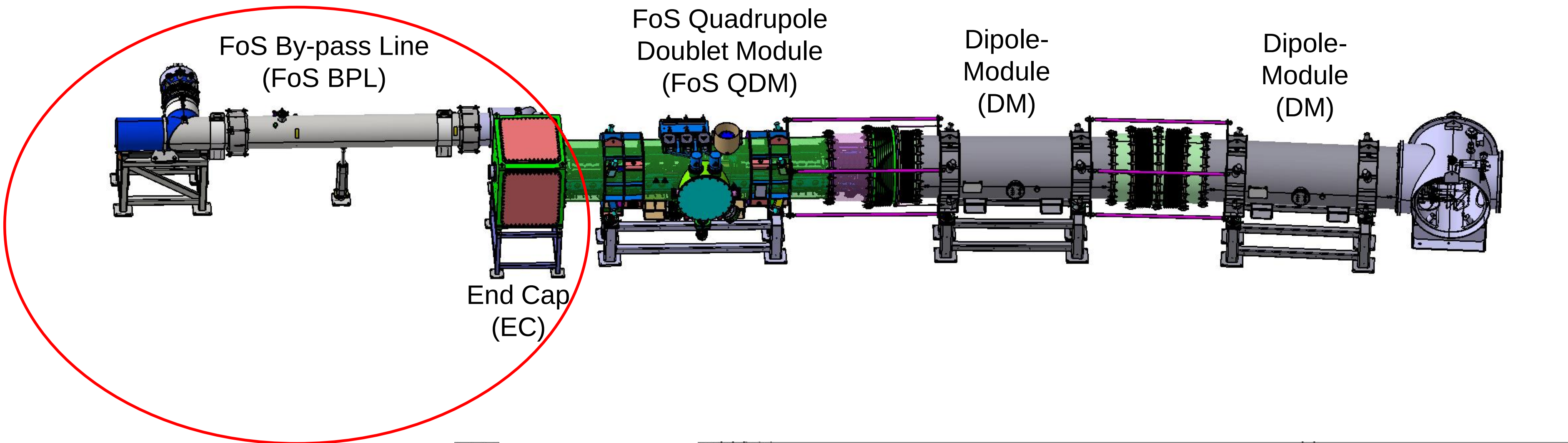
- a short section of SIS100 built of main cryo-magnetic and local-cryo components of the SIS100
- verification of different interfaces and interconnections regarding fitting and mountability
- preparation for installation, commissioning and operation of SIS100

SIS100 String Test: Objectives

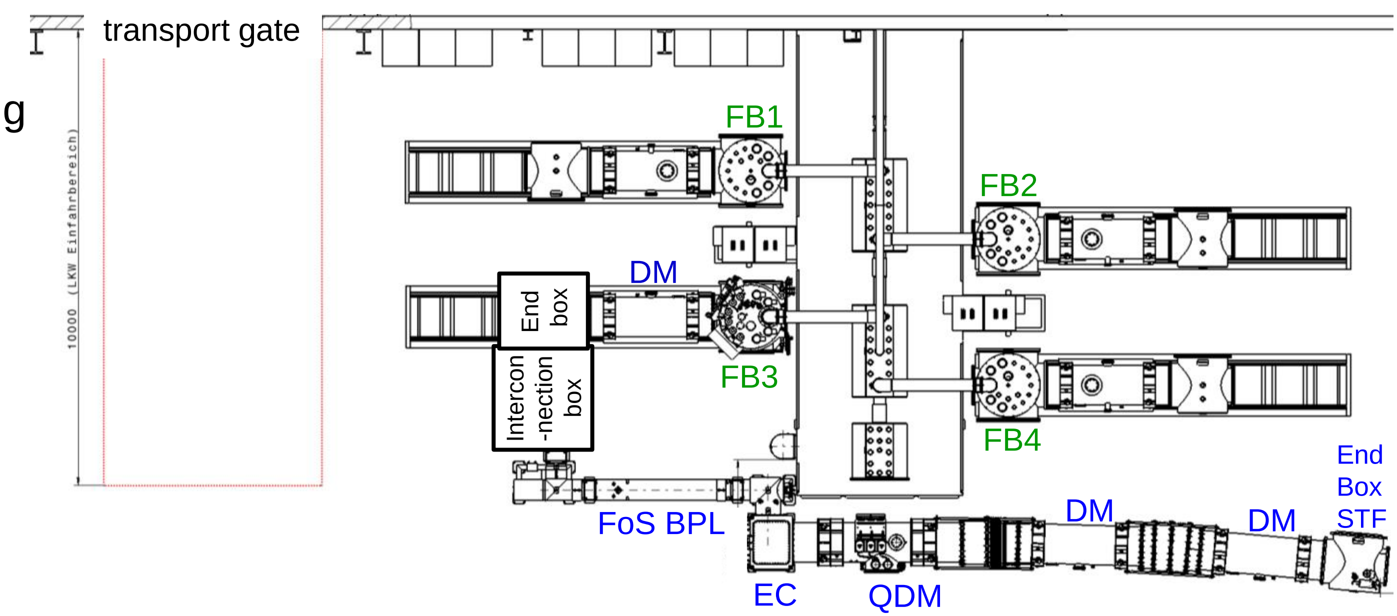


- preparation of work instructions for the machine installation (cooperation of SCM, CRY, UHV, TRI, ENG, TEL,FSB, approval through WPLs, SPL SIS100)
- choosing appropriate tools for installation in the tunnel
- mechanical stability of interconnections
- insulation vacuum stability and performance of the UHV components
- cooling down behaviour, functionality of parallel cooling channels and local cryo-components
- electrical issues – cross-talk between live circuits, degradation of insulation resistance
- testing of new quench detectors and cabling
- testing of the slow control system

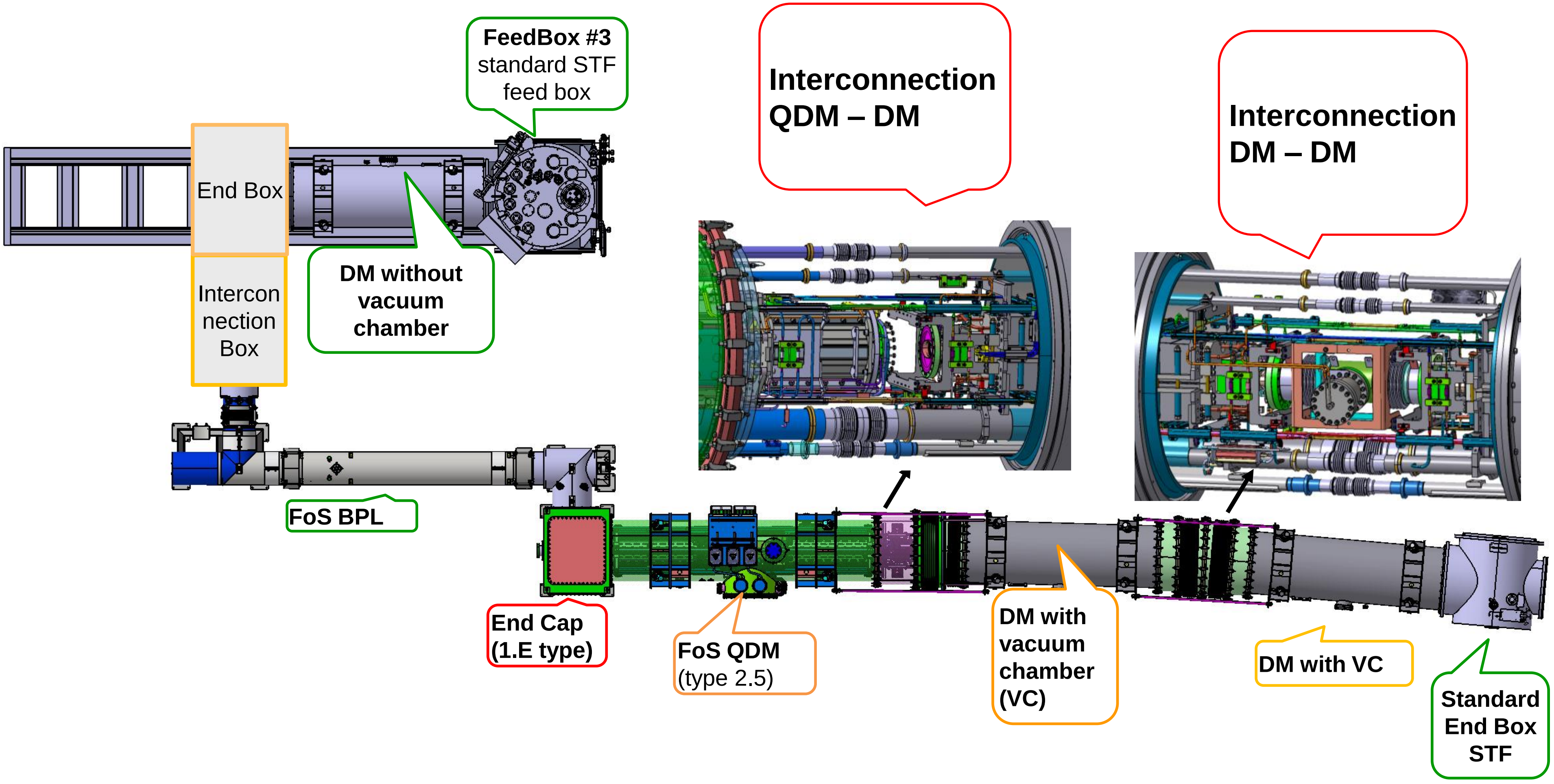
Configuration of the SIS100 String



Arrangement of the string at STF



SIS 100 String Layout and Single Components



Time Line & Required Resources

Milestones for realisation of the string test

definition of the useful configurations	DMU for installation at STF	final decision for the string configuration	design of the auxiliary constructions	procurement of the auxiliary constructions	assembly of the string	testing phase
28.09.2018	23.10.- 31.10.2018	18.01.2019	02.- 06.2019	06.2019 - 01.2020 availability of the end cap and interconnection bellows 01.2020	02.-03. 2020	03. – 08.2020

Requirements:

- upgrade of the infrastructure at STF (e.g. warm cables to the 20kA PC, additional electronics for QuD, DAQ)
- design and production of auxiliary constructions
- human resources: SCM, CRY, EPS, ACO,UHV, TRI, DMU, ENG, MEWE, EKM

Summary and Outlook

- The sc magnets for SIS100 have been developed at GSI based on the Nuclotron magnets
- Magnet development: FEM and CAT models → short magnet models → full size prototypes -> FoS magnet; dipole: 2001 to 2013, quadrupole module: 2001-2017
- The series production of the SIS 100 dipole magnets started in August 2016 and the series production of quadrupole and corrector magnets started in Q2 2019
- The infrastructure required for the qualification of magnets was constructed/set up at GSI by close collaboration of colleagues from CAM, GAT, CRY, EPS, SCM and TRI departments
- Quality control and functionality tests at contractor and GSI site were defined
- High precision measurement systems for magnet evaluation were developed
- The measurement results obtained on the series dipole magnets reveal an excellent performance of the chosen design and high production quality (outstanding magnet training performance, coil stability, etc.)
- Since the geometrical properties of the aperture define the magnetic field quality, they are tracked for all series magnets
- The magnetic field shows very low variation in terms of the field integral and the low harmonic content is satisfactory for beam physics requirements.
- The magnet series production is ongoing: some „childhood diseases“ still to be overcome
- Currently the FoS quadrupole module is expected to be delivered in the end of August.
- The next challenges for magnet testing are the FoS quadrupole module and magnet string tests

Thank you for your attention