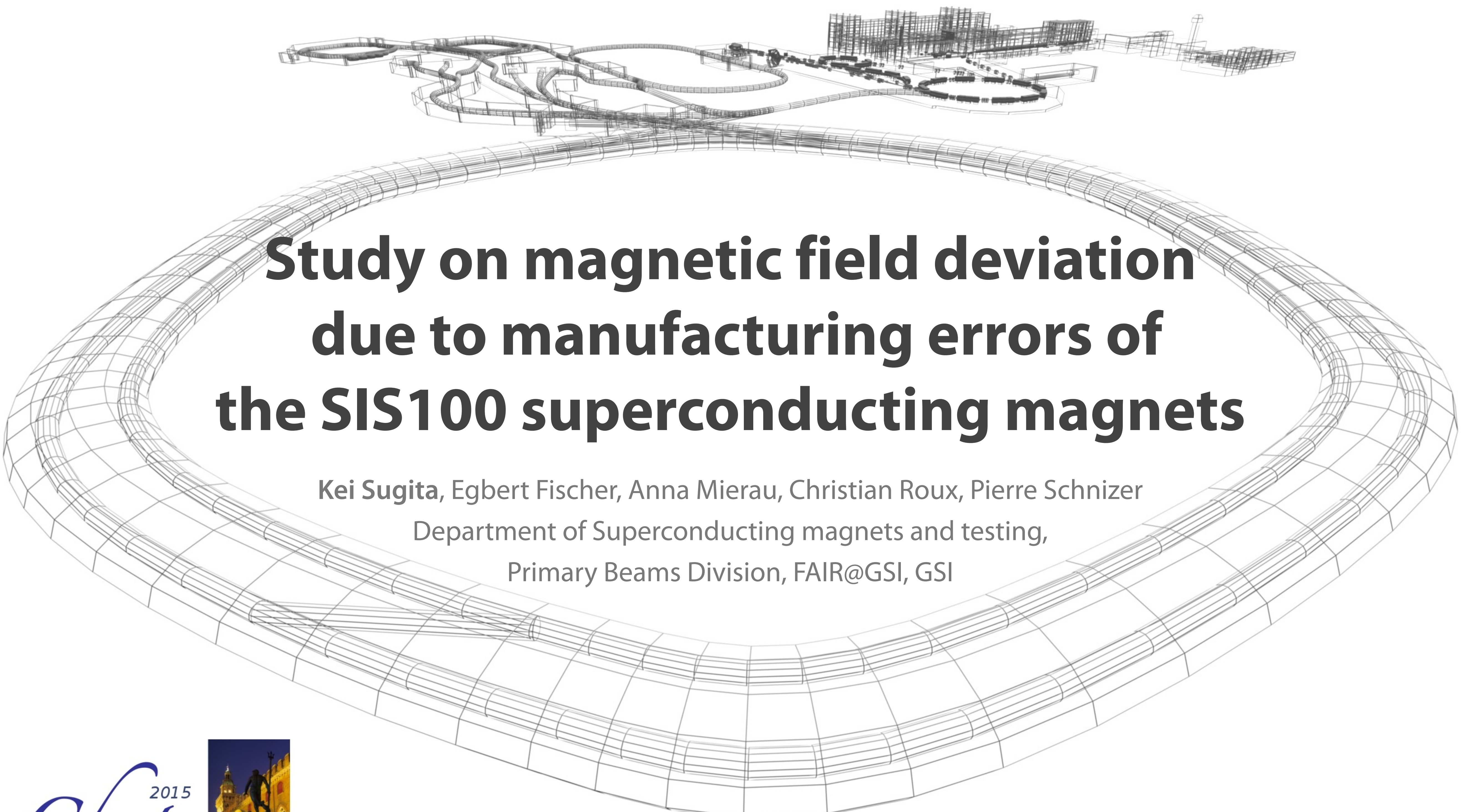


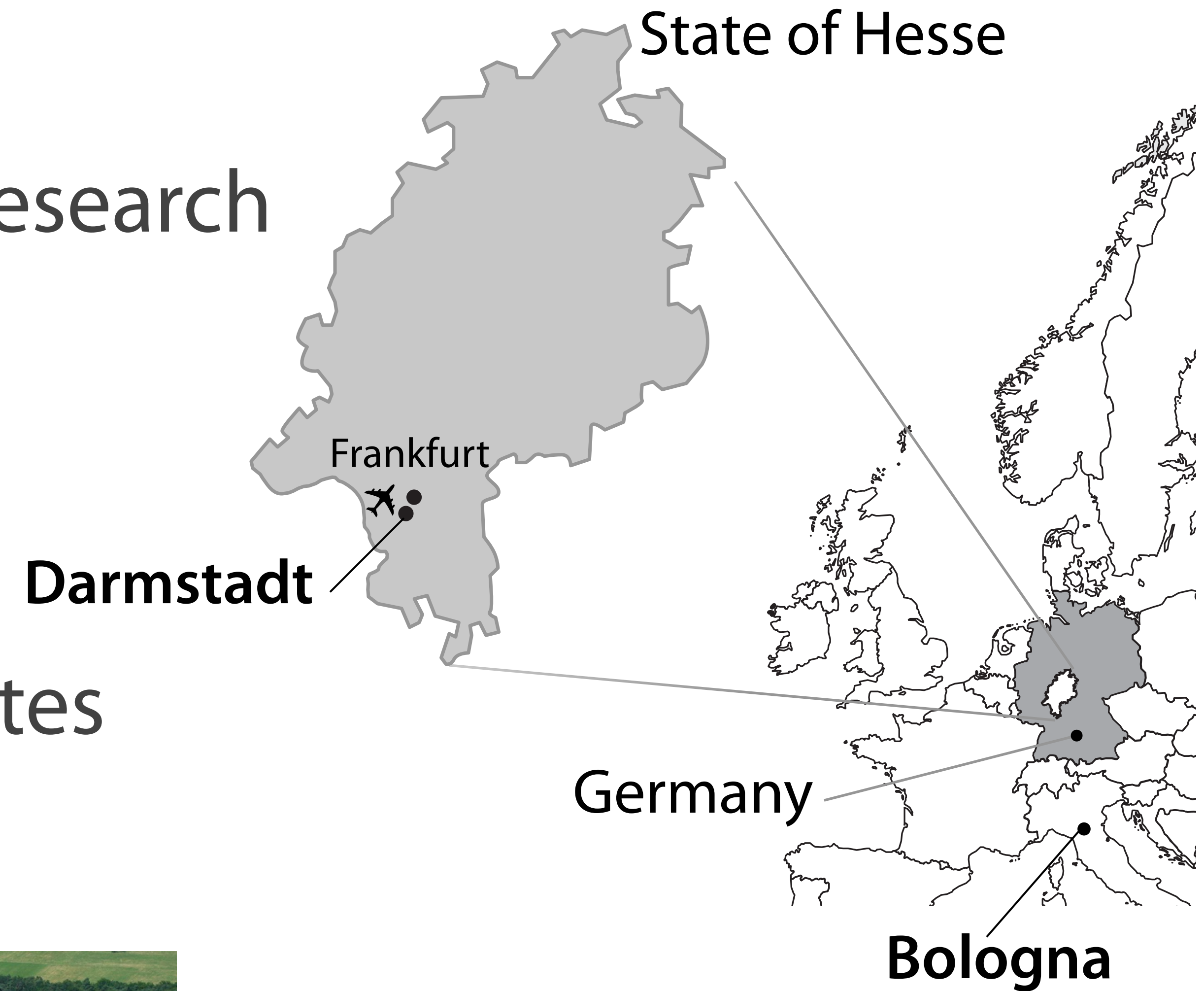
Study on magnetic field deviation due to manufacturing errors of the SIS100 superconducting magnets

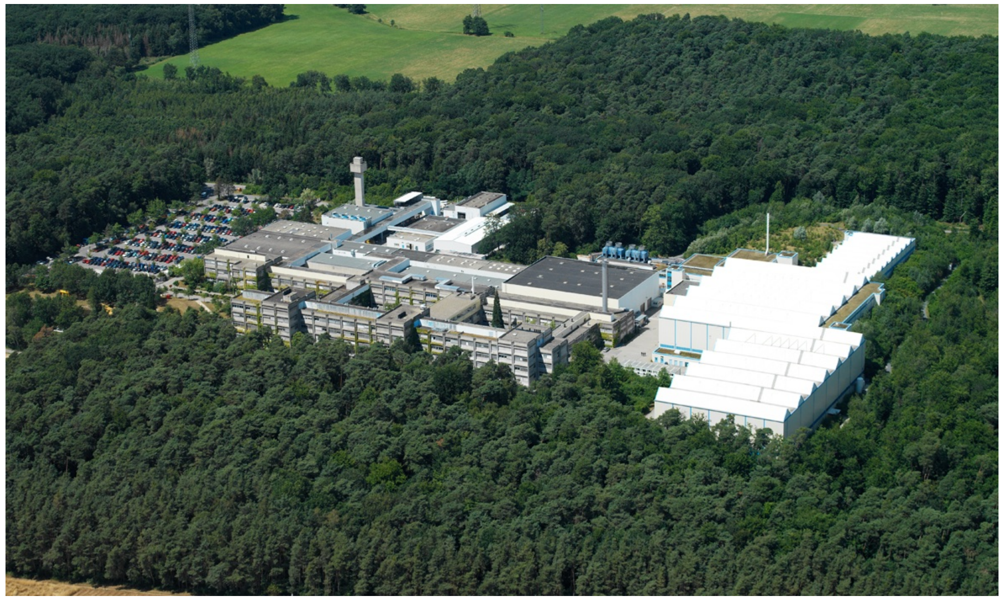
Kei Sugita, Egbert Fischer, Anna Mierau, Christian Roux, Pierre Schnizer
Department of Superconducting magnets and testing,
Primary Beams Division, FAIR@GSI, GSI

Contents

Introduction

- GSI
  - Helmholtz Centre for Heavy Ion Research
  - Employee about 1350
  - Shareholders
    - 90% German government
    - 8% State of Hesse, 2% other states
  - Heavy ion accelerator facility

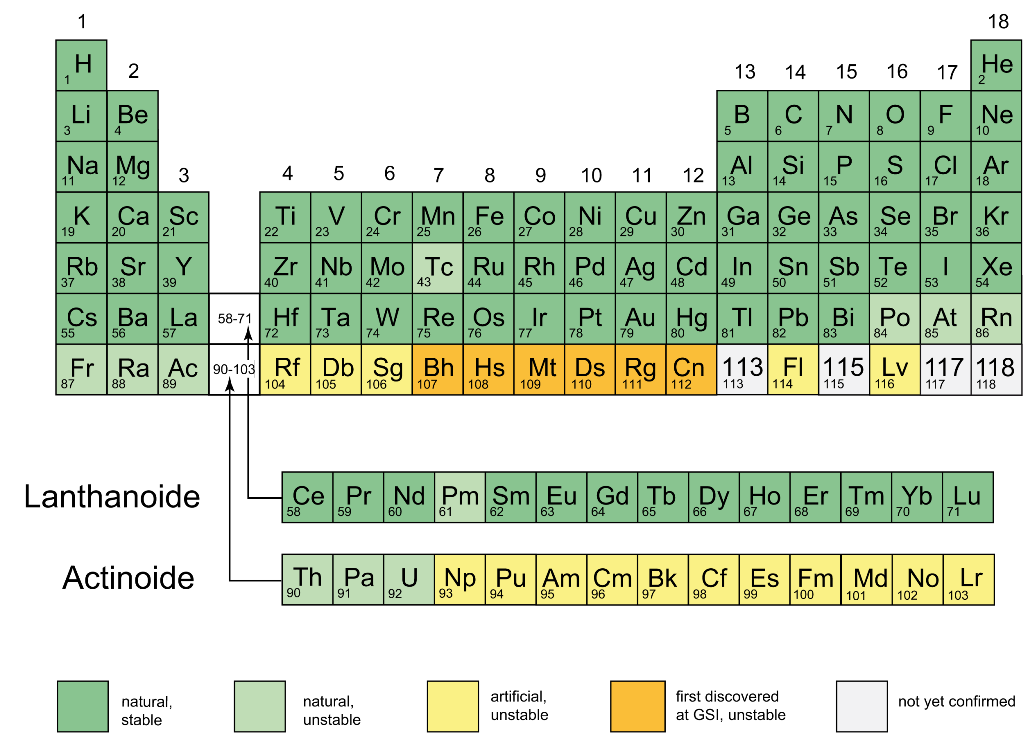




Introduction

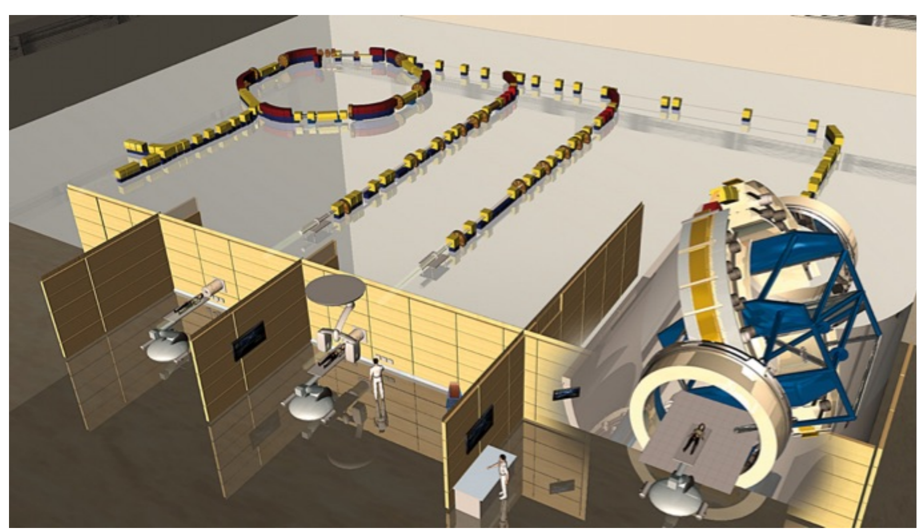
- GSI
  - Research
    - Nuclear and Particle Physics
    - Atomic Physics
    - Plasma Physics
    - Biophysics and medical science
    - Material research

Discovery of new elements



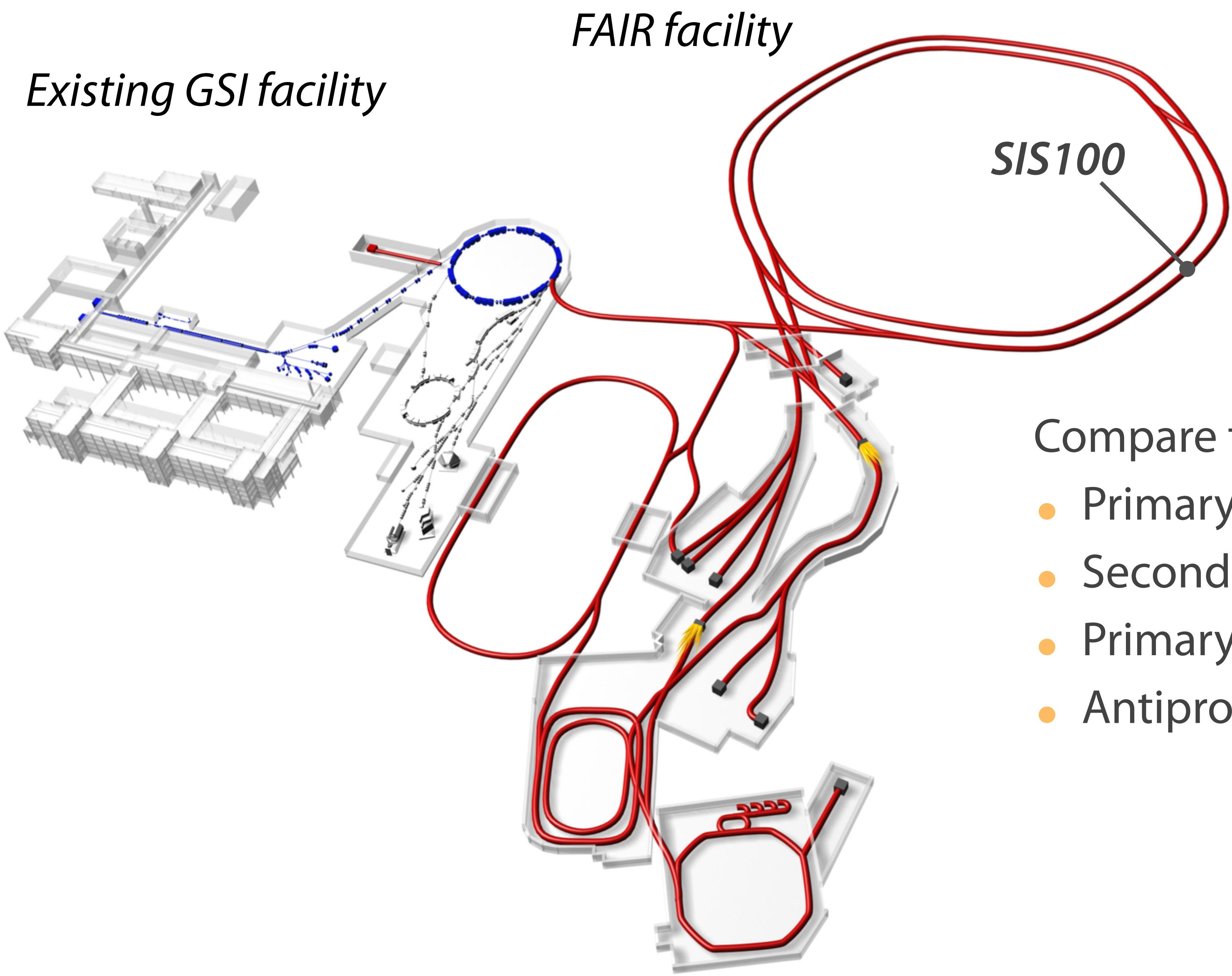
Atomic number	Symbol	Name	named after…
107	Bh	Bohrium	Niels Bohr
108	Hs	Hassium	State of Hesse
109	Mt	Meitnerium	Lise Meitner
110	Ds	Darmstadtium	Darmstadt
111	Rg	Roentgenium	Wilhelm Conrad Röntgen
112	Cn	Copernicium	Nikolaus Kopernikus

Ion Beam Therapy against Cancer

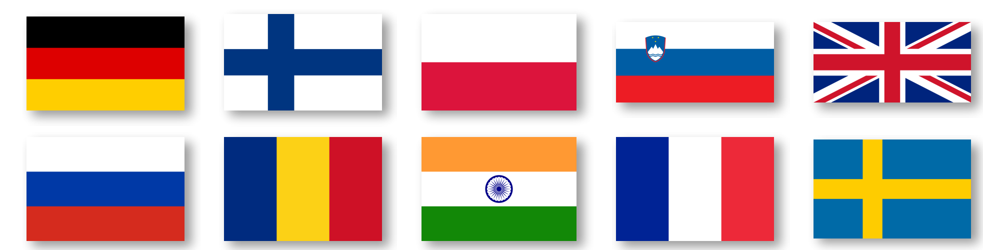


Introduction

- Facility for **A**ntiproton and **I**on **R**esearch



International project

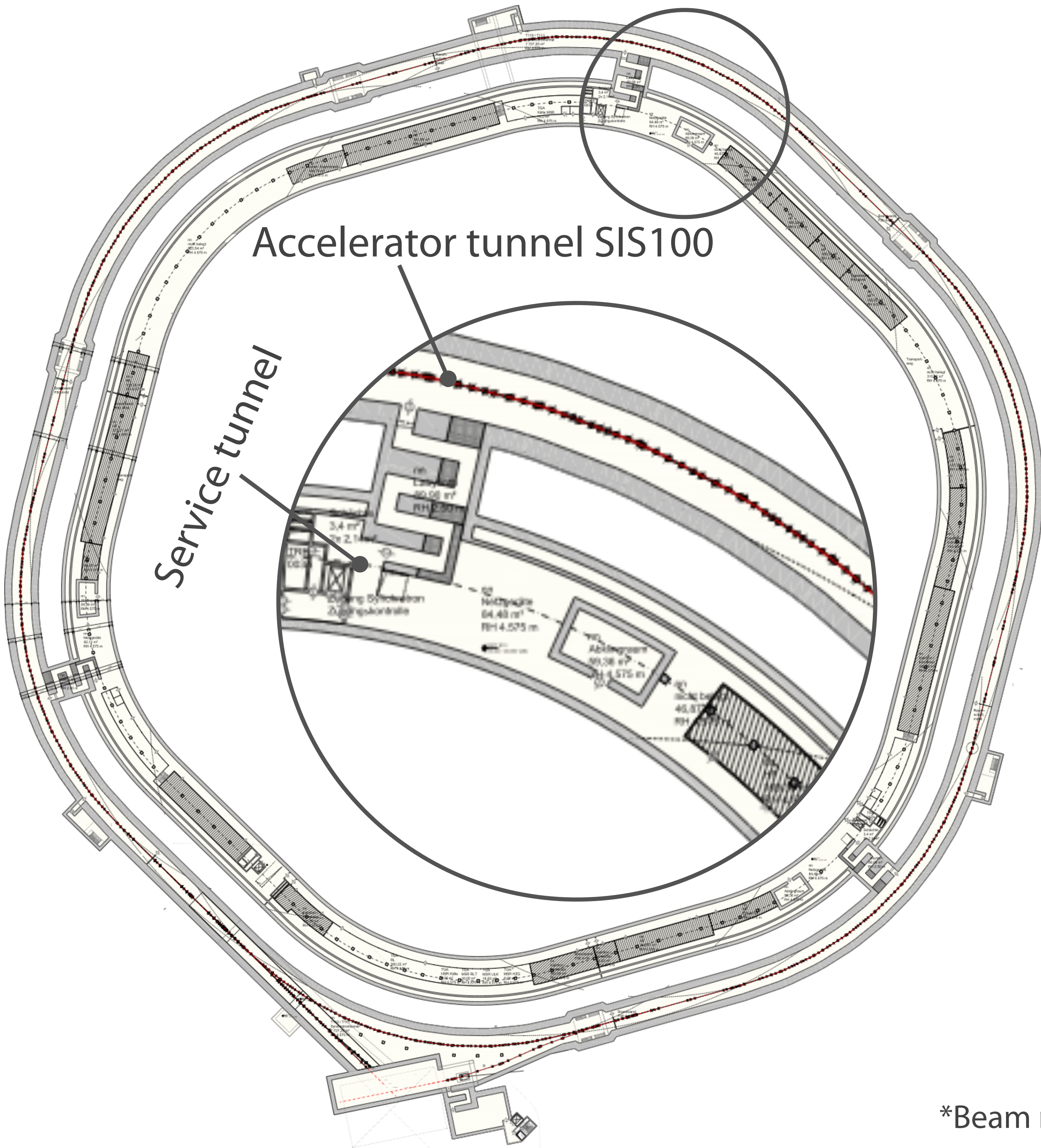


Compare to the existing GSI facility

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

Introduction

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



Hexagonal, circumference 1083.60 m

Key word: Heavy ion

Ultra High Vacuum (10^{-11}mbar)

- Adsorption by cold vacuum chamber (10 - 15K)
- Superconducting (magnet) accelerator
  - Space/energy saving

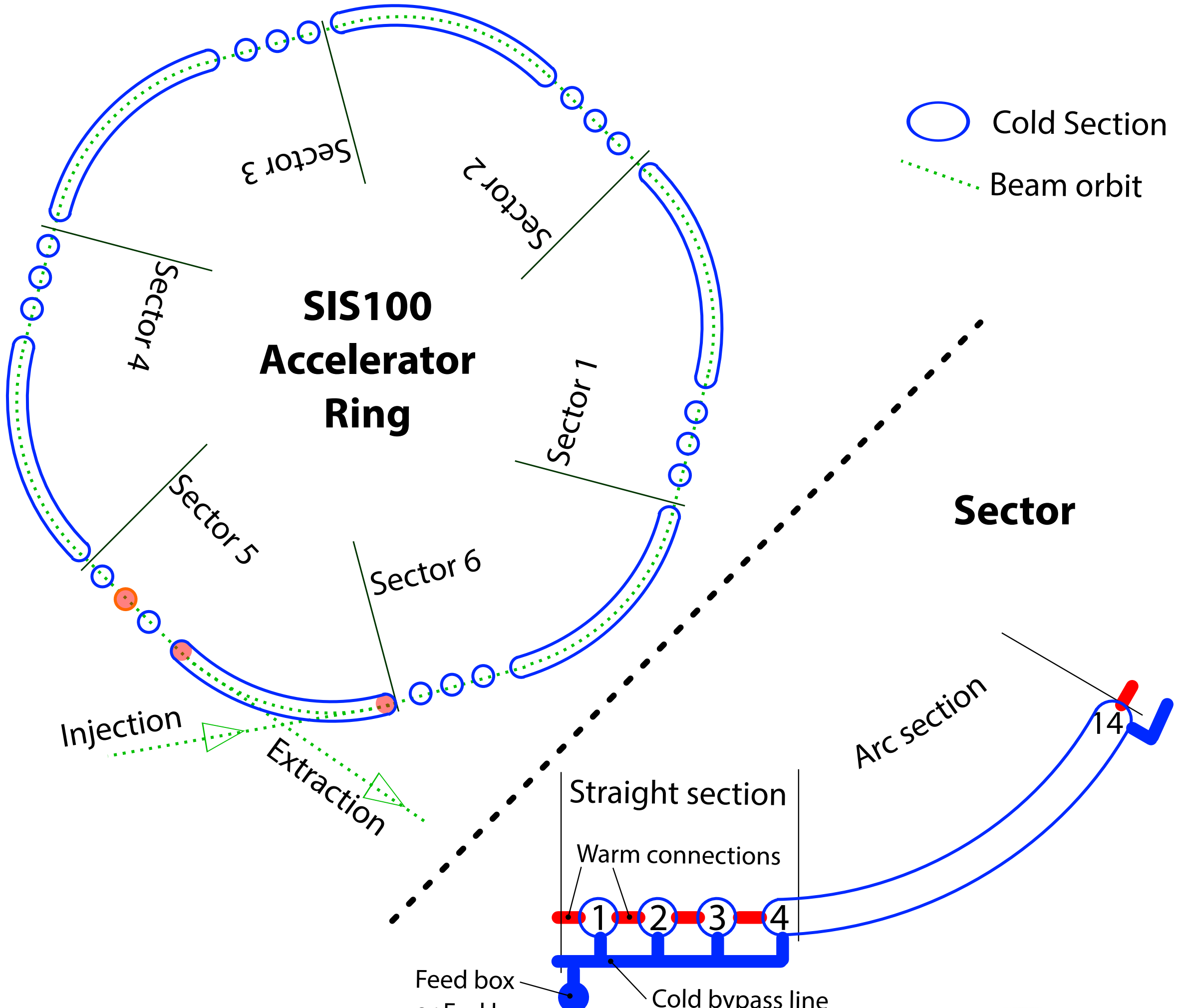
Fast-ramp Machine

- ~0.5 sec. to maximum field.

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

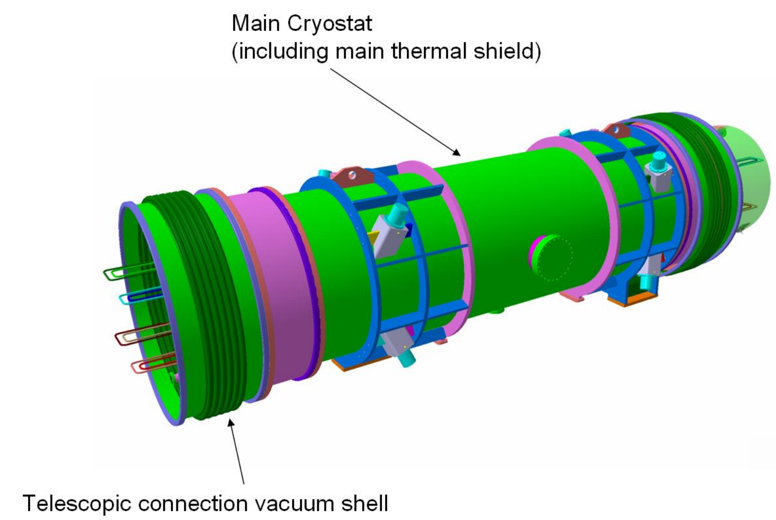
SIS100 Superconducting Magnet System

- Structure

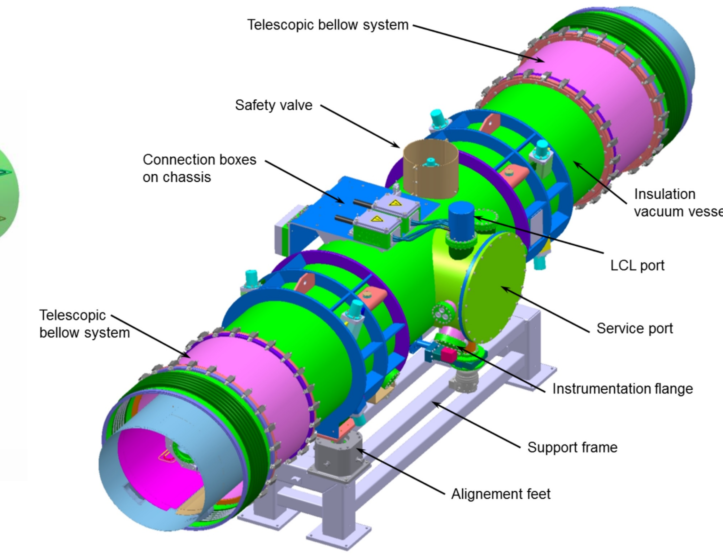


Cell 5 to 13

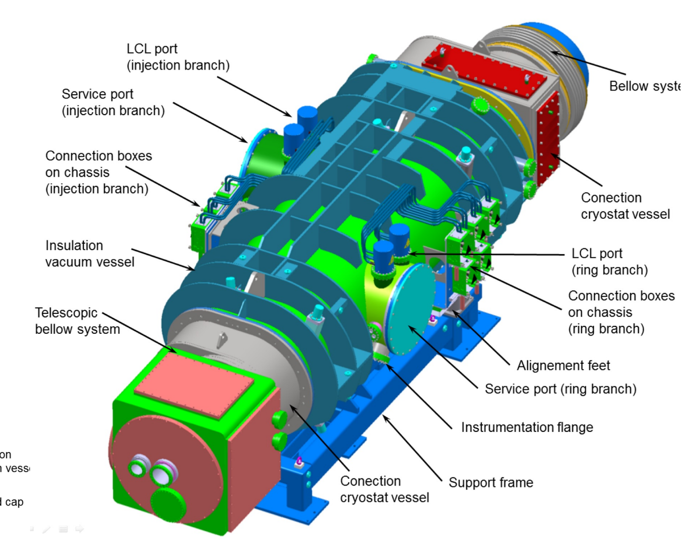
Dipole module



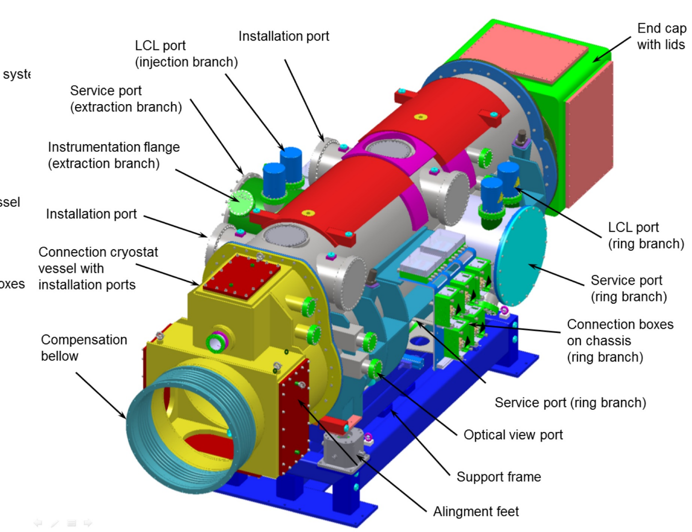
Quadrupole doublet module



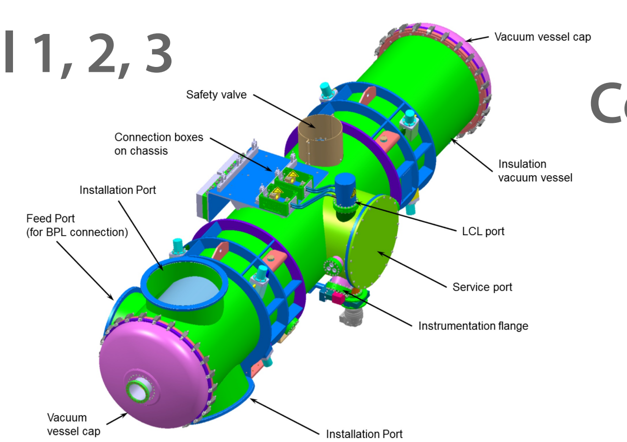
Injection



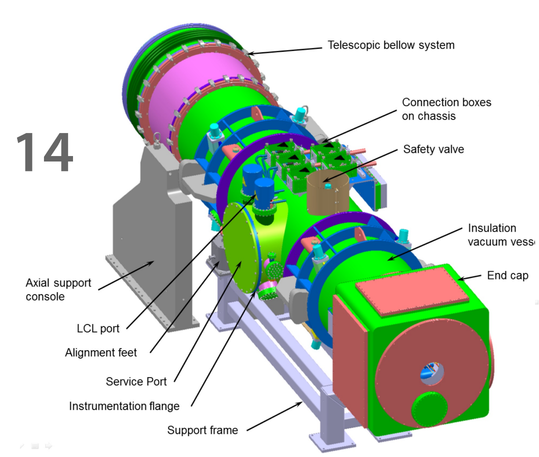
Extraction



Cell 1, 2, 3

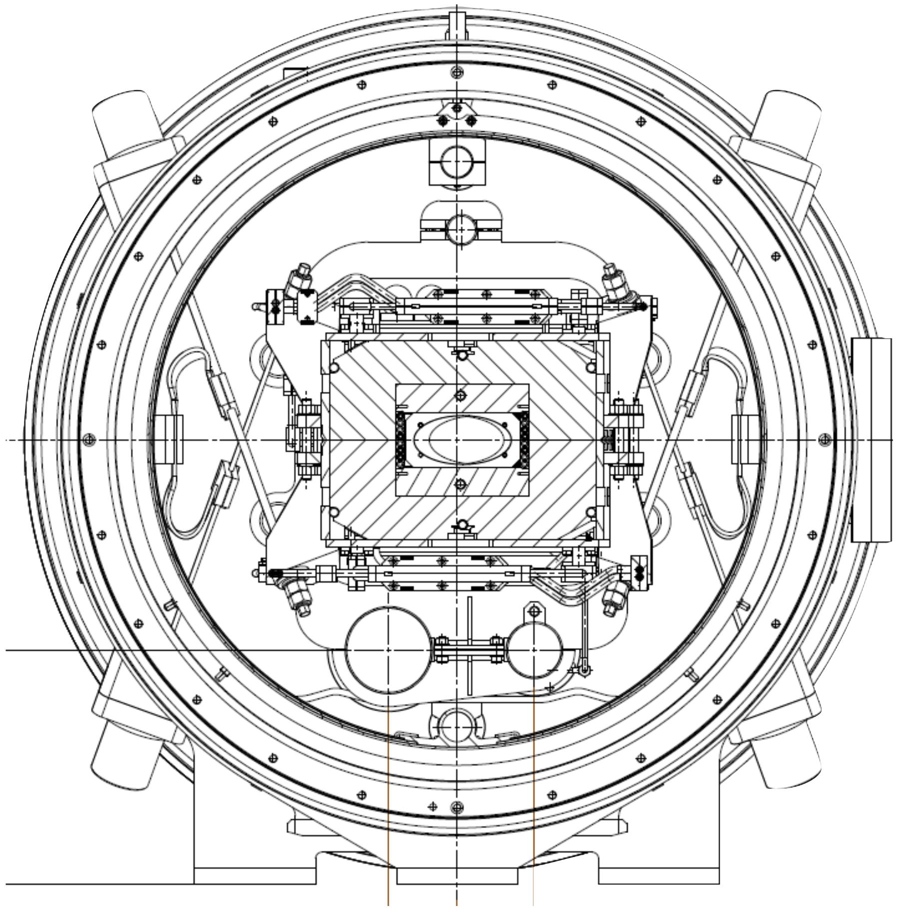


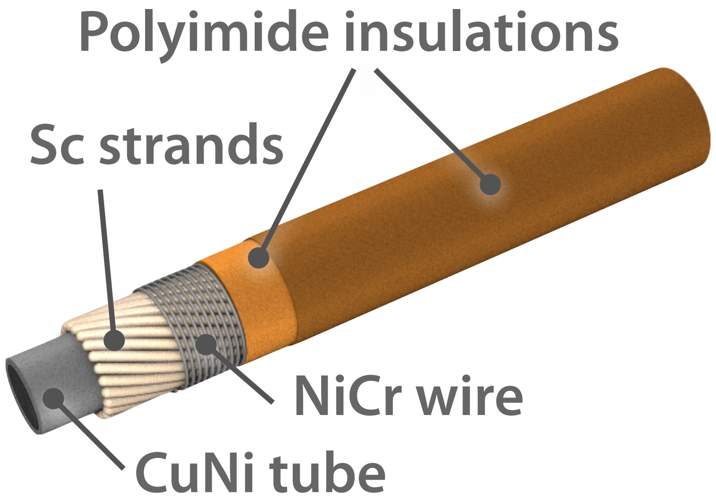
Cell 4, 14

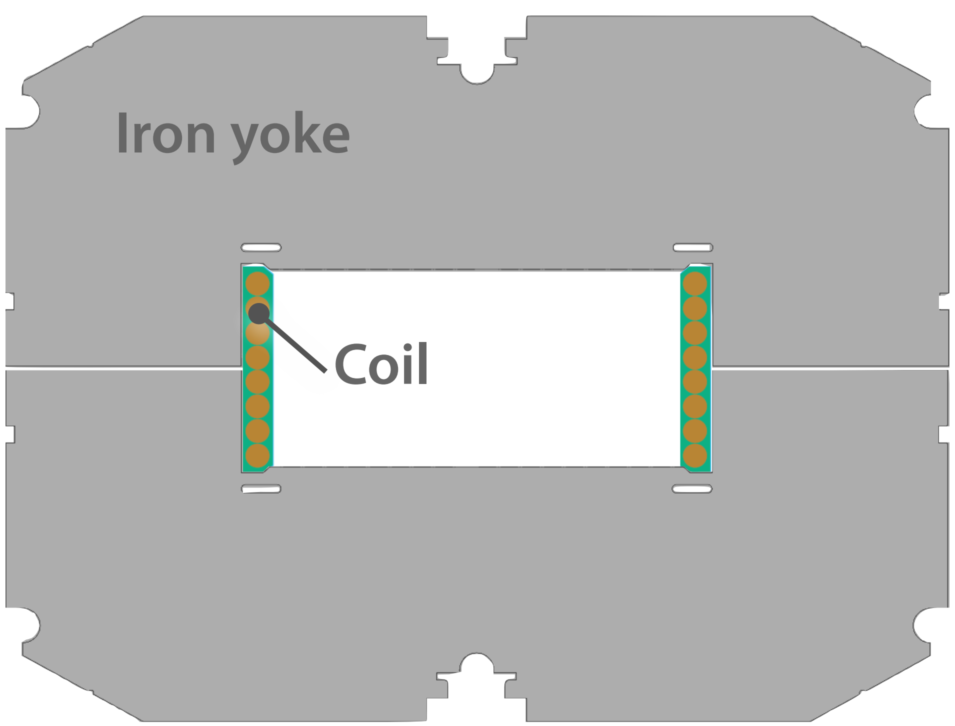


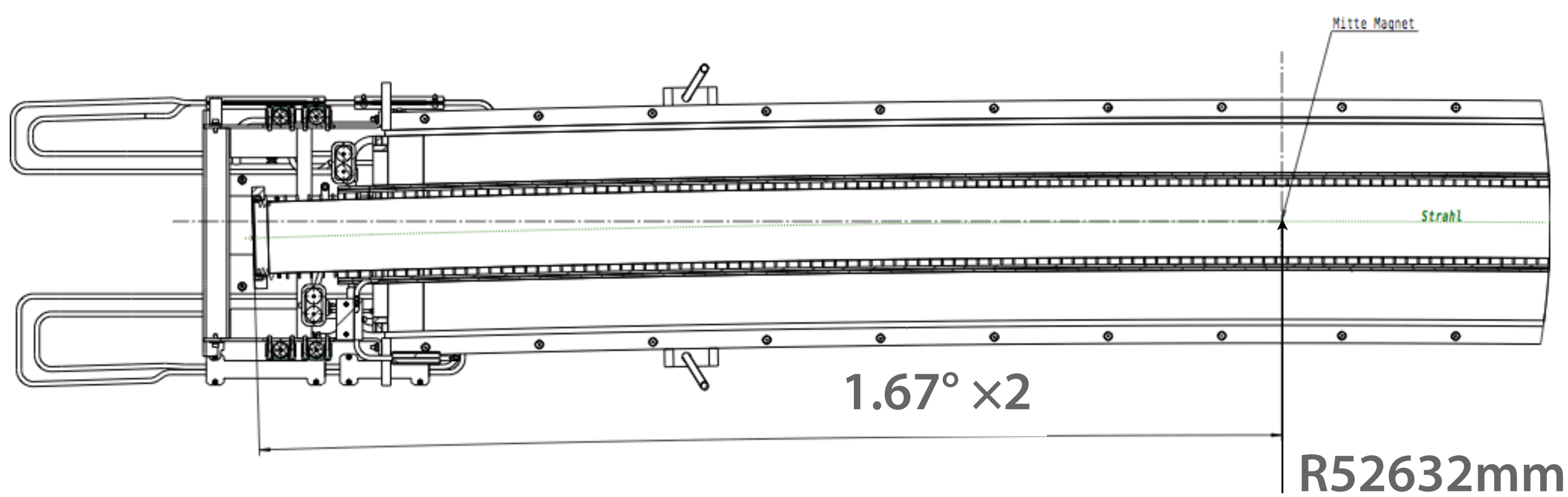
SIS100 Superconducting Magnet System

- Dipole magnet
  - Superferric magnet 1.9 T, 13 kA
  - Nuclotron cable, 2 phase helium cooling
  - Fast ramp magnet 4 T/s
  - Curved magnet









SIS100 Superconducting Magnet System

- Quadrupole doublet modules: 8 standard types and 3 special types

(injection, extraction, high radiation)

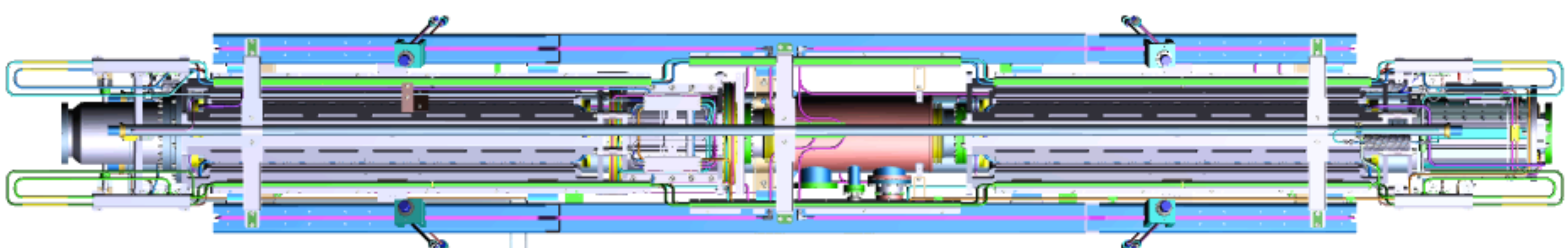
Standard Doublet Modules								
Type	2.123	2.4	2.5	1.6A	1.7B	2.8C	2.9D	1.E
Contents Defocusing Quadrupoles	QD BPM	QD BPM	CV QD	BPM QD	CV QD	BPM QD	BPM QD	MC QD
	DT R-CWT CAP	DT	COL R-CWT	COL	COL R-CWT	COL	COL R-CWT	COL
Focusing Quadrupoles	ST F2	ST F2 MC	ST F2 BPM	ST F1 CH	ST F1 BPM	ST F2 CH	ST F2 QJ	ST F1 BPM
Quantity	15	5	6	12	12	12	12	5

CV: Chromaticity sextupole magnet
BPM: Beam Position Monitor
MC: Multipole corrector magnet

ST: Steering magnet
CH: Chromaticity sextupole magnet
QJ: gamma-t jump quadrupole magnet (NC)
+ BPM, MC

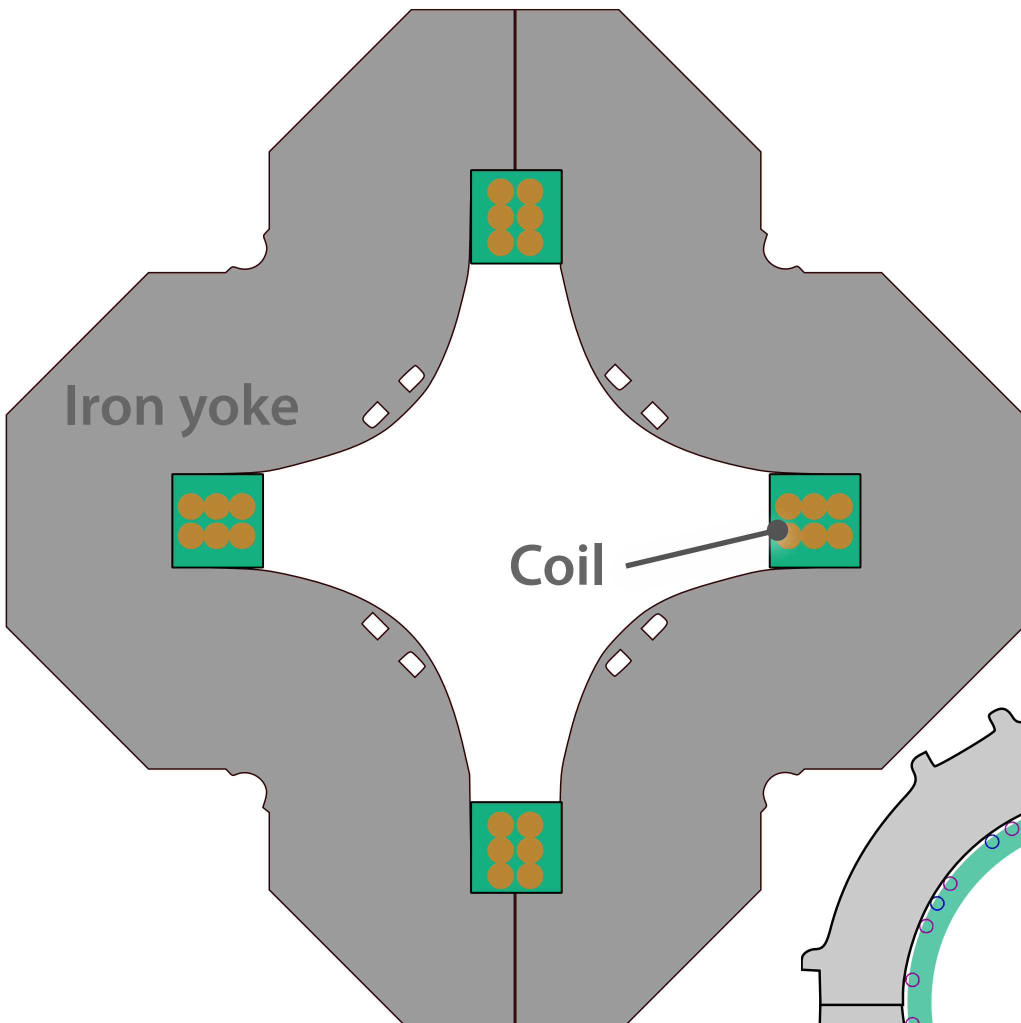
beam direction

type 2.5

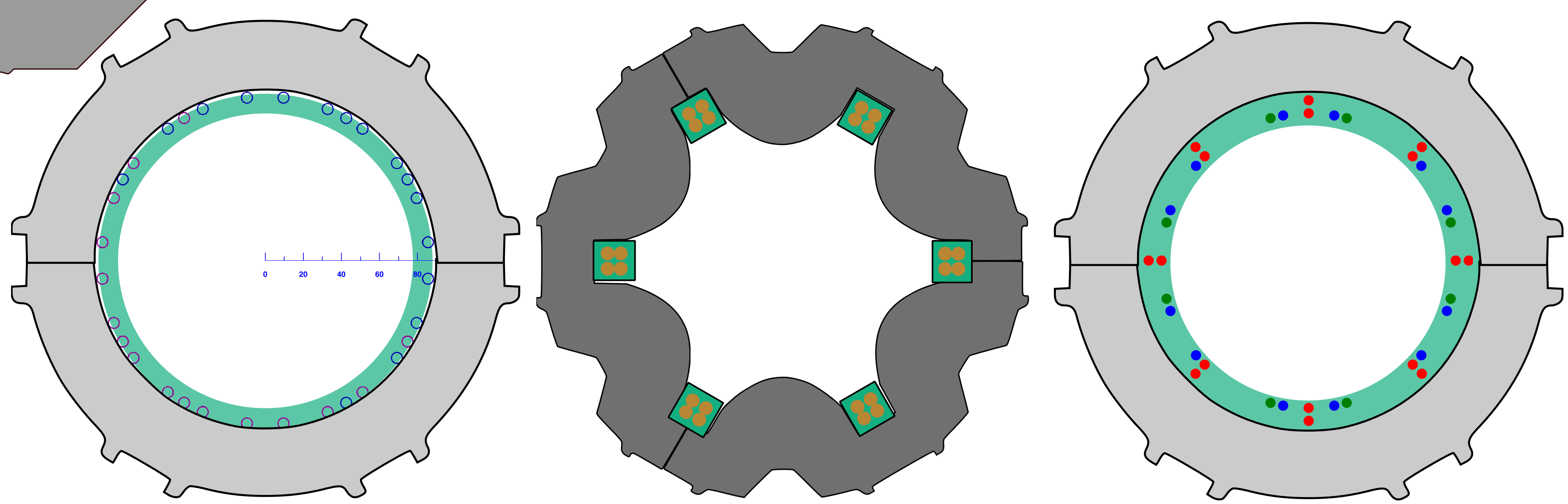


SIS100 Superconducting Magnet System

- Quadrupole magnet
  - 10 kA, 27.7 T/m

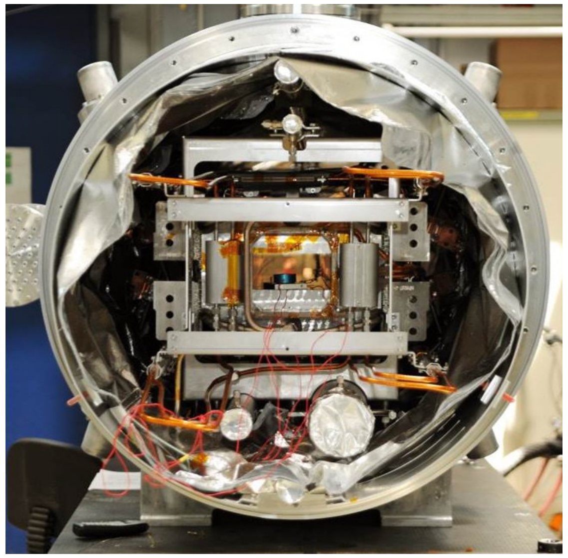


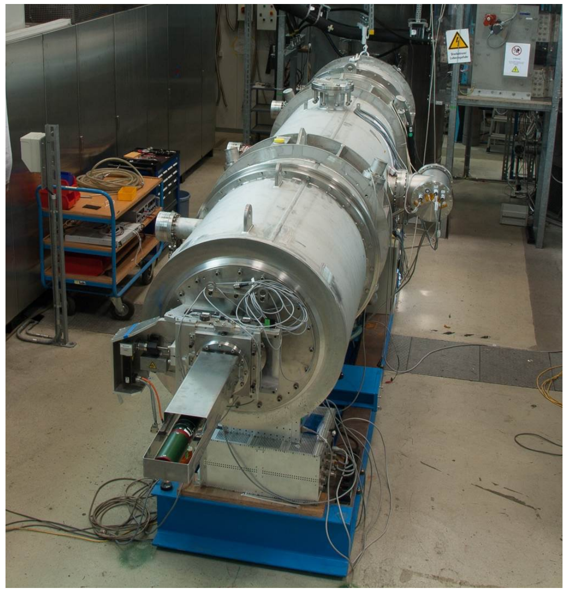
- Corrector magnets
  - Steering magnet (horizontal/vertical embedded)
  - Chromaticity sextupole magnet
  - Multipole corrector magnet (B2, A3, B4)
    - Nuclotron cable with insulated strands
      - 250 A × 27 strands = 6.75 kA



SIS100 Dipole Magnet *-Chronicle-*

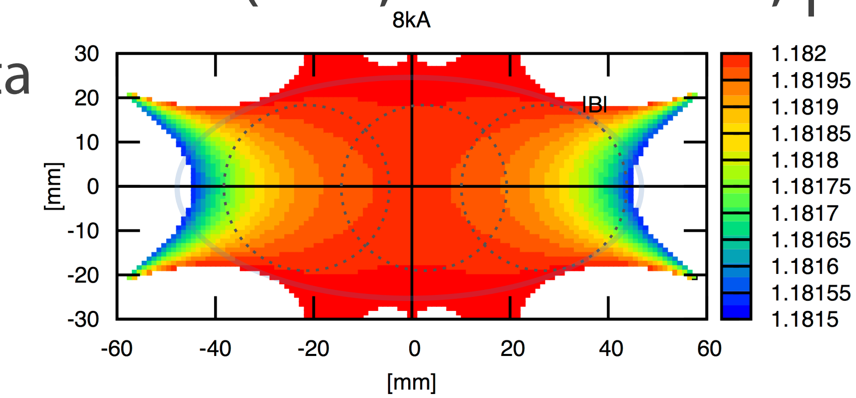
- R&D
  - Prototype: 2-layer coil straight magnet (2007)
  - Re-design to 1-layer coil, curved magnet
    - for adaptation for increased ramping frequency
- Specification (2011)
- Tendering/Contracting (2012)
- “First of Series (FoS)” production (2013)
- Testing/Magnetic field measurements (2013 -)
  - Nominal current reached after the first quench
  - No re-training after thermal cycle
  - Insufficient magnetic field quality
- Magnetic field measurement analysis (2013 -)



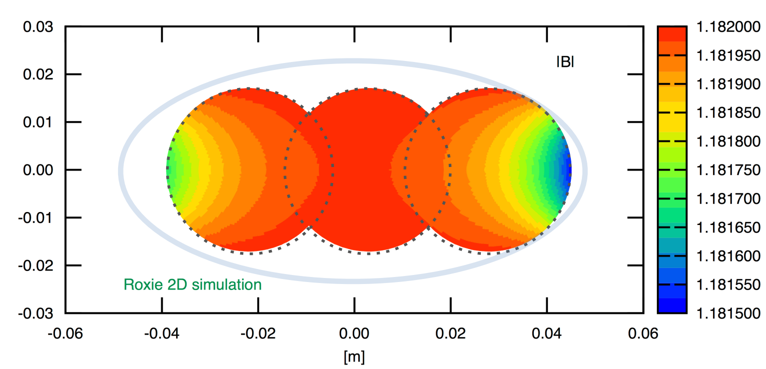


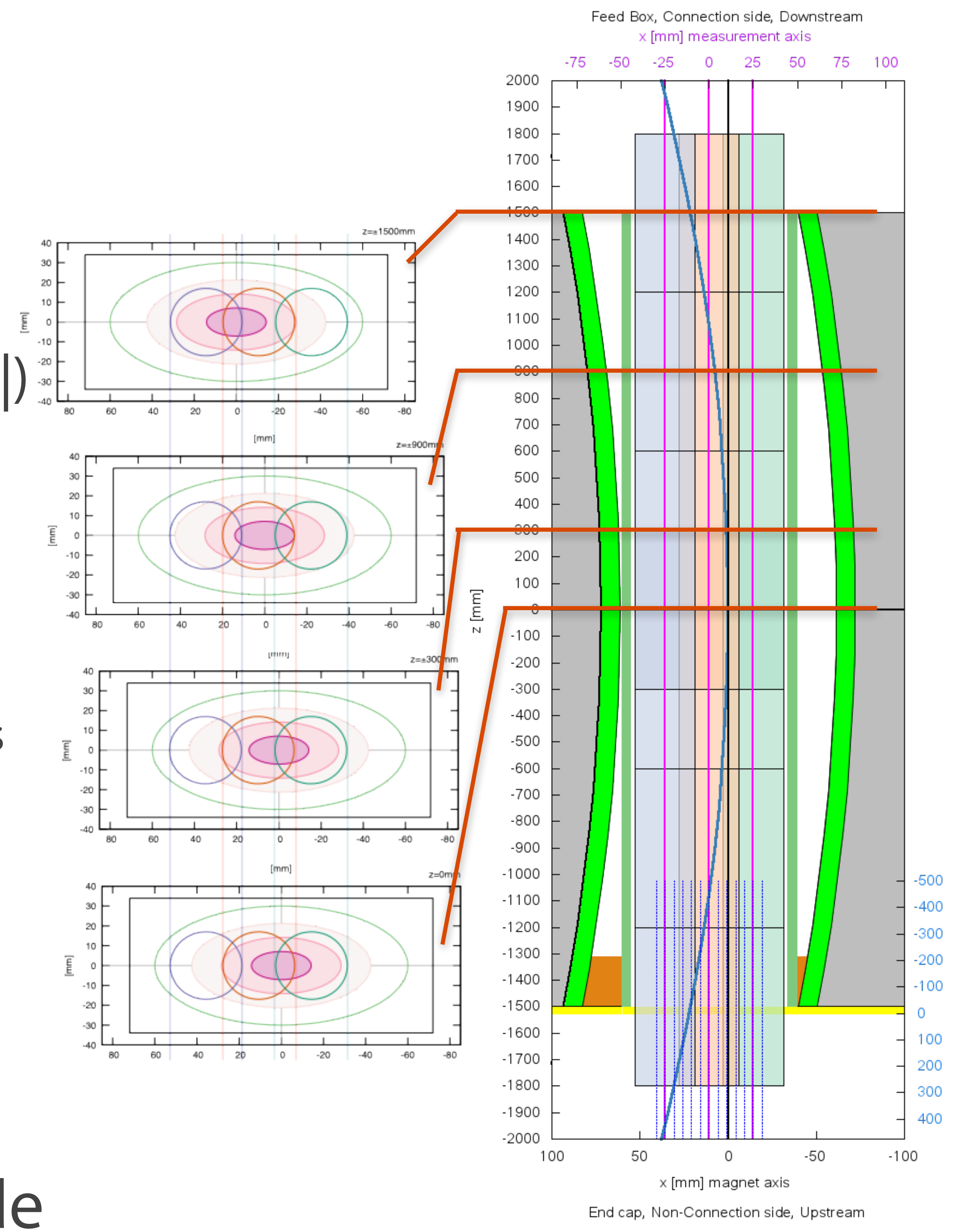
SIS100 Dipole Magnet *-Magnetic field measurements-*

- In warm bore (within anti-cryostat)
  - Rotating coil
    - 17mm radius, 3 lateral position
    - 600mm integral in curved aperture
    - Roxie Simulation (8kA, z=±900mm, |**B**|)
      - Grid data



      - Reconstructed from multipole coefficients





- Hall probe
  - only at the non connection side

SIS100 Dipole Magnet *-Magnetic field measurements-*

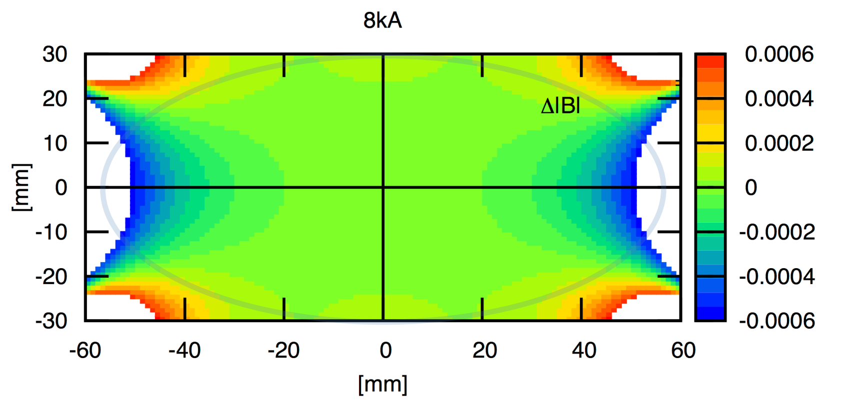
- Measured Results worst case / vary along the magnet length (ex. 8kA, -900mm)

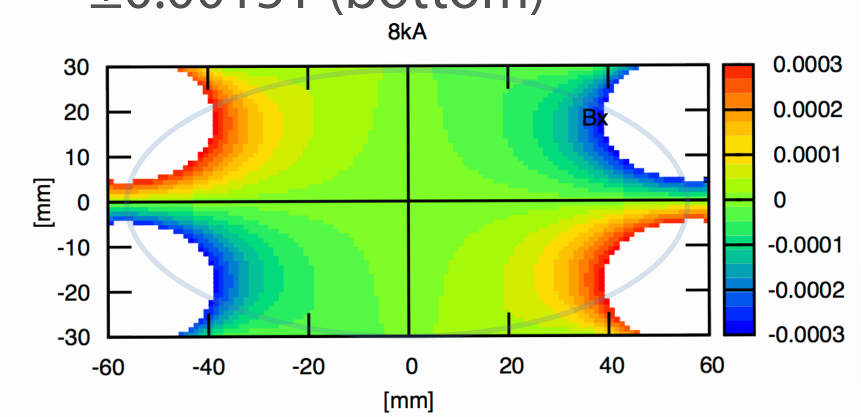
$\Delta|\mathbf{B}|$
colored ±6unit = 0.0006 w.r.t |B(0,0)|

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

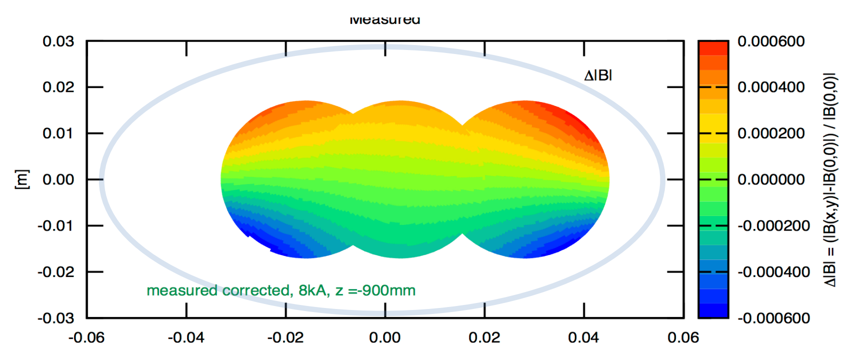
Hall probe measurement Bx

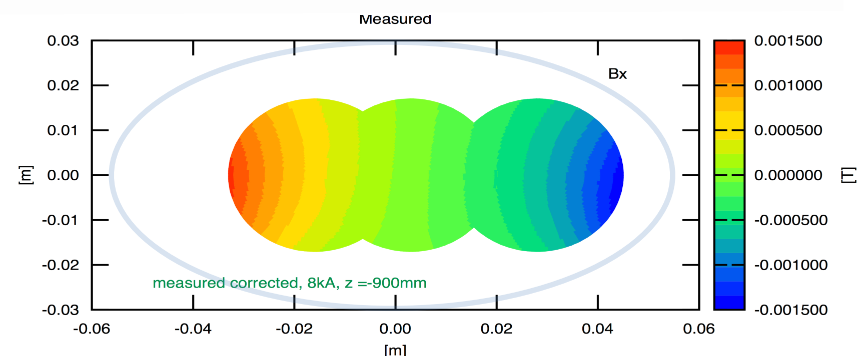
What we expected

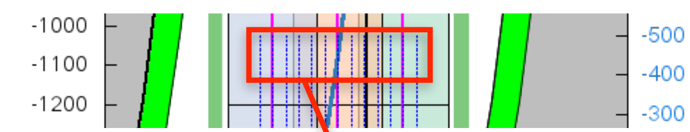


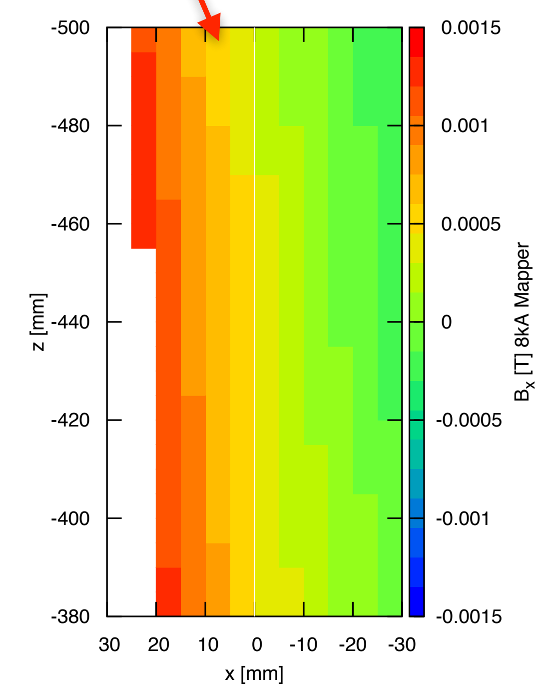


Measured









Top bottom asymmetry?

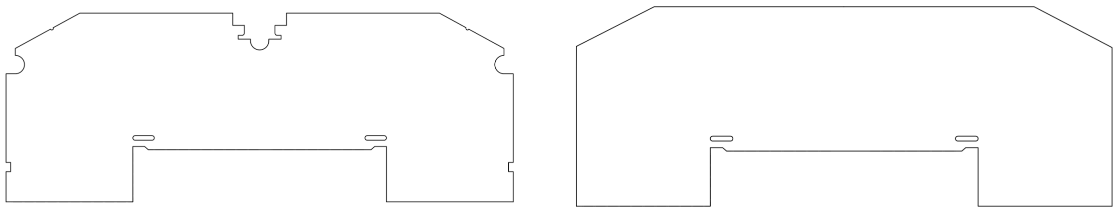
Bx gradient = skew quadrupole?
~15 unit

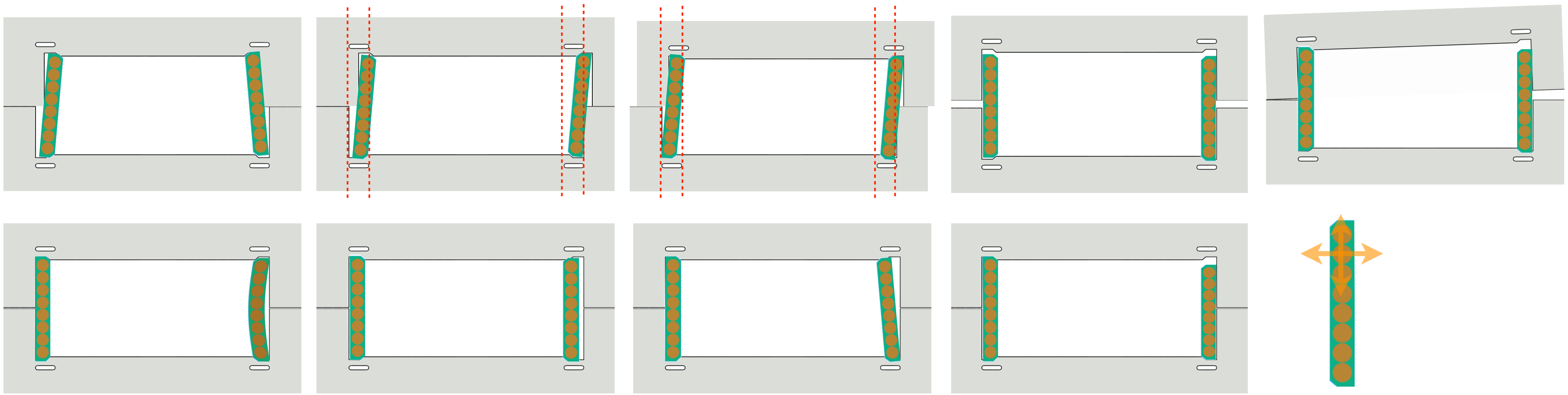
How can we explain unexpected field error?

Manufacturing error: Simulations/Geometrical measurements

SIS100 Dipole Magnet *-Simulations-*

- Modeling
  - There were no assembled (yoke+coil) magnet drawing.
  - No simulations with actual production design
  - Modeling with most probable dimensions with simplified outer profile of the lamella.
  - Manufacturing error possibility



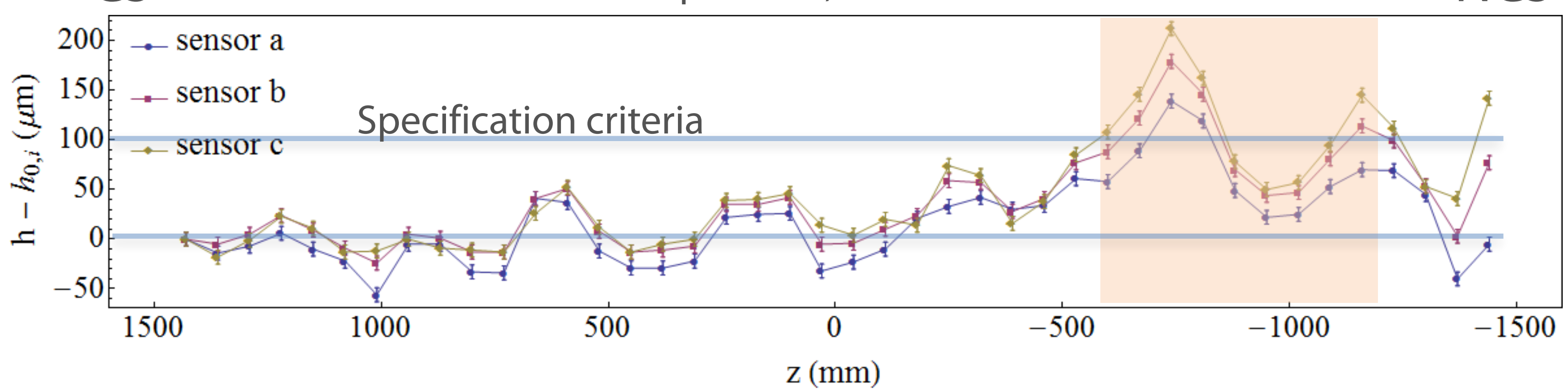


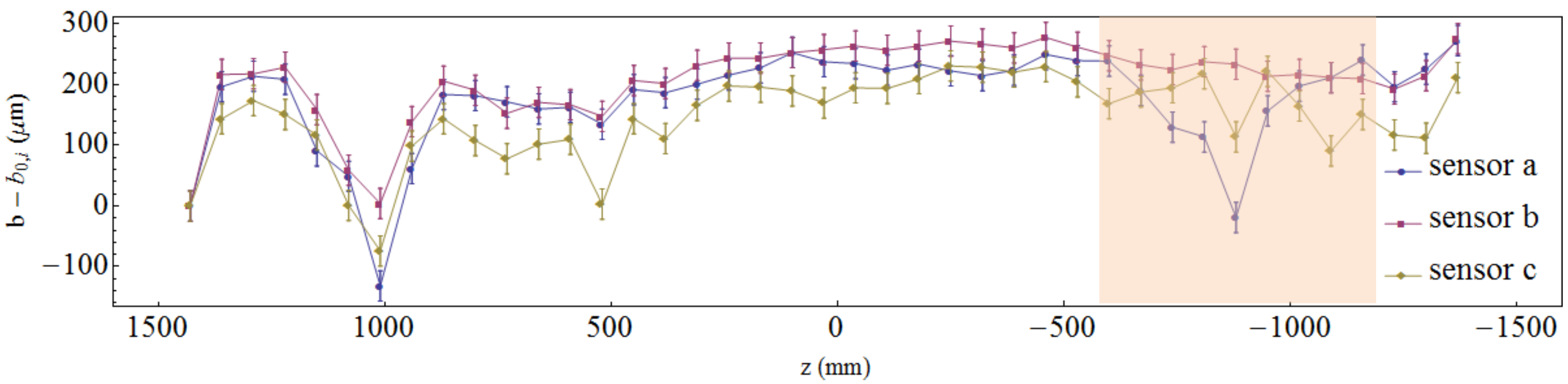
Too many.. + maybe combination of them…

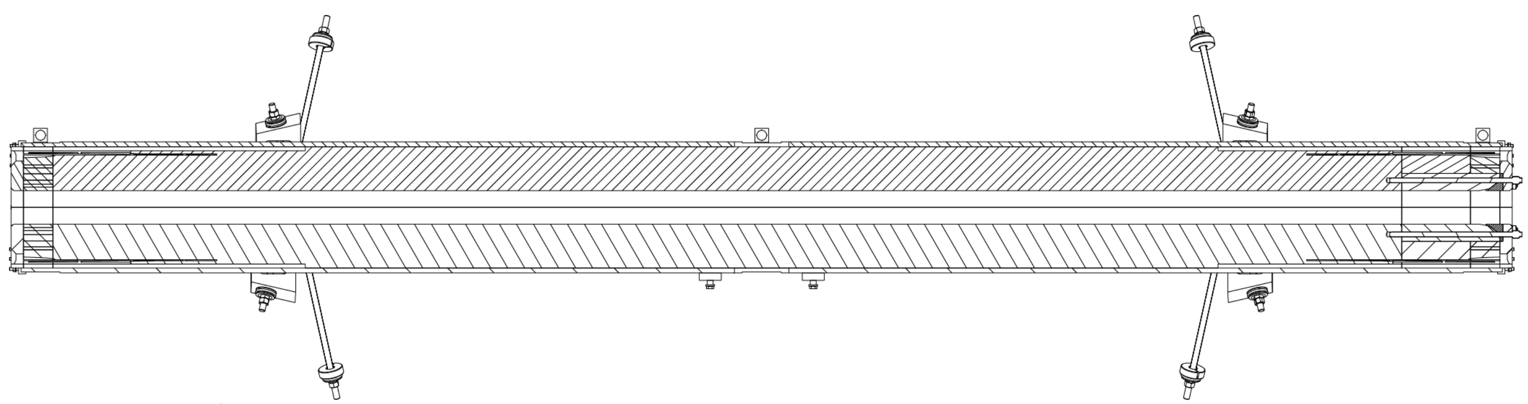
SIS100 Dipole Magnet *-Geometrical measurements-*

Gap height/width measurements

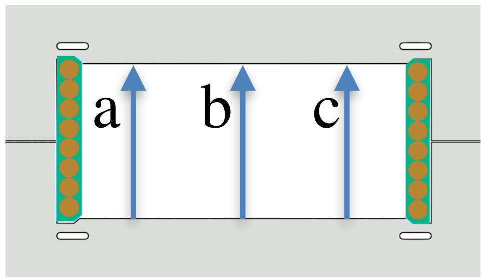
CS — at room temperature, with coil — NCS





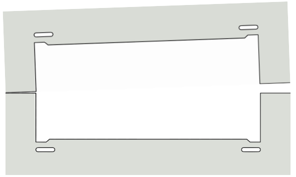


view from NCS to CS

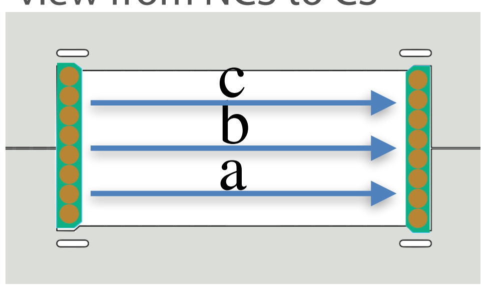


right side is larger
~ 100 µm

?

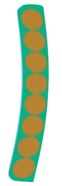


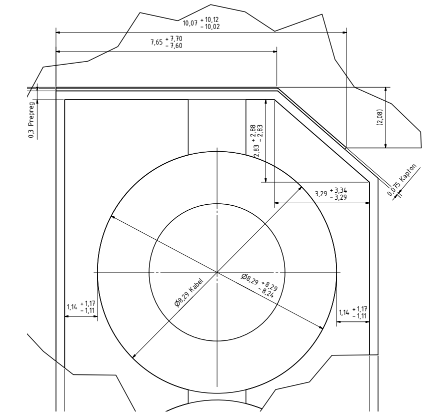
view from NCS to CS

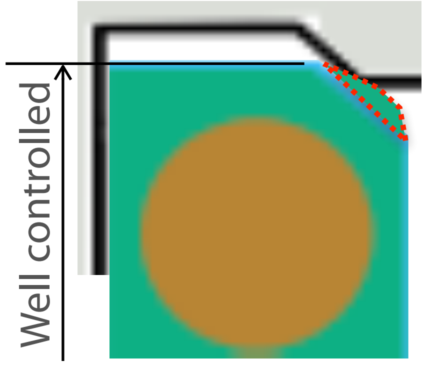


top and bottom is narrow
~ 100 µm/~ 250 µm

??



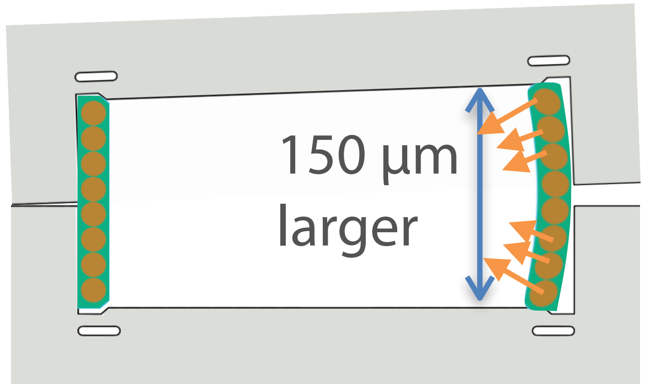




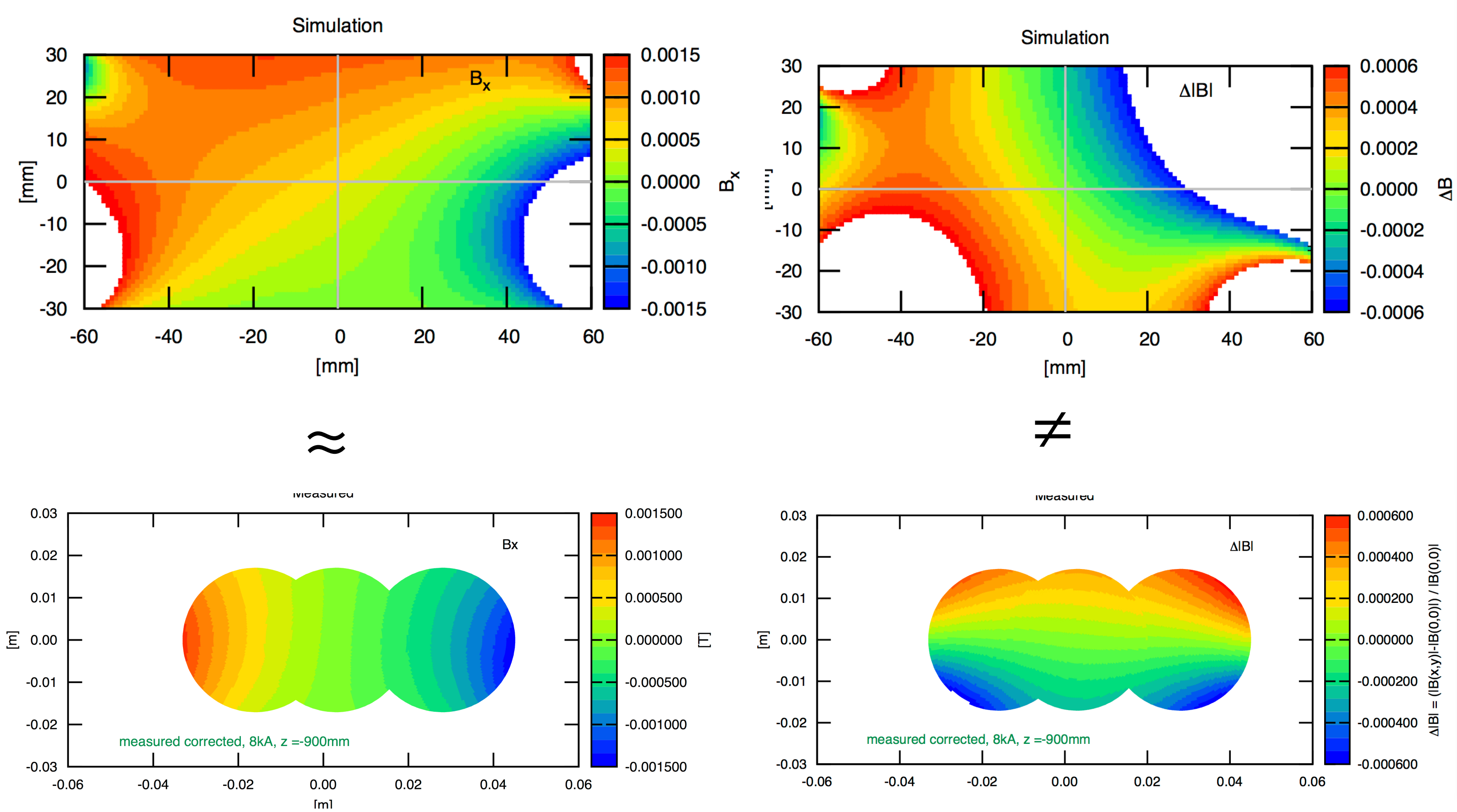
Same profile at cryogenic temperature
After disassembly, “without coil”, the peak disappears.

SIS100 Dipole Magnet *-Simulations-*

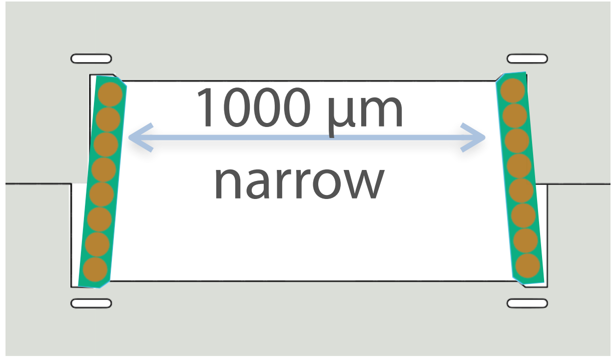
- Model Based on the geometrical measurement results

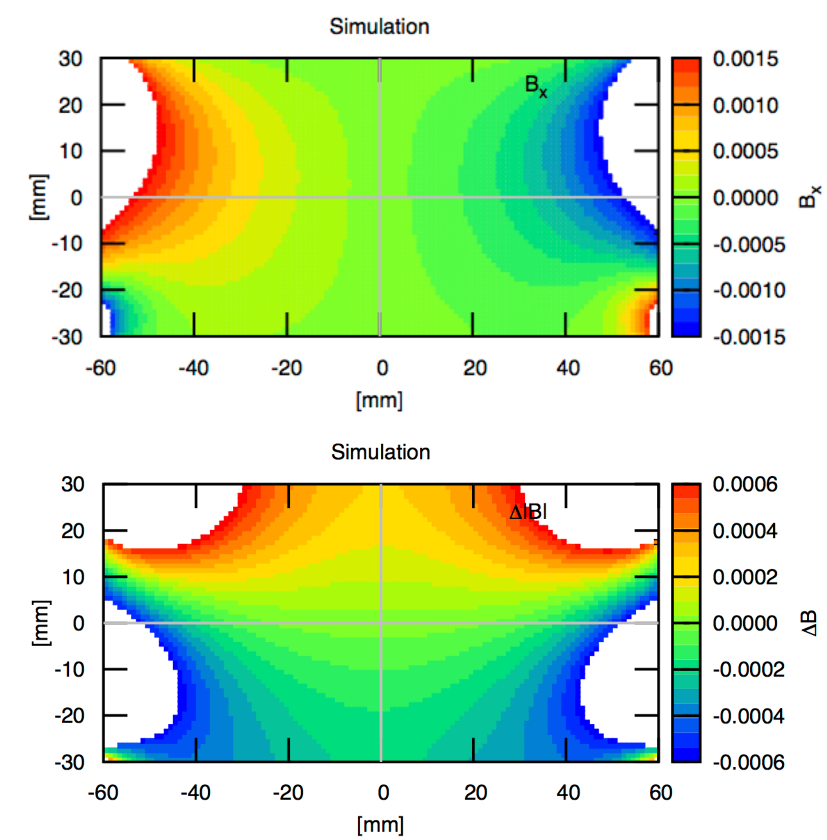


This can explain Bx,
but not |B| top-bottom asymmetry



cf.





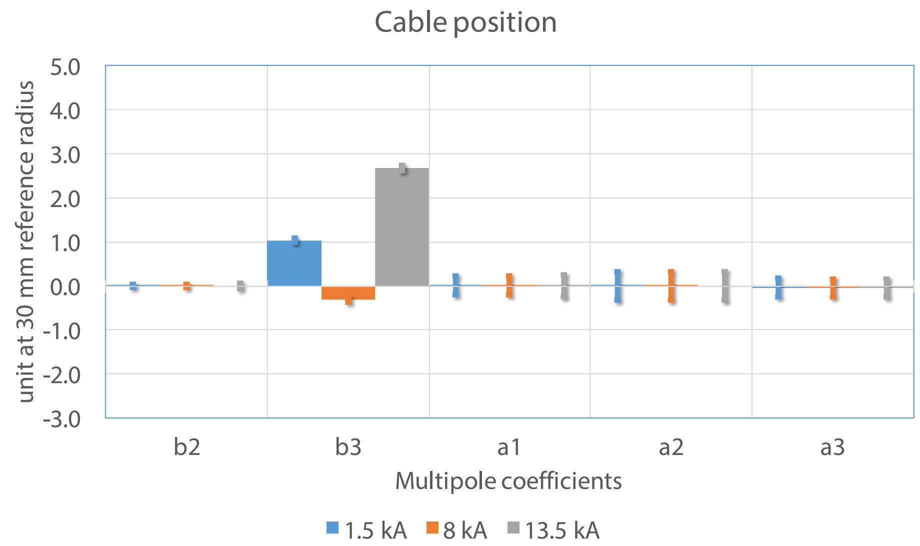
Such huge deviation was not observed.
→Combination of manufacturing errors

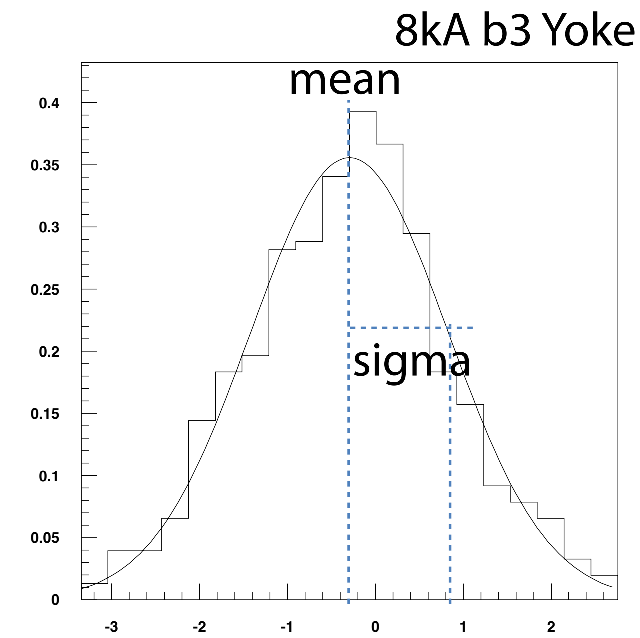
SIS100 Dipole Magnet *-Simulations-*

- How sensitive? cable vs. yoke -random error 500 times-

Position of the 16 cables

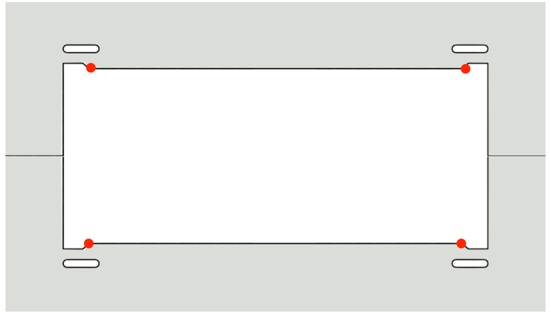
Δx, Δy ±0.05 mm, independently

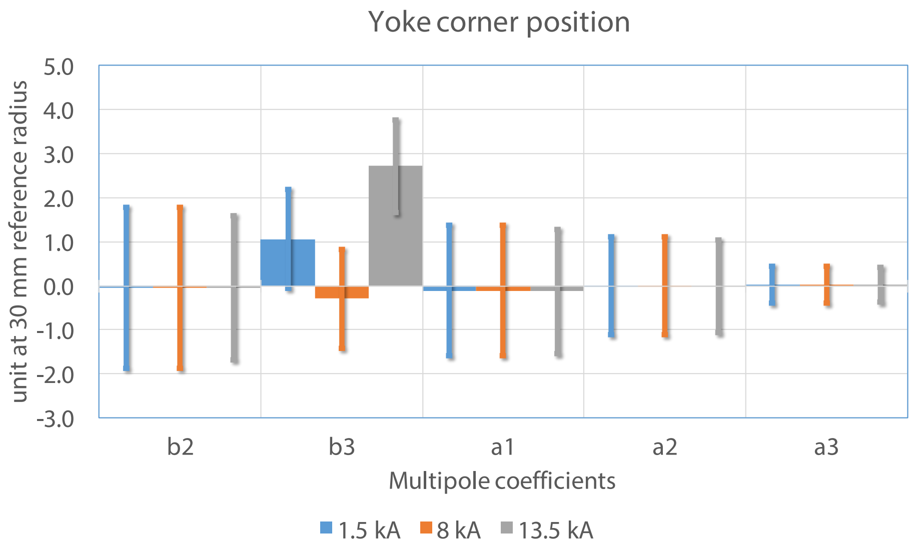


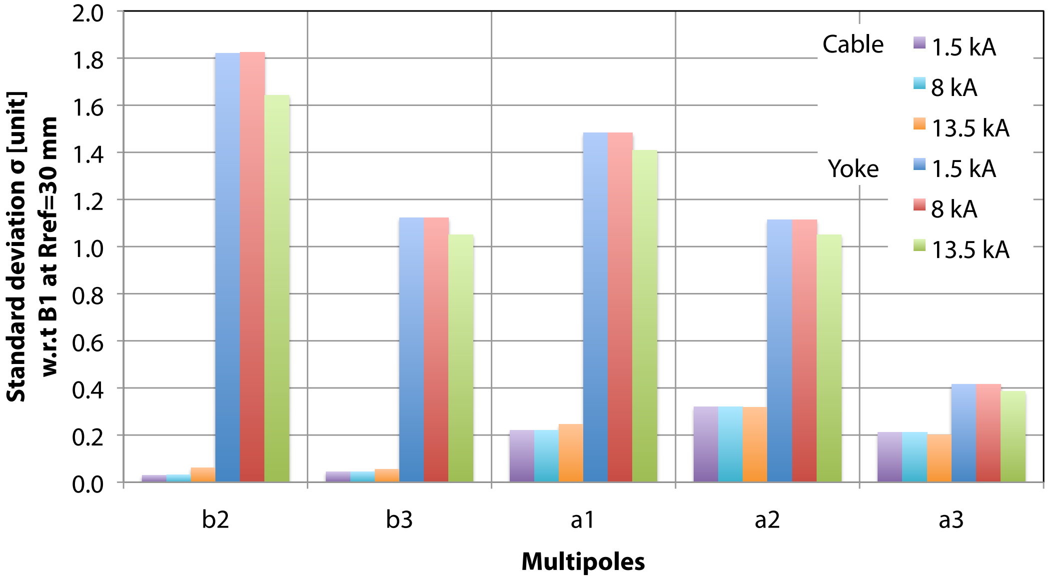


Position of 4 points

Δx, Δy ±0.05 mm, independently







Yoke geometry is more sensitive than cable positions. ~10 times

Cable position errors are sensitive to skew components than normal components.

Yoke geometry control ~ 50 μm seems a limit (field quality and technically as well)

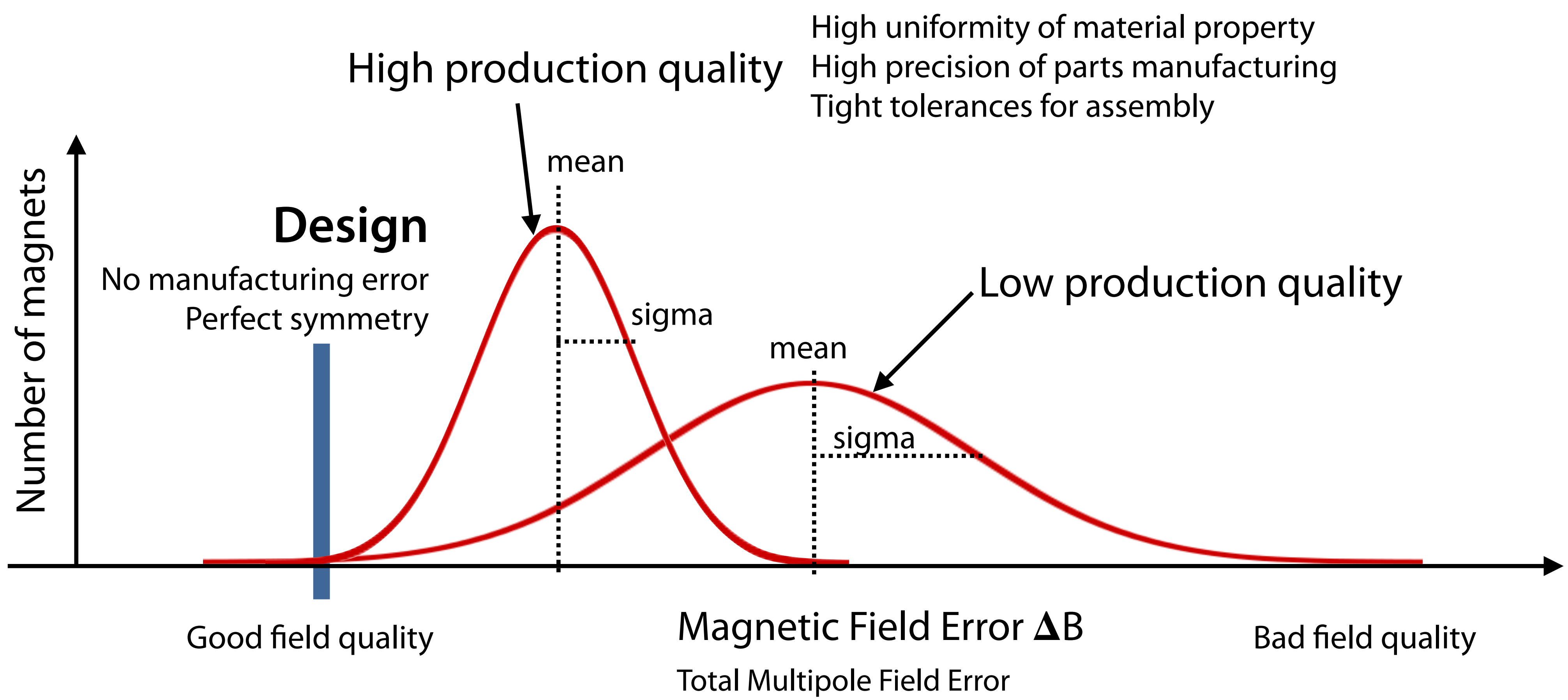
Summary and Discussion

- Developments for the series production of the SIS100 sc. magnets are ongoing.
- Magnetic field measurements (MFM) of the FoS dipole magnet showed **insufficient magnetic field quality**.
- Detailed analysis with MFM, simulations, geometrical measurements have been done.
  - Source of the multipole errors have been considered as **combination of manufacturing errors**.
  - Manufacturing tolerances are reconsidered.
    - **Improvements** are done for next yoke (for FoS-2)

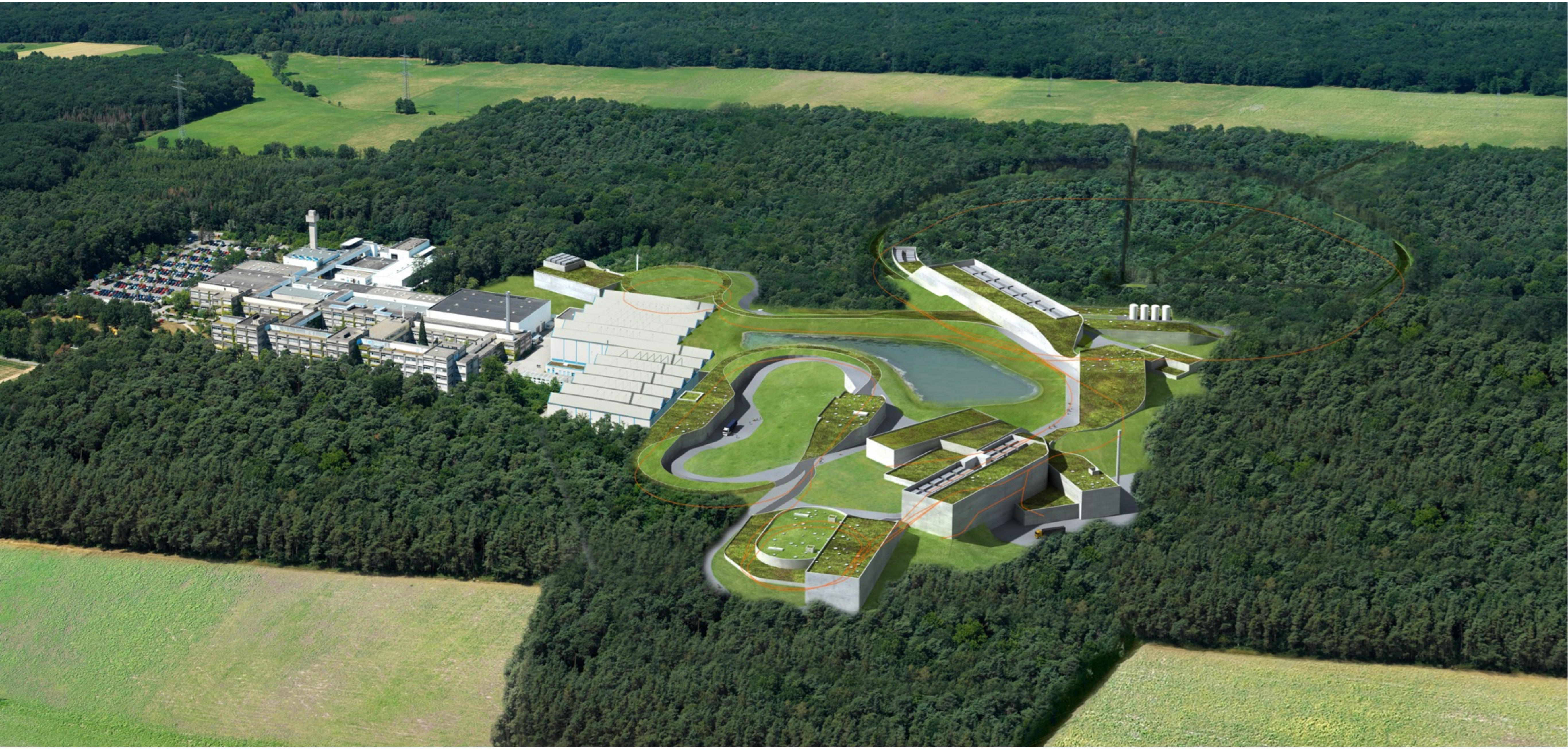
Summary and Discussion

- Evaluation of magnetic field distortions due to manufacturing errors should be done, hopefully in advance!
  - Before series production, simulation/prototypes

Histogram: magnetic field quality - number of magnets for series production



This "mean" and "sigma" are essential for beam optics, and for accelerator performance.



Thank you very much!