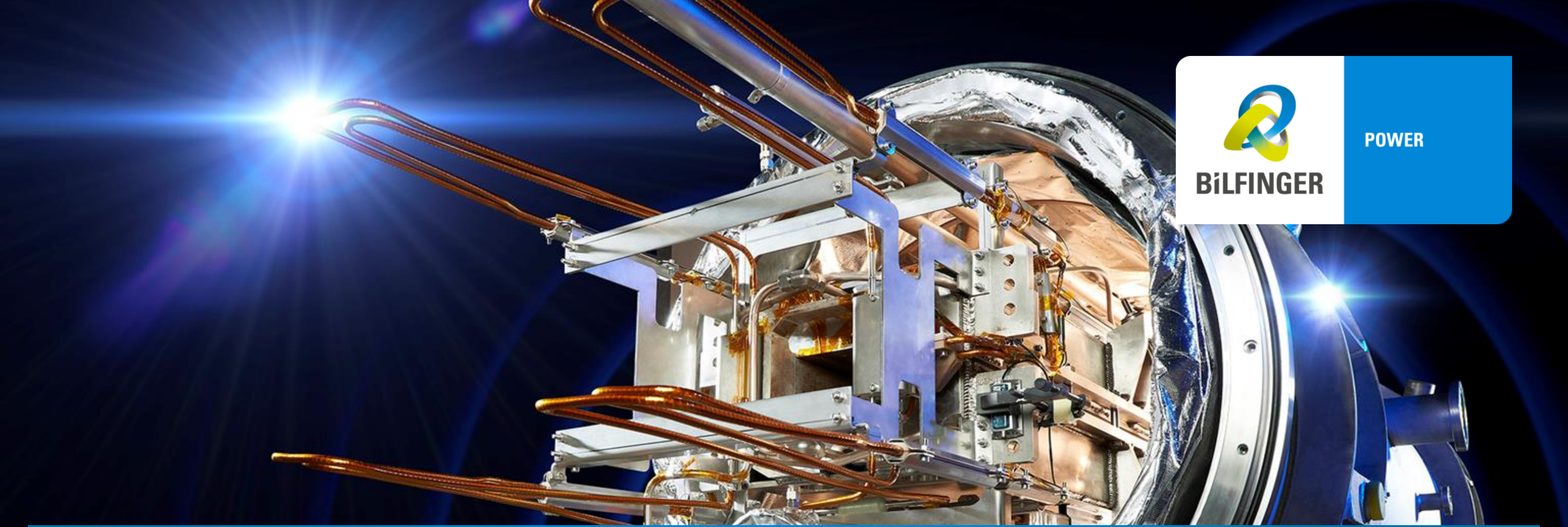


BILFINGER POWER

Babcock Noell GmbH

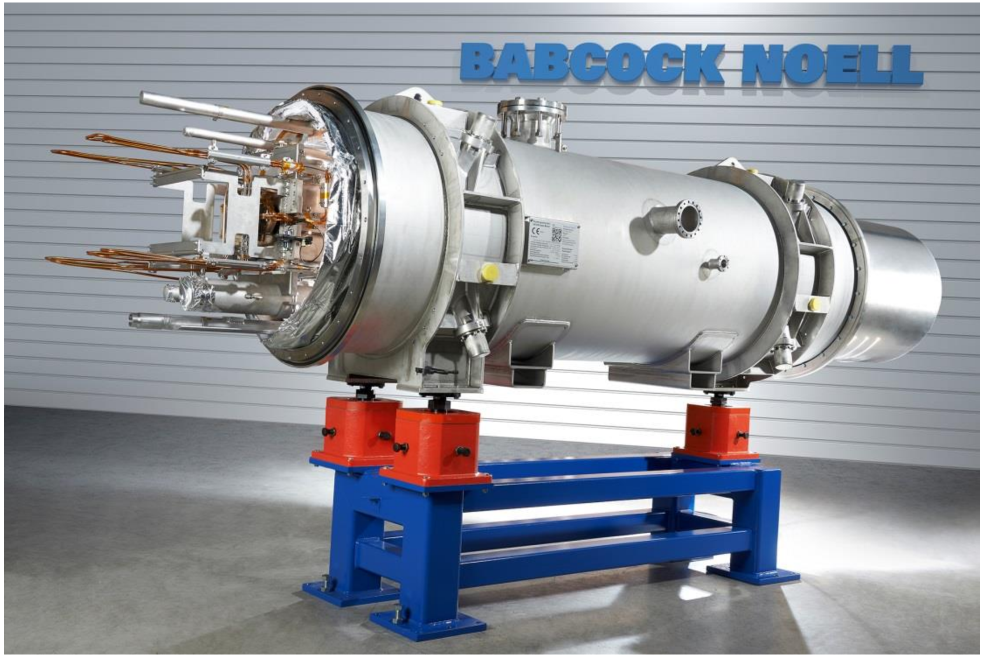
Supraleitende Beschleunigermagnete für FAIR – Entwicklung und Bau der SIS100 Dipole

Dr. Wolfgang Walter | Materials Valley

2016-03-10

Outline

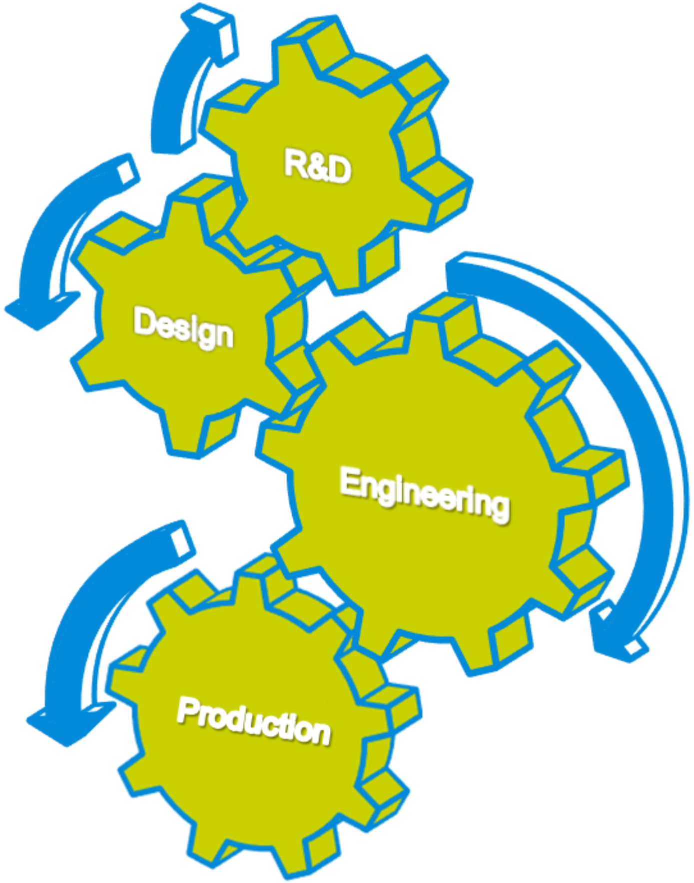
1. Introduction: Babcock Noell GmbH
2. The FAIR Project
3. Superconducting SIS100 Magnets
4. Development of the SIS100 Dipoles
5. Manufacturing of the FOS magnet
   - Cable Production
   - Coil Manufacturing
   - Manufacturing of Yoke
   - Magnet Assembly
6. Outlook on Series Production
7. Conclusion



Magnet Technology at Babcock Noell

- Physicists, Engineers and Technicians work hand-in-hand
- More than 30 years magnet technology experience
- Cooperation with research institutions and industry

WE MAKE RESEARCH WORK!



Babcock Noell: Site and Location

Office

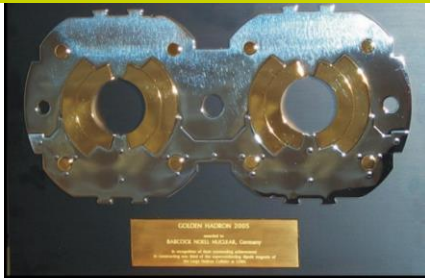
1. Workshop: 2.100m²

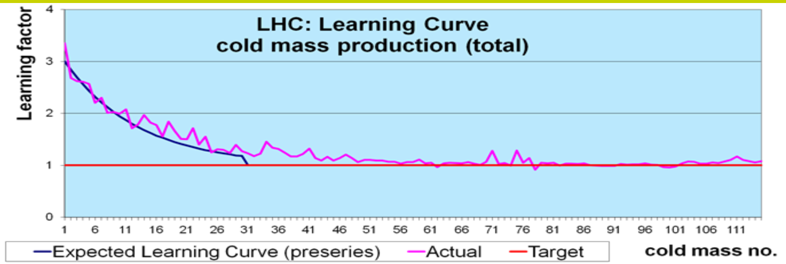
2. Workshop: 1.000m²

Accelerator Magnets at Babcock Noell

POWER
BILFINGER

Superconducting since 30 years





References

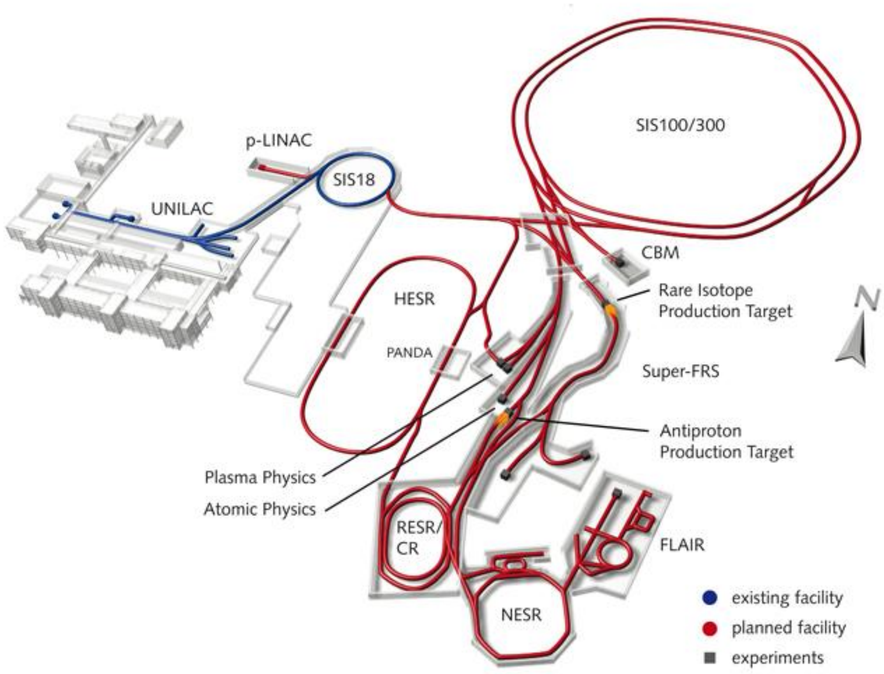
since 2012: FAIR SIS100 @ GSI	113 Series Dipoles
1999-2006: LHC @ CERN	416 Main Dipoles
1986-1989: HERA @ DESY	Quadrupole Assembly

FAIR a Multifunctional Accelerator

- FAIR: **F**acility for **A**nti-proton and **I**on **R**esearch

- GSI: **G**esellschaft für **S**chwer**I**onenforschung

- New international accelerator facility
- Existing GSI accelerators are upgraded and serve as pre-accelerators
- Will provide antiproton and ion beams of high intensity and quality



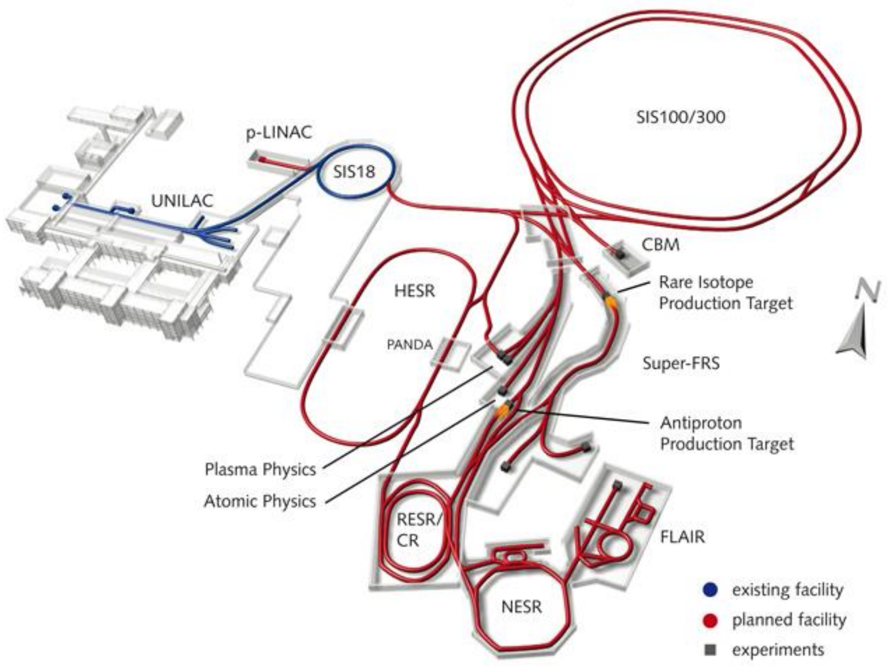
FAIR an International Accelerator Complex

- FAIR startet by BMBF in 2007,
  FAIR GmbH funded October 4th 2010

- 10 member states:
  Finnland, France, Germany, India, Poland, Romania, Russia, Slowenia, Sweden, United Kingdom

- Budget:
  Modularized start version 1,357 Billion € (cost basis 2005)
  major contribution from Germany and Hassia

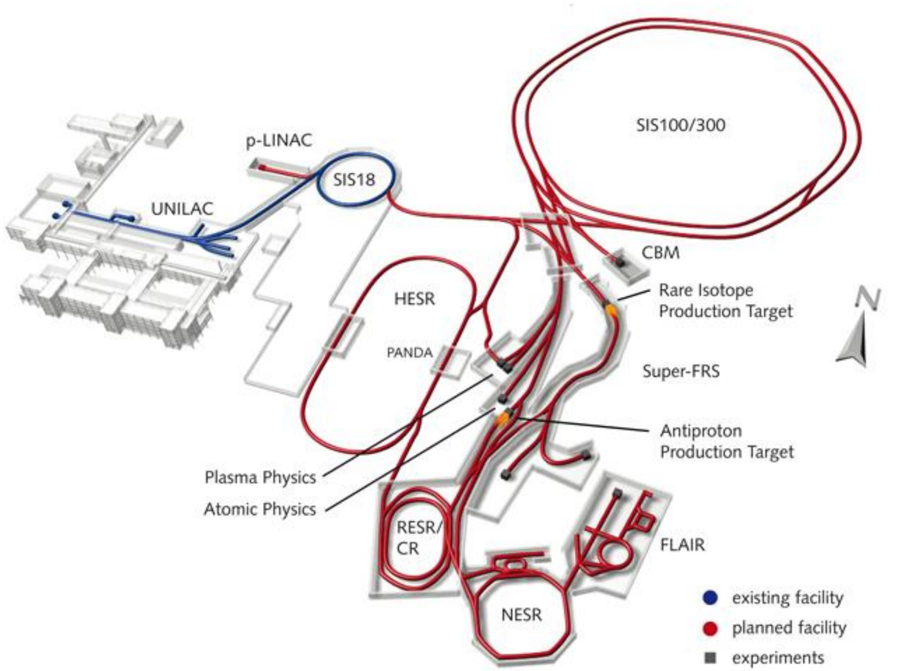
- FAIR Facility will host ~3.000 researchers
  from ~50 countries



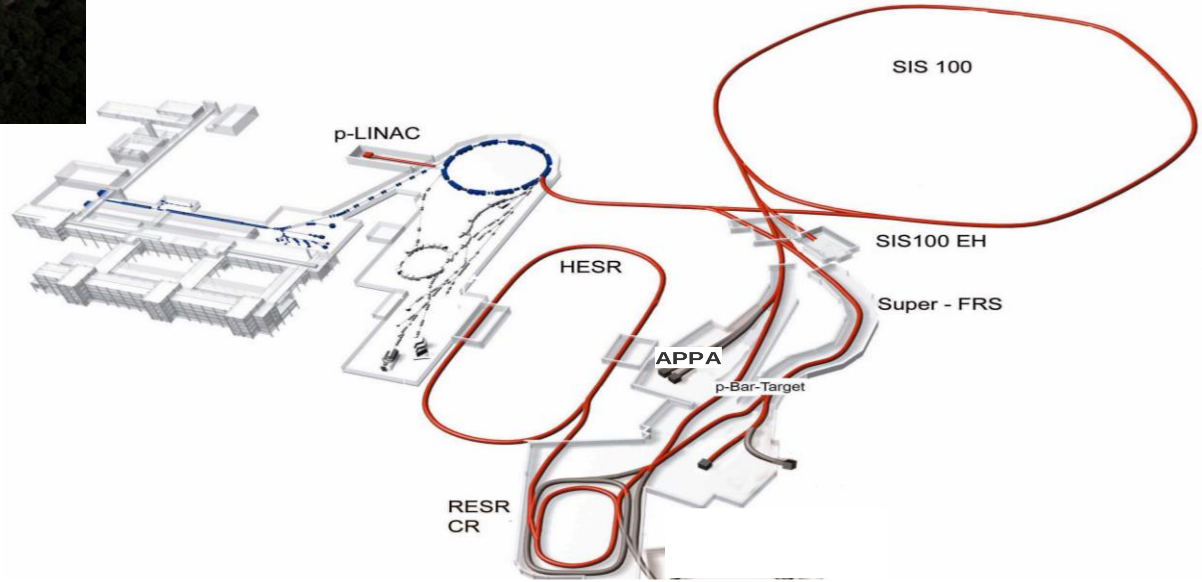
Physics at FAIR

- FAIR is a basic research facility to answer questions on the structure of matter and the evolution of the universe

- Some questions FAIR shall help to answer:
  - Why are quarks confined?
  - Why are nulei much heavier than the quarks forming it?
  - What are the fundamental symmetries of nature?
  - What is the behaviour of matter at extreme pressure and temperature (big bang)?
  - What can we learn about the Quark-Gluon plama?
  - …



FAIR Start Version



FAIR Project Status & Roadmap

Overall project status:

- About 60 % of the overall project cost bound in contracts.
- About 2/3 of the warm straight sections are fully integrated / design or pre-design completed
- All long lead items contracted (dipol series, quadupole series, Rf series)
- System integration and planning for injection system completed. All procurements started.

Plan for 2016:

- Completion of extraction system integration and pre-design. Start of procurements.

Plan for 2017:

- Start of procuremet for main dipole- and quadrupole power converter
- Last single items procurements started (e.g. KO exciter, Q-kicker etc.)

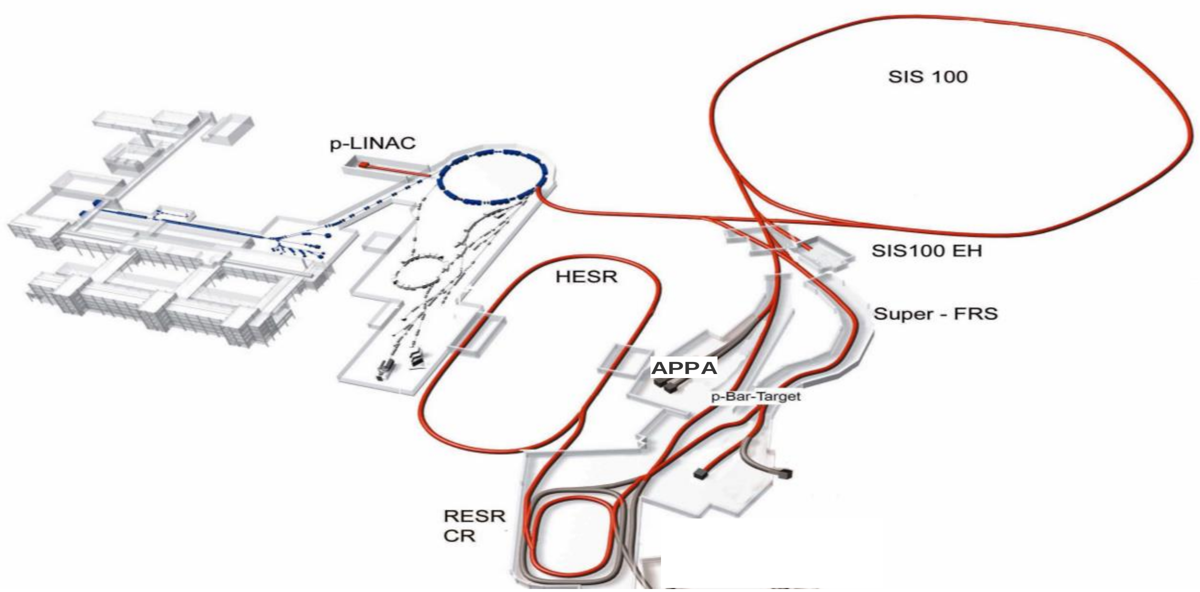
Plan for 2018:

- Start of procurements for standard UHV equipment (catalog orders)

FAIR Superconducting Magnets

- FAIR is a complex accelerator with various different magnet systems.

- Superconductivity is utilized for accelerator and detector magnet systems e.g.:
  - SuperFRS Multipletts and Dipoles
  - R3B Glad Detector Magnet
  - SIS100 Dipole and Quadrupole Magnets

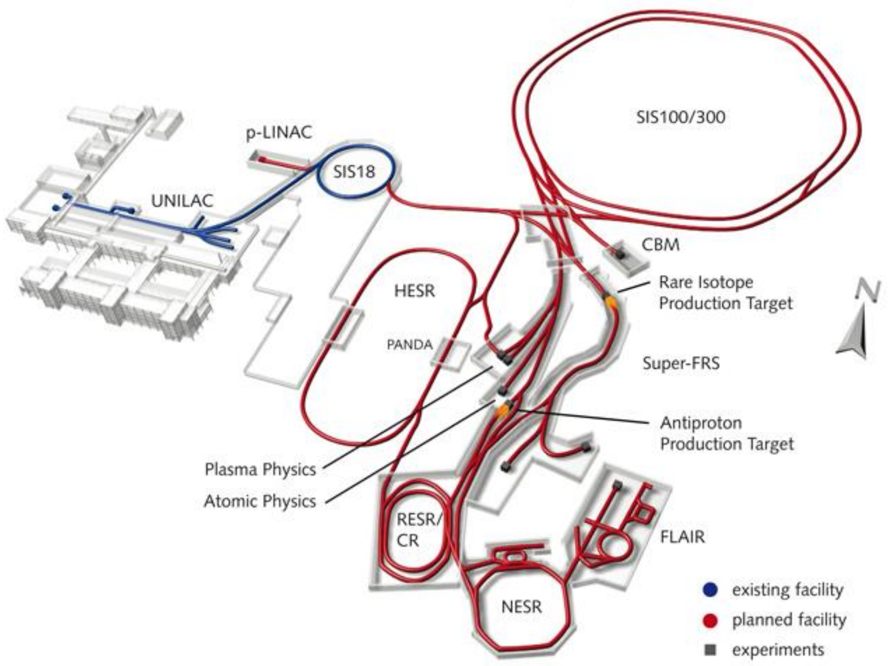


The SIS100 Synchrotron

- SIS100: Heavy Ion Synchrotron (SchwerIonen Synchrotron)
  - magnetic rigidity: 100 Tm
  - circumference: 1100 m

- The 1.100 m circumference SIS100 Synchrotron is the „heart of the facility“ and delivers accelerated protons at highest intensity and high energy to a complex of storage rings and experimental stations

- This enables high intensity secondary beams and antiprotons and exotic nuclei can be used at experiments



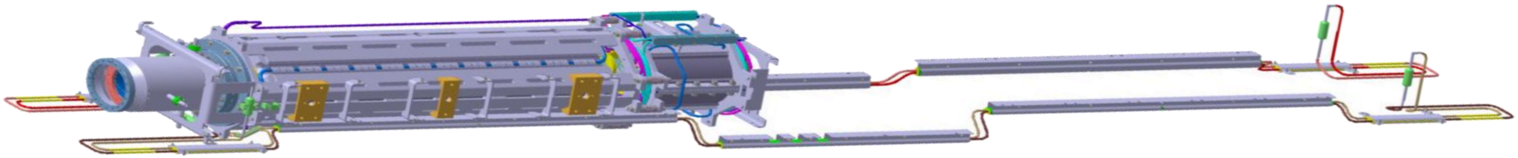
SIS100 Superconducting Quadrupole Units

Quadrupole units comprise quadrupoles, sextupoles, steerer and BPMs;
Arc modules contain cryo-catcher

Quadrupole Units are installed on a common girder

Assemblies of 2 Quadruopole Units into one cryostat are Quadrupole Doubletts

Quadrupole Units are provided as in-kind contribution by JINR (Dubna, Russia)



SIS100 Superconducting Quadrupole Doublets

83 pieces (11 types) of quadrupole doublet modules

length: app. 5.7m

diameter: Ø900mm

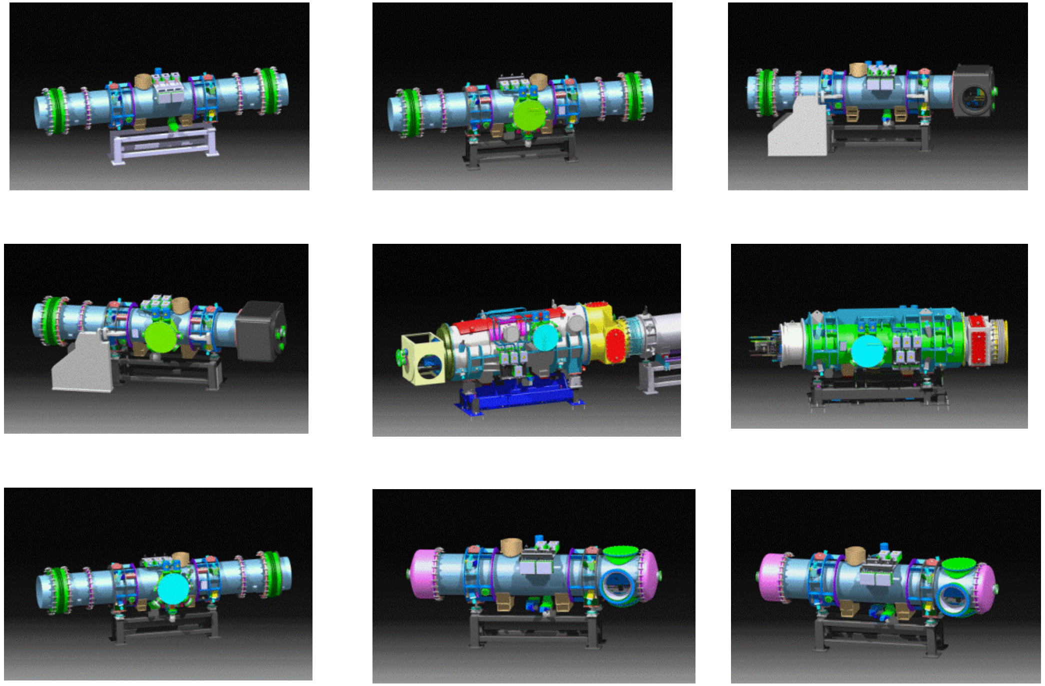
weight: 6300kg

window-frame design

QDM: 2 QP-Units:

maximum magnetic induction B_{max} : 27,8 T

ramp rate dB/dt: 58 (T/m)/s



SIS100 Superconducting Dipoles

113 dipole magnets

length: app. 3.2m

cryostat: Ø900mm

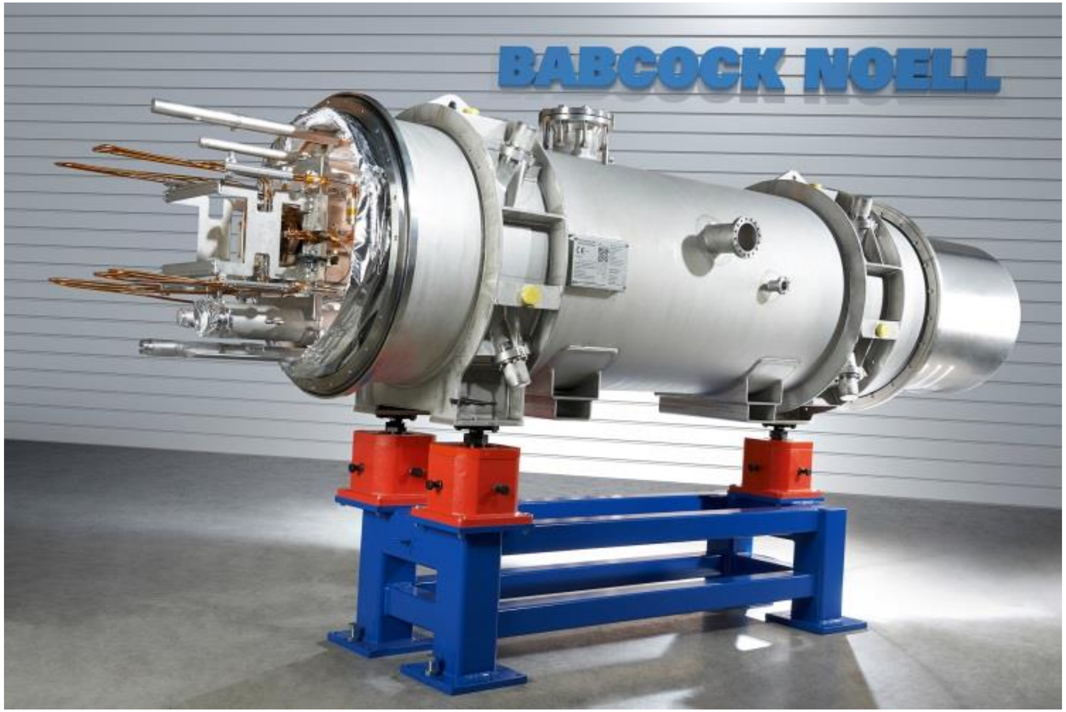
weight: 3500kg

window-frame design

curved (radius of curvature 52.632m)

maximum magnetic induction B_{max} :1.9T

ramp rate dB/dt: 4 T/s



SIS100 Dipole Tests at GSI

Superconducting SIS100 Dipoles are tested at GSI:

- Civil construction including media supply completed
- Cryogenic components are installed and commissioned
- STF ready for testing in spring 2015
- HTS current leads received and tested

1.5 kW at 4 K Cold Box

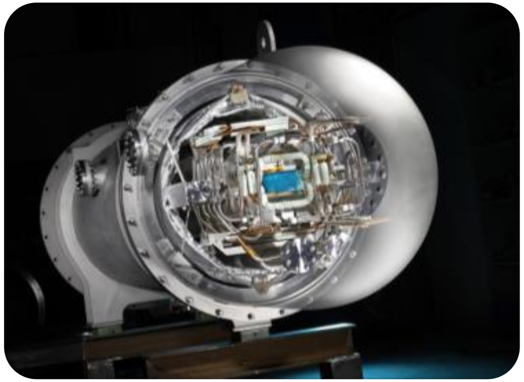
450 kW Compressor

Development, Prototype, FOS and Series

- 2004-2010 Development with Industry

  cable insulation, coil structure

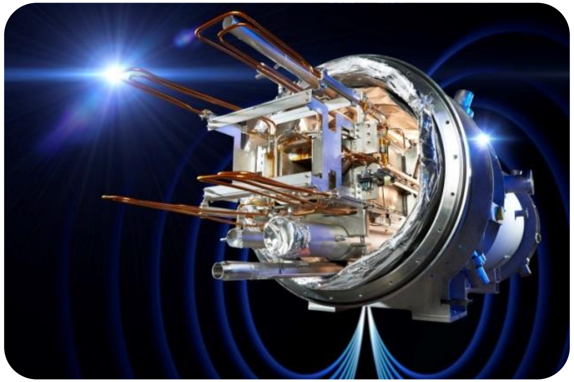
- 2007-2008: Prototype Dipole
  2-layer straight magnet



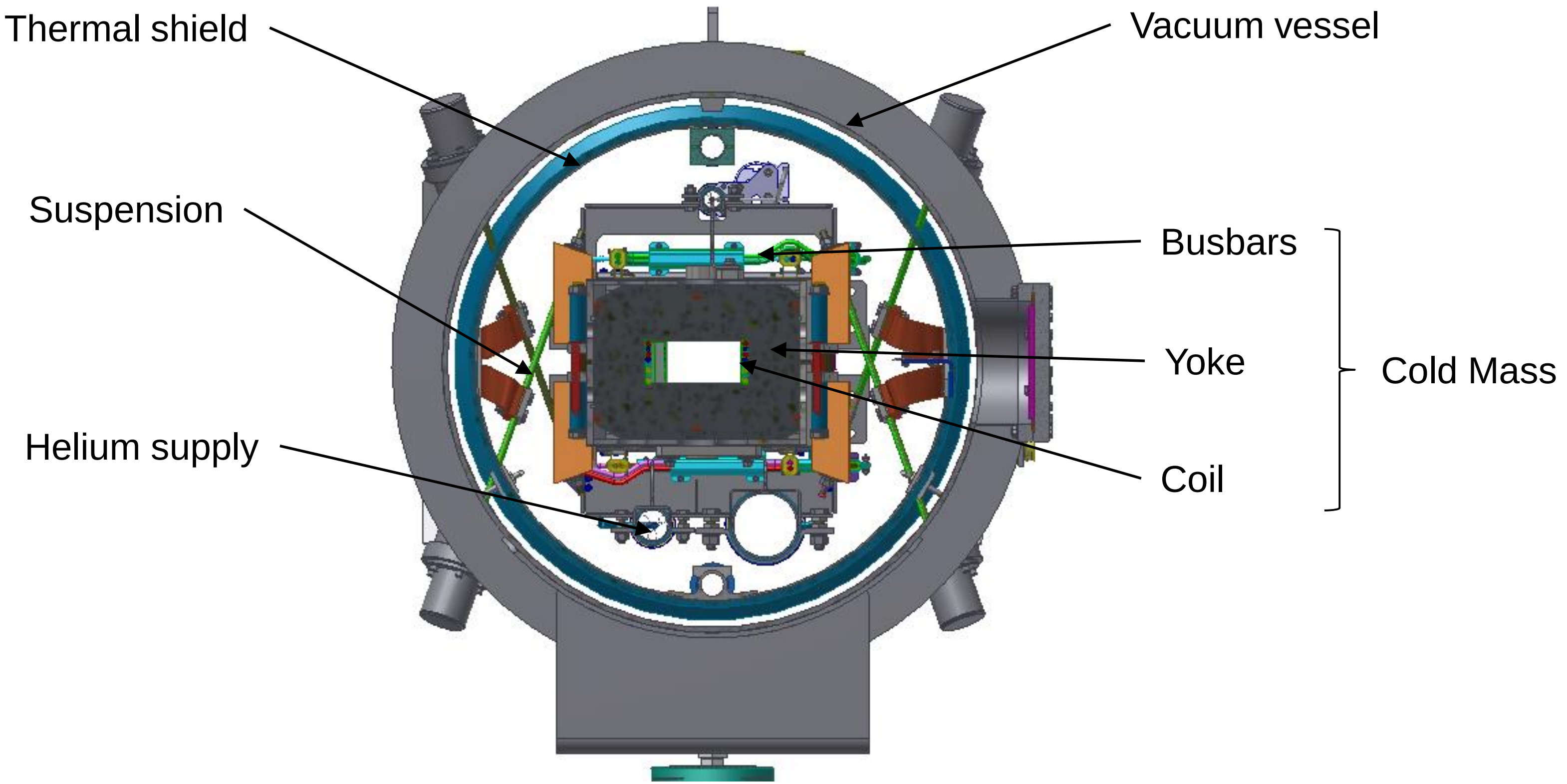
- 2012-2016: First Of Series (FOS) Dipole
  1-layer curved magnet

- 2014-2016: cold test and yoke modification

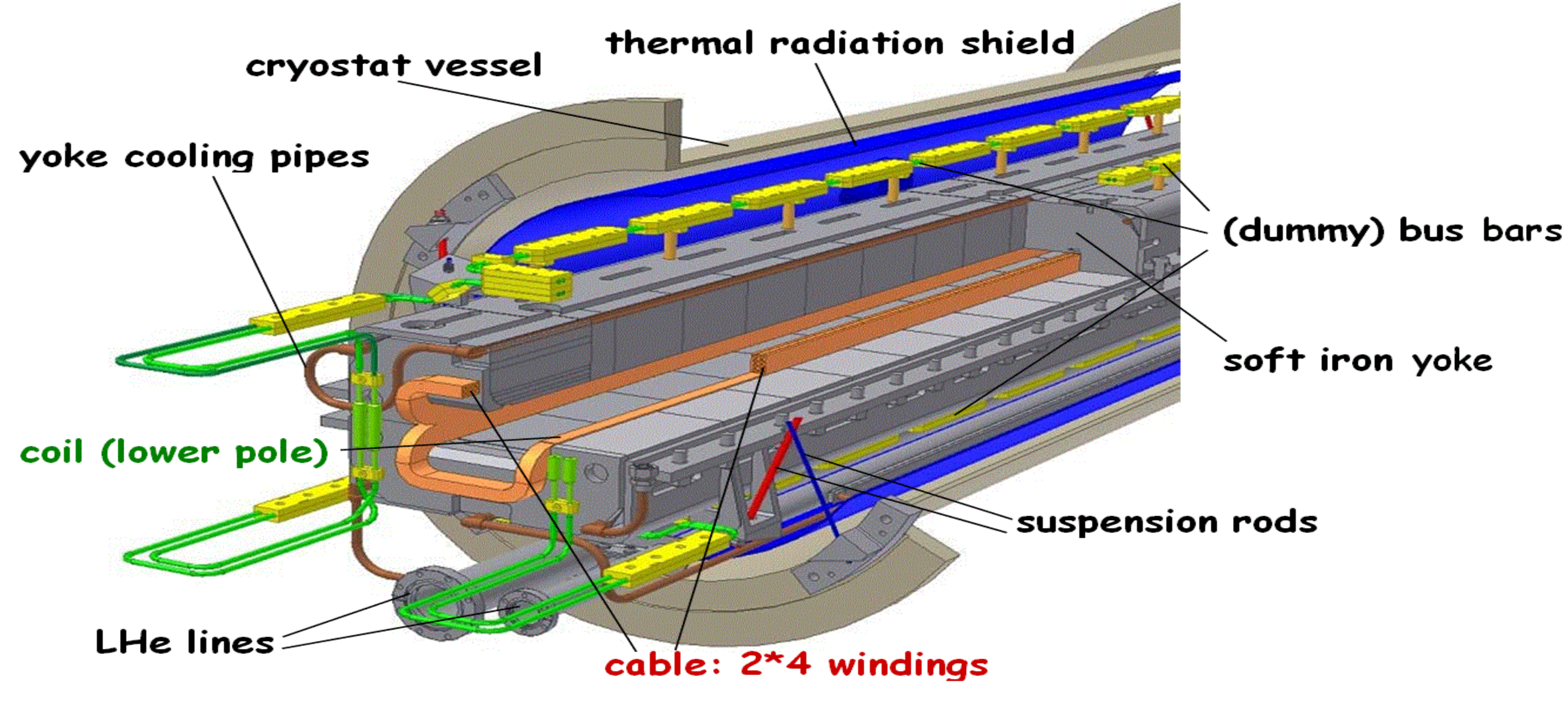
- 2016: start of SIS100 Dipole series production
  108 magnets + 4 spares



Basic SIS100 Dipole Design



SIS100 Dipole Prototype Design



SIS100 Dipole Cable

Main requirements of the magnet design:

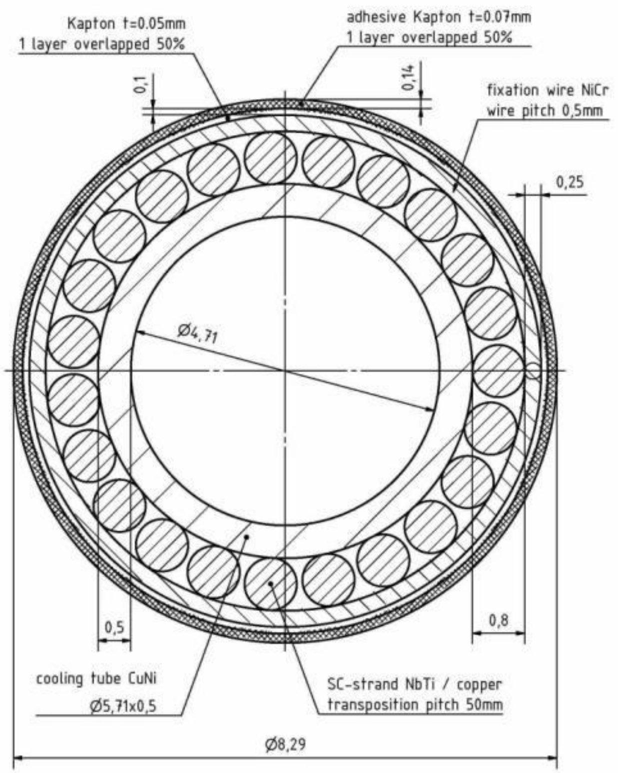
- high field quality
- fast periodic ramp rate (1.9 T, 4 T/s, 1 Hz)

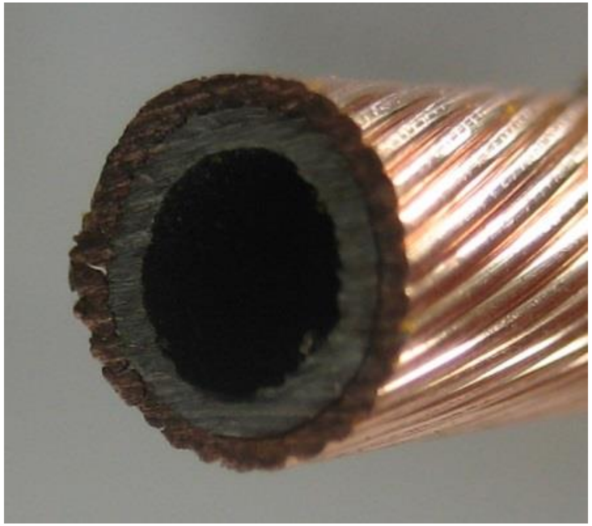
⟶Nuclotron Synchrotron Dipoles (JINR Dubna) were used as basis:

- Superferric window-frame design
- Nuclotron type cable

Evolution of the cable:

- Kapton to replace prepreg impregnation
- Optimization of tube and strand dimensions





Dipole Development within EU 6th Framework Program

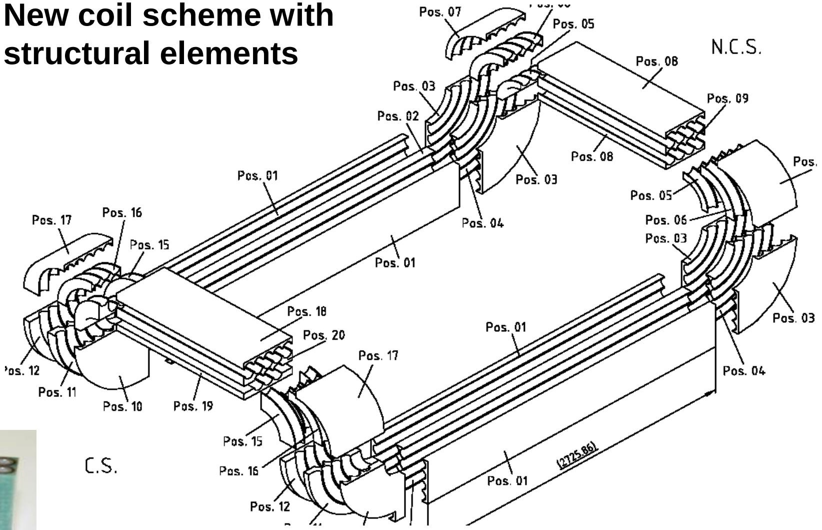
EU-FP6 Development by GSI with partners from institutes and industries:

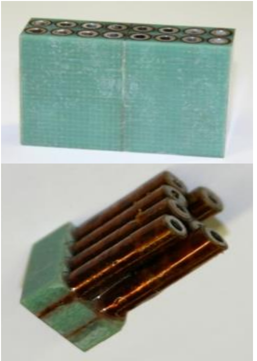
- Strong dynamical forces
- High accuracy and reproducibility

Babcock Noell contributions to EU-FP6 programm:

- Design and layout
- Winding scheme and tooling concept
- Several test pieces
- Measurements mech. and thermal properties

New coil scheme with structural elements



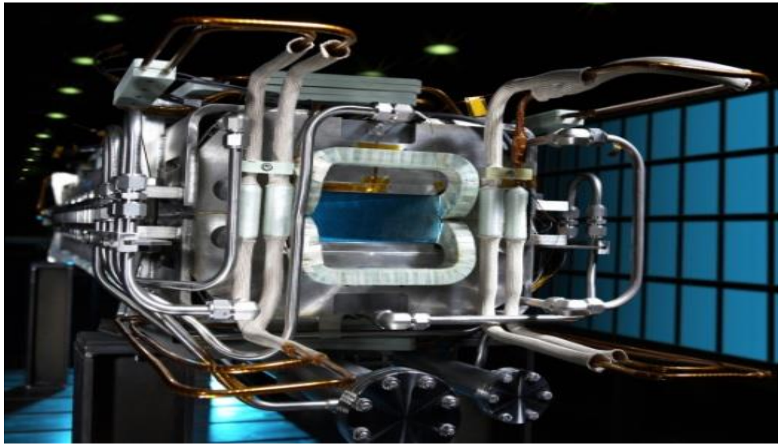


Samples for testing

Industrial Prototype Production

Fast ramped superferric prototype dipole:

- Fast ramping → 4 T/s
- NbTi, Nuclotron Cable
- Length ~3 m straight!
- Magnetic Field 1.9 T



Prototype scope and goals:

- Industrial manufacturing of the SC cable
- Qualification for the industrial production process and tooling concept

SIS100 Dipole Prototype and FOS Magnet

Major step: 2-layer straight -> 1-layer curved magnet!

Advantages of 1-layer curved magnet:

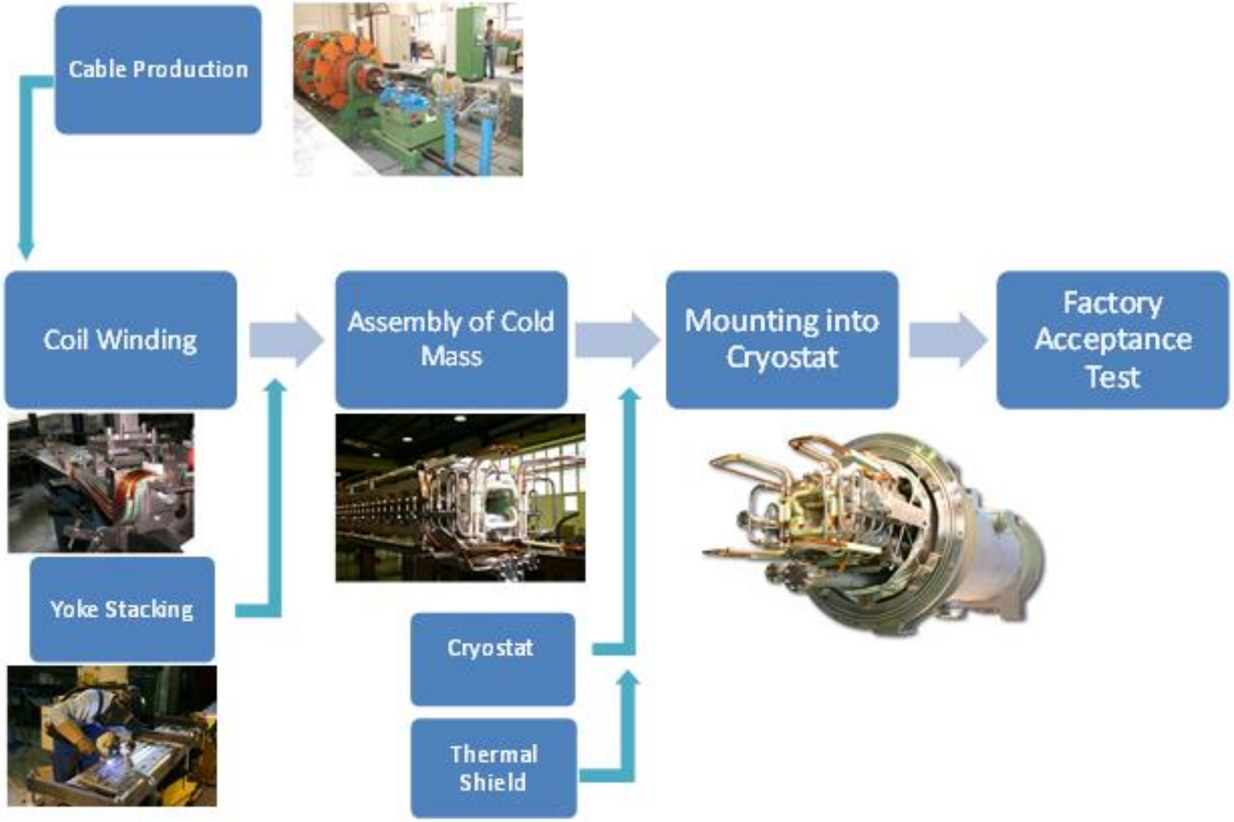
- 4 times lower hydraulic resistance of coil
  -> ramping with continuous triangular cycling mode @ 4 T/s
- Reduction of peak field to 1.9 T
  -> reduction of field errors due to iron saturation limit

-> New challenges in manufacturing:

- winding of bent coil and stacking of bent yoke
- increased cable diameter reduced the available space for electrical insulation and structural components in the coil

Parameter	Prototype	FOS
Effective length	2.756 m	3.062 m
Bending angle	**0 deg**	**3.33 deg**
Bmax	2.1 T	1.9 T
Max. ramp rate	4 T/s	4 T/s
Layers x turns	**2 x 8**	**1 x 8**
Operating current	7 kA	13 kA
Outer diameter of cooling tube	5 mm	5.7 mm
Number of strands	31	23
Strand diameter	0.5 mm	0.8 mm
Cable diameter	**7.36 mm**	**8.29 mm**

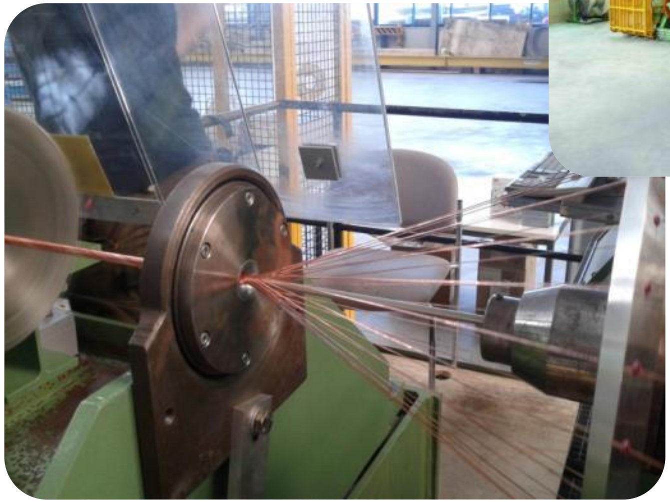
FOS Magnet: Manufacturing Workflow

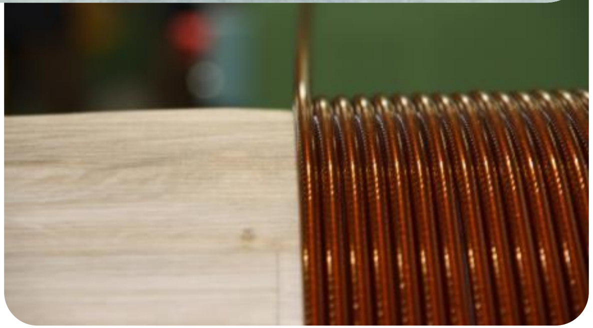


FOS Magnet: Cable Production

- Demand of cable per dipole: 62 m (coil) + 52 m (busbars)
- Cable produced for 1 dummy coil with copper strands
- For the series a total of 16,000 m are needed

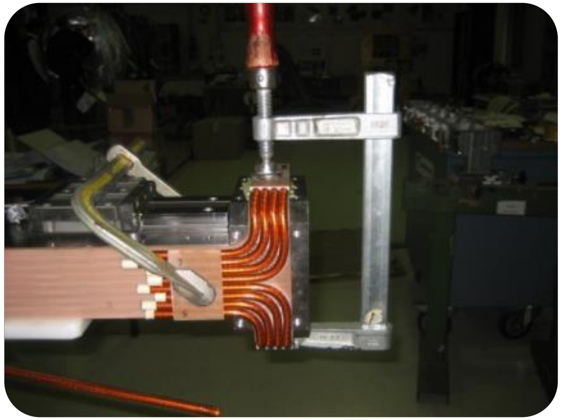
$\upsilon_{\text{Spinner}} = 705$ rpm $v_{\text{Cable}} = 0.35$ m/min

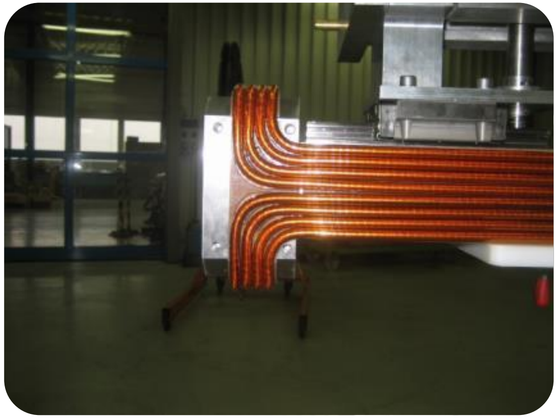


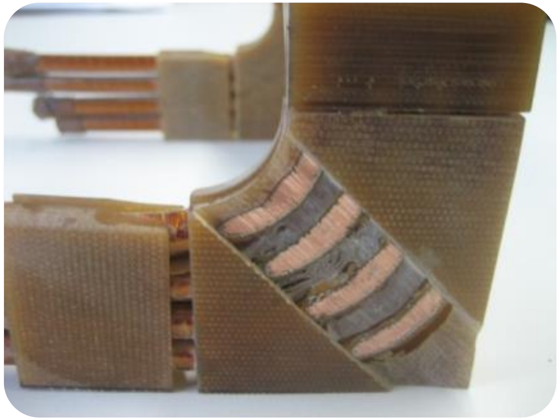


FOS Magnet: Test Winding and Dummy Coil

- Precisely machined G11 elements
  - define position of turns with respect to each other and to yoke
  - avoid relative motions in operation
- Cable is glued into G11 to achieve a monolithic block
- Prepreg used in coil head area



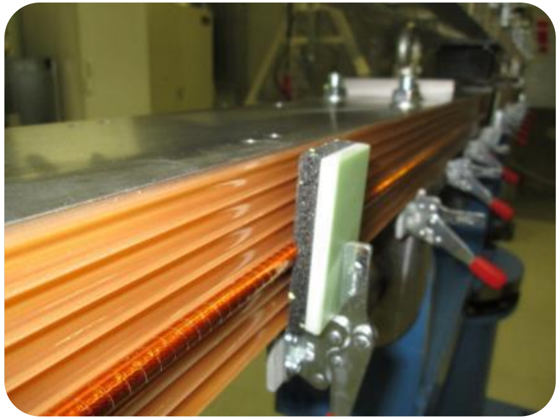


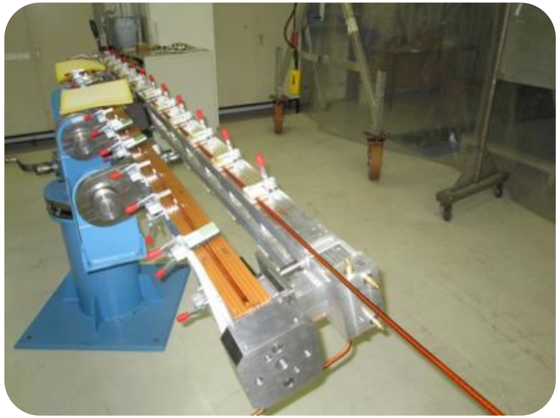


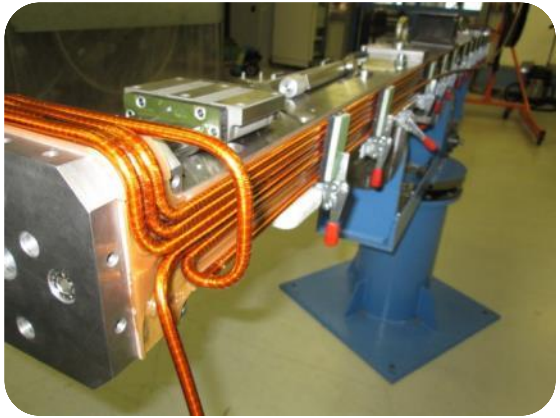
FOS Magnet: Coil Winding on Winding Tool

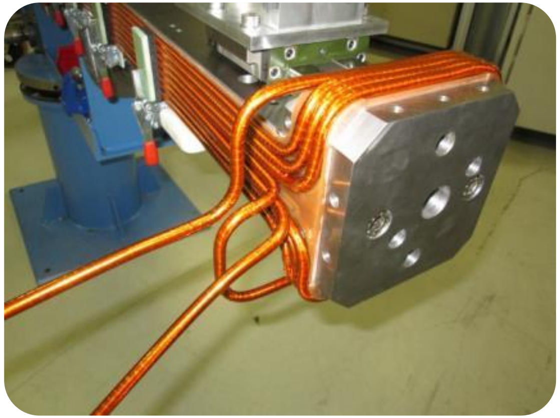
Winding tool developed for bent single layer FOS coil,

same concept as for Prototype coil









FOS Magnet: Gluing of G11 Structure with Coil

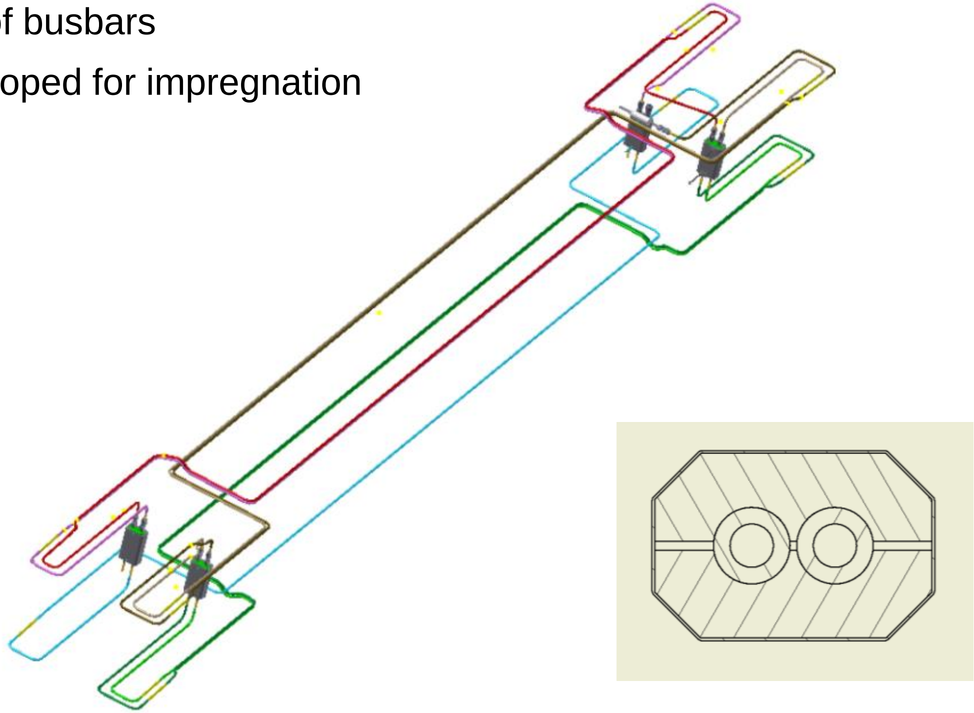
t ~ 5 h
T ~ 180 °C

FOS Magnet: Coil Prepreg Impregnation

t ~ 3.5 h
T ~ 150 °C

FOS Magnet: Bending of Busbars

- Special tool developed for bending 7 different types of busbars
- Special tool developed for impregnation of busbar-pairs

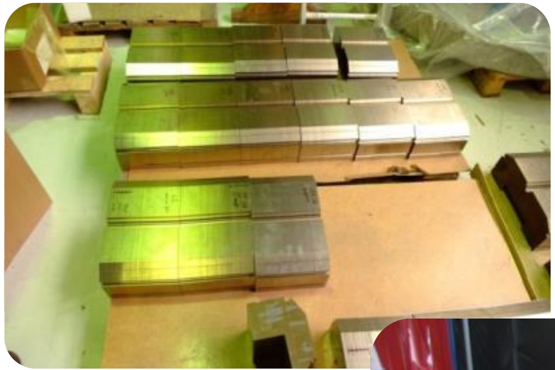


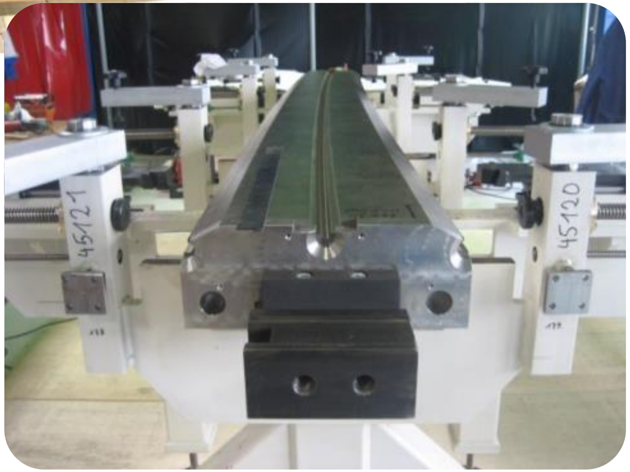
FOS Magnet: Yoke Manufacturing

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





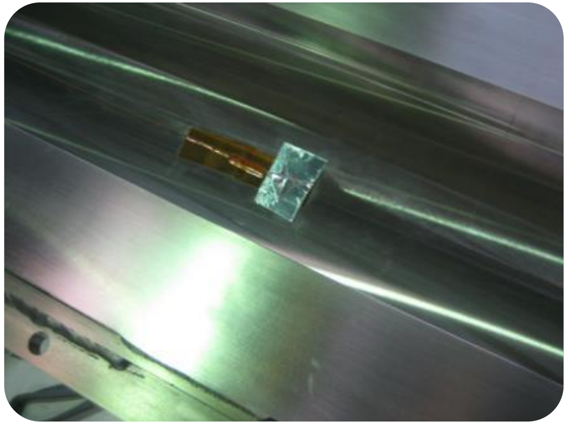
FOS Magnet: Yoke Manufacturing (2)

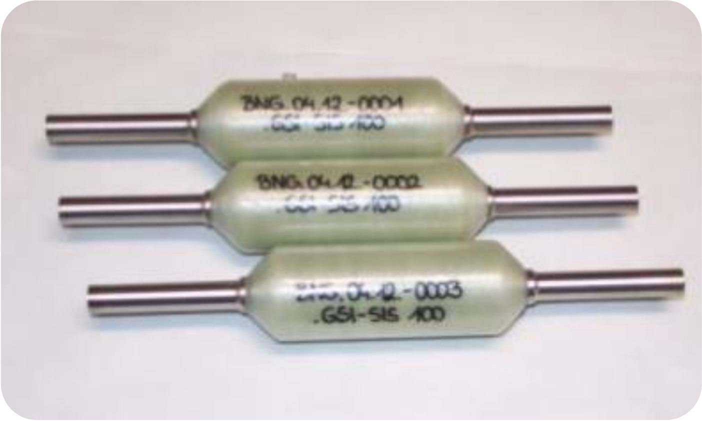
Lamination: M600-100A, 1mm, Stabolit 70 coating

Yoke Manufacturing:

6. Weld side and top covering sheets
7. Machine the half-yokes

FOS Magnet: Shield, Helium Supply-Lines, Potential Breaks, Sensors

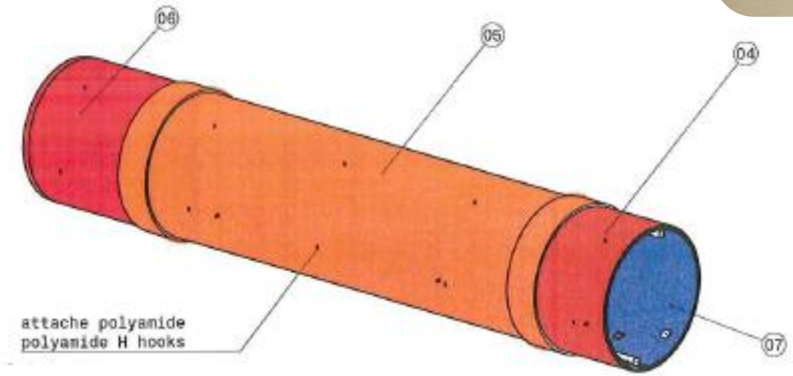




FOS Magnet: MLI-blankets

- MLI Superinsulation:
  - 30 layers external
  - 5 layers internal

- Pre-fabricated MLI-blankets
  with fastener system ready for assembly
  → efficient concept for series production



FOS Magnet: Vacuum Vessel

- Vacuum vessel parameters:
  - Material: 1.4301 / AISI 304
  - Inner diameter: 848 mm
  - Length: 2770 mm
  - Weight: 900 kg
  - Standard operating pressure: ≤ 10-6 mbar
- Manufactured according Pressure Equipment Directive DGRL 97/23/EG / AD2000

Prüfbericht Nr. 06/12/6310N
zur Festigkeitsberechnung des Vakuumbehälters FOS

Antragsteller: **Babcock Noell GmbH, Herr Stefan Sattler, Alfred-Nobel-Str. 20, 97080 Würzburg, Germany**

Projekt: **GSI SIS 100 Dipole**

Hersteller: **Babcock Noell GmbH**

Reg.-Nr. des Herstellers: **N.911037**

Baujahr: **2012**

Bezeichnung: **Vakuumbehälter FOS**

Der Vakuumbehälter FOS liegt außerhalb des Geltungsbereiches der Druckgeräterichtlinie. Auf Wunsch der Babcock Noell GmbH wurde der Behältermantel mit folgenden Betriebsparametern überprüft.

Raum		Innenraum
Zulässiger Betriebsüberdruck	[bar]	-1 / 0,3
Zulässige Betriebstemperatur	[°C]	-50 / +35
Inhalt	[l]	1578
Schweißnahtfaktor	[-]	0,85
Korrosionszuschlag	[mm]	0
Mediumzustand		gasförmig
Füllmedium		Fluidgruppe 2

Verwendungszweck: Vakuumbehälter

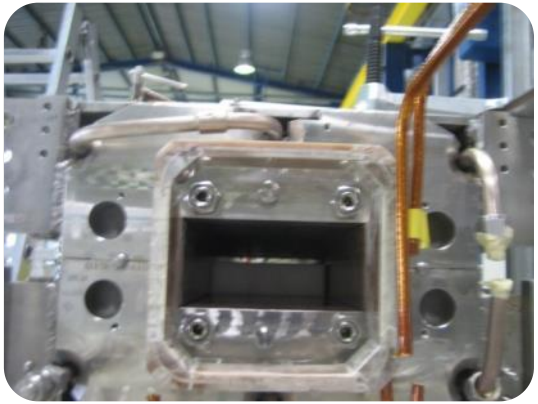
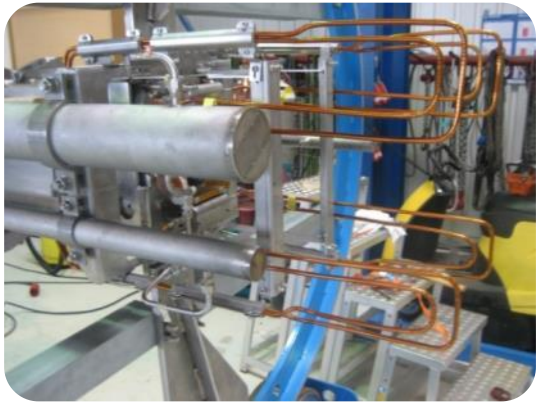
TÜV SÜD
Industrie Service
Mehr Sicherheit. Mehr Wert.

Datum: 03.10.2012
Unsere Zeichen: IS-DD1-DRE/koe
Bericht Nr. 06/12/6310N
Das Dokument besteht aus 2 Seiten
Seite 1 von 2

FOS Magnet: Assembly of Cold Mass

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

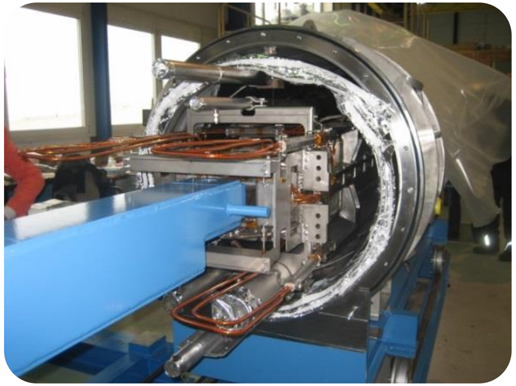


FOS Magnet: Assembly of Magnet

Assembly on dedicated rig:

1. Place thermal shield in vacuum vessel
2. Pull vacuum vessel with shield over cold mass and suspend on rods
3. Align with laser-tracker and pretension the tie rods



SIS100 Dipole FOS Cold Test

FOS has been cold tested successfully at GSI‘s test facility.

Electrical and themal performance is very good.

To improve the field quality of the dipole a second yoke has been produced with laser welding technology and the dipole was re-tested with the new yoke.

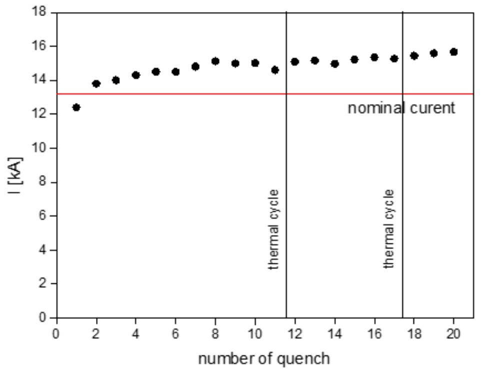
CERN Courier March 2016

„The results … [from the site acceptance test] indicate high mechanical precision and excellent performanceof the superconducting coil.“

Main Test Results for the FoS

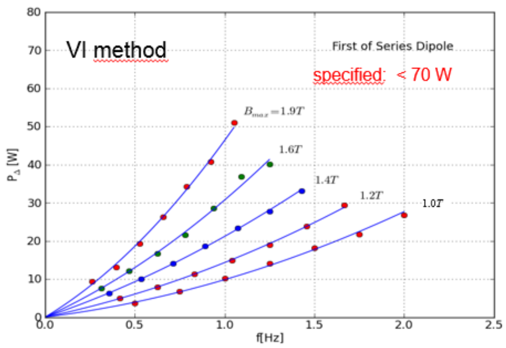
quench performance and AC losses

electrical powering



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

AC losses



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

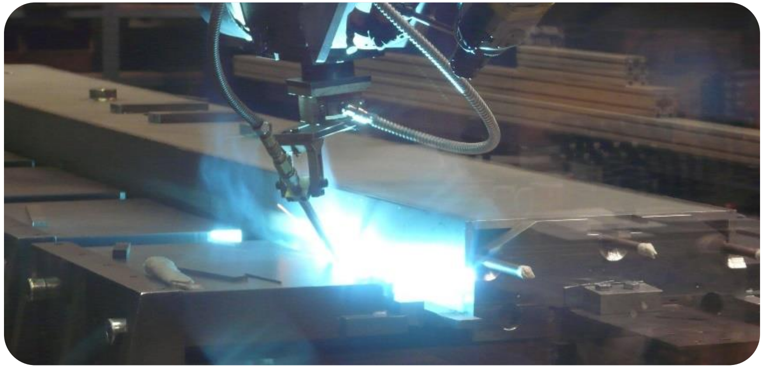
$q_h = 4.2 \pm 0.5$ J „hysteresis“

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

GSI Helmholtzzentrum für Schwerionenforschung GmbH

SIS100 Laser Welded Yoke

FOS yoke	Laser welded yoke
Mag hand welded	Laser machine welded
20-30 cm/min.	200 cm/min.; low heat input
Pole surface machined	No machining of pole surface
Tolerances: horizontal <0,2mm; vertical >5mm	Tolerances: horizontal <0,2mm; vertical <1,5mm



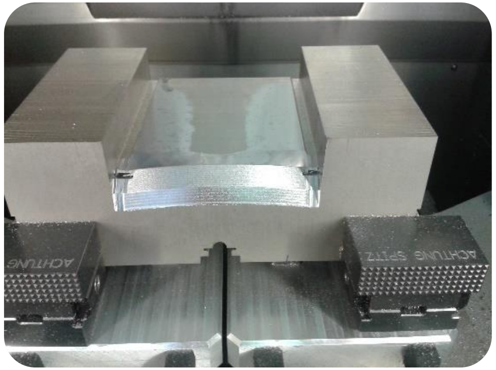
SIS100 Laser Welded Yoke

Endblocks (200mm long):
Lamination M600-100A, 1mm, Backlack Stabolit 70 coating

Middle part:
Lamination M600-100A, 1mm, isolation coating PH2

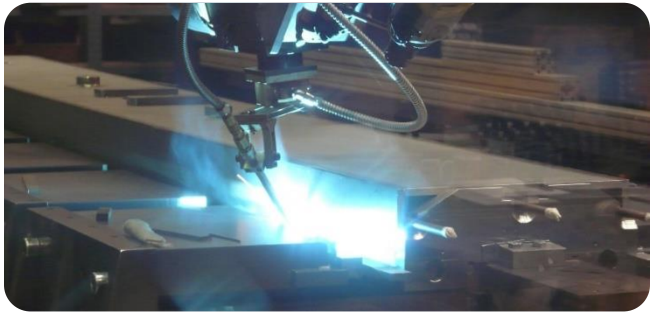
Yoke Manufacturing:

1. Stack 200 mm curved packages for endblocks, filling factor ≥ 98%
2. Glue packages in oven
3. Machine endblock with Rogowski profil
4. Place machined endblock on girder
5. Place single yoke sheets on girder
6. Adjust filling factor, filling factor ≥ 98%
7. Insert cooling tubes



SIS100 Laser Welded Yoke

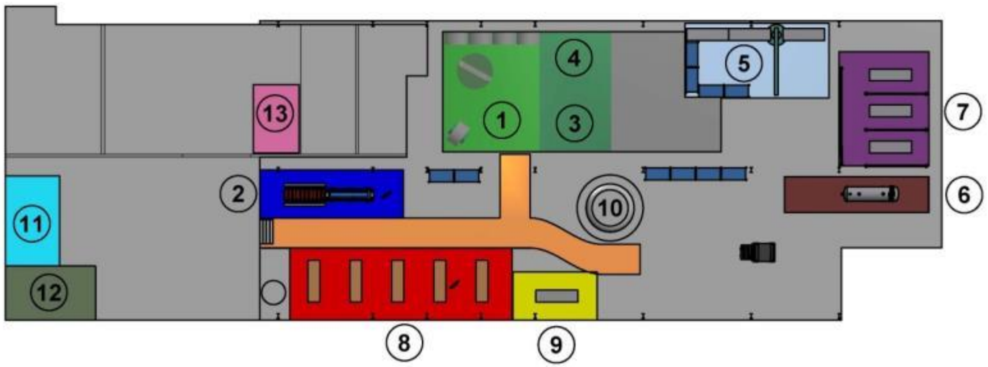
6. Stick side and top covering sheets
7. Laser weld half-yokes
8. Machine holes and reference planes



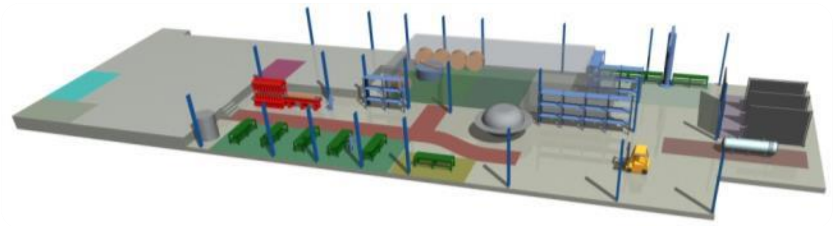
Outlook on Series Production

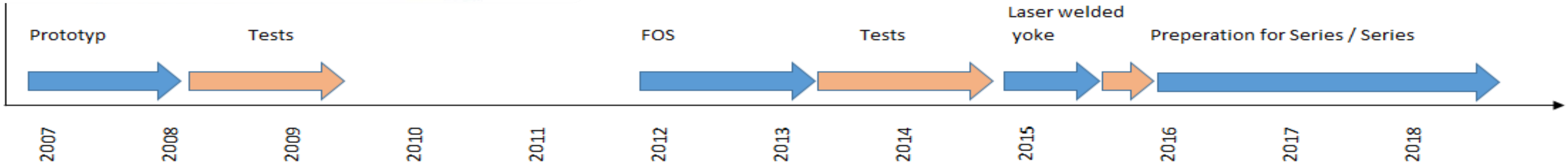
Design modifications for the series production:

- Endblock design
- Stamped yoke sheets instead of lasercut
- Yoke manufacturing process
- MLI on Helium supply lines
- Change to ceramic voltage breakers



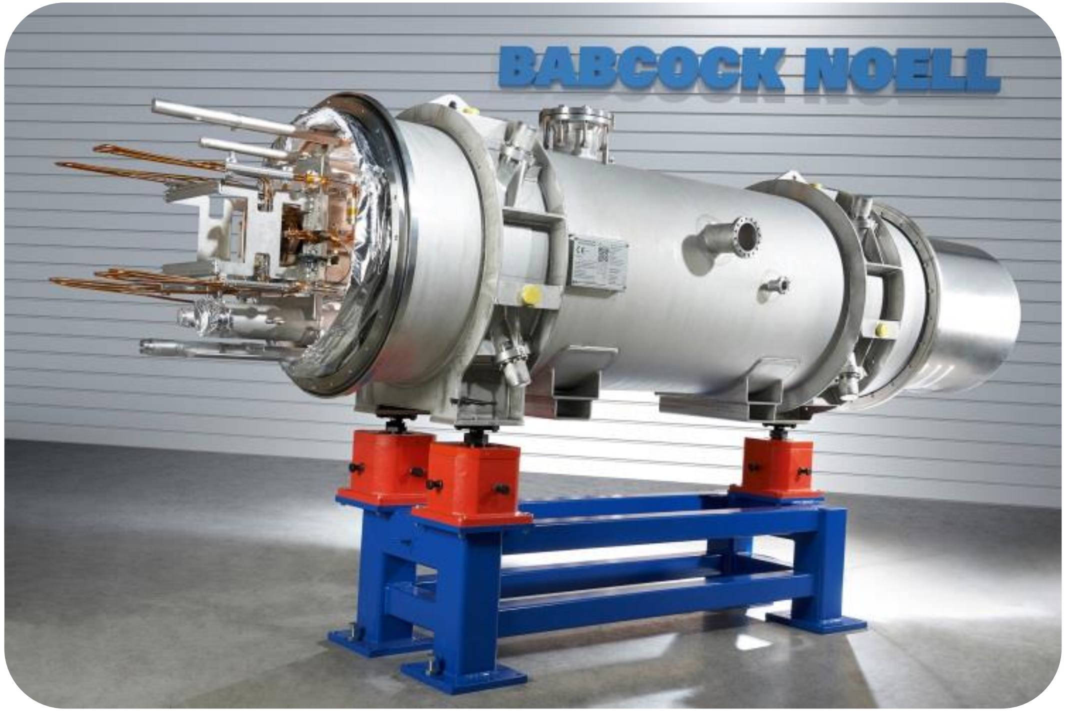
Manufacturing layout for SIS100 series production:
1 = winding, 2 = baking press, 3= coil insulation,
4 = electrical tests of coils, 5 = stacking of yoke packages,
6 = yoke heat treatment, 7 = assembly of half-yokes,
8 = assembly of cold mass into cryostat, 9 = geometrical measurements,
10 = He leak test on coils, 11 = pre-manufacturing of busbars,
12 = leak tests on components,
13 = thermal shield manufacturing





Industrial Challenges in SIS100 Dipole production

- Limited number of industrial prototypes
- 4 years time-gap between industrial prototype and start of FOS production
- Project managment:
  - supply chain for non-standard sub-supplies
  - ramp up and down for series production
  - series production in quality, time, cost
- FAIR requires tolerances on components (curved yoke) that are at the edge of industrial feasibility

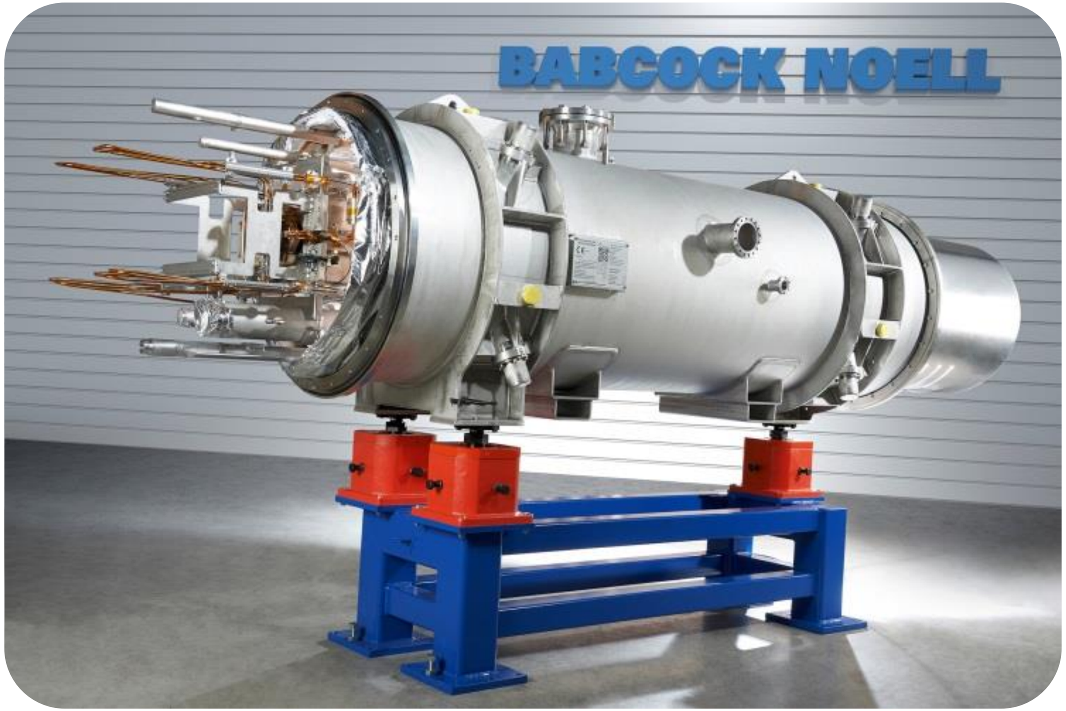


Conclusion

- FOS Magnet: last critical step before industrial series production
  -> successfull performance at cold

- Concepts developed for Prototype could be transferred to FOS Diple.
  Adoptions in manufacturing process necessary especially due to changed yoke dimensions and shape

- Start of series production in 2016 expected



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Thank you
for your attention!