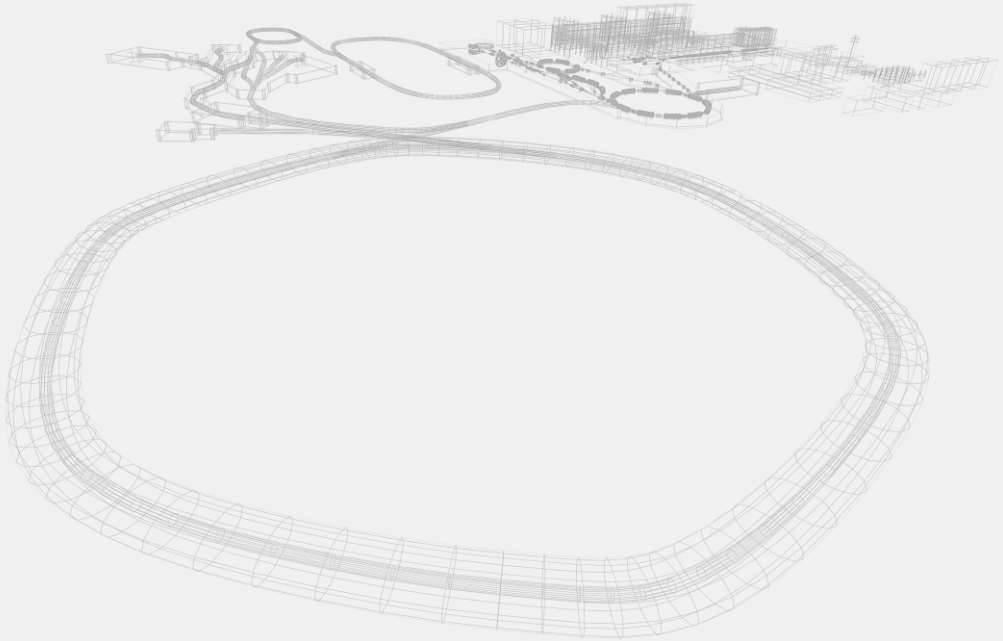
Production and Testing of FAIR's SIS100 Superconducting Magnets

Kamil Kozlowski – GSI Helmholtz Centre for Heavy Ion Research

on behalf of the SCM Department



SPAS `26 | Kraków| October 20-22

Outline

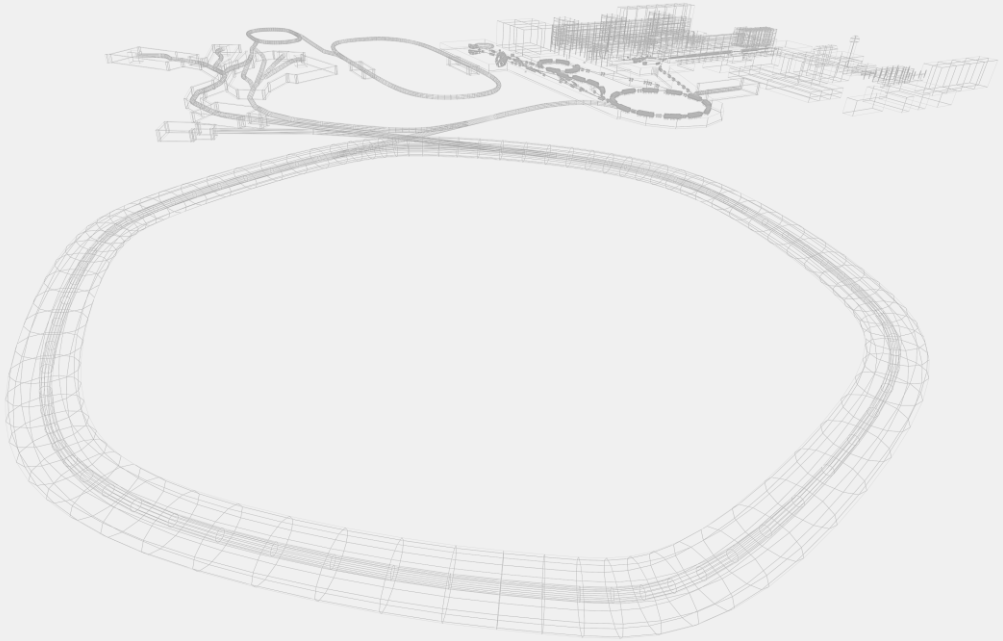
Introduction

- SC Magnets of SIS100

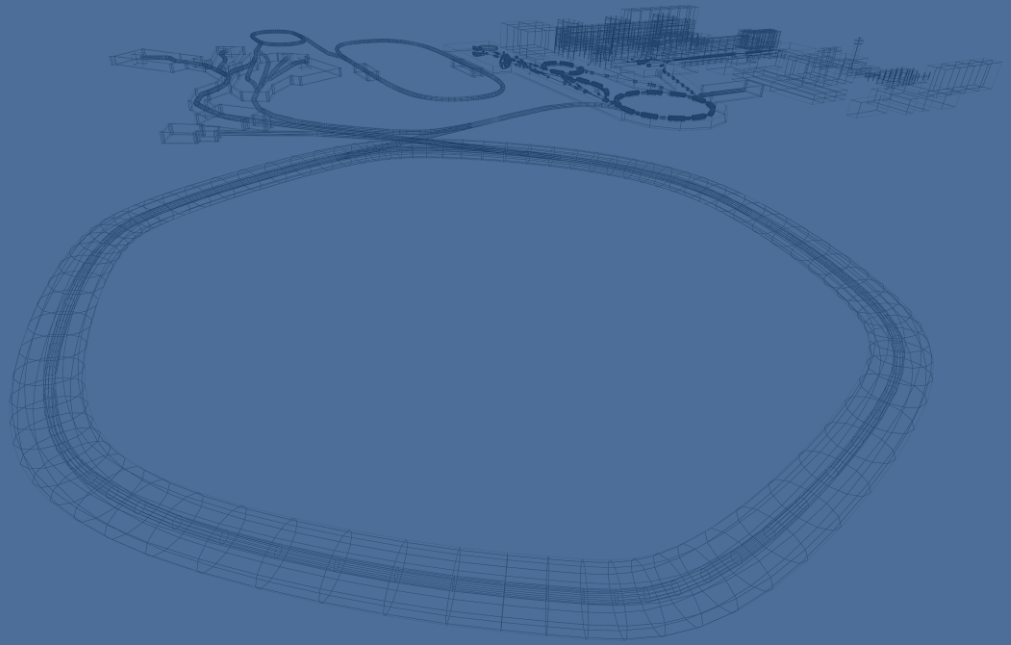
Production and Testing in 2026

- Evolution of the Supply Chain
- Technical Challenges and Open Issues

Current Status

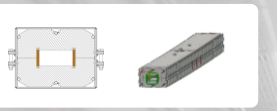


SIS100 magnets



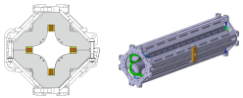
SIS100 - magnets overview

Dipoles

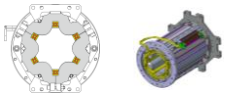


Quadrupole doublet modules (QDMs)

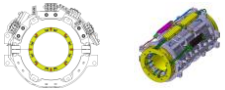
main quadrupoles (166)



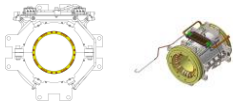
sextupoles (42)



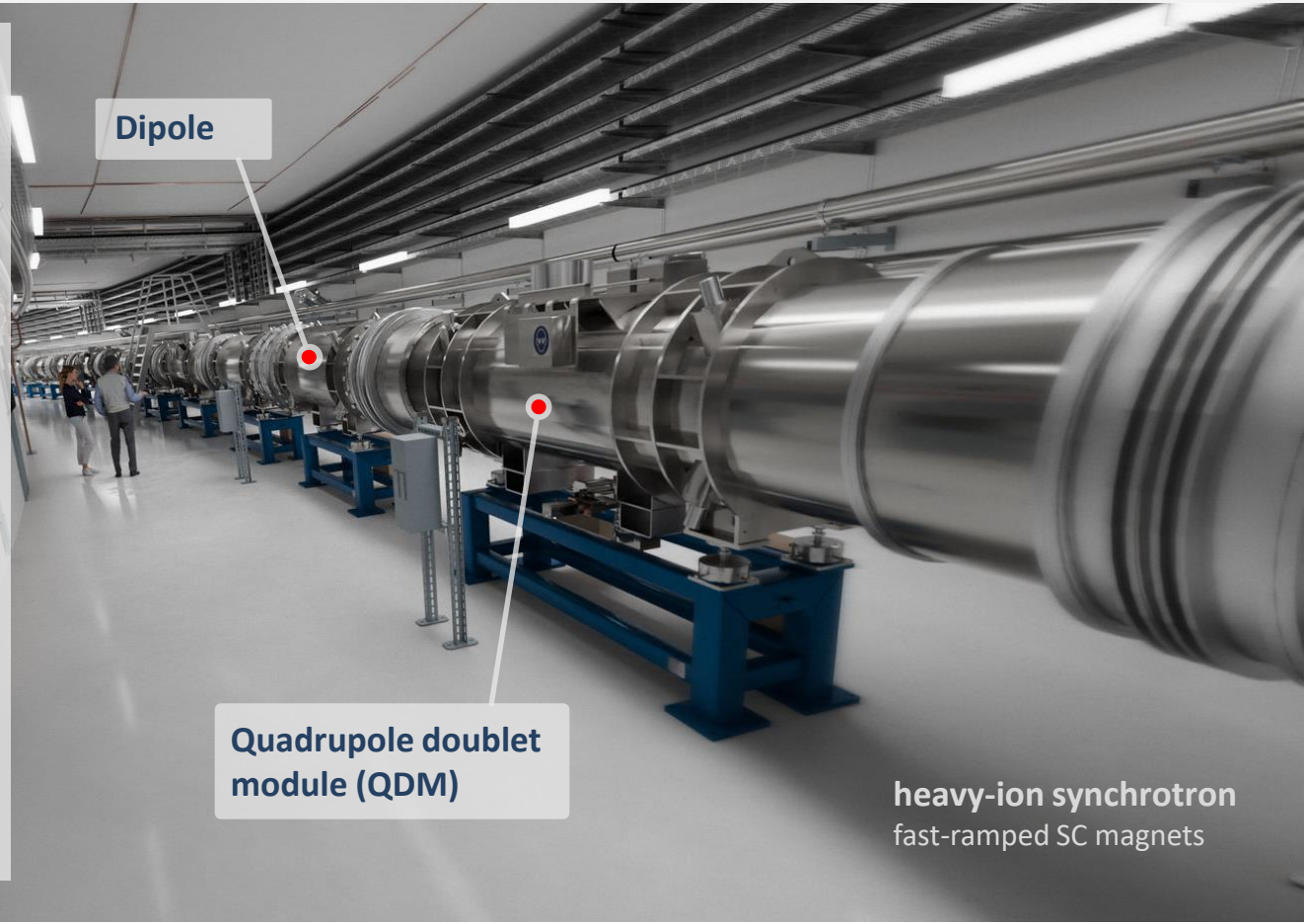
multipoles (12) (B2, A3, B4)



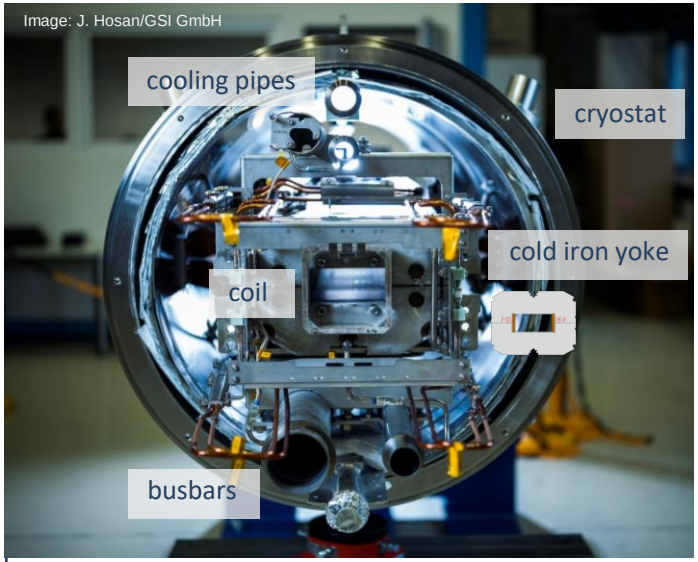
steerers (83)



+ special quadrupoles (16)



SIS100 dipole modules

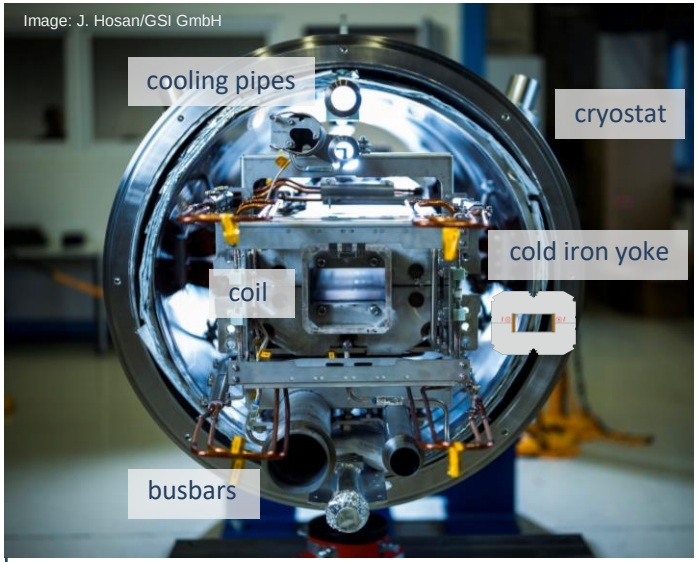


#	108
dim	aperture: h = 68 mm 3 m length, 3 t
field	1.9 T with 4 T/s
current	13.2 kA with 28 kA/s
L	0.5 mH
E	40 kJ

features

- superferric magnet design
- fast ramping
- two phase LHe cooling (forced flow)

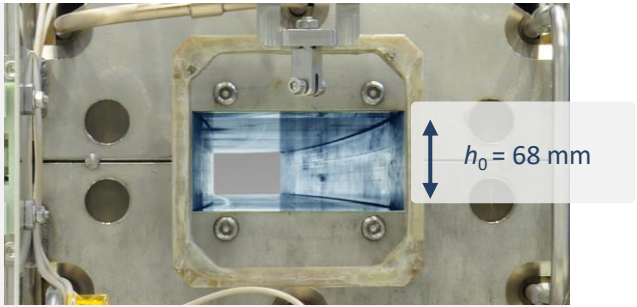
SIS100 dipole modules



features
- superferric magnet design
- fast ramping
- two phase LHe cooling (forced flow)

high-precision iron yoke
- laminated, curved
- height variation: < 50 µm

→ field quality
- TF variation on 10^{-4}
- harmonics below 5 units



Low-loss cables

SIS100: ***4* T/s (*28* kA/s)**

Wire	d_w = 0.8 mm
Filaments	d_f ~3 µm, 25 k/strand
Matrix	CuMn
n-value	≥ 30
I_c (4.2 K, 2 T)	≥ 940 A



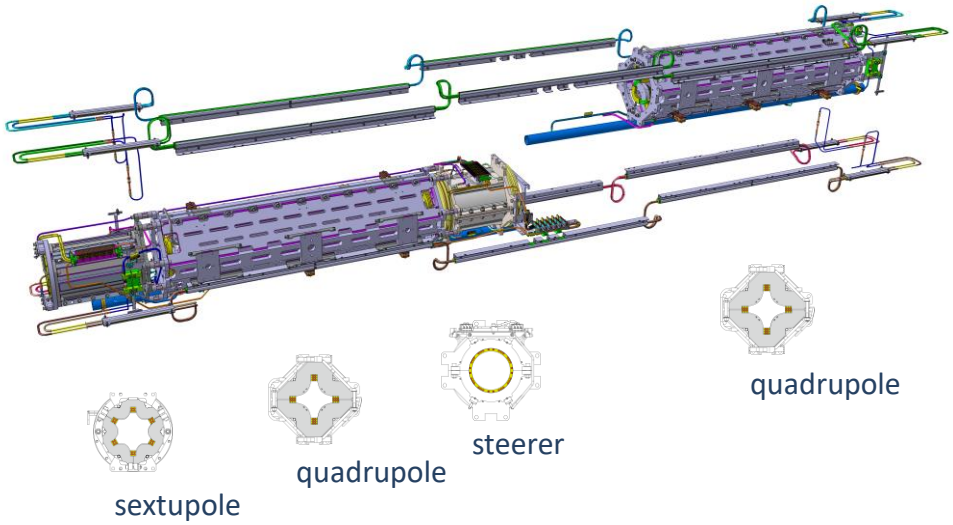
AC losses (≈1 Hz): 35 – 45 W/dipole

SIS100 quadrupole units

#	166
weight	1.2 t
types	
Main quadrupoles:	
dim	aperture: d = 100 mm
gradient	28 T/m
current	10.5 kA



Quadrupole unit: main quadrupole + correctors (steerer, sextupole, multipole)



type SF1H

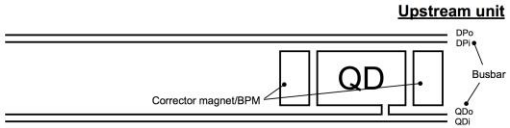
type BQD

SIS100 quadrupole doublet modules

Example – QDM type 2.5

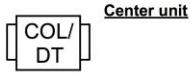
Upstream unit (VQD)





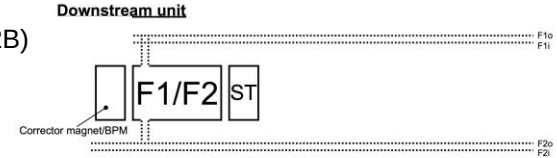
Center unit



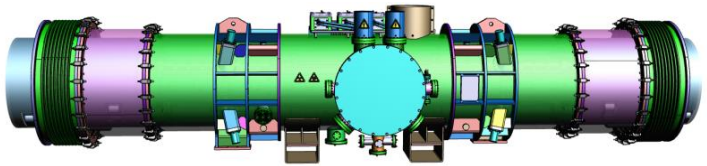


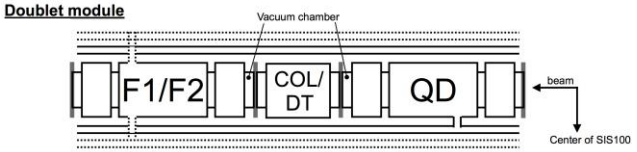
Downstream unit (SF2B)





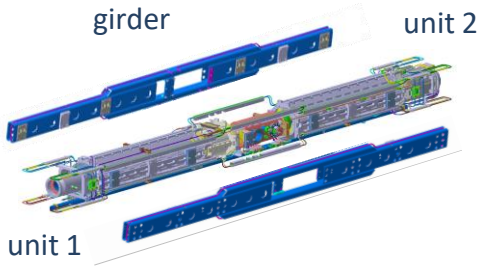
Doublet module 2.5

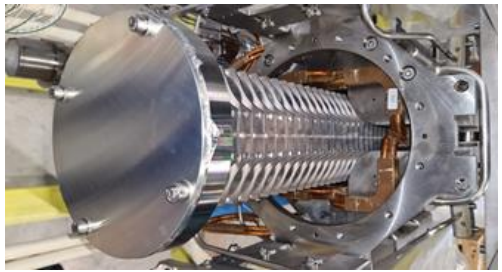




SIS100 quadrupole doublet modules

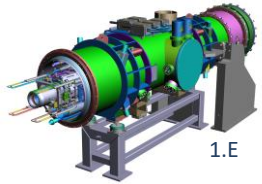
Quadrupole doublet modules (QDMs)
- two units on common girder (precise alignment)
- cryogenic UHV chamber
- integration into common cryostat







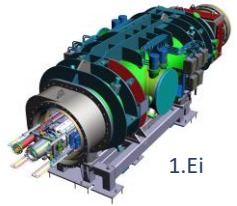
Arc modules



Arc termination modules



Straight modules

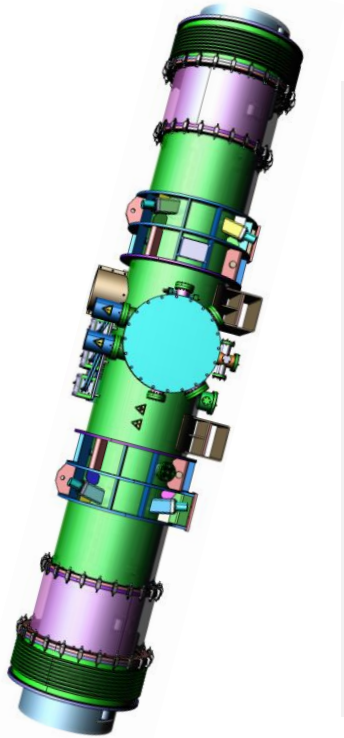


Special modules

- 11 types (unit/component combinations)
- 4 families (cryostat and interfaces)

83 modules needed

SIS100 quadrupole doublet modules



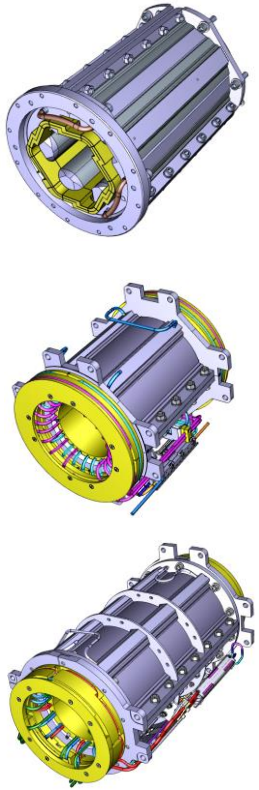
QDM (type 2.5)

Quadrupole doublet modules (QDMs)

- 11 types:
  - 1.123
  - 1.13s
  - 1.6A
  - 1.7B
  - 1.E
  - 1.Ei
  - 2.4
  - 2.4x
  - 2.5
  - 2.8C
  - 2.9 & 2.D

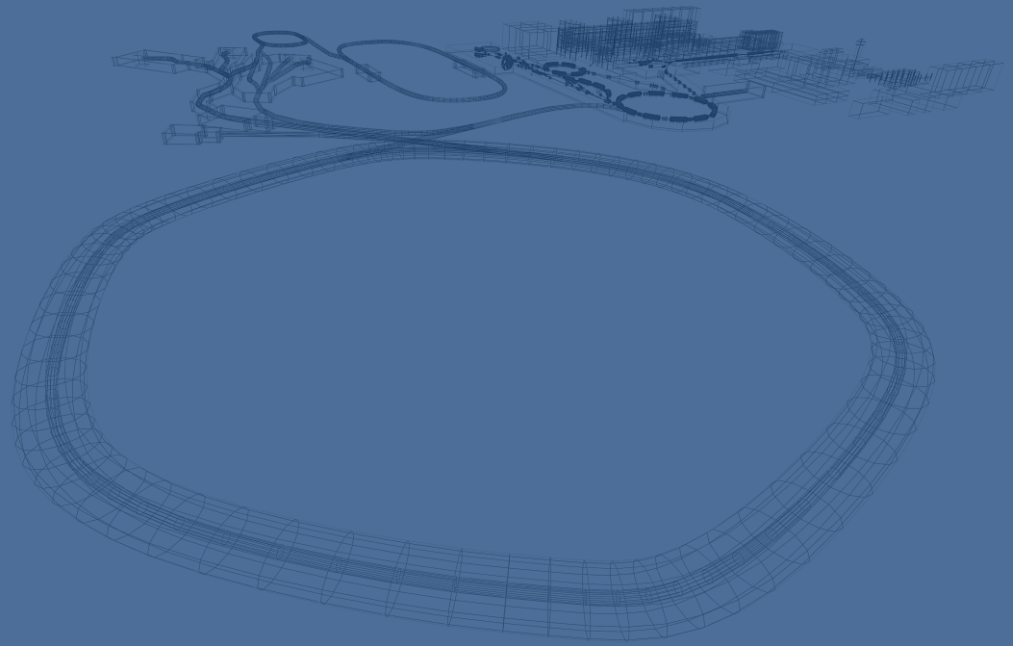
Content:

- **2x Quadrupole magnet**
- Corrector magnets:
  - Sextupole
  - Multipole
  - Steerer
- Vacuum interfaces
- Beam Position Monitors
- Cryocatchers



Corrector magnets

Production and testing



Damaged Dipole #93

Incident:

- A dipole magnet was damaged during storage.
- The damage affected several major components, requiring repairs and replacement of some parts.

Strategy:

- Cryostat, thermal shield, beam chamber scrapped (too much damage).
- New yoke will be build from steel for quadrupoles.
- Delivery of repaired dipole to GSI without beam chamber. After magnetic field measurements beam chamber will be installed.

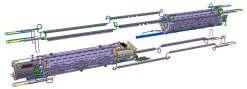
Status:

- Repair scheduled for July 2025 – June 2026.
- Magnet delivered and initial tests has been completed.



The damaged dipole module #93

Original supply chain for quadrupole doublet modules



JINR, Dubna, RUS

quadrupole units

- production
- cold testing





BNET, Würzburg, GER

QDM integration

integration of units into doublet modules





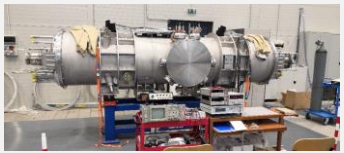


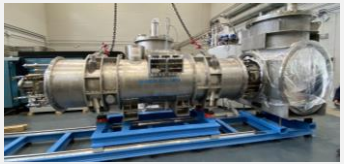
INFN, Salerno, ITA

QDM testing

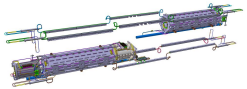
cold testing of quadrupole doublet modules







Original supply chain for quadrupole doublet modules



JINR, Dubna, RUS

quadrupole units

- production
- cold testing



2022: suspension of collaboration
→ missing unit supply



BNET, Würzburg, GER

QDM integration

integration of units into doublet modules





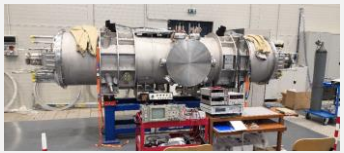


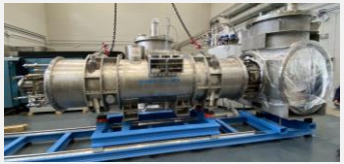
INFN, Salerno, ITA

QDM testing

cold testing of quadrupole doublet modules



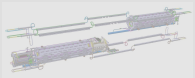




Fallback plan

JINR, Dubna, RUS

quadrupole units



BNET, Würzburg, GER

QDM integration



INFN, Salerno, ITA

QDM testing



Critical: unit supply

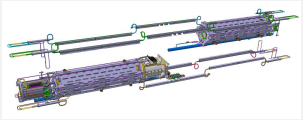
high project risk for multiple reasons if unit supply from JINR is missing

alternative unit production

BNET, Würzburg, GER

unit production

- series material procurement (GSI supply)
- prototype production done
- series production of 36 units approved



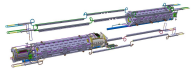
GSI

unit cold testing

testing infrastructure under development



Modified supply chain for quadrupole doublet modules (36 units)



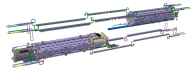
BNET, Würzburg

Quadrupole unit production

Unit production







GSI, Darmstadt

Unit testing

Cold testing of quadrupole units





BNET, Würzburg

QDM integration

integration of units into doublet modules





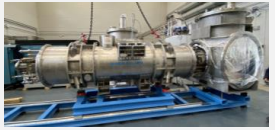
INFN, Salerno, ITA

QDM testing

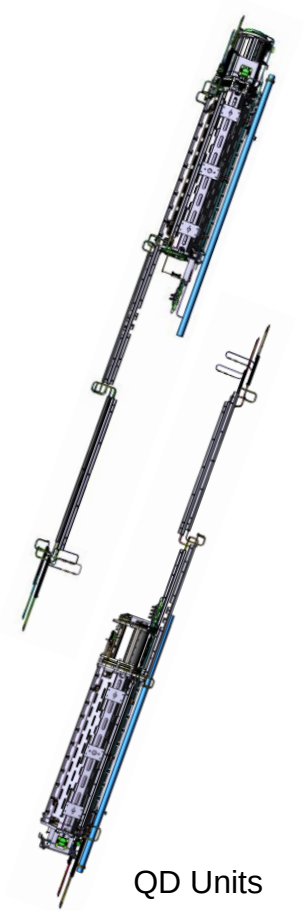
cold testing of quadrupole doublet modules







Prototype Units – Cold Test Results

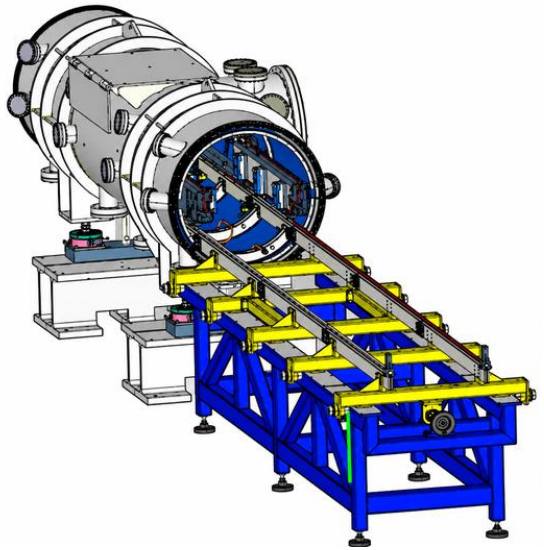


QD Units

Two prototype pairs tested (CS + F1/F2 + ST + QD)

- The prototype set includes a representative selection of SIS100 magnet types:
  - Both types of focusing quadrupole magnets
  - Defocusing quadrupole magnet
  - Two of the three corrector magnet types

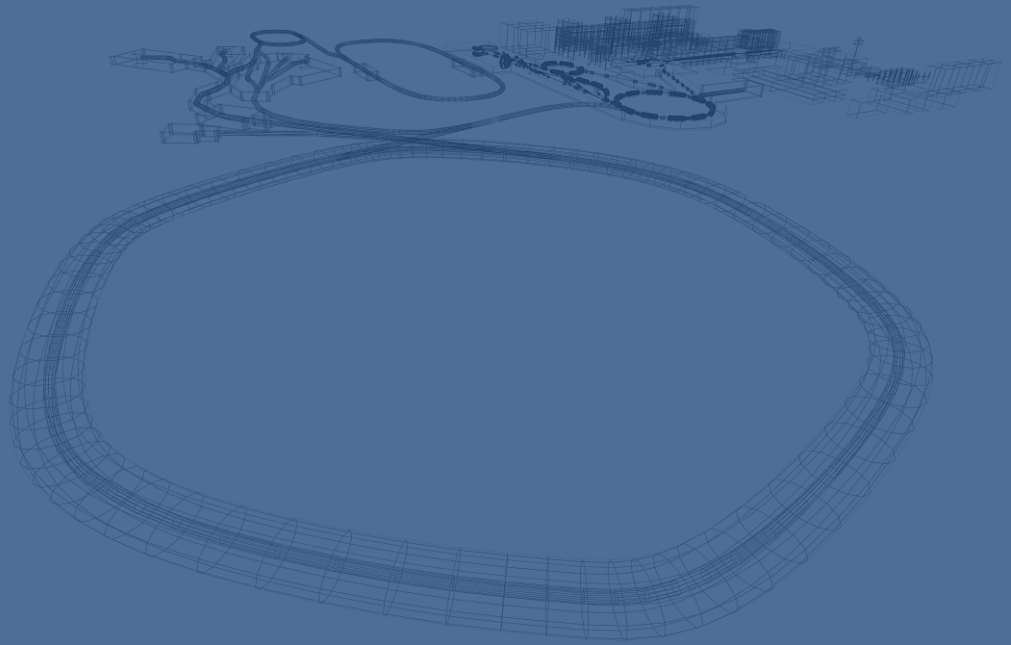
- Main quadrupole and corrector magnets: Cold tests demonstrated sufficient performance for SIS100 operation.
- Technology difference: BNET correctors use dry cable technology, compared to wet cable technology used for the JINR correctors.
- Performance comparison: Overall results are comparable to those achieved with JINR-produced corrector magnets.
- Further optimization: Additional tests are planned to evaluate potential performance improvements, including an updated steerer coil-head design.



Test Cryostat

Test Cryostat delivery is expected in October 2026.

Technical Challenges and Open Issues



HV properties of cold terminals

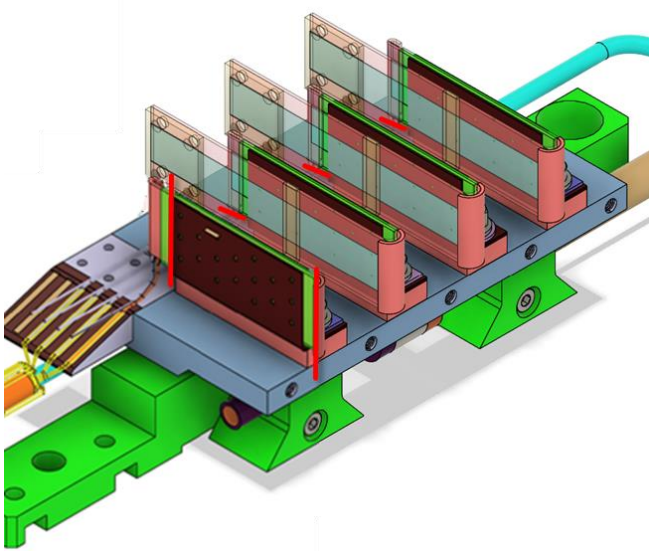
Degradation of HV properties was observed on cold terminals (CT).

Cold terminals are interfaces between the corrector coil strands and the current leads. High electrical insulation resistance and good thermal conductivity are required for reliable operation.

The design combines copper and epoxy insulation, with flexible polyimide PCBs in selected areas.

- Maximum expected voltages during a quench:
  - 375 V (steerer, coil-to-coil)
  - 485 V (sextupole, coil to ground)
- Test requirements:
  - R ≥ 100 MΩ @ 1.1 kV

A decrease in insulation resistance was observed during storage.



Cold terminal assembly

HV properties of cold terminals

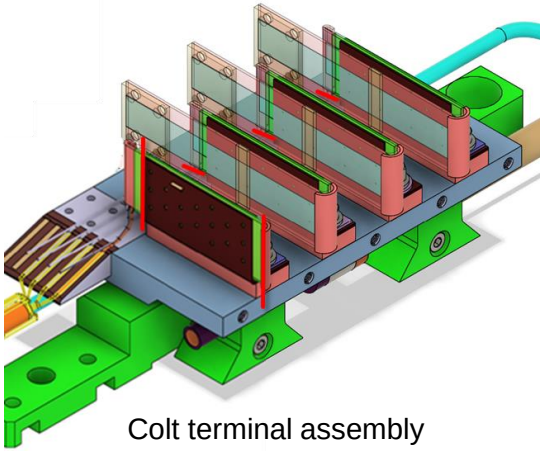
Causes of reduced insulation resistance:

Moderate resistance reduction (hundreds of kΩ to MΩ) – Likely moisture-related

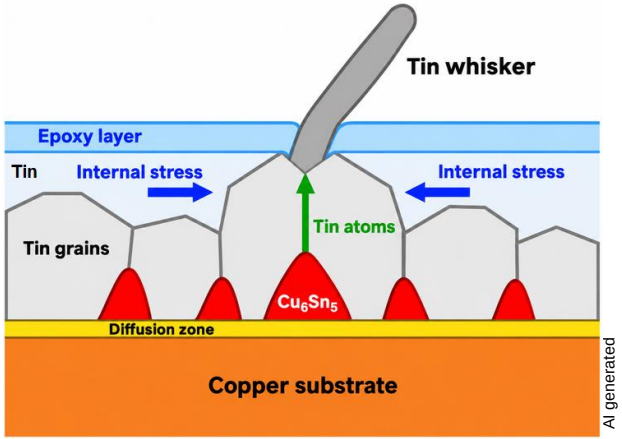
- Epoxy absorbs up to 2 vol.% water from the air. The CTs were not vacuum-packed or stored with silica gel (now added to the containers). Cleaning with isopropanol has no effect; only oven drying (~5 h at 60 °C) improves the resistance.

Severe resistance reduction (below 100 kΩ) – Tin whiskers identified

- confirmed by microscopic examination (ILK, Mr Zerweck, 16 Dec 2025). These tiny tin crystals grow on electroplated copper–tin surfaces due to diffusion, corrosion and/or mechanical stress. They can also grow through insulating layers.



Colt terminal assembly



Mechanism of whisker growth

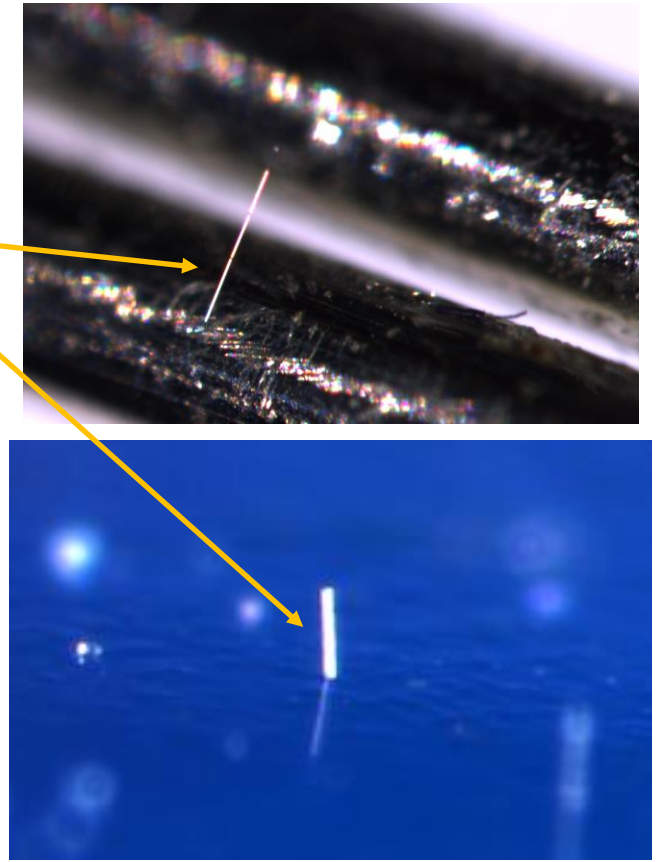
HV properties of cold terminals

Potentially affects tin-plated copper components.

Oxidation of the tin layer (SnO, SnO_2) can spread along the boundaries between tin crystals, reaching the intermetallic Cu_6Sn_5 layer. This creates internal stress, pushing tin atoms towards the surface, where they form thin, needle-like crystals called whiskers.

Whisker growth

- Typically occurs between −55 and 85 °C.
- No applied voltage or current flow is required.
- Needle length: up to 2 mm (up to 41 mm produced in laboratory conditions).
- Current-carrying capacity of the needles: 10–50 mA. Above this level the whisker breaks off (rather than melting). Note: high currents may cause arcing due to a short circuit!
- Needles can grow through plastic insulating layers.
- Damage or contamination of the tin surface (e.g. in the electroplating bath), as well as mechanical stresses after tin plating, promote growth.
- Tin grain size influences whisker formation. Small grains (shiny surfaces) promote growth.

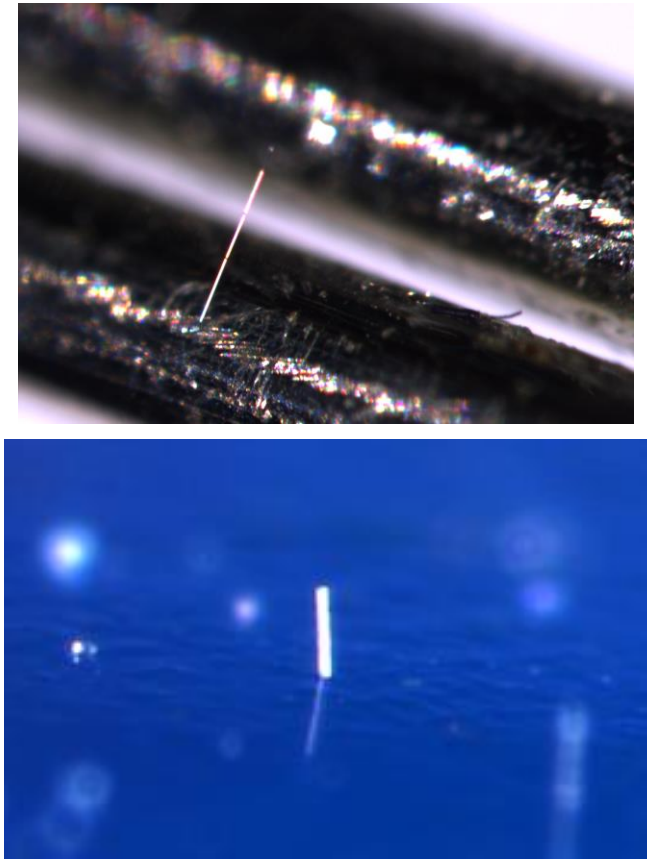


Whisker examples

HV properties of cold terminals

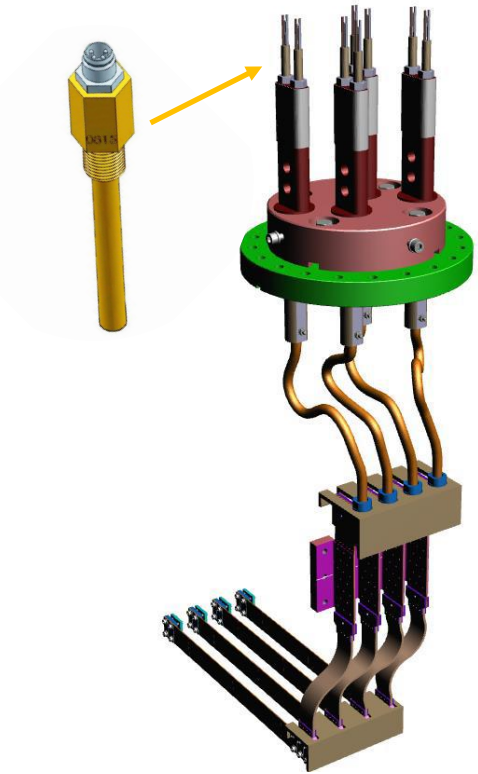
Solution and Implementation Status

- **Technical solution:** Introduce a diffusion barrier by applying an intermediate nickel layer (>2 µm) beneath the tin coating. Silver and Ni/Au layers are also possible alternatives.
- **Selected approach:** Replace all cold terminals on affected QDMs with new components, using nickel instead of tin as the surface coating.
- **Current status:** The improved design has been implemented and tested on the first QDM (#40)
- **Next steps:** Four QDMs are expected to be equipped with the new terminals by January 2027.



Whisker examples

LCL heaters – Unstable HV properties



Local current leads of a steerer magnet

Function of the heaters:

- Heat the copper parts of the current leads outside the cryostat.
- Prevent condensation and ice formation.

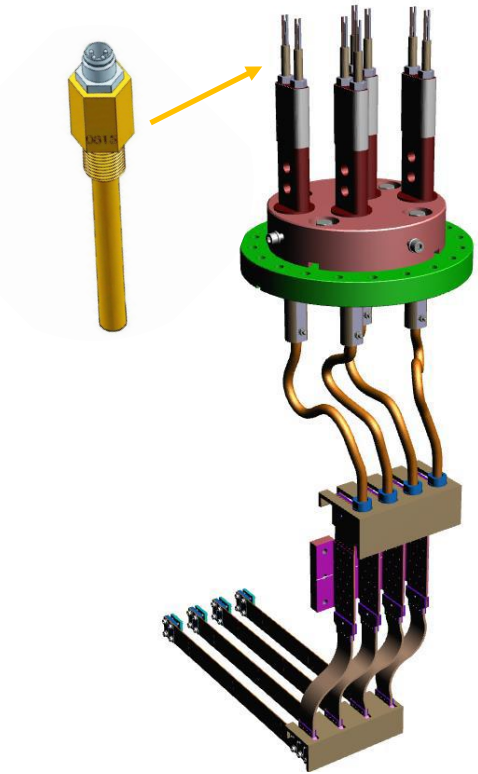
Simple construction:

- Brass rod containing a heating wire and a Pt100 temperature sensor, embedded in Loctite Ablestik 286 epoxy.



LCL with heaters of GEN I and GEN II

LCL heaters – Unstable HV properties



Local current leads of a steerer magnet

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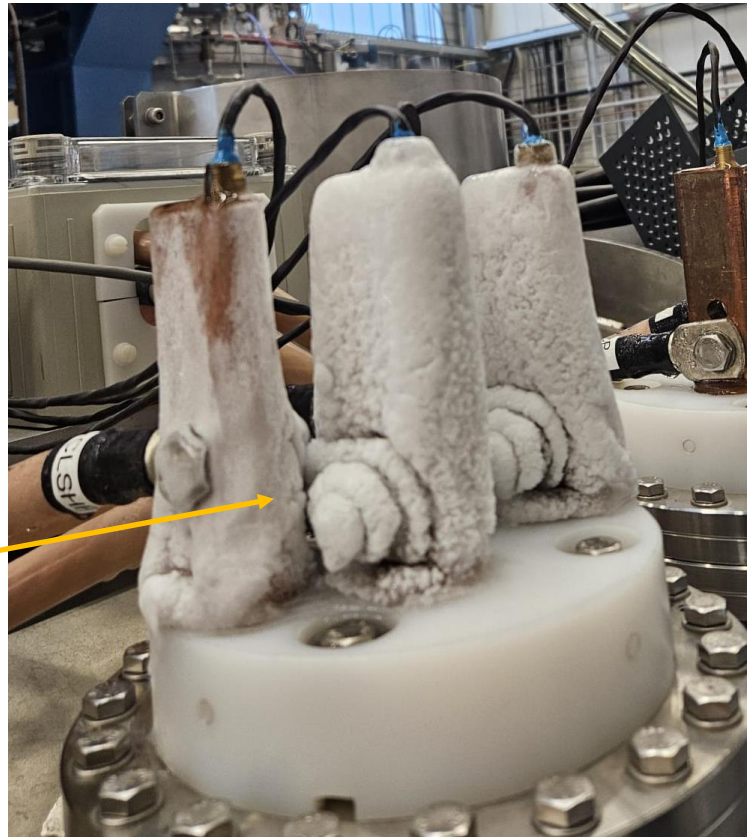
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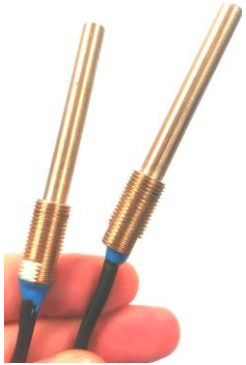
Worst-case scenario:

- Freezing of the current leads and significant ice build-up.
- Time-consuming removal of ice and water.
- Potential damage to the power converters.



Local current leads after a heating system failure

LCL heaters – Unstable HV properties



GEN I
- Heater rod installed directly in the current lead.
- Stable HV insulation properties demonstrated over several months of operation.

Problem: Fragile, handmade electrical leads.



GEN II (prototype for serial production)
- A connector was introduced to replace the fragile leads with an off-the-shelf solution.

Result: No significant HV insulation problems observed.



GEN III (serial production)

- PT1000 temperature sensor replaced with PT100

Problem:
- Significant degradation of HV insulation properties observed during storage.
- Around 10% of the heaters were initially rejected.
- After two months, another 10% fell below the specified limit.
- Further testing confirmed a progressive decrease in insulation resistance.

LCL heaters – Unstable HV properties

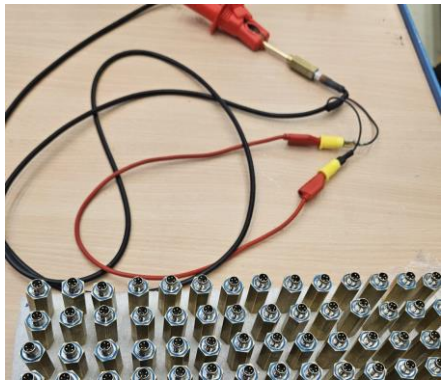


LCL Heaters – Investigation and Current Status

- Extensive investigations over several months, including:
  - X-ray
  - CT scans
  - destructive examinations and numerous HV tests (different heater groups and under different conditions)
- Despite these investigations, the exact root cause could not be clearly identified.
- The connector was suspected, particularly because its manufacturer had changed during the development.

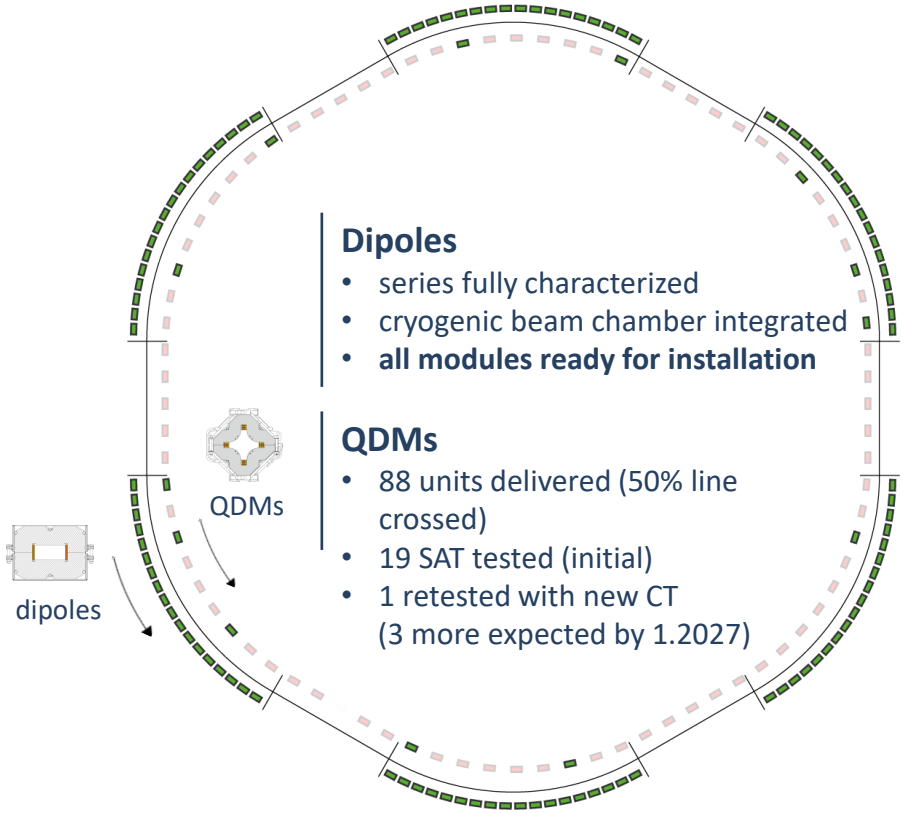
Modified prototypes are currently being tested. All 21 heaters passed the initial HV insulation tests, including under extreme conditions with water and ice exposure. The results are very promising and show a clear improvement over the previous design.





Delivered heaters of GEN III

Current magnet production status for SIS100



Dipoles

- series fully characterized
- cryogenic beam chamber integrated
- **all modules ready for installation**

QDMs

- 88 units delivered (50% line crossed)
- 19 SAT tested (initial)
- 1 retested with new CT (3 more expected by 1.2027)

Dipoles	108 / 108



QDMs	19 / 83

83 QDMs to be completed

GOAL: SIS100 commissioning in 2028

Summary

- **Dipole modules:** All 108 modules are completed, fully characterized and ready for installation.
- **Quadrupole doublet modules:** 88 quadrupole units delivered and 19 QDMs initially tested. Production continues under the modified supply chain.
- **New magnet production:** Initial cold tests of the new BNET prototypes show performance suitable for SIS100 operation. Further optimization and testing are planned.
- **Technical challenges:** Solutions for the cold-terminal insulation problem are being implemented. The modified LCL heater prototypes show promising results, but long-term stability remains to be confirmed.
- **Next milestone:** Continue QDM production, testing and installation preparation towards SIS100 commissioning in 2028.