Superconducting Quadrupole Module System for the SIS100 Synchrotron

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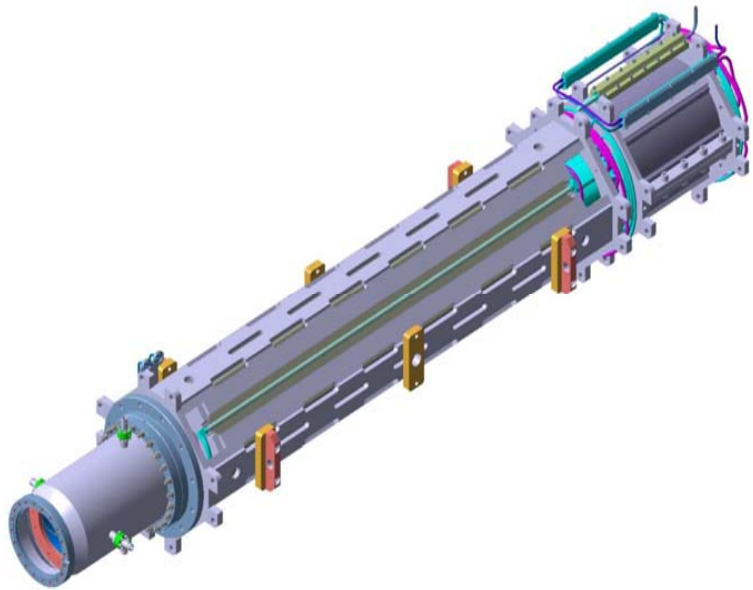


Introduction: SIS100 @ FAIR

Heavy Ion Synchrotron with superconducting magnets

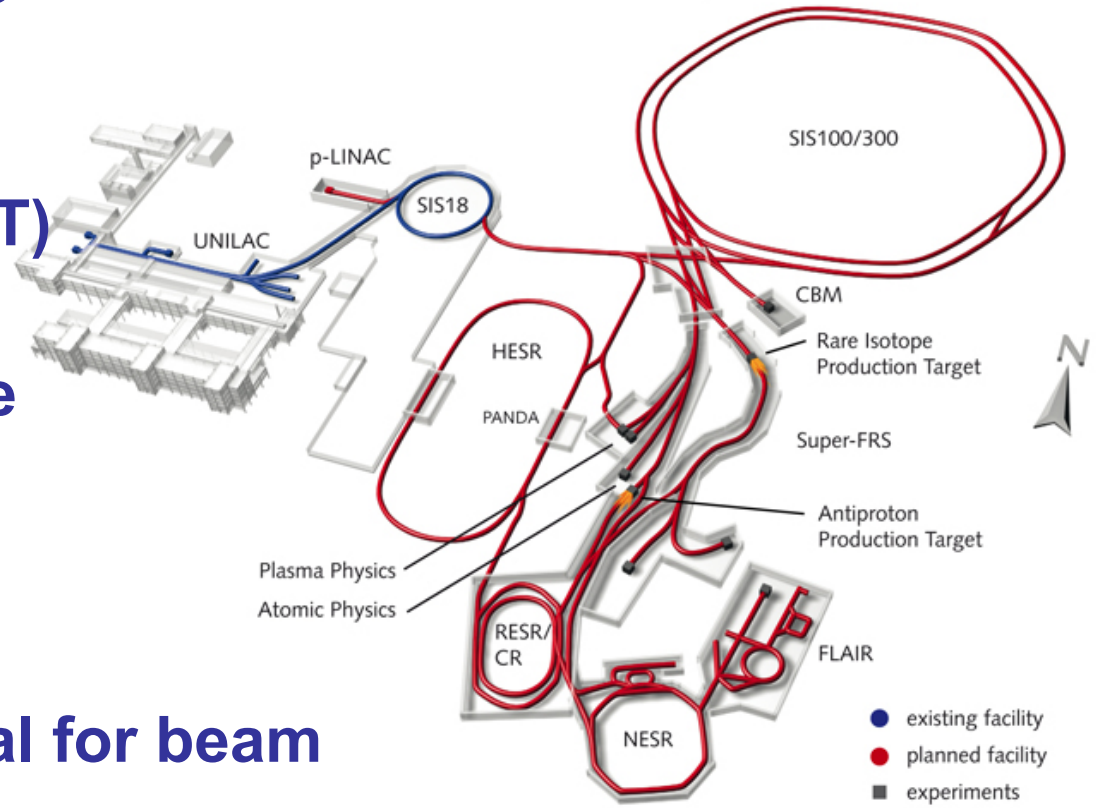
- **core component**
- **100 Tm rigidity**
- **1 s cycle, (B_{max} = 1,9 T)**
- **1100 m circumference**

  108 dipoles

  168 quadrupoles,

  correctors

  vacuum quality critical for beam life time: < 10^{-12} mbar



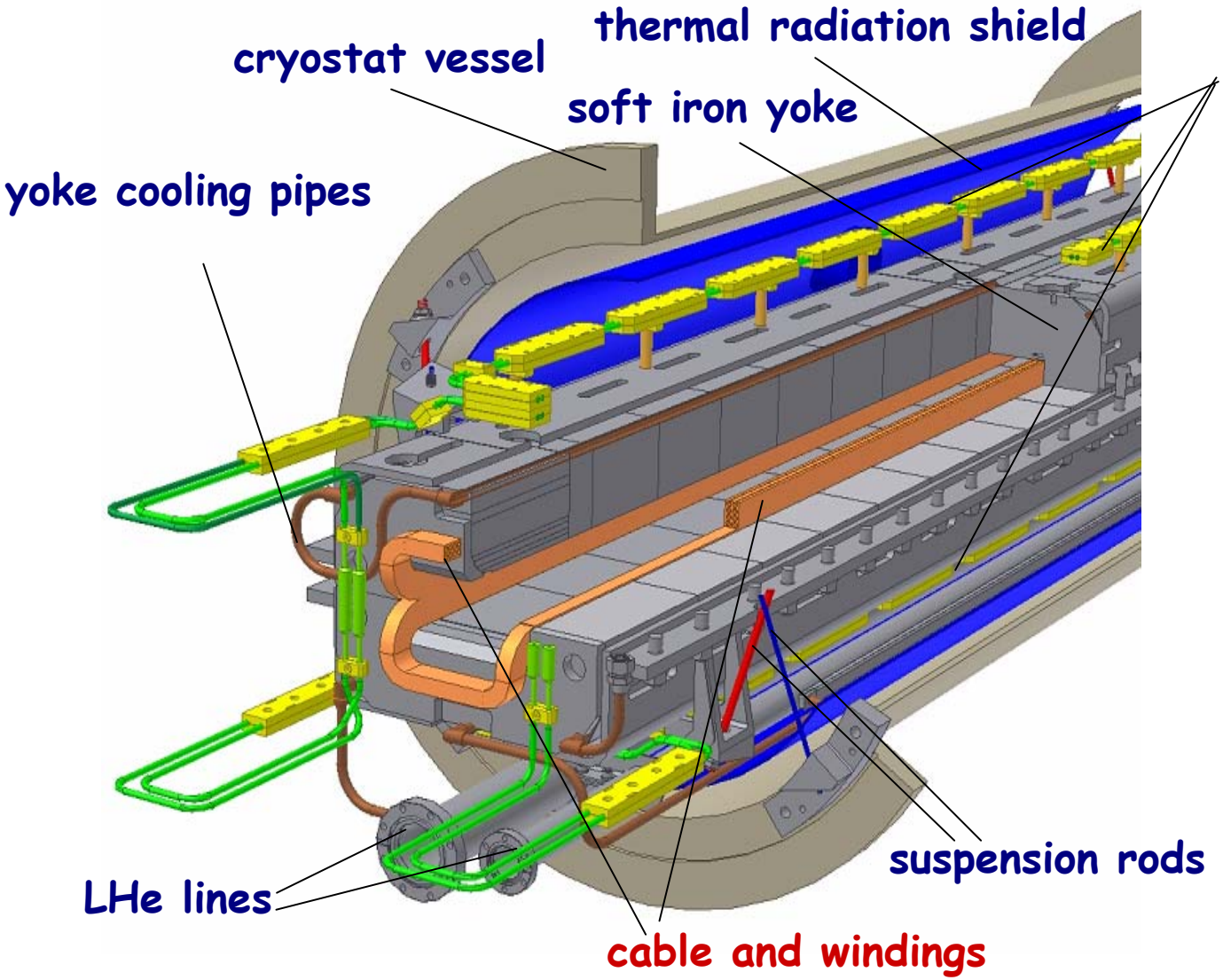
see also: P. Spiller et al., Status of the FAIR Accelerator Project (RuPAC WEZCH02);
www.gsi.de/en/research/fair.htm

SIS100 Dipole: Parameters

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

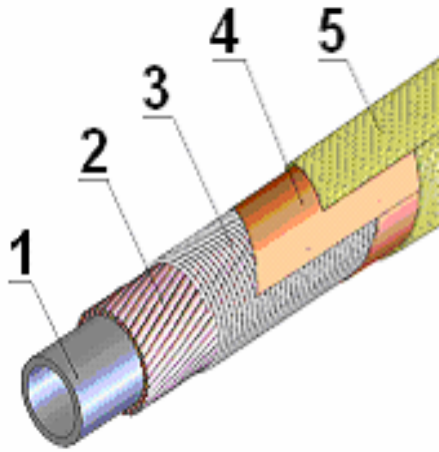
number of magnets	108 + 1	
max. field B_{max}	1.9	T
min. field B_{min}	0.23	T
bending angle	3 1/3	Deg.
orbit curvature radius, R	52.632	m
effective magnetic length, L	3.062	m
good field region	$115 \cdot 60$	mm^2
field quality target	600	ppm
current at max. field	13093	A
inductance	0.55	mH
ramp rate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

SIS100 Main Magnets: Dipol



Nuclotron cable:

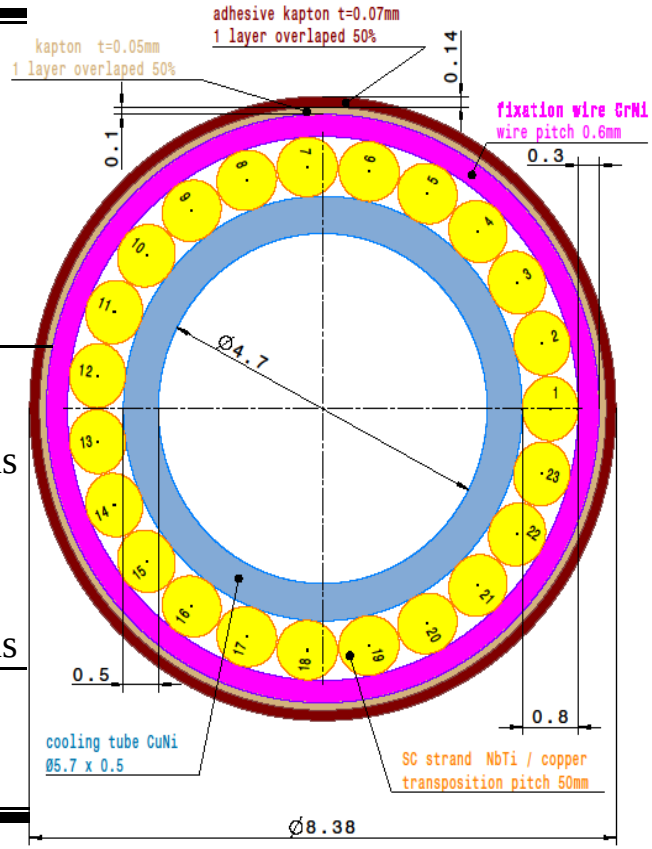
1 - Cooling tube CuNi
2 - SC wire NbTi
3 - CrNi wire
4 - Kapton tape
5 - Glasfiber tape



SIS100 Main Magnets: Wire and Cable

cable parameters

Number of strands		23	
Strand diameter		0.8 ± 0.01	mm
Transposition pitch		50 +0/.5	mm
Cooling tube material		Cu-Ni	
Cooling tube outer diameter		5.7 + 0/-0.05	mm
Cooling tube wall thickness		0.5 + 0/-0.05	mm
Critical current @ 2 T, 4.2 K		21000	A
1st insulating layer			
material	Polyimide tape	2	layers
thickness/layer		50 ± 2	microns
2nd insulating layer			
material	Polyimide (adhesive)	2	layers
thickness		70 ± 2	microns
Fixation of the strands	CrNi-wire		mm
Diameter		0.3 ± 0.01	mm
Transposition pitch		0.6 + 0/-0.1	mm



► the Nuclotron cable is the core component for the fast ramped magnet

SIS100 Quadrupole: Parameters

168 + 3 reference magnet		
design	window-frame, laminated cold iron yoke, lamination thickness 1mm, 3 turns per pole	
max. gradient G_{max}	27	T/m
effective magnetic length, L	1.3	m
good field region	$135 \cdot 65$	mm^2
field quality target	600	ppm
current at max. field	10830	A

SIS100 Quadrupole: High Current Design

From the 6 turn to the 3 design

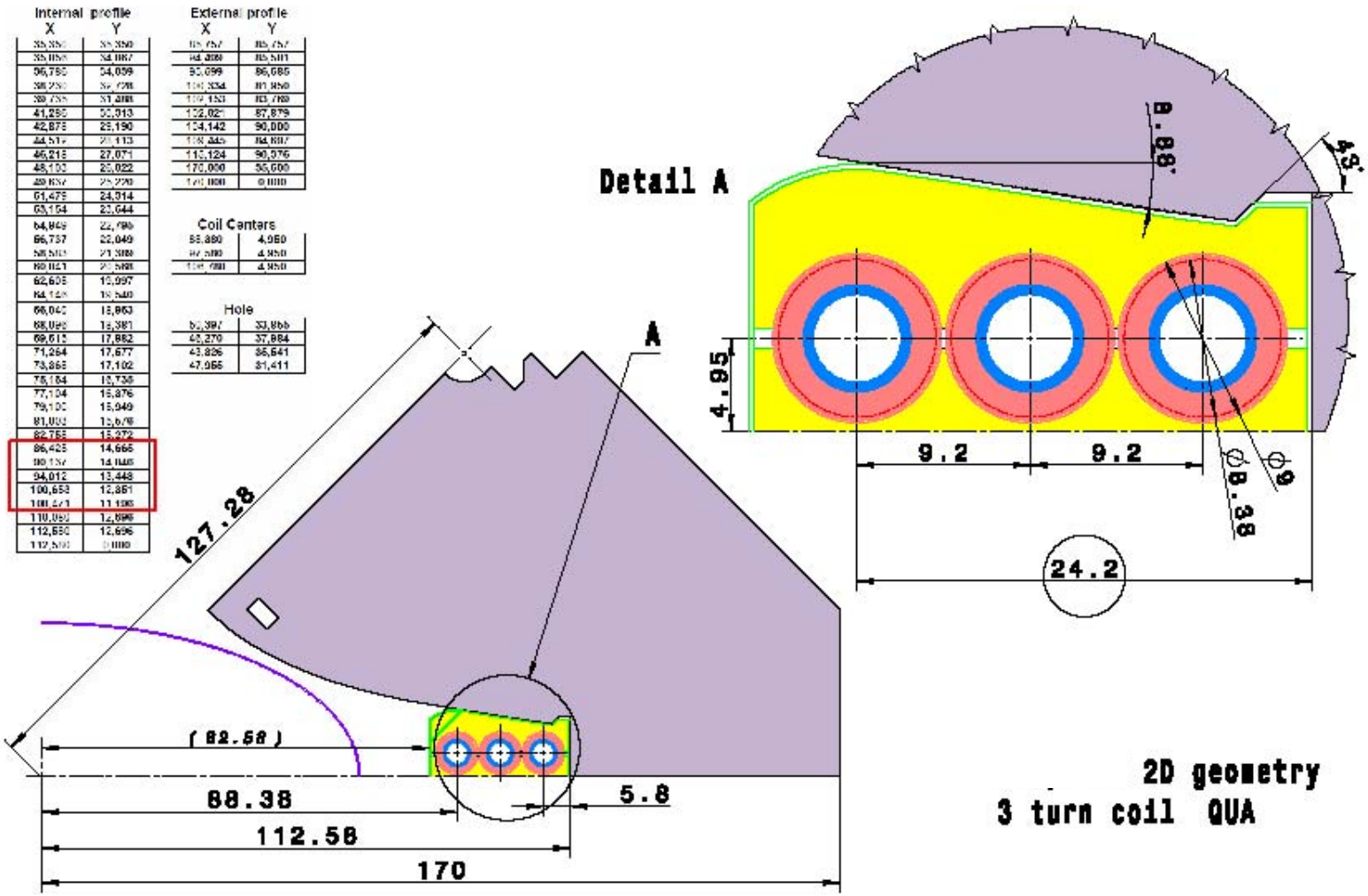
6TQP:

-1. a completely new low current quadrupe must be designed
-2. use a different wire (new wire, development)
-3. two different HTS current leads (5 kA and 14 kA)
-4. two different types of bus bars and voltage breakers in:
dipoles, quadruole doublets, bypass lines, feed in lines, superconducting links, current lead boxes (the design of these objects are more complicated and slightly more costly)
-5. 2 or 3 types of superconducting joints

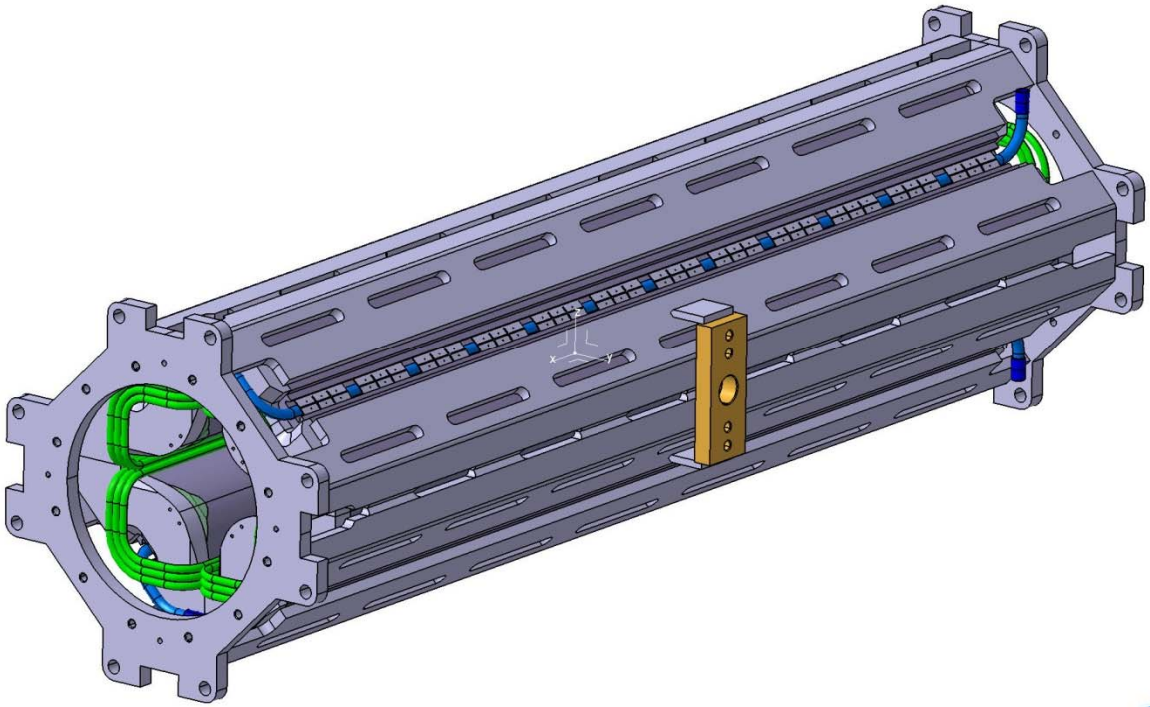
3TQP:

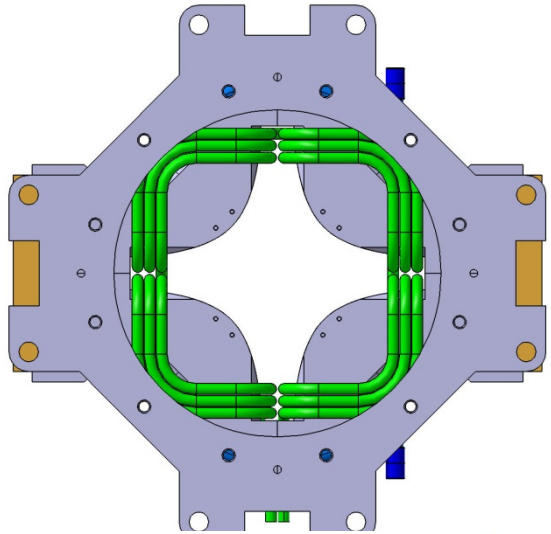
+1. enables to use the same iron geometry for the high and low current quadrupoles
+2. uses the same cable and wire than the dipole (no extra development)
+3. one single type of HTS current leads (14 kA)
+4. only one type of **bus bars and voltage breakers** in:
dipoles, quadruole doublets, bypass lines, feed in lines, superconducting links, current lead boxes (simpler design and less costly)
+5. Quench measurements made on dipoles can directly be use for the quadrupoles
+6. one single type of superconducting joints

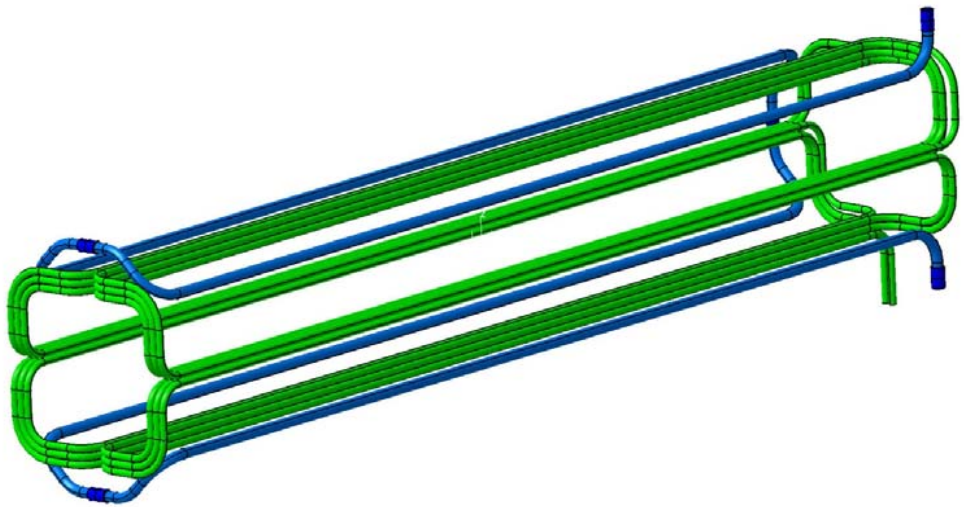
SIS100 Main Magnets: Quadrupole



SIS100 Main Magnets: Quadrupole







3D Design:

yoke and coil

SIS100 Corrector Magnets: Requirements

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

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

SIS100 Corrector Magnets: Parameters

		Multipole corrector (nested)			Steerer (nested)	Chromaticity sextupole
	unit	Quadrupole	Sextupole	Octupole	Horizontal, Vertical dipole	Sextupole
Number of wires in the cable		10	22	20	28	28
Current	A	250	246	240	236/232	243
Self inductance (Static at Max. current)	mH	0.83	4.6	6.4	21	45
Inductive voltage	V	1.4	4.7	6.4	24	63
Stored energy	J	26	139	184	566/558	1333
Superconductor hysteresis loss	J/cycle	0.28			0.38	0.40
Inter-fil. loss	J/cycle	0.33			0.72	1.65
Iron hysteresis loss (analytical)	J/cycle	1.3			2.2	7.1
Peak field on SC. cable	T	0.545			0.918	1.4
Margin on the load line	%	46			39	30
Temperature margin (at operation temp., 4.7K)	K	2.2			1.9	1.4
Peak field on iron	T	0.789			1.5	2.1
Cable length per magnet	m	12	14	17	13/13	12

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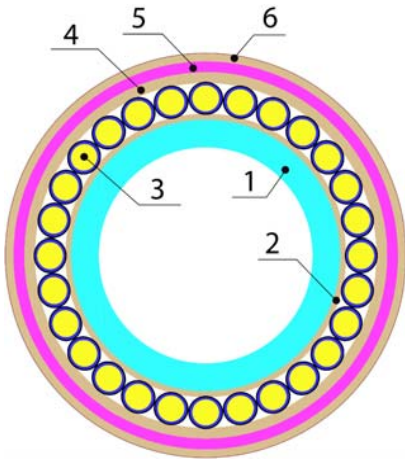
SIS100 Corrector Magnets: Cable Design

- **Nuclotron type cable with insulated wires**

  Connect wires in series

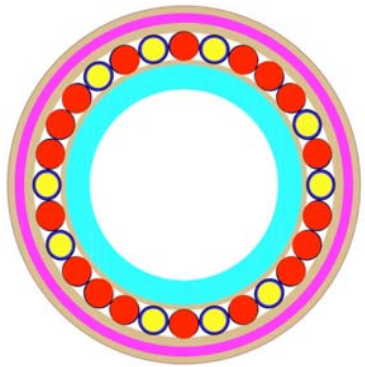
  By replacing sc. wire, operation current is adjustable.



1. CuNi tube
2. Kapton, t=0.05 mm, 1 layer, 50 % overlapped
3. Superconducting wire, 0.5 mm diameter, with enamel
4. Kapton, t=0.05 mm, 2 layers, 50 % overlapped
5. CrNi wire, 0.2 mm diameter
6. Kapton, t=0.07 mm, 1 layer, 50 % overlapped

Maximum 28 sc. wires

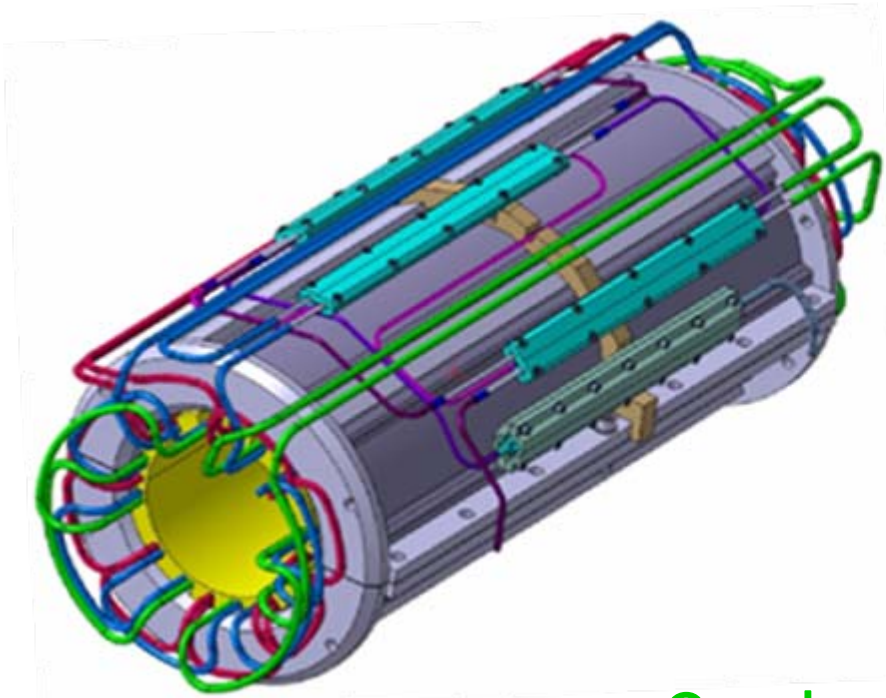
	unit	design value
Strand diameter	mm	0.5
(Cu+CuNi)/NbTi ratio		1.4
Number of filaments		5670
Filament diameter	μm	4.3
Twist pitch	mm	4
RRR		>100
I_c at 4.2 K, 5T, 0.1$\mu V/cm$	A	245

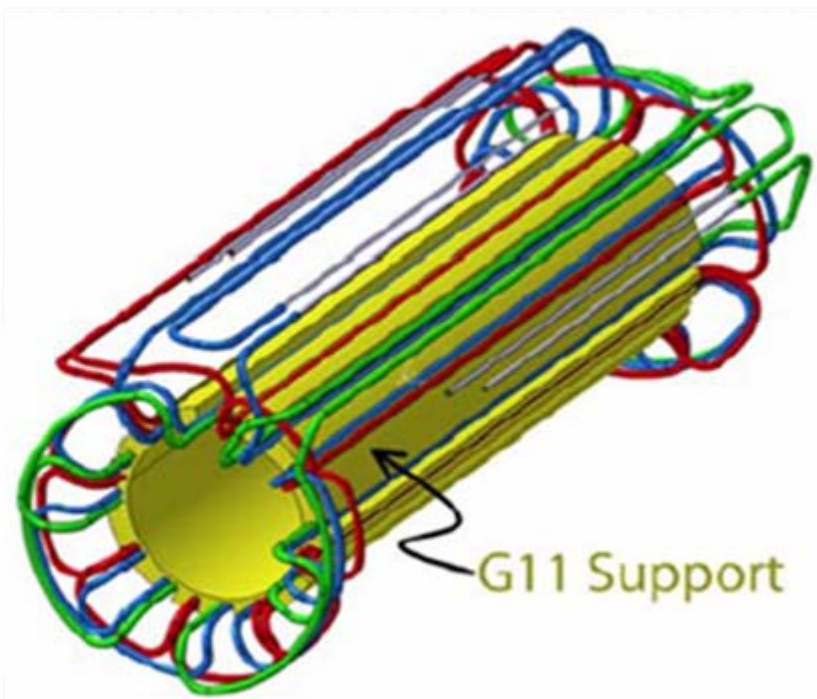


ex. 10 sc. wires cable for the quadrupole corrector

SIS100 Corrector Magnets: Multipole

Error compensation multipole corrector
– Quadrupole, sextupole, and octupole are nested.



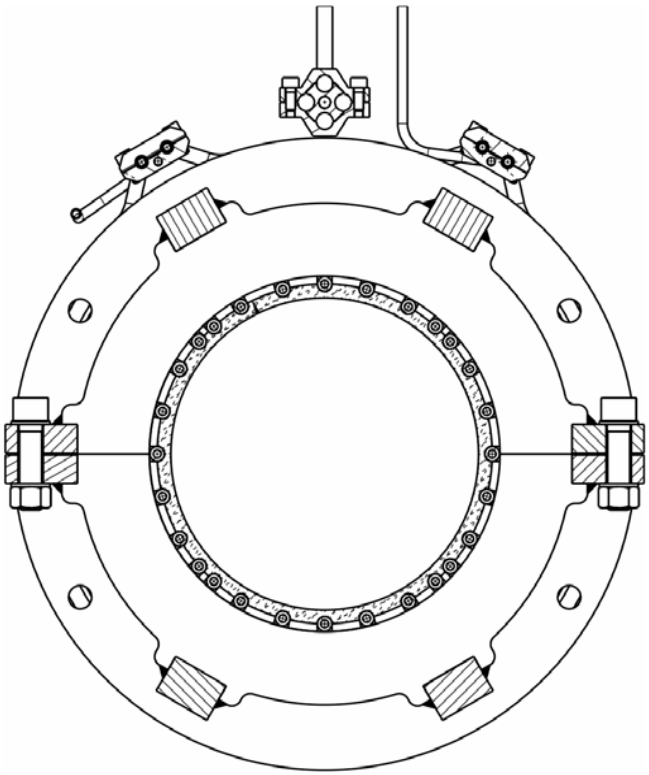


cos(θ) type magnet

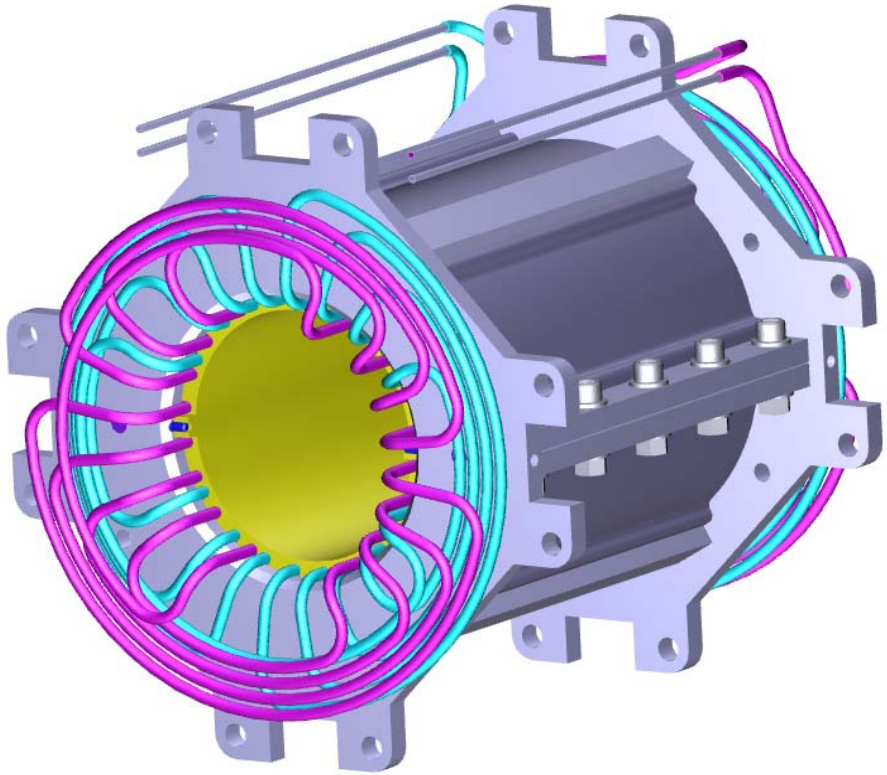
Quadrupole
Sextupole
Octupole

SIS100 Corrector Magnets: Steerer

Horizontal and vertical dipoles are nested.



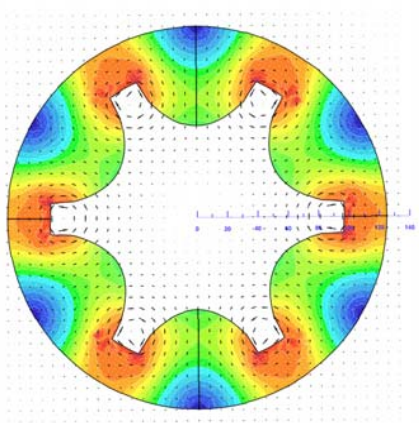
cos(θ) type magnet

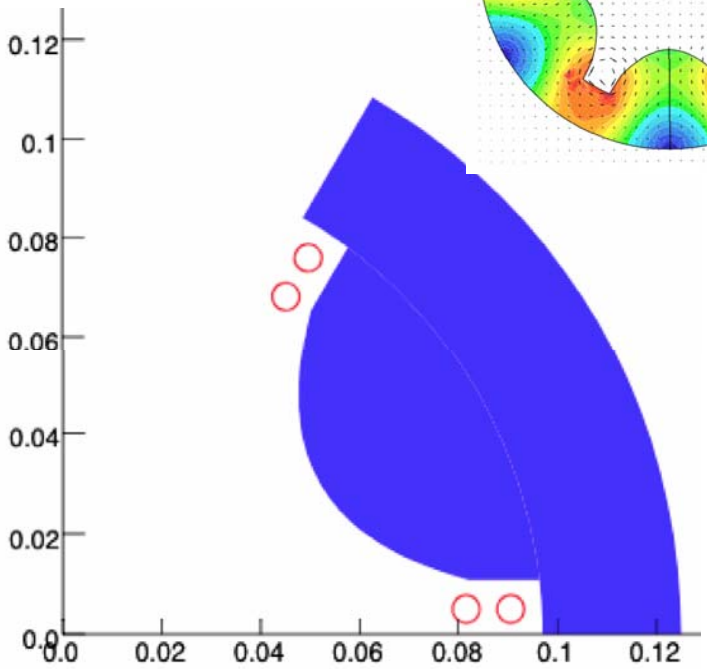


vertical (normal) dipole

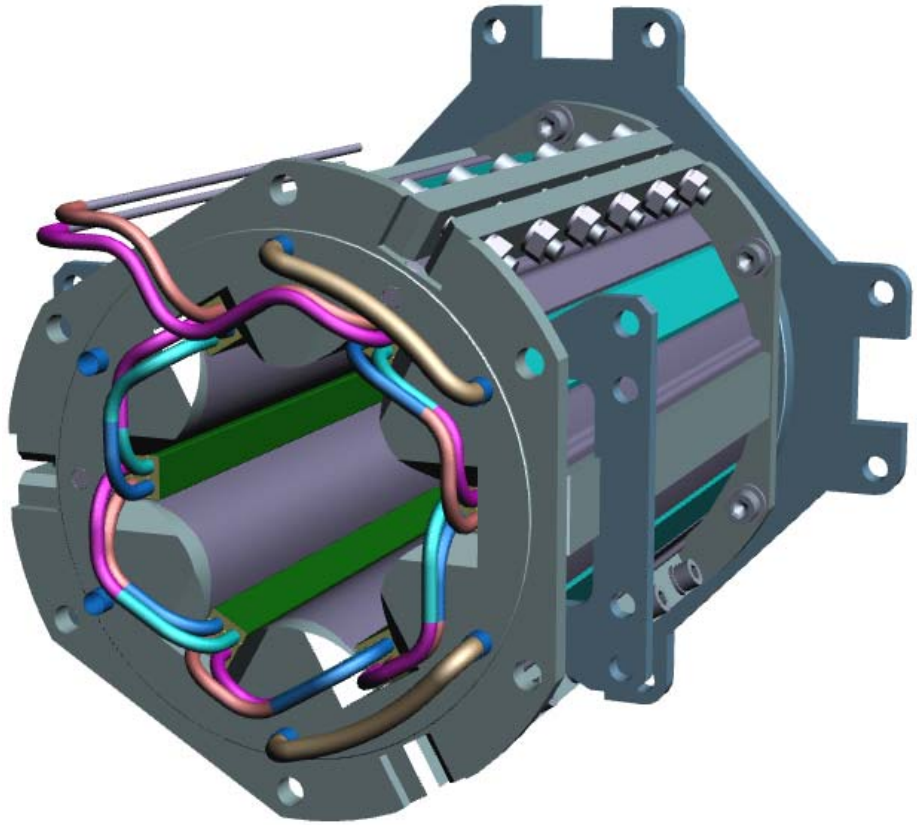
horizontal (skew) dipole

SIS100 Corrector Magnets: Chromaticity Sextupole





superferric type



First prototype magnet is currently under production within a BMBF-JINR project

SIS100 Corrector Magnets: Insulated Strands

Technology adaption and optimisation:

- Cable production
  - Material choice of insulation, cabling machine modifications
- Cable tests
  - Mechanical test: bending radius, bending-stretch
  - Electrical test: high voltage
- Strand joint
  - Design of the connection box
  - Soldering or welding
- Test at low temperature: small solenoid experiments
  - Operation temperature
  - Quench propagation velocity, hot spot temperature
  - Quench studies

SIS100 Corrector Magnets: Technology Optimisation

- Coil production
  - Optimization of winding procedure
    - One continuous cable
    - Development of the tools
  - Embedded into G11 supports
    - Pre-preg bandage (heat treatment) or mechanical fixation
- Magnet assembly
  - Assembly procedure
  - Development of the tool

SIS100 Quadrupole Units: Components

Magnet	Name	Nomenclature	Quantity	Comments
Quadrupole	Focusing Quadrupole 1	F1	36	
	Focusing Quadrupole 2	F2	47	
	Defocusing Quadrupole	QD	83	
Sextupole	Horizontal Focusing Chromaticity Sextupole	CH	24	
	Vertical Focusing Chromaticity Sextupole	CV	24	
Steerer	Horizontal/Vertical Steerer	ST	83	Combined magnet
Multipole	Multipole Corrector	MC	12	Combined magnet
Others		**Nomenclature**	**Quantity**	**Comments**
Beam Position Monitor		BPM	83	
Ion Catcher (Collimator)		COL	60	

- Focusing quadrupole F1 and F2 has different bus bar configuration.
- Horizontal/Vertical Focusing Chromaticity Sextupole (CH/CV) is identical within the cryostat.
  - But the joints between the power cable and the current lead (at warm) is opposite polarity.

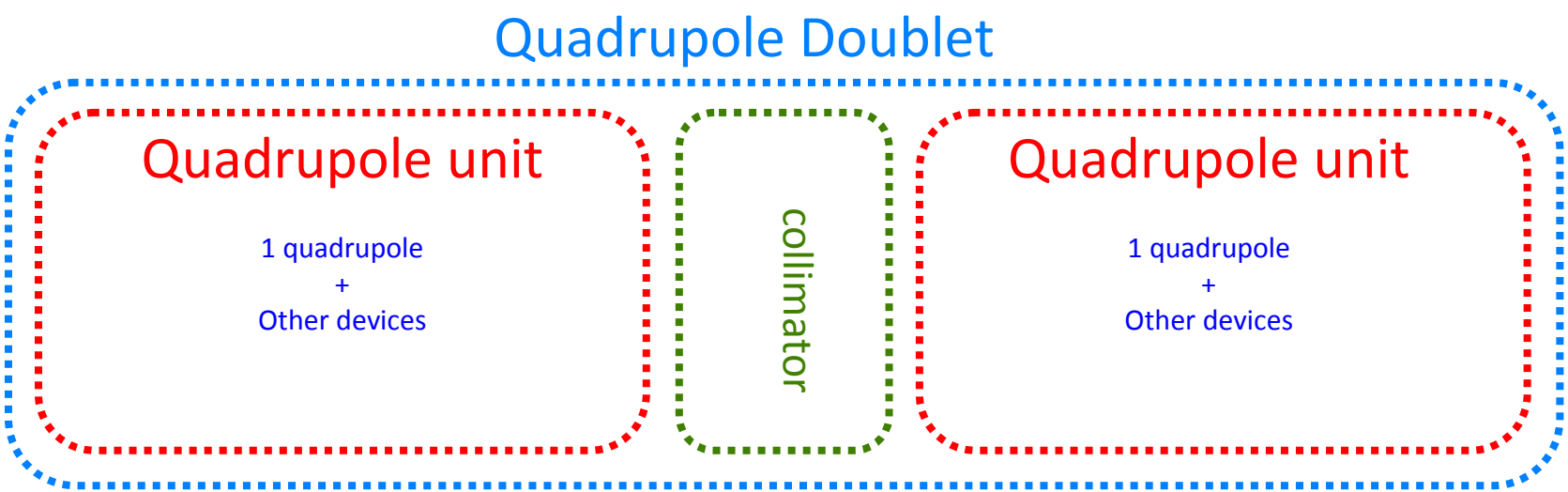
SIS100 Quadrupole Units: 10 Types

Type of the quadrupole unit

Type	1	2	3	4	5	6	7	8	9	10
Contents	QD	QD BPM	BPM QD	CV QD	ST F1	ST F2	ST F1 BPM	ST F2 BPM	ST F1 CH	ST F2 CH
Quantity	12	23	24	24	6	17	18	18	12	12
Position in doublet	upstream				downstream					

SIS100 Quadrupole Units and Cryomodules

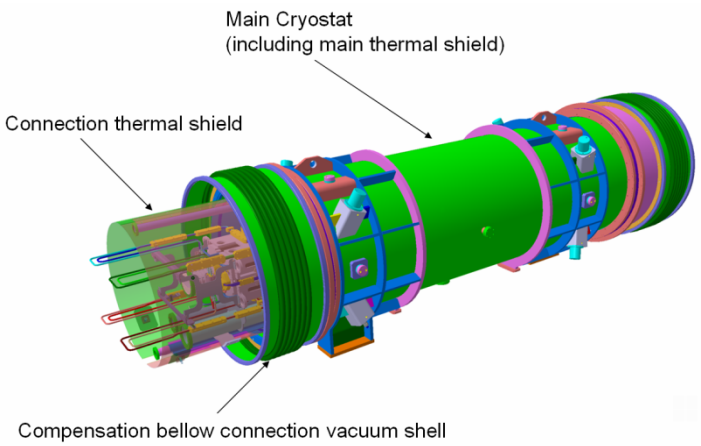
- Quadrupole unit
  - Mechanical assembly 1 quad. + other devices
- Quadrupole doublet
  - 2 Quadrupole unit (+collimator) in one cryostat



SIS100 Quadrupole Cryomodules

Dipole

- one dipole
- bus bars
- helium headers
- thermal shield
- cryostat
- vacuum chamber



Doublet

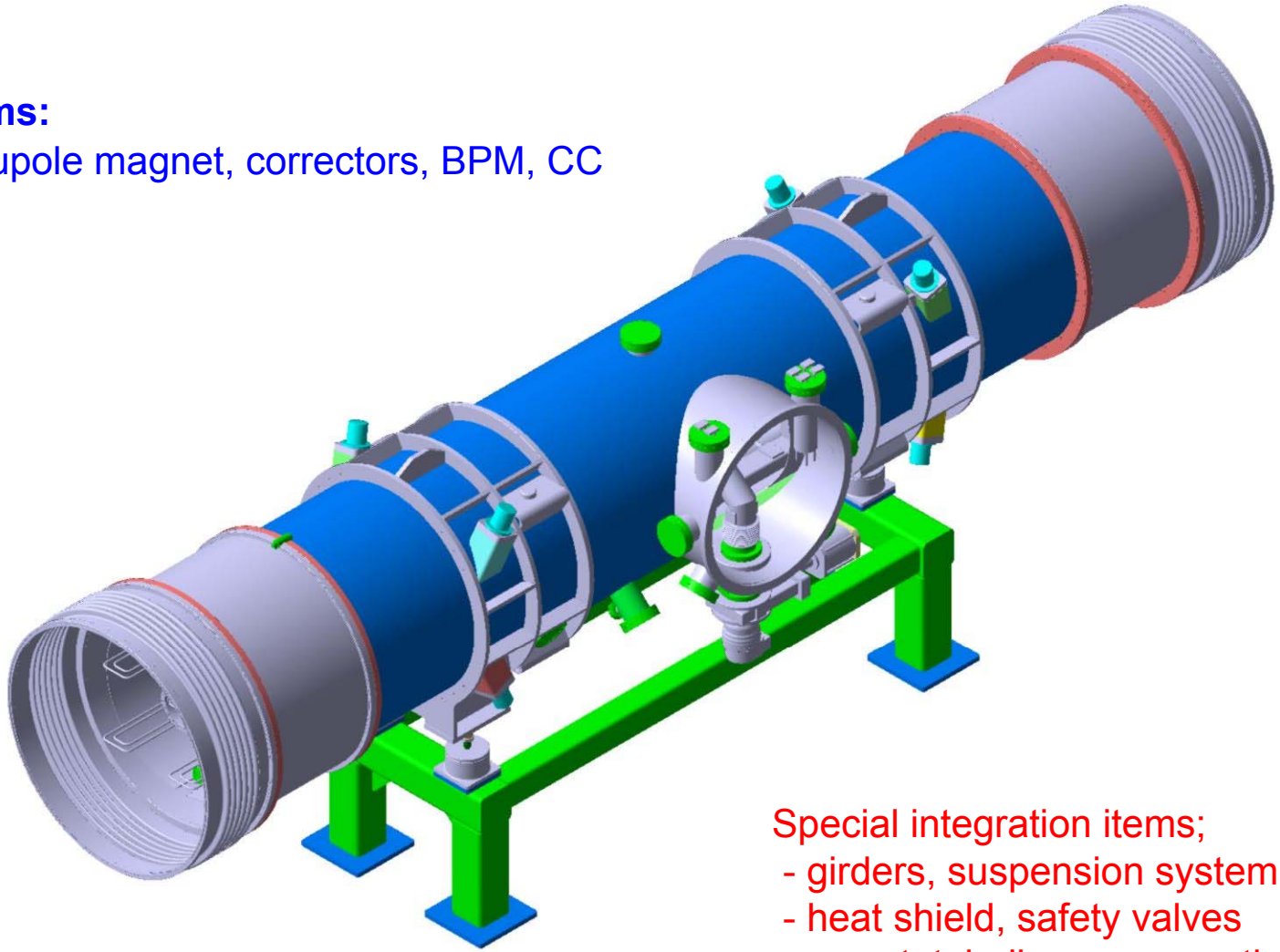
- two quadrupoles,
- multipole corrector, steerer, chromaticity sextupole
- cryocollimator
- beam position monitor (BPM)
- girders
- bus bars
- helium headers
- thermal shield
- cryostat
- vacuum chamber

► more complex system

SIS100 Quadrupole Cryomodules

unit items:

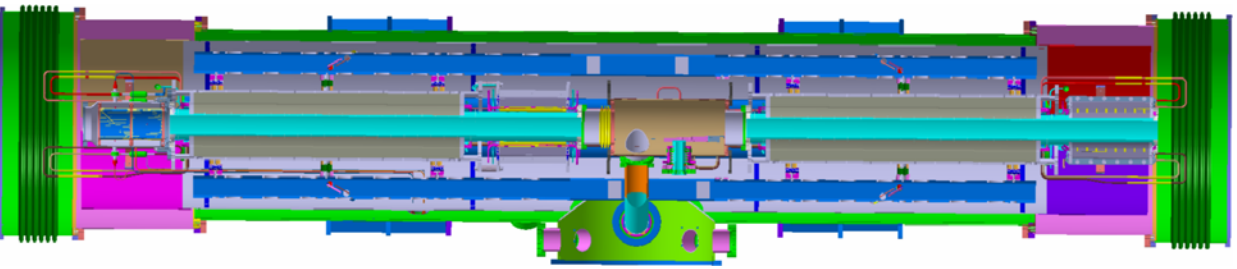
- quadrupole magnet, correctors, BPM, CC



Special integration items;

- girders, suspension system
- heat shield, safety valves
- cryostat, bellows, connection taps

SIS100 Quadrupole Cryomodules



many different elements
constraint in space
piecewise integration

- BPM: Prototype exists
- Collimator: Prototype exists

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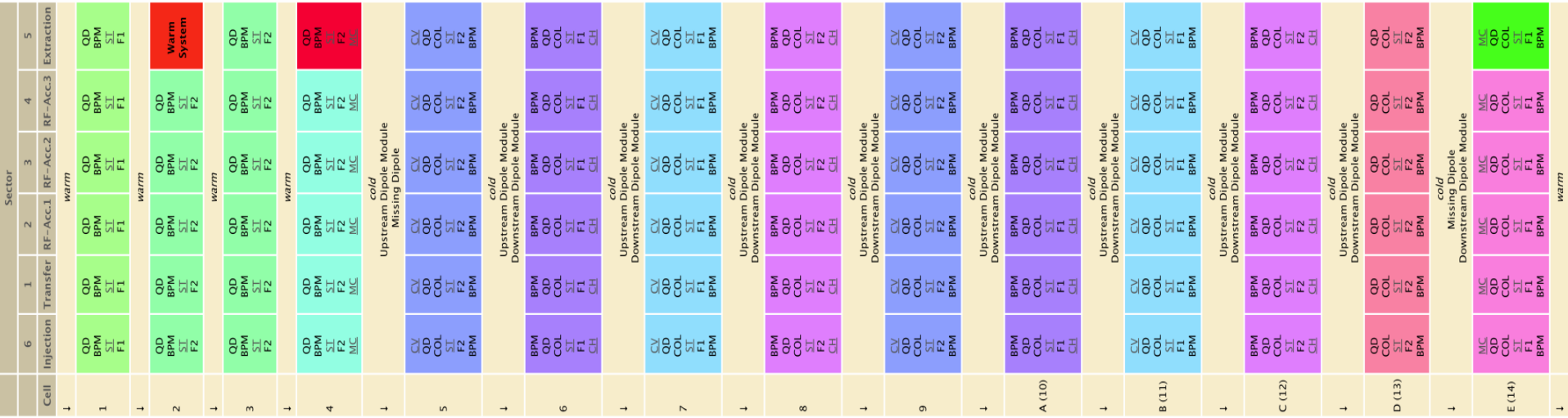
SIS100 Quadrupole Cryomodules

Doublets in SIS100



Sector_5-Cell_2: Warm system due to high radiation.

Sector_5-Cell_4: Y-cryostat for extraction.

Sector_5-Cell_14: Y-cryostat for injection.

Sector_1-Cell_1: Y-cryostat for the transfer to SIS300.

SIS100 Quadrupole Cryomodules

Doublets

Type of the quadrupole doublet

N°	1	2	3	4	5	6	7	8	9	Injection	Extraction	Warm
Contents	QD BPM ST F1	QD BPM ST F2	QD BPM ST F2 MC	CV QD COL ST F1 BPM	CV QD COL ST F2 BPM	BPM QD COL ST F1 CH	BPM QD COL ST F2 CH	MC QD COL ST F1 BPM	QD COL ST F2 BPM	MC QD COL ST F1 BPM	QD BPM ST F2 MC	**Warm System**
Quantity	6	11	5	12	12	12	12	5	6	1	1	1
Comments										Y-cryostat	Y-cryostat	warm system
Quad. Modules	2 5	2 6	2 6 MC	4 COL 7	4 COL 8	3 COL 9	3 COL 10	MC 1 COL 7	1 COL 8	MC 1 COL 7	2 6	

9 + 3 special types

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SIS100 Quadrupole Cryomodules: Procurement

Boundary conditions:

- Many workpackages for SIS100 Magnets
- Test facilities have to be upgrated / built / operated / supervised
- Different magnet production locations in Europe
- QP system is significantly more complex than dipole modules
- No magnet prototypes available
- Large amount of detailed design work is necessary

SIS100 Quadrupole Cryomodules: GSI and JINR

- The SIS100 magnet technology is based on the design and experience of the Nuclotron, operational at JINR since 1993. In order to improve this technology with respect to the specific needs of the SIS100 project, a common R&D program through the last decade has been conducted.
- JINR Dubna has the resources for production and testing of the Quadrupole modules and Russia is interested to contribute the sc magnets for the SIS100 to FAIR.

…

The GSI-JINR Collaboration: Common Inkind

Common work for the QP modules

- Share the work load between JINR and GSI.
- GSI and JINR will interact for the Delivery and Testing of SIS100 Main Quadrupole Modules as German and Russian In-Kind-contributions to FAIR
- The collaboration between the JINR and GSI focuses on the SIS100 Main Quadrupole modules, which include:
  the main quadrupoles, the chromaticity sextupoles, the steerers, the BPM, the vacuum chambers and cryo-catcher, the current leads for the last two magnets, the cryostats, shields and support structures.
- GSI will deliver the final design, specifications and blueprints for all quadrupole modules.

The GSI-JINR Collaboration: Common Inkind

GSI will deliver all standardized components of the cryo-magnetic systems, e.g. the voltage breakers, the quench detection, the cryocatchers, the vacuum chambers, bellows, flanges, CWTs etc.

The integration of the components into the module cryostat and testing of the first complete module at operating conditions will be performed at JINR.

After successful test of the first module the series production of all modules will follow.

In order to keep the time schedule, procurement of the raw materials and preparation of the series production (e.g. production of the toolings), will be started during production of the pre-series module.

SIS100 Quadrupole Cryomodules: Deliveries

GSI	JINR
doublet design	cables
wires	quadrupoles
vacuum chambers	chromaticity sextupoles
cryo-collimators	steerers
beam position monitors	multipoles
voltage breakers	girders
doublet warm test	unit testing
magnetic measurement consulting	integration and assembly of the doublet

The GSI-JINR Collaboration: Testing at JINR

The procurement of the SIS100 Quadrupole Module series is linked to the construction of the series test stand at JINR

- Qualification of the ‚pre-series Q-module', which is mandatory to launch the SIS100 Q-module series (Cryostat safety system; Leak tight systems; Insulation; Voltage taps)
- Specification compliant: hydraulic resistance, AC losses, Inductance, Integral field strength, field quality, axis.
- Specific test capabilities for the 175 SIS100 Quadrupole units of the series: 3 test lines, power distribution for pulsed or DC operation

The GSI-JINR Collaboration: Testing at JINR

New SC-magnet test facility at JINR Dubna under construction

The GSI-JINR Collaboration: Work packages

Work packages structure

Pre-Series Module

- WP1-1 (GSI) Selection of the first preseries doublet. Design, specification and blueprints for the full module including all components. In parallel, completion of the design of the overall cryomagnetic system of SIS100.
- WP1-2 (JINR) Production of the preseries quadrupole module including support.
- WP1-3 (GSI) Production and delivery of the GSI inkind contributions (e.g. s.c. wire, cryo catcher, voltage breaker, pre series BPM, pre series magnet chambers and other electrical and UHV equipment)
- WP1-4 (JINR) Preparation of series production (e.g. order of materials, and production of toolings).
- WP1-5 (JINR) Cold tests of the preseries magnet units.
- WP1-6 (JINR) Integration of the first preseries module.
- WP1-7 (JINR) Cold tests of the first preseries module including vacuum break down.

Series of Modules

- WP2-1 (GSI) Delivery of the final design, specifications and blueprints for all quadrupole modules.
- WP2-2 (JINR) Series production of quadrupole modules including supports.
- WP2-3 (GSI) Production and delivery of all GSI contributions for the quadrupole modules.
- WP2-4 (JINR) Electrical, cold tests and field mapping of the magnet units.
- WP2-5 (GSI) Supervision and quality assurance.
- WP2-6 (GSI) Integration of the modules.
- WP2-7 (JINR) Test of the assembled modules at room temperature.
- WP2-8 (JINR) Delivery and transportation of the modules to FAIR.
- WP2-9 (GSI) Test of the assembled modules at room temperature.

The GSI-JINR Collaboration: Overview

Workpackages for SIS100 Magnets

- Dipole modules (BNG Würzburg)
  - Design
  - Procurement
  - Follow Up
- Doublet modules (GSI Darmstadt /JINR Dubna)
  - Design of the Doublets
  - Interaction with In-Kind partner
  - component supply
- Magnet tests
  - Dipoles (GSI Darmstadt)
    - Upgrade PTF (1. TF)
    - Construction/commissioning STF (2. TF)
    - Operation the STF
  - Quadrupoles (JINR Dubna) (3. TF)
    - Completion of R&D topics
    - Interfaces
    - follow up / supervision
  - String Test (GSI Darmstadt)
  - Analysis
  - Calibration chains
- Strand Design and Procurement
- Magnet Protection / Quench Detection
- Integration of the Magnetes
- Current leads
- Magnet cooling

Also: SuperFRS

- Dipoles:
  - Interaction with InKind Partners
  - Integration
- Multiplets:
  - Design / Procurement / Follow up
- Testing:
  - Interaction with CERN (4. TF)
  - follow up
- Quench Detection

Conclusion

- A large amount of work remains to provide the fast ramped superconducting magnets of the SIS100 for the FAIR project. It will be covered by international cooperation between institutes and industry.
- The SIS100 Quadrupole Modules are an exceptionally complex system also for production and testing.
- The final design, production and testing of the QP modules will be done in collaboration between JINR/Dubna and GSI/Darmstadt as a common German and Russian In-Kind contribution.

Thank you for your attention!

Preliminary Time Scale

Milestones

Topic	Milestone
Design and Specifications Pre Series Module	1.8.2012
Design and Specifications All Modules	1.3.2013
End of Production and Testing of Pre-series Magnets	1.11.2013
End of integration and testing of preseries module	1.2.2014
End of Production of Series Modules	1.11.2016
All modules delivered to FAIR	1.3.2017
Cryomagnetic system of SIS100 assembled	1.7.2017