Document Title	**Detailed Specification on Testing of Superconducting Quadrupole Doublet Modules for the SIS100**
Description	**PSP-Code: G2.14.13.21.03** This document defines the Site Acceptance Tests for the quadrupole doublet modules for SIS100 including testing at cryogenic temperatures
Division/ Organization	SCM
Field of Application	Project FAIR@GSI

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Abstract

This document is a Detailed Specification on Testing of Superconducting Quadrupole Doublet Modules (QDMs) for the Heavy-Ion Synchrotron SIS100 at FAIR. The QDMs are highly integrated cryogenic modules containing multiple magnets. The Site Acceptance Test of the SIS100 QDMs, which will take place at the dedicated test facilities, includes the testing of the assembled module at room and cryogenic temperature to ensure its correct functionality at operating conditions. The specification describes the test program of the QDMs as well as the requirements to the testing infrastructure.

PSP: G2.14.13.21.03

AID:0000845 Quadrupole Doublet Module Type 2.123
AID:0000846 Quadrupole Doublet Module Type 2.13s
AID:0000847 Quadrupole Doublet Module Type 2.4
AID:0000843 Quadrupole Doublet Module Type 1.E

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1. Purpose and Classification of the Document

This document specifies the requirements to the tests of the SIS100 Quadrupole Doublet Modules (QDMs) at room and cryogenic temperatures.

The regulations and requirements are specified in the General Specification [1], Technical Guidelines or Common Specifications for superconducting magnets and other components of the QDM. They are only referenced in the present document.

No legal or contractual conditions are treated in this document. All related information is given in the corresponding contract.

2. Abbreviations, Terms and Definitions

Abbreviation used in this document are given in Table 1.

Table 1: List of abbreviations

Abbreviation	Definition
FAIR	Facility for Antiproton and Ion Research
SIS100	Schwerionensynchrotron (Heavy Ion Synchrotron) 100 Tm
QDM	Quadrupole Doublet Module
BPM	Beam Position Monitor
LCL	Local Current Leads (250 A)
CWT	Cold-Warm Transition
CID	Component ID
RGA	Residual Gas Analyser

3. Scope of the Technical System

3.1. System Overview

All superconducting magnets of the SIS100 except for the dipoles are assembled in quadrupole units which are integrated in the SIS100 Quadrupole Doublet Modules (QDMs) and installed in the SIS100 accelerator ring.

All quadrupole units are tested at cryogenic temperatures before integration into QDMs.

The QDMs will be operated in the SIS100 heavy ion synchrotron, the core accelerator of the FAIR project. In order to qualify the QDMs for the operation of the SIS100, verify the production quality, and acquire data required for the machine control, an extensive test program was defined.

The test program for the QDMs consists of the tests at room and cryogenic temperatures.

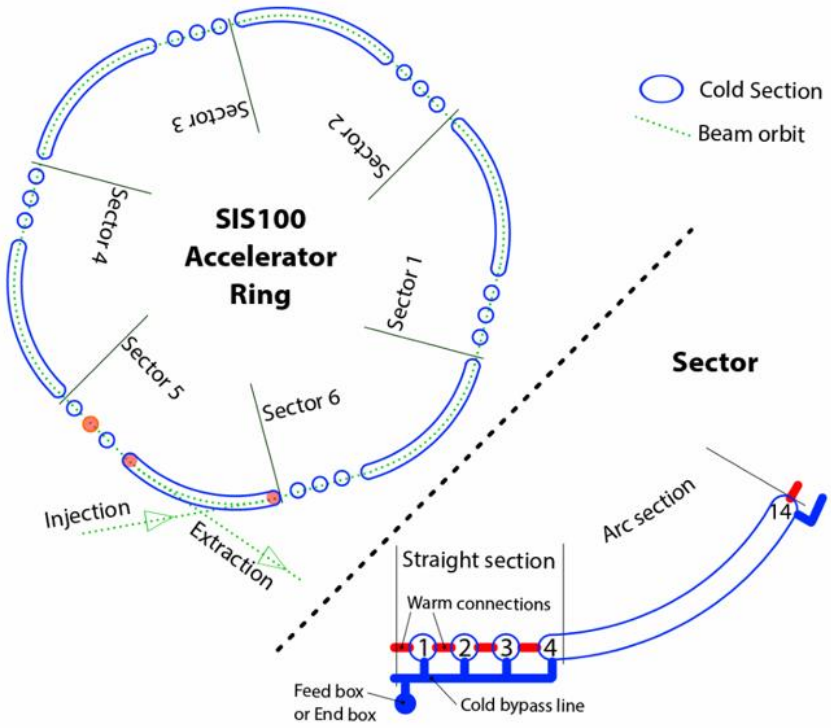


Figure 1: Overview of the SIS100 ring, the core component of the FAIR project.

The needs of the ion optical lattice of SIS100 define a set of twelve different configurations of magnet equipment (see Table 2), distributed to four families of QDMs which are the straight section type, the arc section type, the arc termination type and the special types for beam injection and extraction purposes. The SIS100 ring consists of 6 sectors with 14 cells in each sector which are numbered from 1 to E according to the hexadecimal notation (Figure 1).

Each quadrupole unit consists of a main quadrupole magnet and up to two corrector magnets. Other parts of the quadrupole unit are the superconducting bus bars, helium supply line with embedded heat exchanger (recooler), cold terminals of the current leads for corrector magnets, heater/flow restrictor assembly, temperature sensors and voltage taps wires.

There are 7 types of upstream units and 10 types of downstream units. These are assembled to 10 standard QDMs and 2 special QDMs (for injection, extraction, and high radiation areas [2]).

Table 2 shows an overview of the different QDM types. The first digit in the QDM type denotes the type of the focusing quadrupole, F1 or F2. The character(s) after the decimal point denote the cell number(s) in the ion optical lattice of the SIS100 in each sector. The QDMs in cells 1, 2 and 3 are mounted in the stand-alone cryostats with warm sections in-between. The cryostats of all other QDMs (sections 4 to E) are connected to each other by means of the telescopic compensators with vacuum bellows (see Figure 5).

Table 2: All types of QDMs in SIS100 ring. For information only, the testing scope is defined elsewhere.

Module Family	Configuration			IOL cell	Doublet name		Quantity of doublet
	Up-stream unit	Center unit	Down-stream unit		Joint name	Short name	
Straight section	QD*B	-TRP-	SF2*	1,2,3	QD*B-TRP-SF2*	2.123	14
	QD*Bs	-TRP-	SF2*s	1.3	QD*Bs-TRP-SF2*s	2.13s	3
Arc termination	QDBb	-T-	SF2M	4	QDBb-T-SF2M	2.4	5
Special	QDBx	-T-	SF2Mx	4	QDBx-T-SF2Mx	2.4x	1
Arc section	VQD	-CR-	SF2B	5	VQD-CR-SF2B	2.5	6
	BQD	-C-	SF1H	6, 10	BQD-C-SF1H	1.6A	12
	VQD	-CR-	SF1B	7, 11	VQD-CR-SF1B	1.7B	12
	BQD	-C-	SF2H	8, 12	BQD-C-SF2H	2.8C	12
	BQD	-CR-	SF2J	9	BQD-CR-SF2J	2.9	6
	BQD	-CR-	SF2J	13	BQD-CR-SF2J	2.D	6
Arc termination	MQD	-C-	SF1Bb	14	MQD-C-SF1Bb	1.E	5
Special	MQDi	-C-	SF1Bi	14	MQDi-C-SF1Bi	1.Ei	1

Abbreviations in Table 2:

QD	Defocusing quadrupole;	S	Steering magnet;
QD*	Defocusing quad. type 1 in Module 2.123, 2.13s magnet with reduced bus bar configuration;	M	Multipole corrector;
LD	Low current defocusing quadrupole;	C	Cryo-Catcher;
LF	Low current focusing quadrupole;	T	Drift tube;
F1	Focusing quadrupole type 1;	P	Cryo-sorption-pump;
F2*	Focusing quadrupole type 2;	R	Roughing pump with CWT;
J	γ - t - jump quadrupole;	b	extended bus bars in the unit;
B	Beam position monitor;	i	injection Y cryostat;
V	Vertical chromaticity sextupole;	x	extraction Y cryostat
H	Horizontal chromaticity sextupole;	s	Star shape chamber;

The scope of the specification in hand contains the execution of the Site Acceptance Test (SAT) of straight modules (blue colored rows) and arc termination type modules (green colored rows), (see Table 2).

The main parts of the QDM are [2]:

- Two quadrupole units: upstream unit and downstream unit (related to the beam direction)
- Two beam vacuum chambers
- Cryo-sorption pump for the straight section modules
- Cryo-catcher for arc section type, arc termination type 1.E and special type 1.Ei QDMs

- Local Current Leads (LCL) and the corrector magnets
- Beam Position Monitor (BPM)
- Helium supply and return headers
- Support structure for the cold mass (common girders and suspension rods)
- Thermal radiation shield
- Vacuum vessel

Figure 2 and Figure 3 show the general structure of a straight section module and, Figure 4 and Figure 5 show the arc termination type modules 2.4.

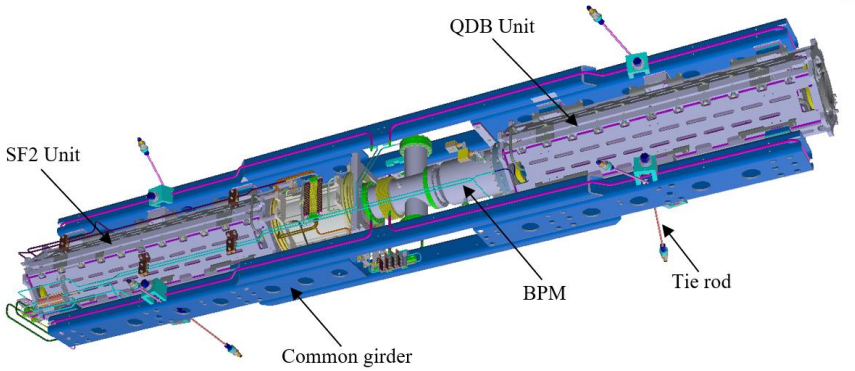


Figure 2: QDM cold mass integrated in the common girder. Upstream and downstream units are shown.

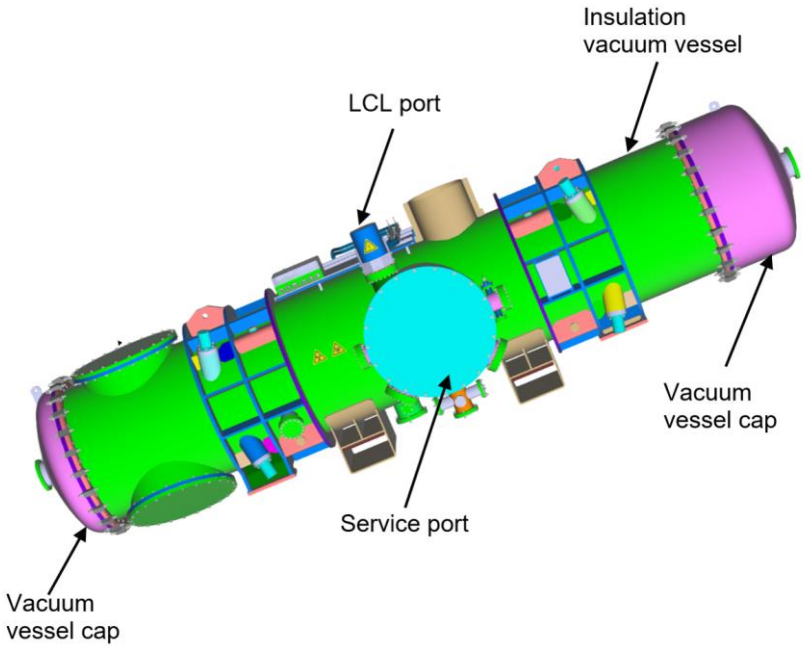


Figure 3: SIS100-QDM, type 2.123**.**

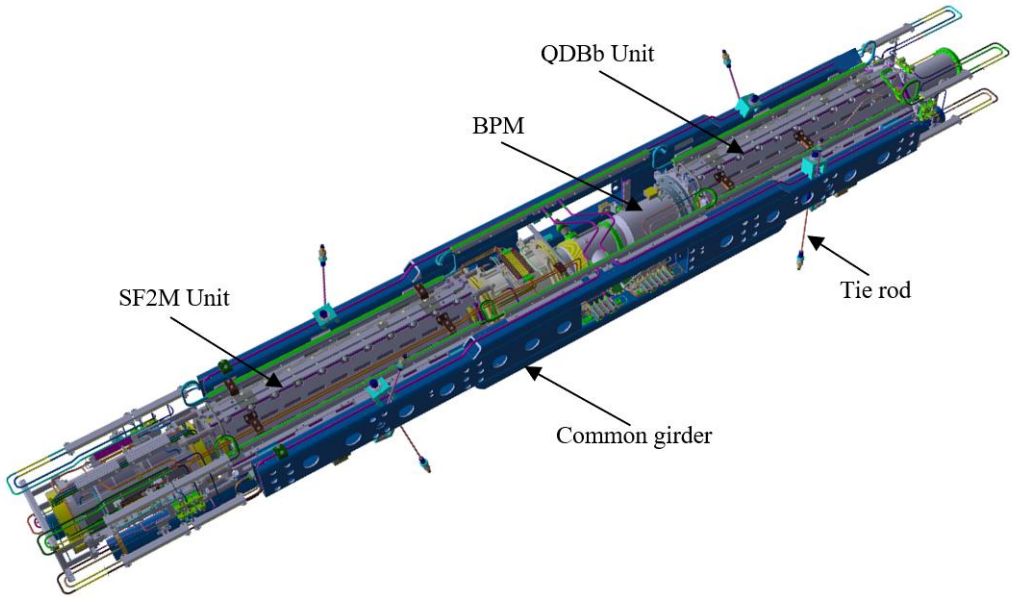


Figure 4: QDM arc termination 2.4 type cold mass integrated in the common girder. Upstream and downstream units are shown.

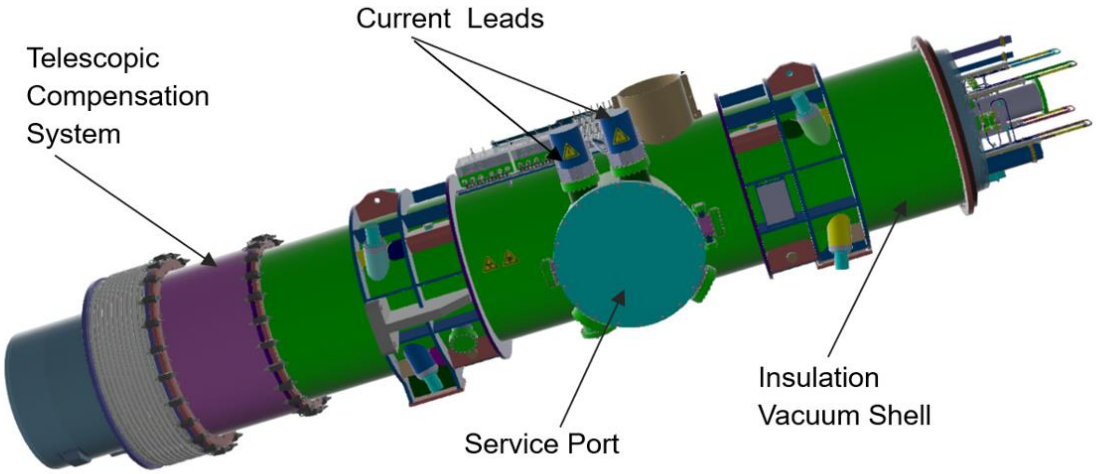


Figure 5: Sketch of an arc termination quadrupole doublet cryostat. The cold mass and the thermal radiation shield are assembled inside the cryostat. The location of the current leads and the telescopic compensation system is given. The telescopic compensation system will not be used during execution of SAT (see Figure 6).

All QDMs in the SIS100 are supplied with subcooled liquid or two-phase Helium at 4.4 K. The liquid helium supply pressure in normal operation is about 1.6 -1.8 bar, however the pressure at cool down and warm up may be higher (up to QDM design pressure, 20 bar).

The QP units are each supplied with helium by one or two cooling channels connected in parallel to a parallel supply line (Figure 7, Figure 9). Besides, all QDMs have a separate supply for the cooling of the beam tubes indicated on Figure 7 and Figure 9 as channel V.

The thermal radiation shield is cooled by gaseous helium at T = 50 – 80 K and the design pressure of all process lines is 20 bar.

During the execution of SAT, liquid nitrogen at 77 K may be used for the cooling of the thermal radiation shield instead of gaseous helium at T= 50 – 80 K.

The mass flow rates through the cooling channels are balanced for the operation at 4 K. To assure the equal cool down of both QP units and of the beam chambers, the cooling system of the test facility should provide the helium flow at variable temperatures to ensure a maximum $\Delta T < 15$ K between He inlet and outlet during cool down.

With regard to the layout of the helium supply and return lines the modules can be subdivided into two groups: QDMs for the arc sections of SIS100 (including arc termination modules) and QDMs for the straight sections.

The simplified cooling scheme of modules for the arc termination is shown on the Figure 7. Each module has one helium supply header DN50 for the cooling circuits of both QP units, one supply header DN25 for the cooling of beam chambers and one common return header DN100 [3]. Besides, the modules have two DN40 cooling tubes for the thermal radiation shield (supply and return).

In the arc section of the SIS100, the helium headers of all magnet modules as well as the helium tubes of the thermal radiation shields are interconnected by means of compensation bellows or flexible metal hoses. The compensation bellows on the process lines between QDMs are not the part of the magnet module and will not be tested within this work package.

The module shall be connected to the test bench (feedbox) by a flange on the front side (Figure 6). The opposite side shall be closed by an end box (not a part of the module). For all QDMs, except of the straight type modules, additional installation can be implemented in the end box to facilitate the operation of the test bench.

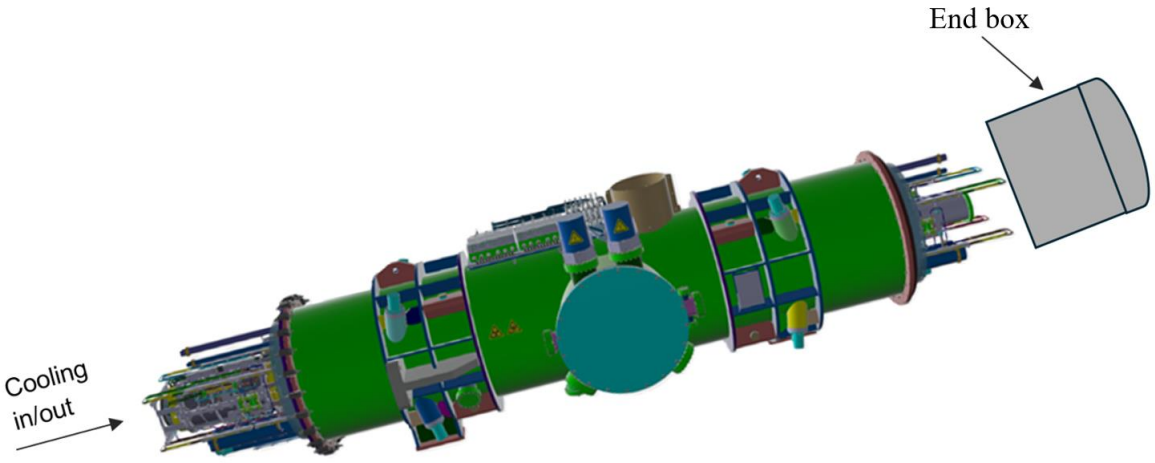


Figure 6: QDM in the arc section. The helium connections are in a feedbox. For testing the opposite side will be closed by an end box (not a part of the module).

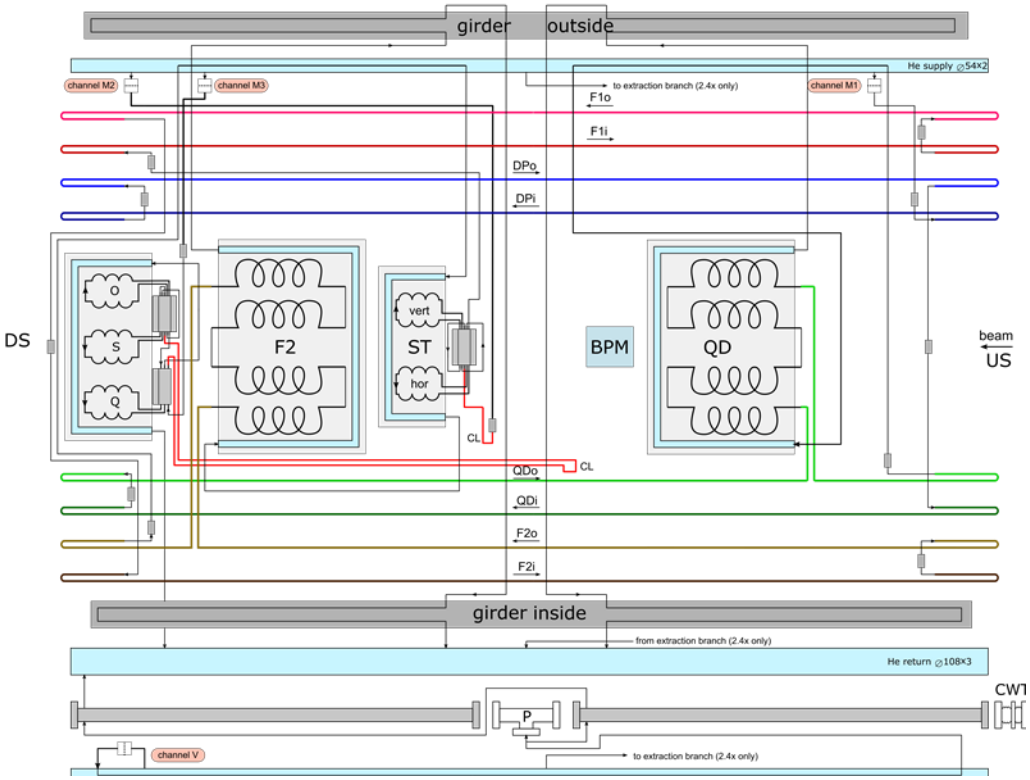


Figure 7: Simplified cooling scheme of an arc termination QDM 2.4. Thermal radiation shield is not shown.

The helium connections for the QDMs in the straight section are on the side (Figure 8). In the SIS100, the inlets and outlets of the cooling channels M1, M2 and V are connected to the helium headers in the bypass line (Figure 9) [see 4].

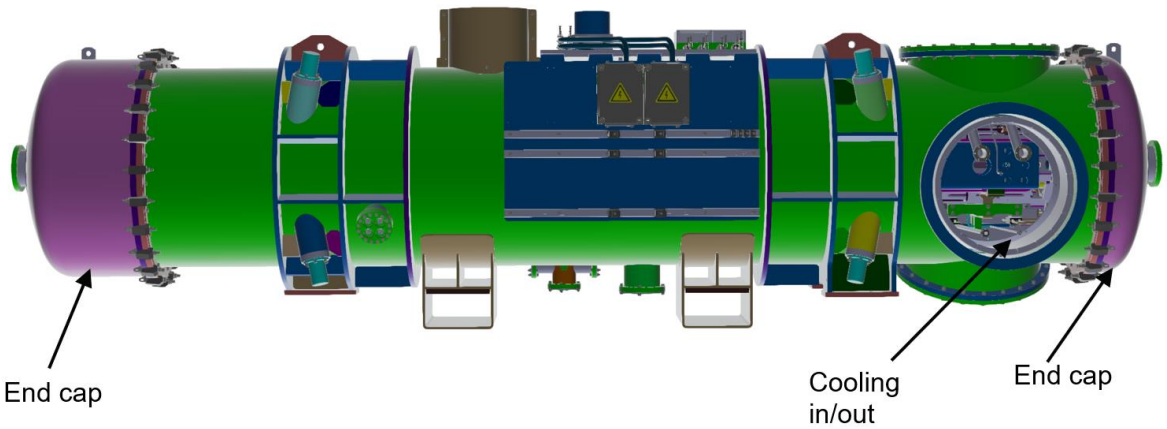


Figure 8: QDM in the straight section. Both sides of the cryostat are closed by two end caps. The end caps are parts of the module.

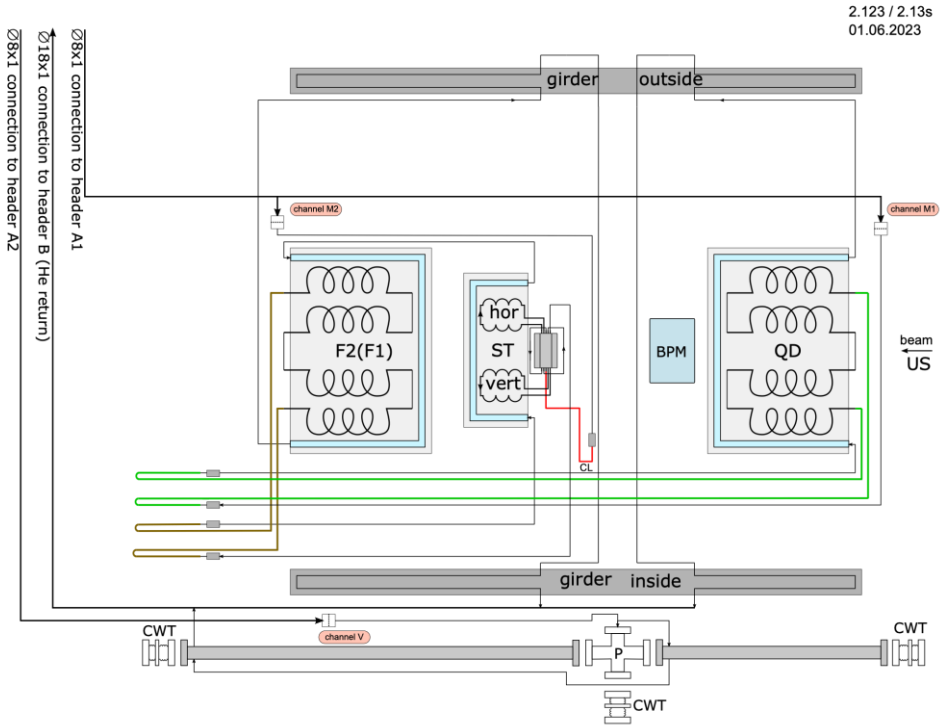


Figure 9: Cooling scheme of the QDM in the straight sections (2.123). Thermal radiation shield is not shown.

3.2. Scope of Delivery by the Contractor

This specification covers:

- The preparation and qualification of the cryogenic test infrastructure
- The execution of the QDM tests, documentation and evaluation

In general, the deliverables are the site acceptance tests (SAT) at cryogenic and room temperatures for each doublet module of SIS100 as defined in Section 4.7.

The Contractor shall prepare the cryogenic infrastructure such as a feedbox and endbox with an interface of 4K helium supply and return, 50K thermal shield supply and return line (gas helium or liquid nitrogen) in insulation vacuum.

The Contractor is responsible for the designing, constructing, and qualifying the infrastructure required for caring out of the acceptance tests on the SIS100 QDMs. The facility is a property of the Contractor. During the testing of the first module, the Contractor shall demonstrate the testing program and prove that it is executed with sufficient precision and accuracy. The mutually agreed testing rate must be guaranteed.

The Contractor executes the testing of QDMs according to the test schedule, the test contents and sequence provided by the Company. The Contractor shall declare that the testing is executed accordingly and issue the test reports. If QDMs deviate from the expected performance, the contractor should support diagnosing, and re-testing after rework was done.
After successfully passing SAT, all tested modules will be shipped to GSI for installation in the accelerator tunnel.

Regarding the acceptance tests (see Section 4.7), the following tasks should be done by the Contractor:

- Timeline and resource plan for realization of the facility enabling the intime execution of the SAT program
- Building up or upgrading a testing infrastructure for execution of SAT program
- Procurement of calibrated measuring equipment for execution of all tests listed in Section 4.7 within the agreed time scale
- Commissioning of the facility and demonstration of the desired performance
- Provide relevant documents of the safety and risk assessment of the testing facility
- Execution of all Site Acceptance Tests according to the test program listed in Section 4.7.1 for the agreed number of QDMs
- Data analysis and final test reports for each executed test on QDMs
- Raw data for all type of the acceptance tests

The main parts of the test facility are:

- Test hall with transportation system (crane) of at least 5t and with sufficient capacity
- Helium distribution system
- Feed-boxes
- Control system for heaters of the warm terminals of the local current leads
- Vacuum pump stations and instrumentation for the cryostat vacuum (insulation vacuum)
- Oil –free vacuum pump stations for the beam vacuum chambers
- 300 A power converters including magnet protection (dump resistors) and quench trigger interface for powering of the steerers (SV, SH) and multipole corrector magnets
- Quench detection system including event data acquisition and HV-cabling to test object
- Measurement systems including cabling infrastructure for all tests listed in the Section 4.7.1
- Data acquisition system for all sensors installed in the QDM and the infrastructure for the data analysis required for conduction and validation of the tests listed in the Section 4.7.1

Shipment of the QDMs:

- Shipment of the tested QDMs from the contractor test facility to the Company or to the supplier of the QDMs (Würzburg, Germany).

  Due to the design constraints of the QDMs (see [2], sections 4.2.5, 5.1.2), only transport by truck on the roads is acceptable (see [5] as an example).

3.3. Deliveries by the Company

The following parts will be provided by the Company:

- Drawings and 3D models of QDMs including interface information required for preparation of the facility interfaces for operation with QDMs.
- Delivery of the specific documentation for each QDM which is required for performing of the acceptance tests (instrumentation tables, etc.)
- Acceptance criteria for validation of the test results for QDMs

- End box for testing the arc termination modules
- Vector Analyzer (4 - ports); Time Domain Reflectometer (TDR) option for VNA

Shipment of the QDMs:

- Shipment of the QDMs from Company to the contractor test facility.

3.4. Spare Parts and Maintenance Plan

The Contractor shall assure the infrastructure is operational during the testing phase.

The contractor must prevent downtime during testing. This requires establishing failover systems, backup power or data solutions.

Also, the contractor must identify single-points-of-failure and maintain a readily available stock of critical components to minimize repair time.

The maintenance plans (facility, devices, and test equipment) shall be implemented into the timeline.

4. Testing Specification

This section covers the tests required for the assurance of the functionality of the assembled QDM at operational conditions with respect of:

- mechanical interfaces of QDM
- leak tightens of the vacuum vessel and He-process piping installed in the thermal radiation shield and cold mass (especially with respect to the cold leaks)
- leak tightness of the beam vacuum chambers against insulation vacuum
- static heat loads for the cold mass
- integrity of the magnet power circuits
- acceptance test of the current leads with the corrector magnets at operating conditions
- training and functional tests of the corrector magnets (nominal current about 250 A)
- integrity and functional tests of the instrumentation (temperature sensors, voltage taps, heaters, vacuum gauges)
- integrity and functional tests of the beam position monitors
- integrity and functional tests of the cryo-catchers

4.1. Magnet Parameters

The parameters of superconducting magnets are summarized in Table 3. The data presented in this table are for information only. More details can be found in the detailed specifications of the magnets (see [6]).

Table 3: Main magnet parameters for SIS100 (for information only)

Magnet		Quantity	Nominal Current	Ultimate Current	Main Field at I_{max}	Inductance	Maximal Voltage *(3)*
Main Quadrupole *(1)*		166	10512 A	11600 A	28 T/m	0.41 mH	± 10 V
Chromaticity Sextupole		42	± 250 A	± 275 A	232 T/m^2	46 mH	± 60 V
Steerer	Horizontal coil	83	± 250 A	± 275 A	0.37 T	27 mH	± 34 V
	Vertical coil		± 250 A	± 275 A	0.37 T	27 mH	± 34 V
Multipole corrector Type I	Coil 1 (quadrupole)	6	± 250 A	± 275 A	0.91 T/m	1.1 mH	± 2 V
	Coil 2 (sextupole)		± 250 A	± 275 A	31.8 T/m^2	5.6 mH	± 7 V
	Coil 3 (octupole)		± 250 A	± 275 A	446 T/m^3	7.4 mH	± 10 V
Multipole corrector Type II	Coil 1 (quadrupole)	6	± 250 A	± 275 A	0.91 T/m	1.1 mH	± 2 V
	Coil 2 (decapole)		± 250 A	± 275 A	12198.34 T/m^9 *(2)*	33.4 mH	± 42 V
	Coil 3 (octupole)		± 250 A	± 275 A	446 T/m^3	7.4 mH	± 10 V

(1) Not powered within this scope; *(2)* From simulations; *(3)* Inductive voltage at specified ramp rate

4.2. Functional Requirements

4.2.1. Infrastructure Requirements

The testing hall shall provide space for:

- at least two preparation benches for performing of the incoming and outgoing tests at room temperature and ambient pressure
- the temporary storage of 2 or 3 QDMs
- the test benches for performing functional tests on QDMs at 4K

The required number of test benches shall be derived from the capacity of one test bench and from overall time schedule of the contract. The minimum testing rate shall be 1QDM/month but 2QDMs/month will be desired.

The hall shall be equipped with an indoor crane of at least 5 t capacity.

4.2.2. Cooling Requirements

The helium distribution system shall be able to provide:

- Controlled cool down rate of the QDM (about 5 K per hour)
- Cooling capacity to allow a temperature of 4.2 K of the cold mass at an estimated heat load of the test object of below 30 W (static + dynamic)
- Operation at 4.2 K to enable module cooling according to [7]

  - Option 1: saturated LHe at pressure ranges between 1 – 1.9 bar, or
  - Option 2: subcooled LHe at 4.2K and 1.1 – 1.9 bar (preferred solution)
- Operation at supercritical conditions in order to evaluate the static heat load of each module
- Independent adjustment of the mass flow in the DN25 supply header by additional valve and mass flow meter
- Measurement of the helium mass flow rate, separately for the magnet cooling branch and the vacuum chamber cooling branch
- Helium at 50 – 80 K for the cooling of the thermal radiation shield and of the HTS current leads (cooling with liquid nitrogen can also be accepted)
- Overpressure protection for the feed box for the He lines and insulation vacuum

4.2.3. Measurement Equipment Requirements

All the devices and the equipment required for the QDM tests must be provided by the Contractor. The main measurement systems to be procured are:

- Measurement system for the HV insulation tests (see [8])
- Measurement system to perform leak test measurements and pressurized leak test (see [9])
- Measurement system for the integral leak tests procedure (see [10])
- Measurement system for the mass flow rate tests at room temperature
- Measurement system for the beam vacuum and for the residual gas analysis (range 1-100amu)
- Measurement system for the testing of the beam position monitor
- Measurement system for testing of the electrical integrity of the cryo catcher
- Temperature monitors for all temperature sensors installed in the QDM (up to 20-30 cryogenic temperature sensors). See instrumentation lists and schematics [11], [12]
- Control and measurement of the power of the heaters for the warm terminals of the local current leads
- Equipment for a functional test of a CRYO heaters: power supply and Multimeter

The main measurement systems for all tests listed in Section 4.7 have to be set up within this work package. The requirements to the measuring systems are to be derived from the tests demanded and shall be agreed upon in the design reviews.

4.3. Interfaces

The testing objects (QDMs) have the following interfaces to the testing infrastructure [2].

Mechanical:

- Feet and support system of the QDM
- Main vacuum flanges on the vacuum vessel
- Vacuum flanges of the beam vacuum chamber
- Flanges on the helium cooling lines (for the arc termination modules) DN25, DN40, DN50 and DN100. The dimensions for adaptions are given in according drawings.
- Flanges on the helium cooling lines (for the straight section modules): flanges 2 x CF40, 2x VCR8, 1 x VCR18

The mandatory documents for the mechanical interfaces are the drawing sets and CAD models for each type of the QDM. The drawing sets of the straight section modules are given in [13] and [14].

Electrical:

- Warm terminals of the Local Current Leads with I_{nom} = 250 A (see section 4.6.)
- Sockets for voltage taps rated at 3 kV and 1.1 kV. Connectors are Fischer type.
- Low voltage sockets on the instrumentation flange
- Connection Boxes for the LCL heaters

Additional documents for the electrical interfaces and electrical schemes for each type of the QDM are referenced in [15].

4.4. Quench Detection and Magnet Protection for Corrector Magnets

Each coil of a corrector magnet is equipped with six (3 x 2) voltage taps. The voltage taps are doubled for redundancy. The voltage taps are installed on both ends and in the middle point of the coil. Besides, each coil is equipped with one co-wound pick-up coil for the Mutual Inductance quench Detector (Figure 10). Both the standard voltage taps and the pick-up coil can be used for quench detection. Requirement is the detection of quench at a level of +/- 300 mV of resistive voltage at the presence of inductive voltage up to 60 V within 5 ms (validation time). The detection system should be protected to withstand an overvoltage of up to 600 V and shall be insulated to ground.

HTS current leads for corrector magnets (Section 4.6) are rated at 250 A DC. The quench detection system for the HTS stacks including their copper part (warm section) can be based on single channel detection with a total threshold of ±75 mV within 10 ms. Additionally, the copper parts can be protected against overheating by thermal switches (to be installed on the warm terminals).

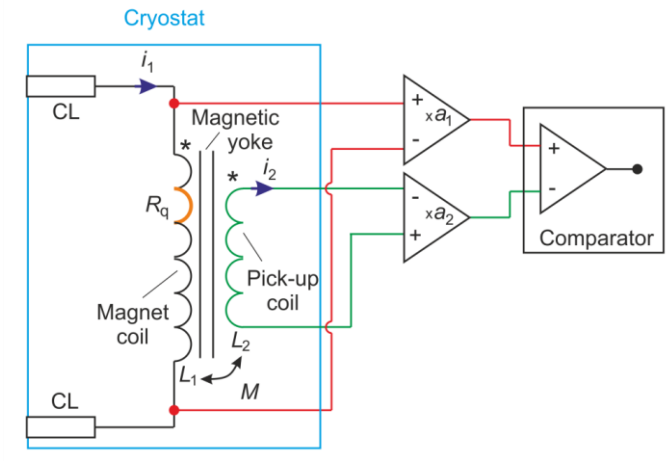


Figure 10: Quench detection scheme for corrector magnets with mutual induction quench detector (MID)

4.5. Local Current Leads

The Local Current Leads (LCL) for corrector magnets are conduction cooled HTS current leads rated at 250 A DC. The main parts of the LCL assembly (Figure 11) are the top flange with warm terminals, optimized copper parts, HTS stacks, heat sinks at 80 K and at 4 K and gold-plated joints.

Each warm terminal is equipped with two redundant heaters [16] and PT100 temperature sensors for keeping the temperature above the dew point. The heaters must be connected to the temperature controllers and turned on before starting cool down. The power consumption of the heater is about 10 W when the QDM is cold. Temperature controllers are not a part of QDM and shall be included in the testing infrastructure.

The LCL assemblies are equipped with voltage taps for protection of the HTS part in case of quench and for protection of the copper part against thermal run away (Section 4.4).

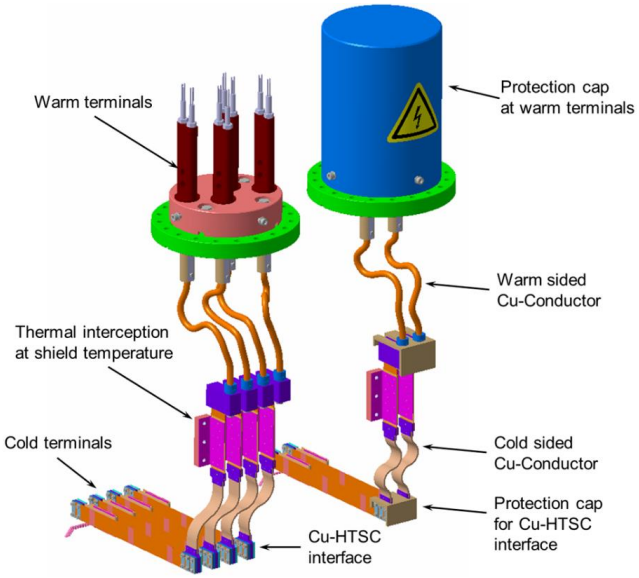


Figure 11: CAD-models of steering magnet LCLs without protection caps (left) and sextupole magnet LCLs with protection caps (right). Not shown: connection boxes for heaters and power converters.

4.6. Overpressure Protection

The design pressure for the QDM cooling circuit is 20 bar. The QDMs are not equipped with overpressure protection devices for helium process lines. Overpressure protection devices must be included in the testing infrastructure.

An overpressure protection for the insulation vacuum volume to be provided by CRYO infrastructure of Contractor (feedbox or endbox). This assembly needs to be prepared before the module can be cooled down.

4.7. QDM's Site Acceptance Tests (SAT)

The execution and reporting on the Site Acceptance Tests for the QDMs are the major deliverables of the Contractor. This chapter gives an overview on the standard tests and defines the execution.

4.7.1. Standard Test Program – Overview

The testing process of each QDM at the dedicated test facility consists of several key-steps (see Table 4)

Table 4: Overview on the SAT program for QDMs

Tests at room temperature	• Incoming Inspection (visual inspections) • High voltage tests • Electrical integrity tests and measurement of the electrical impedance parameters • Tests of temperature sensors at room temperature • Tests of the mass flow rate at room temperature • RF tests measurements on Cryo collimator, UHV diagnostic components and BPM
Preparation for the tests at 4K	• Installation on the test bench • Hydraulic and electrical connections • Leak tests of the process lines (vacuum leak) • Leak tests of the beam vacuum system • Instrumentation tests: temperature sensors with calibration curves • Checking the power circuits for electrical integrity (voltage taps) • High voltage tests
Closing cryostat and pumping	• Leak check of the cryostat vessel • Leak monitoring of the process lines during pump and purge process
Cool down	• Data logging, recording of the cool down curves
Tests at 4K	• Measurement of the helium mass flow rates and estimation of the static heat load • High voltage tests at cold conditions for all coils, BBs and low voltage tests for instrumentation • Validation of the voltage taps connectivity • Test of individual quench trigger before powering of corrector magnets • Powering tests on the corrector magnets (including magnet training, unipolar and bipolar AC powering) • Testing the functionality of the LCL with the magnet • RF tests measurements on Cryo collimator, UHV diagnostic components and BPM • Test of cryo heaters
Warming up and dismounting from the test bench	• Data logging, recording of the warming up curves • Monitoring of the partial pressure evolution in the beam pipe vacuum system • Warming up the cold mass
Final tests-Outgoing tests at 300K	• High voltage tests • Continuity test • Sensor tests • RF tests measurements on Cryo collimator, UHV diagnostic and BPM • Visual outgoing inspection
• **Preparing of the test report** • **Preparing and signing the SAT protocol**	
• **Preparation QDM for transport and organizing of shipment**	

4.7.2. Unloading of the QDM and Incoming Inspection

Quadrupole doublet modules will be delivered to contractor by mean of a heavy load track and need to be unloaded at the facility.

Steps of the incoming inspection to be performed after delivering the QDM unit to the test facility:

- checking the cargo for visible damages and shock sensors
- after unloading at the facility:
  - read out of the transport logger (at least two per QDM)
  - check of the delivery for completeness
  - visual inspection according to a check list (to be agreed)

Data presentation: protocol of the visual inspection, data from the transport data logger

4.7.3. Electrical Integrity Tests, Measurement of Electrical Impedance Parameters

Electrical integrity tests (see [17]) at room temperature include checking of the presence and correct order of the voltage taps along the magnet electrical circuit (continuity tests). The electrical continuity tests respectively the validation of the voltage taps have to be performed for all magnet circuits main quadrupoles, corrector magnets, including local current leads and all bus bars.

There are two methods:

- 2-wire method - direct electrical resistance measurement along the magnet electrical circuit using a digital multimeter (DMM). Measurements shall be performed with respect to a reference voltage tap in the circuit. This includes the ohmic resistance of test leads, voltage tap wires, magnet coil and copper current leads.

- Indirect electrical resistance measurement via the “V/I-method”. A constant DC current is impressed into the magnet electrical circuit on top of the current leads. The voltage drop at each voltage tap with respect to a reference voltage tap in the circuit is measured using a precision digital voltmeter (DVM).

The test current at room temperature shall be in the order of max. 5A for main quadrupole coils and 250mA for corrector coils to avoid overheating and floating results. The voltage drop along the electrical circuit shall be measured for each voltage tap and compared with a reference values.

After cooling down the voltage taps continuity shall be checked again. This can be done by “beeping” with a continuity tester as there is no electrical resistance of the coil.

Data presentation: Table with voltage tab number and measured voltage

Electrical impedance parameters shall be measured at room temperature during incoming tests. Values to be measured for the quadrupole coil and for each corrector coil:

- Resistance R
- Inductance L at 120 Hz and 1 kHz
- Loss angle (tan δ) at 120 Hz and 1 kHz

Data presentation: Test protocol: R, L and tan δ values for each coil

4.7.4. High Voltage Tests

Each straight QDM has two independent high current power circuits:

- defocusing quadrupole with bus bars DFi and DFo
- focusing quadrupole type 1 or type 2 with bus bars F1i / F1o or F2i / F2o

Each arc termination QDM has four independent high current power circuits:

- defocusing quadrupole with bus bars DFi and DFo
- focusing quadrupole type 1 or type 2 with bus bars F1i / F1o or F2i / F2o
- dipole bus bars DPi and DPo passing the dipole current trough QDM
- additional pair of quadrupole bus bars, F1i / F1o or F2i / F2o passing the F1 or F2 quadrupole current trough QDM

Besides each QDM has up to 5 low current (250 A) circuits for corrector coils with their bus bars and current leads.

Electrical insulation of all power circuits shall be tested several times within the standard test program (see [8], [17]):

Electrical insulation integrity of each magnet coil including its bus-bars as well as possibly associated current leads and all instrumentation (e.g. VTaps, sensors, heaters) connected to this electrical circuit ("life circuit") are verified at defined DC HV test voltages with reference to ground/PE.

The test voltage shall be applied to every single magnet coil within a QDM module with reference to ground/PE in two or three consecutive steps for a duration of 60 to 120 seconds each, while all other instrumentation and magnet electrical circuits in the module (this also includes bus-bar circuits just passing the module, e.g. DPi/DPo) are grounded.

HV tests shall be performed for the quadrupole coils and busbars as well as corrector coils and MID strands according to Table 5. The acceptance criterion is Rins ≥ 1 GΩ in each case. For HV tests, hermetic connectors of the voltage taps on the instrumentation flange can be used. The HV test must be performed at 300 K and 4.2 K. During the testing, ambient temperature and relative humidity must be recorded. For connectors see [11] and [12]. A suitable measurement device would be a Megger (type S1-568 or S1-1068) or comparable.

Raw data to be provided: Recorded data R(t)

Table 5: HV test overview. The acceptance criterion is R_{ins} > 1 GΩ

Connection	Positive	Quadrupole coil/Main busbars	Corrector coil and MID strand
	Negative (ground)	Ground + other live circuits	Ground + other live circuits
Test steps	1	0.6 kV for 1 min.	0.5 kV for 2 min.
	2	1.5 kV for 1 min.	1.1 kV for 2 min.
	3	3.0 kV for 2 min.	-

4.7.5. Low Voltage Tests

The DC-Low-Voltage (LV) test shall verify electrical insulation integrity of all instrumentation (sensors, thermocouples, heater elements). A single sensor/heater shall be electrically insulated with

respect to ground/PE and to other electrical circuits, in particular adjacent devices attached to the same connector at the instrumentation flange.

The test voltage shall be applied to the instrumentation circuit under test with reference to ground/PE for a duration of 60 seconds, while all other instrumentation and coil circuits in the test module are grounded (see Table 6).

Table 6: The test voltage acceptance criteria

Ref.	Object	Test Voltage / Duration	Acceptance Criterion Rins @ 293 K	Remarks
1	SIS100 QDM **Sensors**	50 V @ 60 s	≥ 100 MΩ (sensor) ≥ 5 MΩ (TC)	Insulation to ground & other electrical circuits
2	SIS100 QDM **Heater Element**	100 V @ 60 s	≥ 5 MΩ	Insulation to ground limited due to strong hygroscopic behaviour

4.7.6. Validation of Voltage Taps @ cold

All voltage taps for the quench protection of main quadrupoles, corrector magnets and current leads must be checked for their presence and connection to the magnet circuit (see test at room temperature section 4.7.3).

4.7.7. Tests of Temperature Sensors and Heaters

Each QDM is equipped by up to 20 - 30 temperature sensors of various types, Cernox, TVO, PT1000, CLTS and thermocouples. All sensors have to be tested at room temperature and at helium temperature in order to check functionality and to verify the correct assignment of calibration curves.

The sensor alive test is performed on all temperature sensors and other instrumentation (heaters), installed within a QDM. The objective is to verify the presence and functionality of all instrumentation at given test conditions. Sensor's resistance values shall be compared in line with their calibration curve values at the actual test object temperature to verify the acceptance limits. The "4-wire method" shall be applied for testing of temperature sensors.

Raw data:

The logged data for the complete test run and for all temperature sensors shall be provided as CSV file or in MS-Excel format in addition to a proper test protocol.

Data presentation:

Table in the test report with following fields:

- sensor name according to instrumentation list
- CID number of the sensor
- number of the calibration curve (series number of the sensor)
- temperature reading at warm conditions (resistance a room temperature)
- temperature reading at 4 K (stable conditions, magnets are not powered)

Additionally, the test report shall contain the cool down and warm up plots for all temperature sensors vs time (cool down and warm up curves).

4.7.8. Test of Helium Heaters

Each magnet cooling circuit is equipped with two helium heaters located on the inlet on the cooling channel. Each heater has a thermocouple of type K (Nickel-Chromium / Nickel-Alumel). Rated power is 20W in continuous operation. However, in the standard operation both heaters will be connected in parallel and will be operated at P ≤ 10 W for each heater.

The performance of the heaters should be tested at helium temperatures.

The test of the helium heaters consists of following steps:

- Applying 20 W to the heater 1 and recording of the thermocouple voltage
- Applying 20 W to the heater 2 and recording of the thermocouple voltage

The thermocouple voltage must be recorded after some stabilization time (typically few minutes).

4.7.9. Pressure Test and Leak Tests of the Process Lines and of the Cryostat Vessel

The QDM is a pressure vessel of the category 1 according to the European Pressure Equipment Directive 2014/68/EU. The company responsible for the integration of the QDM will perform the pressure test at 28.6 bar according to the PED 2014/68/EU.

Then the process lines shall be leak tested using a pressure drop method at design pressure of 20 bar(a) according to the technical guideline “Pressurized Leak Testing of the Cryogenic Tubing” [9].

All next leak tests are done with helium leak detector or RGA.

The vacuum vessel of the QDM has to be tested for leak tightness before starting cooling down.

The 50 K helium circuits of the QDM have to be tested for leak tightness at warm and at cold conditions several times within the standard test program (Section 4.7.1).

The leak detector must be calibrated prior to conducting a leak detection and the required sensitivity is of 10^{-11} mbar/l/s or better.

The leak test sequence of the process lines and for the vacuum vessel are presented in Table 7.

Table 7: Leak test sequence of the process lines and for the vacuum vessel

Step	cryostat	Process lines
After arrival	No	Obligatory after installation of the flange adapters
Warm, connected to feed box	No	Obligatory after making all hydraulic connections
After closing cryostat and pumping	In case of slow pump down or if air is visible in RGA spectrum	Integral leak test with pumping and flushing of process lines with helium
Cool down	If air is visible in RGA spectrum	Continuous logging of insulation vacuum and of RGA spectrum
Cold		Integral leak test at increased pressure
Warm-up		Continuous logging of insulation vacuum and of RGA spectrum
Warm	No	No

Data presentation:

The leak rate shall be documented either in test protocols or in the quality plan, depending on the step of the test program (to be agreed in the design reviews). Preferable units for the leak rates are mbar·l/s.

4.7.10. Tests of the Beam Vacuum System

4.7.10.1. Acceptance Tests on the beam vacuum system of QDMs 2.123 and 2.13s

The CF-type flange openings located on the beam axis of the beam vacuum system, which were provisionally sealed with protective aluminum end caps for transportation purposes, must be closed using standard CF blank flanges with conventional copper (Cu) gaskets. QP modules 2.123 and 2.13s are equipped with dedicated pumping ports formed by so-called Roughing Cold–Warm Transitions (RCWTs). On the outer side of the cryostat, each RCWT terminates in a pipe socket chamber located below the service flange of the cryostat. This chamber provides access from the room-temperature side for evacuating the cryogenic beam-vacuum system of the QP modules. A DN100 all-metal gate valve, vacuum-diagnostic equipment (quadrupole mass spectrometer, extractor ion gauge or wide range gauge), and the associated pumping system shall be connected to the pipe socket chamber, as shown in Figure 12.

The test sequence of the cryogenic beam vacuum system of the QDM is to be performed as follows:

1. **1st leak test before cold run under room temperature conditions (cryostat is non-evacuated)**

   A local leak test shall be performed on all flange connections closed for SAT testing of the beam vacuum system. This applies to the two DN160CF blank flanges sealing the two BVCWTs and to the complete vacuum test system installed below the service flange on the pipe socket chamber. In case the straight modules are not equipped with bv-cwts, the vacuum system needs to be equipped with additional flanges for sealing the insulation vacuum (provided by the Company).
   Compliance with a leak rate of $q_L \leq 1\times10^{-10}$ mbar·ℓ/s shall be demonstrated. Any leaks found shall be fixed before continuing the test procedure.

2. **Residual Gas Analysis of beam vacuum**
   - when UHV system is at 5 K (steady state conditions)
   - during warming up of the UHV system monitoring AMU 4 (= helium)

   Cooling down the QP module under test shall begin once the beam-vacuum pressure has decreased to below p < 1E-6 mbar. When the cold vacuum chambers of the quadrupole module have reached temperatures close to liquid helium level, the external turbomolecular pump shall be isolated by closing the all-metal gate valve. An RGA spectrum shall then be recorded after stable vacuum conditions have been reached.

During warm-up of the vacuum system, mass-spectrometric monitoring shall be performed with the gate valve closed in the temperature range between 5 and 25 K. At temperatures above 25 K, the gate valve to the TMP shall be reopened and the warm-up process shall further be monitored using the RGA.
These measurements are performed to determine whether helium has entered the beam vacuum from the insulation vacuum through a potential cold leak. If this were the case, the helium would be rapidly adsorbed on the 5 K surfaces or by the cryosorption pump, which makes it almost impossible during the cold phase to verify whether helium has leaked from the insulation vacuum into the beam vacuum. Verification becomes possible during warm-up of the cryogenic chambers, since helium desorbs from the cold surfaces as soon as temperatures rise above approximately 10 K. Any helium that may have accumulated during the cold phase would desorb during warm-up and be detected by the helium leak detector. To verify this, the QMS shall be operated in time-resolved mode throughout the warm-up of the cryogenic beam-vacuum system. The ion-current signals at (m/z = 2) and, in particular, (m/z = 4) shall be continuously recorded and monitored at one-second intervals over the entire warm-up period, resulting in plots of I+ as a function of time t. Ideally, during the entire warm-up of the QDM, the helium partial pressure in the system should not increase and should approximately remain constant. If a significant increase in the helium signal is observed during the warm-up of the cryogenic beam-vacuum system, the Company shall first be informed. The test procedure shall then continue with Step 4, “2nd leak check after the cold run under room-temperature conditions”.

3. Functional test of the temperature sensors and vacuum diagnostics

- prior to cool-down
- when UHV system is at 5 K (steady state conditions)
- during warm-up

Continuous monitoring and readout of the vacuum gauges (cryogenic CCG, extractor ion gauge, WRG) and internal vacuum chamber temperature sensors throughout the entire acceptance test phase.

4. 2nd leak check after cold run at room temperature conditions (if needed only, cryostat is vented)

Provided that an increase in the helium partial pressure was detected by RGA during a warm up in the temperature range between 5K and 15K, a second leak check shall be performed.

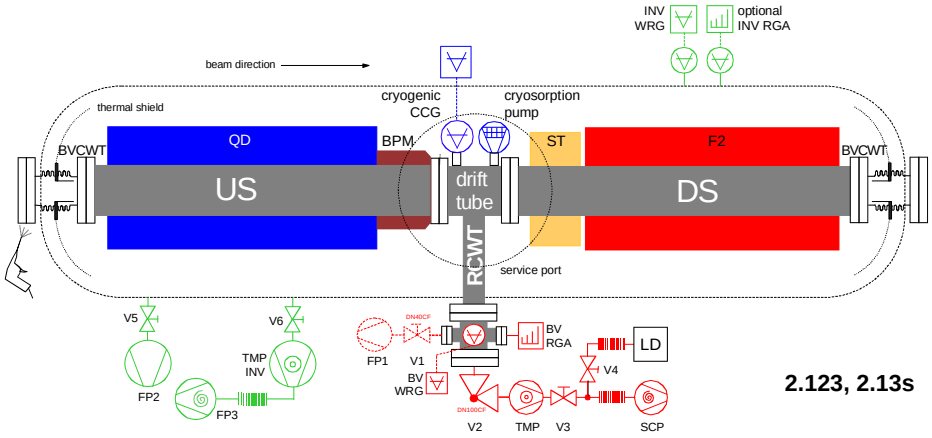


Figure 12: Schematics of recommended setup for vacuum testing the QDM types 2.123 and 2.13s. Abbreviations: BVCWT Beam vacuum cold warm transition, DS Downstream chamber, US upstream chamber, BPM Beam position monitor, ST Steerer magnet, QD+F2 Quadrupole magnets, TMP Turbo molecular pump, WRG Wide range gauge, RCWT Roughing cold warm transition, CCG Cryogenic cold-cathode gauge, LD Leak detector, RGA Residual gas analyser (mass spectrometer), SCP Scroll pump, FP1, FP2, FP3 Water-vapor tolerant fore pump, V1+V2 All-metal angle valve, V3+V4+V5+V6 Valves, BV Beam vacuum, INV Insulation vacuum

Instructions on how the local helium probe technique is to be carried out in detail are given in F-TG-V-7.38e [18]. It must be demonstrated that the connections done at all CF flange connections must have the leak rate below $q \leq 1 \cdot 10^{-10}$ mbar ℓ/s.

Following issues must be taken into account while performing the tests:

- During the pump-down, significant amounts of water vapor must be removed from both the beam and insulation vacuum. In particular, the beam vacuum system of the QPMs is equipped with a charcoal-based cryosorption pump, which releases large quantities of water vapor during the first phase. Therefore, a separate water-vapor-tolerant fore pump should be used for roughing from atmospheric pressure (~1000 mbar) down to 0.1 mbar to protect the high-vacuum pumps. Once the pressure drops below 0.1 mbar, the pump-down should be continued using a combination of a turbomolecular pump (TMP) and a dry backing pump.
- To prevent helium back-streaming into roughing pumps or leak detectors, connect all exhaust/outlet sockets to a dedicated vacuum exhaust system (if available), or alternatively use flexible hoses attached to the exhaust/outlet sockets and lead them outside the testing area (e.g. testing hall). Additionally, covering Viton flange connections with e.g. polyethylene foil and tape is advisable.
- The use of regularly calibrated leak detectors is mandatory. For device calibration it is sufficient to use the internal test leak which is on-board of all commercially available leak detectors. However, commercial leak detectors are equipped with internal test leaks with typical leak rates of some (10^{-7}...10^{-6}) mbar ℓ/s range, which is generally not suitable for precise measuring of low leak rates. Use instead an external calibration leak with a leak rate in the (10^{-10}…10^{-9}) mbar·ℓ/s range to calibrate the leak detectors.
- Sniffing leak checking techniques are not allowed, and must not be used for UHV leak checking.
- All measurements shall be recorded in a separate report entitled “SAT Vacuum Acceptance Tests.”

Required equipment:

RGA (Faraday type or channeltron type)

Helium leak detector with sensitivity of 1.10^{-11} mbar/l/s or lower

Vacuum diagnostic (Extractor ion gauge or WRG) and pumps according to the equipment shown in Figure 12.

4.7.10.2. Acceptance Tests on the beam vacuum system of QDMs 2.4 and 1.E

Acceptance tests for QDM 2.4 and 1.E follow the same procedure as described above. Note, however, that unlike 2.123 and 2.13s, these modules lack cryostat end caps, an RCWT and a pipe socket chamber, requiring the beam vacuum system to be pumped from the cryostat side for QDM testing (Figure 13).

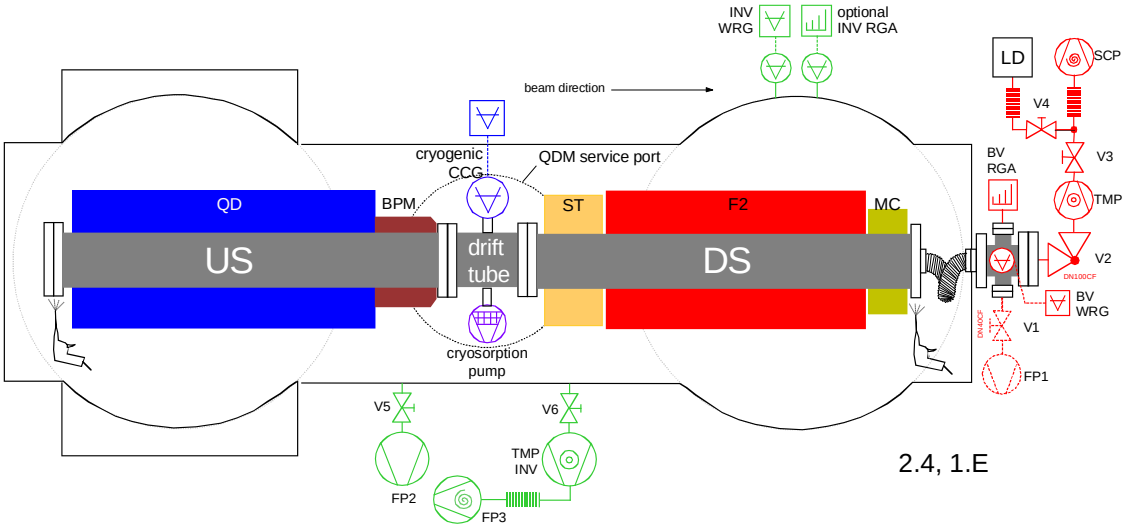


Figure 13: Schematics of recommended setup for vacuum testing the QDM types 2.4 and 1.E.

Abbreviations see caption Figure 12.

4.7.11. Measurement of the Helium Mass Flow Rates and of the Static Heat Load

The helium mass flow rate shall be independently measured for

- The magnet cooling circuit M1 + M2 (Figure 7) (the expected mass flow rate for one QDM is 2 – 3 g/s)
- For the beam chamber cooling circuit V (Figure 7) (the expected mass flow rate is about 1g/s)

As a first step, the mass flow rates shall be measured at room temperature for ΔP of several bar (typically between 2 and 10 bar). Helium, nitrogen or another inert gas might be used for mass flow measurements at room temperature. The reference values for the mass flow rates will be given by the company.

After cooling down the mass flow rates shall be measured at cold conditions using either supercritical helium or two-phase helium. The two-phase measurement is the preferred method.

The static heat load to the cold mass of the QDM shall be measured with thermal radiation shield at 50 – 80 K. Supercritical helium is recommended for the static heat load measurements. The expected value for the static heat load is about 10 W.

4.7.12. Powering Tests on Corrector Magnets

A superconducting magnet needs to be trained to its final operating conditions. Powering the magnet induces large forces on the wires or between sections of the magnet due to the Lorentz force. These stresses might lead to frictional movement of the wires or coils with respect to each other which in turn generates heat. At cryogenic temperatures the heat capacity of the materials is very low, and even small heat input can increase the temperature significantly and drive the superconductor into its normal conducting phase. When powered for the first time a magnet needs to adjust to the stresses and loads. Energizing the magnet again and again these pre-mature quenches occur at higher and higher currents until saturating at the final operating current the magnet is capable of.

Training

Within the test program only the corrector magnets will be trained and are all individually powered.

Each coil for the steerer magnets and multipole magnet has a nominal current of I_{nom} = 250 A and is trained to an ultimate current of $I_{ultimate}$ = 275 A with ramp rates up to 1225 A/s (see [6]).

The training of the magnet involves running individual cycles with a specified amplitude equal to the ultimate current. If the magnet quenches, the cycle is repeated.

Specifically, training of the magnet involves increasing the current flowing through the magnet at a specified ramp rate, starting from an initial current of 10 A up to the ultimate current $I_{ultimate}$. The current is maintained at this level for 2 seconds (without quenches) before returning to the initial current at the maximum available rate. After each successful cycle, the ramping rate is increased up to a maximum of 1225 A/s. Figure 14 shows a typical example of a current cycle for the ramp rate 600A/s.

All specific ramp rates used during the magnet training are labeled in Figure 14. The training cycles for the multipole magnets will be similar and are agreed among the parties after first operation of the multipoles.

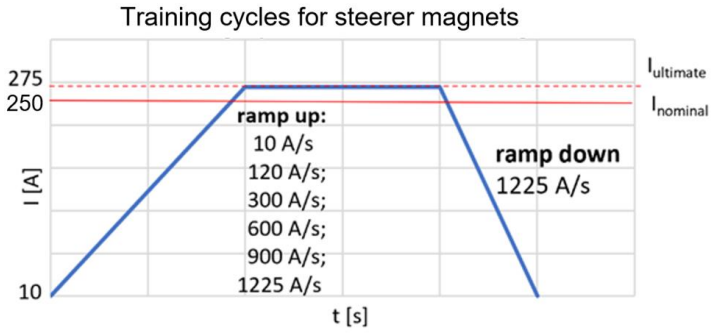


Figure 14: A typical example of a current cycle for the steerer magnet (ramped rate: 600A/s)

Acceptance Criteria (for information only)

Each magnet must meet the following criteria

Quench Performance: The magnet should reach its nominal operating current:
at least at the 3rd quench during the 1st cold run

Quench Degradation: The quenching current degradation criteria must be fulfilled:
The quenching current shall be above the nominal current in any case
The current difference at a de-training quench to the previous quench shall be less than 5% of the nominal current

AC stability test (unipolar and bipolar operation)

Magnet stability clearly is an important issue that strongly affect the performance of accelerator magnets. Two aspects are critical for the proper functioning of the steering magnets: their strength must be sufficient to achieve orbit correction and required bumps even at the nominal magnetic rigidity of 100Tm; and their ramping speed must be high enough to keep up with the intended operational cycles.

Stability test on corrector magnets should be performed using both bipolar and unipolar ramp cycles. The magnet must demonstrate stable operation for at least 10 minutes without experiencing a quench.

Stability test involves ramping the current flowing through the magnet at a specified ramp rate (see Table 8), starting from the initial current (10 A) up to the nominal current and then back down at the same rate. This cycle is repeated for 10 minutes. A typical example of stability test is shown in Figure 15.

Table 8: Stability ramp rates for the steerer

Test number	Nominal current I_{nom} (A)	Ramp rate I_{RR} (A/s)
1	250	+/- 120
2	250	+/- 300
3	250	+/- 600
4	250	+/- 900
5	250	+/- 1225

In addition, a bipolar stability test is performed to validate the correctors operation and to find out the limit of their bipolar performances. It involves checking the stability of the magnet under alternating current directions. The bipolar cycles for the steerer are designed to provide ramping at constant ramp rate between the starting current and the nominal current during the accelerator ramp duration.

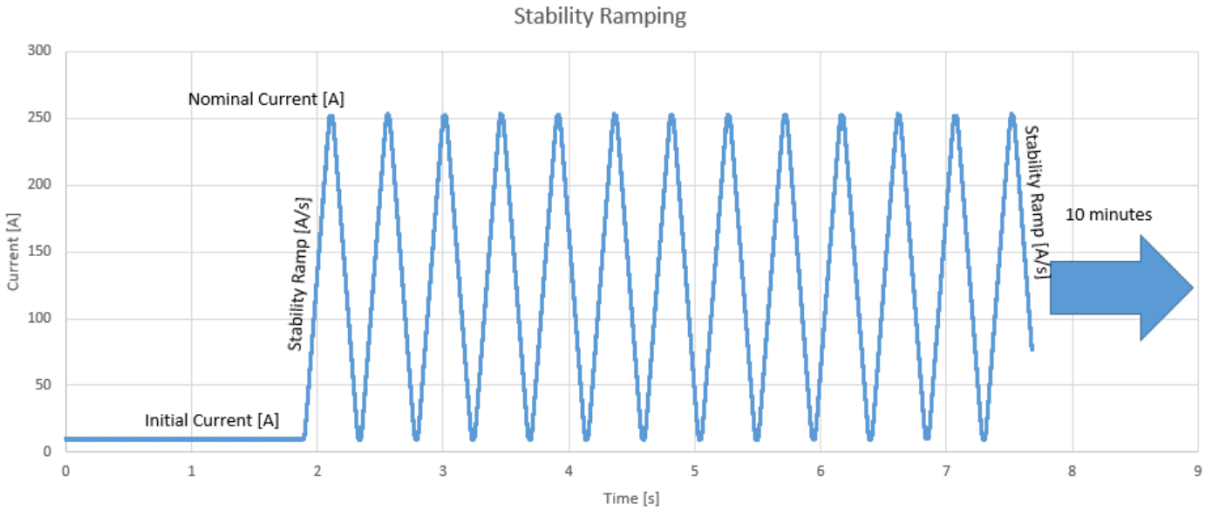


Figure 15: Stability test for the steerer

Figure 16 displays the bipolar cycles for the coils of the steerer. The calculated ramp rate keeps the duration of the ramps both up and down the same in different cycles. The blue trace with a ramp rate of ±1225A/s, corresponds to the triangular cycle. Details of the cycles both unipolar and bipolar will be agreed in the FDR among the parties.

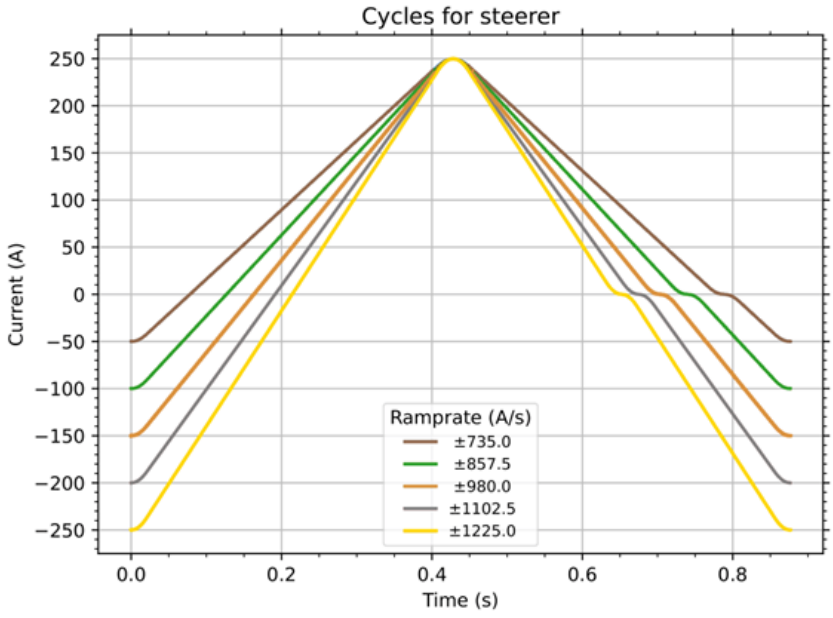


Figure 16: Current ramps used for steerer testing, shifted in phase such that minimum and maximum current occur at the same time.

4.7.13. Test of Local Current Leads

The standard test program includes powering of corrector magnets in DC mode in order to test their local current leads (Section 4.5).

All voltage taps must be checked before powering as well as the quench detection system.

The heaters on warm terminals must be connected to the temperature controllers and turned on before cooling down of QDM. The power consumption of heaters shall be measured in order to estimate the heat load to the thermal radiation shield through the copper part of the LCL.

The test includes the powering of each corrector coil in DC mode up to 250 A in several steps and recording the voltage signals on the screwed joints, HTS stacks and across the copper parts.

4.7.14. Collimator/Cryocatcher Tests

The ion optical lattice of SIS100 has been optimized such that stripped beam ions (U29+) are lost at well defined highly localized positions in the cryogenic arcs. This allows the installation of an efficient ion catcher system (10 catchers are foreseen in each arc) with perpendicular low desorption surfaces. Thereby, the amount of charge exchange processes in collisions with residual gas molecules and consecutive ionization beam loss is stabilized during operation.

Since the ion catchers will be installed in the superconducting quadrupole doublets, their design has to be suitable for a cryogenic environment. The cryocatcher is located between two QP units, inside the quadrupole cryostat. It consists of a cryocatcher block cooled to 50 – 80 K by thermal link the thermal radiation shield and a cryocatcher chamber cooled by two-phase helium flow [19].

The cryocatcher module allows the measuring of the electrical current of the lost ions hitting the cryocatcher block and requires a good electrical insulation in combination with a good thermal contact to the thermal radiation shield.

The tests of the cryocatcher module at warm include the tests of electrical integrity of all components (insulation tests, test of heaters at room temperature). The test of the cryocatcher at cold includes temperature measurements of the collimators for the different powering of the heater and the electrical isolation against ground test.

The electrical integrity of the connection cable of the cryocatcher block shall be also checked by measurement of the total capacity or TDR measurement of the cable with cryocatcher block (see section 4.7.15).

Regarding the QDMs to be tested within the scope of this specification, only the arc termination type 1.E module includes a cryocatcher (see Table 2).

4.7.15. RF Tests Measurements on Cryo Collimator, UHV Diagnostic Components and BPM

The QDM RF measurements include testing the beam position monitor (BPM), the cryocollimator/cryocatcher, and the cold cathode system.

These tests deliver information about the correct cabling of the aforementioned components and their integrity. They allow for the detection of interchanged cables and failures during QDM integration, such as missing or improperly installed elements. They also help to identify any issues that could occur during transport, cold testing or any other incident

The measurement system will be set up and calibrated by a GSI RF expert to ensure accurate and reliable measurements and compliance with requirements. The setup of each test step will be finalised by creating the corresponding setup file, which will consist of the appropriate calibration. The measurements conducted by the contractor will be reduced to:

- connection of the device (Network Analyzer) to the component under test
- recall of the setup files
- comparing the obtained results with the reference traces
- storing the results in graphic file format

- Preparation of the test record
- Notification of any deviation from the reference

GSI personnel will support the interpretation of the obtained results. Furthermore, a GSI expert will assess the determination of non-conformities. GSI experts will also support the contractor by dealing with any non-conformities and providing troubleshooting advice.

GSI will provide training to the contractor personnel on the testing procedure and acceptance values, in addition to setting up the system described above.

Measurements should be performed by a trained engineer or technician at the designated test facility.

BPM tests measurements

BPM allows a non-intercepting determination of the transverse position of the bunched ion beam. A total number of 84 BPM stations will be distributed over the whole 1089 m circumference of SIS100. The BPM pick-ups are installed inside the QDM cryostats and coupled to the yoke of the neighboring focusing or defocusing quadrupole depending on the QDM type. Each QDM consist of one BPM.

In the arcs the BPMs will be located at the down-stream (DS) or up-stream (US) end of the cryostat, while in the straight sections the BPMs will be installed in the middle of the QDM (

Figure **17**).

All BPMs are equipped with electrodes for both horizontal and vertical beam position measurements. Figure 18 shows the schematic diagram (left) and the main components (right) of the BPM system that are operated at cryogenic conditions (components that are installed inside the QDM cryostat).

The main technical features of BPM are listed in Table 9. For further details see [20].

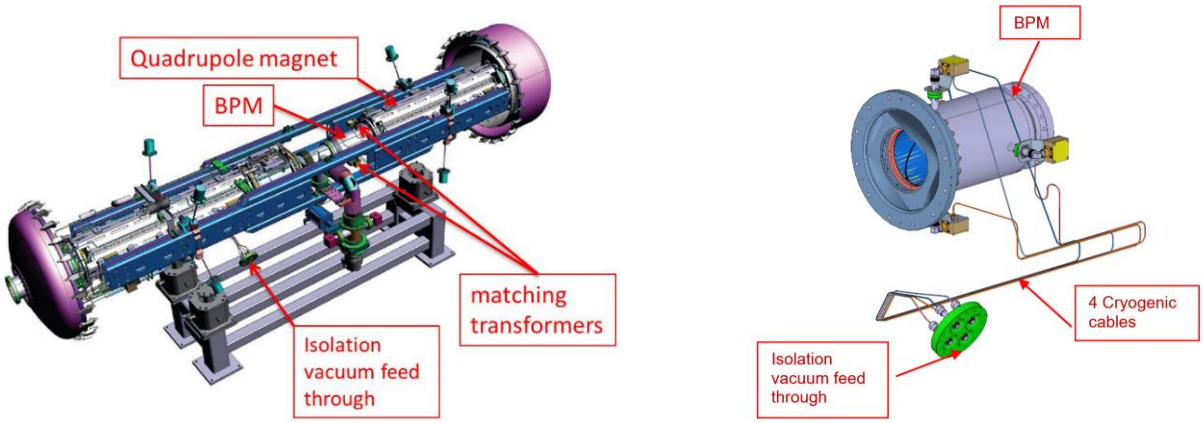


Figure 17: Left: Position of BPM in the straight sections type QDMs. **Right:** BPM components and cryogenic cables which are installed inside the QDMs [20].

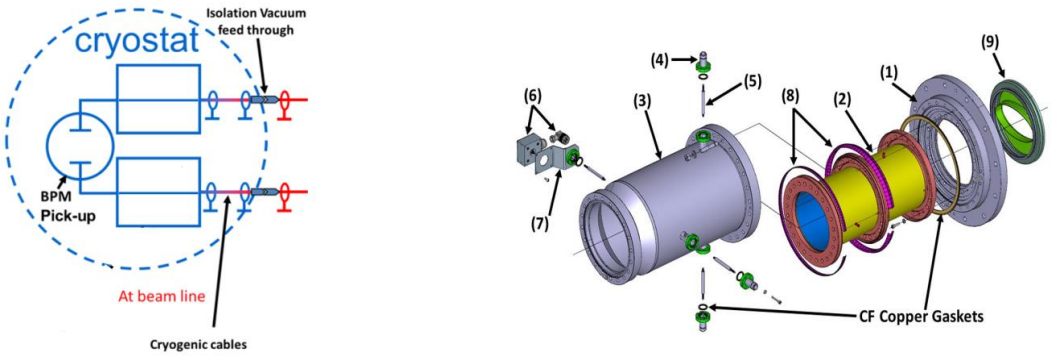


Figure 18: **Left:** Schematic diagram of the SIS100 BPM. **Right:** SIS100 BPM pick-up: 1. Main flange being the main reference plane that after welding becomes an integral part of the quadrupole chamber, 2. Metal coated ceramic pipe with electrodes and appropriate guard rings, 3. BPM Chassis, 4. UHV signal feedthroughs interconnecting electrically the UHV region with the insulating vacuum region, 5. Feedthrough contacts, 6. 90° N-type adapter installed in the insulating vacuum, 7. Supporting plate that supports the transformer chassis, 8. RF contacts in form of CuBe ribbons, 9. Compensation below and adapter flange.

Table 9: The main technical requirements of the SIS100 BPM

Parameter	Value
BPM Detector	
Pick-up frequency range (minimum)	0.4 MHz-95 MHz
Capacitance between electrode and ground	85 ± 5 pF
Capacitance between two electrodes of same plane	1 0 ± 2 pF
UHV signal feed-throughs	
Pcs. / BPM	4
Flange type	NW16 CF-F (ISO/TS 3669-2)
Characteristic impedance	50 ± 2 Ohm
Output connector	N-type
Cryogenic signal cables (inside cryostat)	
Pcs. / BPM	4
Cable length	210 cm
Characteristic impedance	50 Ohm ± 1 Ohm
Matching between cables within the set	± 10 ps
Characteristic capacity	200 pF ± 10pF
Insulation vacuum Feedthrough	
Flange type	NW16 CF-F (ISO/TS 3669-2)
Characteristic impedance	50 ± 2 Ohm
Vacuum-side connector	N-type
Air-side connector	N-type

In the framework of this specification, the tests of the BPM will include the integral electric test of all BPM connections and the response function measurements at warm and cold conditions [20]. The electrical integrity of the connection cables and the BPM system should also be checked using total capacity measurements and time domain reflectometry (TDR).

The BPM will be characterised by comprehensive S-parameter measurements. An integral electrical test of all BPM connections should be performed using a 4-port network analyser as follows:

- Connect the 4-port network analyser to the N-type outputs of the isolation vacuum flange
- Measure the response functions between ports 1 and 3, and ports 2 and 4 (the S31 and S42 scattering parameters)
- Moreover, measurements of the crosstalk between the orthogonal plates of the BPM should be performed (the S41 and S32 scattering parameters, and other combinations)

Figure 19 shows the assignment of the BPM feedthrough on the instrumentation flange for the straight section and arc termination QDMs type (the QDMs which are the scope of this specification)**.**

In addition, the capacitances of the BPM electrodes with respect to ground and between two adjacent electrodes must be measured. This can be extracted directly from S-parameters; therefore, no other device or test configuration is required. It is simple enough to recall the appropriate setup. The creation of the setup is described in the above section.

If the capacitance measured at any feedthrough diverges from the specified values (see Table 9), the connections of the signal pins to the feedthrough have to be rechecked and the measurements have to be repeated.

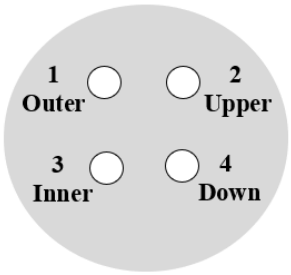


Figure 19: Assignment of the BPM feedthrough on the instrumentation flange

The RF measurements for BPM are to be finalized by the TDR measurements. These measurements should be performed using the same network analyzer with an appropriate TDR application (so called option). This step does not require the BPM to be reconnected, but only another setup file to be recalled. TDR measurements help to locate any discontinuities in the BPM signal path. Moreover, the condition of cryogenic cables and signal feedthroughs can also be judged.

Cryocollimeter/cryocatcher integrity tests

The cryocatcher module consists of the actual cryocatcher block, its support structure and a UHV chamber (see section 5.6.12.). Figure 20 shows an overview drawing of the cryocatcher module and the cryocatcher block.

The front part of the cryocatcher block is electrically insulated from the wedge part by a 4 mm thick ceramic spacer. This enables the electrical current of the lost ions hitting the cryocatcher to be measured via a cable attached to the front block. The stainless-steel cable connects the front part of the cryocatcher with the electrical feedthrough in the chamber body. The cable is surrounded by ceramic bushings to provide electrical isolation [19].

The correct cabling inside the integrated quadrupole module must be tested by measuring the capacitance of the cryocatcher, which can be extracted from Smith chart measurements. The correct cabling from room temperature (the exterior of the cryostat) to the cryocatcher block must also be

confirmed using the TDR method. Both measurements are to be performed using a network analyzer by recalling the appropriate setup. The results should be compared with those obtained in the FAT measurements and documented in the report.

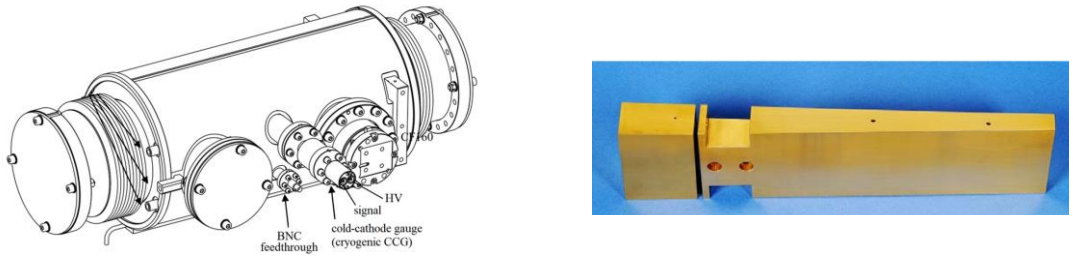


Figure 20: Left: Overview drawings of the cryocollimator (installed in QDM type 1.E)**. Right:** Picture of the cryocatcher block

Cold Cathode vacuum gauge integrity tests

The cryogenic beam vacuum system of all four module types is equipped with a cold-cathode gauge (cryogenic CCG) positioned between the quadrupole chambers to monitor the beam vacuum pressures during operation. In modules 2.123, 2.13s, and 2.4, these CCGs are mounted on an outlet flange of the drift chamber. In module 1.E, however, the CCG is mounted on the cryocatcher (see Figure 20).

To verify the correct wiring of the gauge, time-domain reflectometry (TDR) tests are required. Measurements must be taken for both the high-voltage (HV) and signal cables, using the network analyzer and an appropriate TDR application.

The integrity of the cold cathode should be tested using the time-domain reflectometry (TDR) method. Measurements must be taken for both the high-voltage (HV) and signal cables, using two ports of the network analyzer and an appropriate TDR application.

The results should be stored as plots of impedance and the reflection coefficient, expressed as a function of time. This is to be obtained by recalling two corresponding setup files.

These TDR measurements provide meaningful information about potential faults, such as:

- interchanged or mixed-up cables
- shorts to ground
- broken cables or cable screens
- squeezed cables

Any significant differences between the obtained traces and the reference traces must be reported in the form of a nonconformity report [21].

Required equipment:

- Vector Analyzer (4 ports), Frequency range 9 kHz – 4 GHz
- Time Domain Reflectometer (TDR) option for VNA
- High quality, phase-stable test cables
- Calibration-Kit (N-type, Female)

Although it is possible to use a two-port network analyzer, it is not recommended due to the necessity of frequently interchanging the connections and the increased risk of mixing up the obtained results.

In addition, a four-port E-Cal kit with N-type female connectors could significantly speed up the calibration process. However, if high-quality test cables are used, the calibration remains stable for many months and does not necessarily need to be repeated for every new measurement campaign.

5. Procedure

5.1. Kick-off Meeting

A successful project kick-off meeting between the Company and the Contractor is essential to align all stakeholders on the project goals, and execution plan. It ensures mutual understanding of the contract objectives and establishes clear operational, commercial, and communication protocols right from the start.

To ensure a successful start to the project, the kick-off agenda should include:

- **Project Objectives & Scope**: Review the technical specifications, performance requirements of facility, and exact parameters of the QDM's to be tested.
- **Execution Program:** The Contractor must present a detailed execution timeline outlining the test facility specification and storage space, tooling and device procurements, and testing phases.
- **Milestone Dates**: Agree on critical deadlines, including the Final Design Review (FDR, see Section 5.2.2), test facility acceptance test and Site Acceptance Testing of QDM (SAT, see Section 4.7).
- **Quality Assurance & Safety**: Establish the QC protocols, documentation tracking, and on-site module safety requirements.

Schedule

A detailed project time schedule (Integrated Master Schedule (IMS)) shall be prepared, including all the project review milestones. The IMS must reflect realization of the testing rate of 1QDM/month (minimum), but 2QDMs/month is desired. The schedule shall also show the project organization, including manpower, production capabilities, and a detailed material procurement plan. The schedule shall also show all the links between the project tasks and reflects the minimum testing rate to guarantee the project goals.

Project Communication / Monthly Progress Report

On a monthly basis, the Contractor shall provide the Company with an appropriate progress report and an updated project schedule that indicates activities status (started, progress, completed, late), corrective actions required, and any schedule changes. The Contractor shall also communicate on a weekly basis with the Company and its representatives to update them on the project status.

5.2. Design Phase for the Test Facility

The design of the test facility and of the measuring systems shall be done by Contractor. A conceptual design review (CDR) and a final design review (FDR) are foreseen.

5.2.1. Conceptual Design Review

The Conceptual Design Review (CDR) presents the principal design of the testing infrastructure and of all measurement systems. The following must be included:

- The testing concept, number and occupation of test benches, total time schedule
- Concept for building up or upgrading the existing cryogenic infrastructure including time and resources planning
- Piping and instrumentation diagram for the cryogenic infrastructure
- The cooling procedure and the cooling scheme of the test benches (P&ID diagram)
- The concept for installation, alignment and mechanical and electrical connections for all types of QDMs
- Parameters of existing measuring equipment, procurement plans of additional equipment for all measurement systems described in Section 4.7.
- The concept for the data evaluation and the final report generation
- Risk assessment
- The list of the main standard components and of the measuring instruments to be procured
- Concept for the quality assurance and for calibration chains
- Concept for the data acquisition
- Time schedule

5.2.2. Final Design Review and Report (FDR)

The following items must be presented in the Final Design Review [22]:

- A schedule of the facility construction
- Technical drawings of the main components
- Quality plans for the test facility construction
- List of the required equipment for operation and tests
- The calculation for the layout of the haul means (lifting bars, load handling devices, etc.)
- Project plan including time and resource planning
- Work instructions for test preparations and for execution of tests
- Templates for test reports
- Updated risk assessment
- A verification that the design complies with the Pressure Equipment Directive (PED 2014/68/EU) and other relevant standards

In case the Contractor suggests changes to the functional requirements provided by the Company, an Engineering Change Request (ECR) document shall be submitted to the Company, reflecting any single change. The Company shall reserve the right to reject any suggested change without a justification required. Any change suggested by the Contractor shall be applied only after a written approval by the Company.

5.3. Test Facility Construction Phase

Contractor's core responsibilities during the construction and procurement phase of test facility:

- The construction of the test facility and procuring all required test devices
- Purchase the necessary devices, and maintain strict, transparent communication with the Company

- Provide regular updates to the Company on how the work is advancing
- Escalate deviations and immediately notify the Company if the project veers from the agreed-upon plans or specification

5.4. Commissioning of the Test Facility

The completion of the test facility can be declared with commissioning and dedicated test of the facility to indicate the facility is functional to fulfill the QDM testing agreed timeline. The testing can be done with and without a QDM module

5.5. Test Facility Operation and Test Execution

This part of the work package includes the operation of the facility, the execution of all tests, the data analysis and the generation of the final reports. Contractor shall provide the staff needed for the operation of the test facility, execution of all tests, data analysis and for the generation of the final reports.

5.6. Tentative Timeline and Tests Completion Dates

The tentative timeline of the project is shown in Table 10.

The tentative timeline for a typical SAT is shown in Figure 21, which present the execution of the site acceptance tests corresponding to the test program described in sections 4.7.1.

Table 10: Tentative Timeline of the project

#	Item	Due Date	Responsibility
MS0	Contract signed	tbd	Contractor, Company
MS1	Kick-off meeting	2 weeks	Contractor, Company
MS2	Conceptual Design Review (CDR)	1.5 months after MSO	Contractor, Company
MS3	Final Design Review (FDR) for test facility including testing equipment	2 months after MS0	Contractor, Company
MS4	Preparation of the facility for QDM testing	2 to 7 months after MS0	Contractor
MS5	Test facility factory acceptance tests (F-FAT)	7 months after MS0	Contractor
MS6	Test facility site acceptance tests (F-SAT)	7 months after MS0	Contractor
MSS	Start of the series testing for SIS100 QDMs	7 months after MS0	Contractor
MS7	Acceptance tests on the straight section modules, 17 pieces	9 -11 months after MSS (till 08.2028)	Contractor
MS8	Acceptance tests on the arc end modules, 4 pieces	till 12.2028	Contractor
MSE	End of series testing	12.2028	Contractor

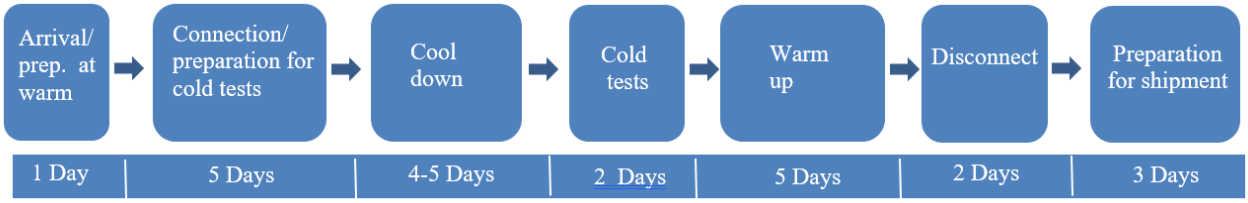


Figure 21: QDM SAT tentative timeline

6. Quality Assurance, Tests and Acceptance

6.1. Quality Assurance System of the Contractor

The basic requirements to quality assurance of the Contractor are defined by [1]. Regulations as defined by [1] must be adhered without exception.

The Contractor must prepare the quality plans for execution of tests at room and cryogenic temperatures both for the facility and QDMs. The quality plan should indicate how the required activities will be carried out, either directly or by reference to other documents (work instruction, checklists).

The Contractor will prepare templates of the test protocols and work instructions for the testing procedures described in section 4.9. The list of templates and work instructions will be fixed in the Conceptual Design Review.

All measurement equipment needed for execution of tests must have valid calibration certificates.

6.2. Factory Acceptance Test of the Facility (F-FAT)

After the physical construction of the facility has been fully completed, the Contractor executes Factory Acceptance Tests of the facility at room temperature (F-FAT).
A report with:

- High-resolution photographs showing the completed facility from multiple angles, including close-ups of critical components, shall be submitted to the Company
- Endoscopic survey of the cryogenic process lines
- Protocol of the integral leak test for the LHe- and LN2 cooling circuits of the CRYO infrastructure
- Protocol of the integral leak test regarding leak tightness of the Feed box and endbox vacuum vessel

For planning and preparation of F-FAT, the Contractor shall work through all relevant detailed specifications and technical guidelines to identify detailed requirements of F-FAT. All planning shall be based on the documentation referred to in these documents.
Also, the Contractor shall perform the development and procurement of required testing equipment

6.3. Site Acceptance Test of the Facility (F-SAT)

After acceptance of F-FAT, the test facility undergoes a Site Acceptance Test (F-SAT) to verify its thermal and operational performance. While F-FAT validates equipment baseline functionality at room temperature, a cryogenic F-SAT simulates actual operating conditions to test system integration and structural behavior under operational temperatures. The F-SAT of the facility can be done with a dedicated end-cap for the feedbox without QDM, or possibly with one of the QDMs (to

be agreed among the parties). In case of problem or non-conformity, we have to be able to localize the issue if it is from the facility or from the QDM.

The F-SAT must prove also that the relevant test equipment can conclude the acceptance of QDM with enough precision and accuracy for the obtained test data. A F-SAT report must be issued by the Contractor. Also, the Contractor declares readiness of the facility for the series QDM testing.

6.4. Series QDM Testing Phase

The Contractor is responsible to keep the facility operational and run the testing until end of the project. Preparations of the spare parts, equipment, maintenance plan, shall be reviewed in a timely manner.

7. Documentation

After finishing the SAT of each QDM the Contractor must submit:

- the test reports
- single test protocols
- raw data if required

All test results and raw data must be stored as digital data.

For the document handling, the document management system EDMS [23] will be used. The Company will provide an EDMS structure based on Component IDs (CID) of the QDM.

Contractor shall upload in EDMS all raw data files as well as the hard copies of the test reports, test protocols and filled out quality plans in PDF format.

8. Related Documents

[1] Mandatory: General Specification for the FAIR Accelerator Facility Project, F-GS-F-01e
EDMS ID: 1365092

[2] Mandatory: Detailed Specification of Cryostat Construction and Module Integration for the SIS100 Quadrupole Doublet Modules, F-DS-MT-107e
EDMS ID: 1533009

[3] Mandatory: Detailed Specification for SIS100 of the Cooling System of the Arc Termination Quadrupole Modules, F-DS-MT-83e
EDMS ID: 1532603

[4] Mandatory: Detailed Specification of the Cooling System of the Quadrupole Modules in the Straight Sections of SIS100, F-DS-MT-79e
EDMS ID: 1346794

[5] For Information: Transportation concept for QDM
EDMS ID: 1916935

[6] Mandatory: Detailed Specification for SIS100 Quadrupole Units Production, F-DS-SCM-en-MT_0152
EDMS ID: 2913884

[7] Mandatory: Common specification of the cooling system of the superconducting SIS 100 magnets, F-CS-MT-04e
EDMS ID: 1274168

[8] Recommended: DC high voltage insulation tests for SC magnets, Technical Guideline F-TG-MT-7.01e
EDMS ID: 1173079

[9] Mandatory: Pressurised Leak Testing of Cryogenic Tubing, Technical Guideline F-TG-K-7.24e
EDMS ID: 1172845

[10] Mandatory: Technical Guideline for Vacuum Testing of Complete Cryogenic Modules, F-TG-K-7.28e
EDMS ID: 1172848

[11] Mandatory: Instrumentation Lists (for 2.123 modules)
EDMS ID: 1916986

[12] Mandatory: Instrumentation Lists (for 2.13s modules)
EDMS ID: 1917026

[13] Mandatory: Drawings & 3D Model of the Straight section Modules type 2.123
EDMS ID: 1916976 (3D model)
EDMS ID: 1916977 (2D)

[14] Mandatory: Drawings & 3D Model of the Straight section Modules type 2.13s
EDMS ID: 1917017 (2D)

[15] Mandatory: Detailed specification of Bus-Bars and Voltage Taps in the SIS100 Quadrupole Modules, F-DS-MT-80e
EDMS ID: 1447831

[16] Recommended: Detailed Specification for the SIS100 Local Current Leads Heaters, F-DS-SCM-en-MT_0145
EDMS ID: 2488298

[17] Recommended: Test Instruction, Electrical Integrity Tests for Integration of SIS100 Dipole & Missing Dipole Modules into the Beamline, F-PA-SCM-en-MT_0004
EDMS ID: 3076803

[18] Mandatory: Detailed Specification of Leak Detection of UHV Components, F-TG-V-7.38e
EDMS ID: 1390813

[19] Mandatory: Detailed Specification for a SIS100 Cryocatcher Module, F-DS-SI-01e
EDMS ID: 1261923

[20] Mandatory: Detailed Specification of Cold section BPM Detector SIS100, F-DS-BD-67e
EDMS ID: 1530448

[21] Mandatory: Document template, Non Conformity Report, Q-FO-QA-0003
EDMS ID: 1503137

[22] Mandatory: Design Reviews (CDR, PDR), Q-VA-QA-0006
EDMS ID: 1514206

[23] Engineering Document Management System, https://edms.cern.ch