Title:	**Acceptance tests of the SIS100 quadrupole units**
Purpose:	This document describes details of the acceptance test of the SIS100 quadrupole units. It is an annex to the Detailed Specification for SIS100 Quadrupole Units Production F-DS-SCM-en-MT_0152.
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1. Purpose

This document describes acceptance tests of the SIS100 quadrupole units.

2. Scope

Detailed information of both Factory Acceptance Test (FAT) and Site Acceptance Test (SAT) including criteria is described. The manufacturer of the SIS100 units shall produce the deliverables successfully fulfilling the given acceptance test criteria.

3. Responsibilities

The Contractor shall execute FAT relevant tests and the Company decides on the acceptance of the deliverables. The Company executes SAT relevant tests and then decides on the acceptance and informs the Contractor.

4. Content of Tests

Tests of the SIS100 quadrupole units are classified into Factory Acceptance Test (FAT) and Site Acceptance Test (SAT).

4.1. Factory Acceptance Test

Figure 1 shows a possible production organization of the units. The cables for the quadrupole magnet and the corrector magnets are produced. The same cable is used for the coil as well as the busbars. The yokes for the quadrupole magnet and the corrector magnet are produced. The magnets are assembled with the coil and the yoke. The corrector magnet is mounted onto the quadrupole magnet. The busbars and the helium supply pipe are mounted to the quadrupole magnet.

The contractor has to structure the production process such that the contractual and technical requirements are met. The production process has to be presented to the company during the FDR. The contractor has to modify this process upon request of the Company. Changes requested by the Company do not release the contractor from the responsibility to meet contractual and technical requirements. At least each process step should be documented by a Quality Inspection and Production Plan (QIPP). The QIPP lists each task to be performed with reference to related documents (i.e. drawing, work instruction, WPS, TG), documents at least its execution, if necessary its inspection accompanying the inspection result and if needed gives reference to a test report. The referenced documents have to be available in the latest version at the production site for inspection by the production personnel at all times.

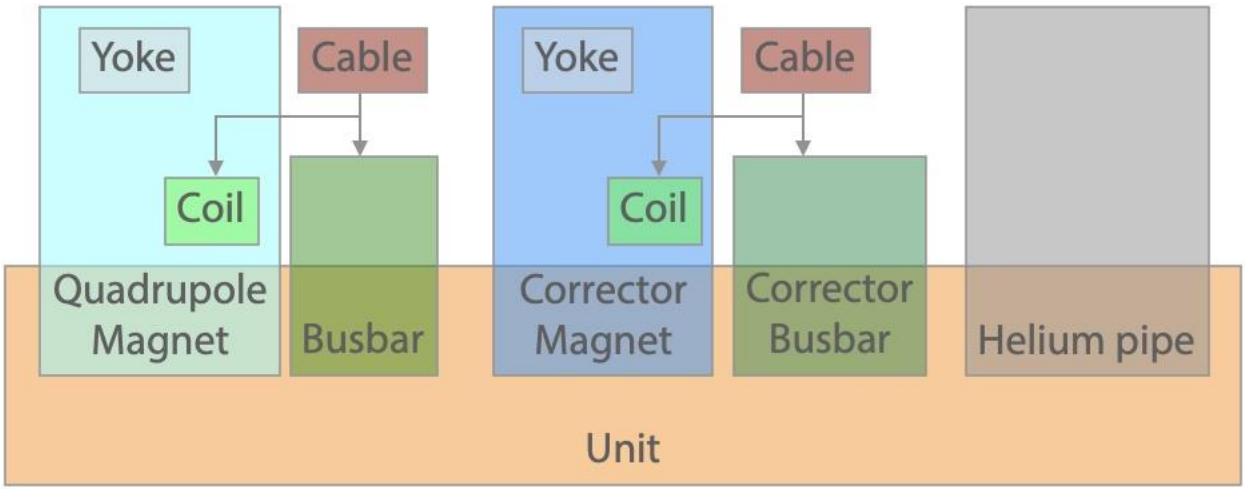


Figure 1: Schematic of a possible unit production process.

Table 1 shows a proposed list of QIPPs for the production. There are some variations for the items, for example, the quadrupole coil due to different shaping of the coil busbars. In such a case, identical QIPPs can be applied but geometrical control should be done with proper drawings.

Table 1: List of proposed QIPPs

	QIPPs for production of	Comment
Cable	Quadrupole cable	
	Corrector cable	With insulated sc 0.5 mm wire
	Low current quadruple cable	With insulated sc 0.8 mm wire
Coil	Quadrupole coil	QD: 5 types, F1: 2 types, F2: 4 types
	Steering magnet coil	Two nested coils
	Sextupole coil	
	Multipole corrector coil	Three nested coils
	Low current quadrupole coil	
Yoke	Quadrupole yoke	
	Sextupole yoke	
	Steerer yoke	
	Multipole corrector yoke	
	Low current quadruple yoke	identical lamella with quadrupole, but different length
Magnet	Quadrupole magnet	
	Sextupole magnet	
	Steering magnet	
	Multipole corrector magnet	
	Low current quadrupole magnet	
Busbar	for upstream units	12 types
	for downstream units	15 types
Unit	for upstream units	7 types
	for downstream units	10 types
Unit pair for QDM		11 types, transport preparation

The tests are categorized into visual inspection, geometrical inspection, electrical test, leak and pressure, mass flow tests, and magnetic tests. Table 2 shows the necessary tests for each production step. Visual inspection shall be done for the material used in the production step and after the completion of the production step.

Table 2: Production steps and the test categories

production of		visual	geometry	electrical	leak, pressure, mass flow	magnetic
Cable	material	×			×	
	completion	×	×			
Coil	material	×	×			
	completion	×	×	×		
Yoke	material	×				
	completion	×	×			
Magnet	material	×				
	completion	×	×	×		
Busbar	material	×				
	completion	×	×			
Unit	material	×	×			
	completion	×	×	×	×	×

4.1.1. Geometrical inspections

The Contractor shall produce the parts and assemblies within the dimensional tolerances specified in the drawings. The Contractor shall check all dimensions in general, and particularly the following dimensions must be reported.

Crucial dimensions for the magnetic field quality:

- The magnetic field quality is defined by the geometry of the coil and the magnetic yoke, as well as the relative position between the coil and the yoke. Therefore, the dimensions must be precisely measured with appropriate calibrated tools according to the given tolerances.
- For instance:
  - Yoke: length, packing factor, inner profile
  - Coil: length, coil cross section size
  - Assembly: coil position in the yoke (x, y, z), neighbouring parts (connection flanges etc.).

Interface positions:

- The quadrupole units will be integrated into a quadrupole doublet module cryostat together with other components like a beam position monitor. Therefore, positions of the interfaces shall be controlled before the shipment. In the cryostat the component must be assembled very closely with very limited space margins. Outer dimensions must also be well controlled.
- Examples:
  - Electrical connections: main busbar connection part, local current lead cold terminals
  - Hydraulic connections: helium supply pipes positions, length
  - Mechanical connection: contact surface of the quadrupole magnet yoke (e.g. the reference surfaces, or connection to the corrector magnets or Beam position monitor), reference holes at the connection flanges
  - Beam chamber interface position
  - Collision with cryostat thermal shield
- A mechanical template for position checks is helpful to avoid mechanical collisions in later quadrupole doublet module assembly process.

Check-sizes

- Check-sizes are defined in the drawings.
- The contractor shall confirm that the check-sizes are kept within the specified tolerances and submit measurement protocols.
- The protocol must include indication of the location of the measured dimension in the drawing.
- The protocol must include nominal dimension/value and the tolerance, as well as the measured value and judgement if it meets the specified tolerance.
- An example of the protocol template and related drawings is given in Unit-Production-CheckSizes.pdf (see Sect. 5).
- Details of the reporting template must be agreed with the Company.

4.1.2. Material properties

Critical material properties, such as the magnetic permeability of the metal used for yoke production, shall be measured before production (during incoming inspection) and after critical production processes such at heat treatment or welding.

4.1.3. Electrical tests

4.1.3.1. High and low voltage tests

Dielectric strength of the insulation of the magnet powering circuit including the voltage taps shall be tested against ground and other powering circuits. The insulation of temperature sensor as well as MID strand insulation shall be tested against ground and other electrical circuits as well. Since many conductive parts around the target circuits exist, grounding must be carefully done.

Figure 2 shows some relevant parts for electrical test. Table 3 shows general condition of the testing. In the QIPPs and the test report, the variation of the units, e.g. the number of corrector magnet circuits etc. must be properly reflected. During the testing, ambient temperature and relative humidity must be recorded.

For the corrector wires the individual wire's insulation is checked after coil production. Each wire must be tested against the cooling tube and against the neighbouring wires.

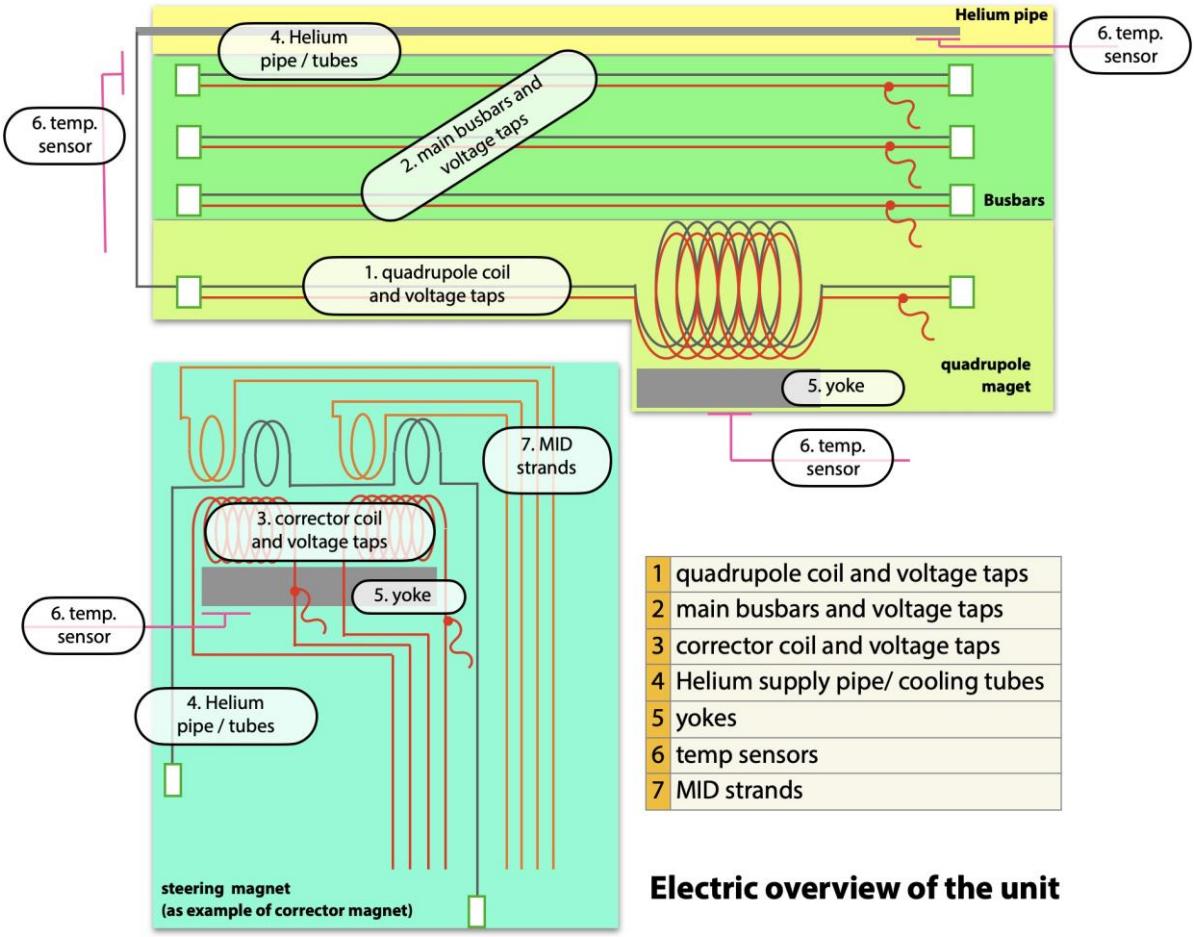


Figure 2: Schematic overview of electric situation of the unit. Only one corrector magnet (steering magnet) is indicated. Its terminal box and cold terminals have been omitted for clarity.

Table 3: HV and LV test conditions and criteria. Test conditions are at ambient temperature and pressure.

	HV test				LV test
	Quadrupole coil	Main busbar	Corrector magnet	MID strand	Sensor
When	–	–	coil completion (w/o TB, neighbouring wires, see Sect.4.1.3.4)	coil completion (w/o TB, neighbouring wires, see Sect. 4.1.3.6)	–
	coil completion	–	magnet completion (w/o epoxy, wire connected)	magnet completion (w/o epoxy, wire connected)	–
	magnet completion	–	magnet completion (w epoxy)	magnet completion (w epoxy)	–
	unit completion	unit completion	unit completion	unit completion	unit completion
Positive	Quadrupole coil and voltage taps	Main busbars and voltage taps	Corrector coil and voltage taps	MID strand	Sensor
Step					
1	0.6 kV for 1 min.	0.6 kV for 1 min.	200 V for 1 min.	200 V for 1 min.	50 V / 100 V for 1 min.
criteria	R_{ins} > 1 GΩ	R_{ins} > 1 GΩ	R_{ins} > 1 GΩ	R_{ins} > 1 GΩ	R_{ins} > 100 MΩ
2	1.5 kV for 1 min.	1.5 kV for 1 min.	600 V for 1 min.	600 V for 1 min.	–
criteria	R_{ins} > 1 GΩ	R_{ins} > 1 GΩ	R_{ins} > 1 GΩ	R_{ins} > 1 GΩ	–
3	3.0 kV for 2 min.	3.0 kV for 2 min.	1100 V for 2 min.	1100 V for 2 min.	–
criteria	R_{ins} > 1 GΩ	R_{ins} > 1 GΩ	R_{ins} > 1 GΩ	R_{ins} > 1 GΩ	–
Negative (ground)	–	Quadrupole coil and voltage taps	Quadrupole coil and voltage taps	Quadrupole coil and voltage taps	Quadrupole coil and voltage taps
	Main busbars and voltage taps	Other main busbars and voltage taps	Main busbars and voltage taps	Main busbars and voltage taps	Main busbars and voltage taps
	Corrector coil and voltage taps	Corrector coil and voltage taps	Other corrector coil and voltage taps	Corrector coil and voltage taps	Corrector coil and voltage taps
	cooling pipe/tubes	cooling pipe/tubes	cooling pipe/tubes	cooling pipe/tubes	cooling pipe/tubes
	–	–	terminalbox frame	terminalbox frame	–
	yoke	yoke	yoke	yoke	yoke
	MID strands	MID strands	MID strands	Other MID strands	MID strands
	temp sensors	temp sensors	temp sensors	–	Other sensors
Floating	–	–	–	temp sensors	–

4.1.3.2. Impedance test

The impedance of the coil shall be measured before and after assembly with the magnetic yoke. The measurement shall be done with a LCR-meter with an accuracy of 0.2% or better. The following parameters shall be protocolled:

- DC Resistance of the coils, DC resistance of the main busbars
- Inductance of the coils measured at 100 Hz and at 1 kHz
- Inductance of the magnet (coil + yoke) at 100 Hz and at 1 kHz

This applies to both quadrupole coil and corrector coils. For reference, the results need to agree within 1 % for all produced units.

Table 4: Impedance test conditions

	Impedance test	
	Quadrupole coil	Corrector coil
When	coil completion	coil completion (w/o. TB, single wire)
	–	magnet completion (TB w/o. epoxy, wires connected)
	magnet completion	magnet completion (w. epoxy)
	unit completion	unit completion
100 Hz	resistance	resistance
	inductance	inductance
	quality factor *Q*	quality factor *Q*
	tan *δ*	tan *δ*
1000 Hz	resistance	resistance
	inductance	inductance
	quality factor *Q*	quality factor *Q*
	tan *δ*	tan *δ*

4.1.3.3. Test of inter-turn insulation

The turn-to-turn insulation will be checked by a capacitor discharge. A reference curve needs to be defined at the first unit of production. The measurement device needs to be chosen to provide a reasonable signal curve with at least five significant oscillations.

Criteria: check of the oscillation curve, which should not be distorted and consistent with reference curve as well as one from the other coils. The oscillation frequency per magnet needs to be constant for all applied test voltages.

Table 5: Capacitor discharge test

	Capacitor discharge test	
	Quadrupole coil	Corrector coil
When	coil completion	–
	magnet completion	magnet completion (TB w. epoxy, wires connected)
Apply	1 kV	200 V
	2 kV	600 V
	3 kV	1100 V
Report	Oscillation frequency	Oscillation frequency
	Q-factor	Q-factor
	Coil voltage curve	Coil voltage curve
	Coil current curve	Coil current curve

4.1.3.4. Test of wire-to-wire insulation for corrector coils

This applies only for corrector coils. The wire-to-wire insulation shall be measured individually for each pair of the neighbouring wires at the following test voltages: 200 V, 600 V and 1100 V. The cooling tube and all other wires shall be grounded.

Besides the insulation resistance between neighbouring wires, the insulation between each wire and the cooling tube shall be measured at voltages of 200 V, 600 V and 1100 V. All other wires shall be grounded. Those tests must be done before installation of the terminal box.

4.1.3.5. Voltage taps continuity & order test

Voltage taps are attached to the live circuits (coil and busbars) to pick up the voltage signal of a quench event. Therefore, it must be ensured that the voltage taps are properly connected to the live circuits. In addition, the order of the voltage taps on the connectors and the live circuit is crucial for quench detection and must be verified.

The test needs to be performed after the unit assembly (including the voltage tap connectors). For the quadrupole magnet circuit (coil and busbars are electrically connected for the test) a DC current of 5 A is supplied from busbar and to the coil. The voltage drop from upstream to downstream at each voltage tap shall be measured, protocolled and compared to reference values.

The presence and the correct order of voltage taps for the corrector magnets shall be done at 200 mA. The voltage drop from upstream to downstream at each voltage tap shall be measured, protocolled and compared to reference values.

Criteria: voltage tap is attached with low impedance and the order is correct.

4.1.3.6. Corrector wire continuity test

The insulated wires in the corrector cable require proper tests. The individual wire's insulation is checked after coil production as described in Sect. 4.1.3.4. After that, most of the wires are connected in series, the others are used for Mutual Inductance Detection (MID). The order of the wire connections and presence of the MID wire must be checked by a resistance measurement.

The polarity of the MID wire must be checked by analysing the phase of signal voltage in MID wire due to mutual inductance with the corrector coil circuit powered with AC (e.g. 10 V, 6 kHz).

Criteria: corrector wires are connected properly and the MID wires are present showing correct polarity.

4.1.3.7. Temperature sensor alive test

Cernox sensors are installed in the units. From the four-wire-measurements, the resistivity and the calculated temperature from the calibration data shall be recorded.

Thermocouple sensor temperature should be read out with a properly compensated meter.

Criteria: Presence of the sensors indicating ambient temperature within ±3 K.

4.1.4. Leak tests

After the final assembling of the quadrupole unit, an integral leak rate shall be measured. For this test, the unit must be placed in a vacuum vessel connected to the leak detector. The helium circuit of the unit must be filled with helium according to DIN EN 1779 testing procedure B6. The integral leak rate must not exceed 1·10-10 mbar/(l*s). This test shall be included in the FAT.

Besides, another leak test must be performed at least at following production steps:

- before cable production: incoming test of CuNi tube
- after coil and bus bar production
- leak tests of the yoke cooling tubes after yoke production

The test procedure and results shall be recorded and submitted to the Company.

4.1.5. Pressure test according to the Pressure Equipment Directive

The tests according to the Pressure Vessel Code AD2000 must be performed for each quadrupole unit. As a general rule this test is a part of FAT. However, this test must be repeated in case of any repairs on the pressure-loaded piping of the quadrupole unit also after adjustment of the flow restrictors.

According to AD2000 – HP30 the test pressure for the quadrupole units is the design pressure (20 bar) multiplied by 1.43. The applied test pressure must be ramped up slowly in steps (i.e. 3bars), each pressure level should be retained for at least 5 minutes; the final pressure has to be retained for 30 minutes.

The test procedure and results shall be recorded and submitted to the Company.

4.1.6. Mass flow rate test

After assembling the quadrupole unit, a test of the mass flow rate shall be performed according to the technical guideline F-TG-K-7.26e “Flow Rate Test for Cryogenic Processing Pipes”. For this test, nitrogen or dry air shall be used at $\Delta P = 0.1 – 0.2$ bar.

The test procedure and results shall be recorded and submitted to the Company.

4.1.7. Magnetic test

The magnet polarity must be checked at warm condition. For corrector magnets, the polarity test must be done after mounting of the cold terminals.

Criteria: correct polarity of the magnet when a current is supplied with proper polarity direction.

4.2. Site Acceptance Test

Site Acceptance Test (SAT) is executed by the Company. The following list of tests and criteria is non exhaustive and given only for information. The company is free to verify the conformity to all aspects defined by the drawings and the specifications by additional tests.

For the SAT at least all FAT acceptance tests can be repeated. The HV and LV test must be performed at ambient temperature and pressure, at ambient temperature and under vacuum, and at operating temperature (4 K) and under vacuum. In addition, the performance of the unit at 4 K will be tested and verified.

Any non-conformity can lead to a rejection of the unit as a whole.

4.2.1. Unit performance

4.2.1.1. Magnet powering & training test

The magnets shall be excited with the following powering tests:

- Training test:
  - The magnet shall reach the ultimate current in at least one cycle with slower ramp rate. From there the ramp rate is increased until nominal is reached.
  - In case of a quench, the quench current and number of the quench are recorded.
  - Criteria: More than 5 quenches under the same conditions is judged as non-conformity.
- Cycling test:
  - The magnet is subjected to continuous cycles up to the nominal ramp-rate and the nominal current for 10 minutes each.
  - The inductance of the magnets shall be recorded (from voltage and current).
  - In case of a quench, the quench current and number of the quench are recorded.
  - Criteria: no quench.
- Endurance test:
  - The magnet is subjected to a continuous DC current for 10 min.
  - In case of a quench, the quench current and number of the quench are recorded.
  - Criteria: no quench.

For the corrector magnets, the polarity of the current, combination of powering in case of a nested magnet (horizontal and vertical coil of the steering magnet; quadrupole, sextupole and octupole coil of the multipole corrector magnet) must be specified.

Table 6: Magnet powering test

	Powering test	
	Quadrupole magnet	Corrector magnet (bipolar)
	4 K cryogenic condition	4 K cryogenic condition
Training test		
Ramp rate	20-22000 A/s	10-1225 A/s
Max. current	11600 A	275 A
Plateau	3 s	3 s
Report	Quench current, number of quenches	Quench current, number of quenches
Cycling test		
Ramp rate	200-22000 A/s	10-1225 A/s
Max. current	10500 A	250 A
Rounding time	20-50 ms	20-50 ms
For	10 min.	10 min.
Report	Inductance Quench current, number of quenches	Inductance Quench current, number of quenches
Endurance test		
Max. current	10500 A	250 A
For	10 min.	10 min.
Report	Quench current, number of quenches	Quench current, number of quenches

4.2.1.2. Hydraulic adjustment

The length of the flow restrictor must be adjusted in order to establish a helium mass flow rate needed for a reliable cooling of the quadrupole and corrector magnets in each operating mode of the SIS100.

The SAT program includes a checking of cooling conditions for each unit. For this test, the pressure drop of the cooling helium will be set to 0.55 bar and all magnets will be simultaneously ramped in the reference cycle. The helium outlet temperature shall be in the range 5.5 ± 0.5 K. If the temperature is not within the range, the length of the flow restrictor must be adjusted and the cold test must be repeated.

In general, the correction of the restrictor length is needed only for the first of each new unit type.

4.2.1.3. Heat load measurement

The heat load under static and dynamic conditions must be measured. In case of the dynamic heat load measurements, the magnet shall be powered with the cycle specified in Table 7. Both cases of powering the single quadrupole magnet and all magnets of the unit shall be measured.

Table 7: Magnet powering cycle for unit dynamic heat load test

	Heat load test	
	Quadrupole magnet	Corrector magnet
	4 K cryogenic condition	4 K cryogenic condition
Ramp rate	21000 A/s	1225 A/s
Min. current	1300 A	0 A
Max. current	10500 A	250 A
Rounding time	20-50 ms	20-50 ms
For	30 min.	30 min.
Report	Observed parameters: temperatures, pressure drop, mass flow calculated heat load	

4.2.1.4. Leak test

During SAT, the pressure drop test according to DIN EN 1779, procedure D1 will be performed before cold testing of the unit. For this test, the helium circuit of the unit will be pressurized up to P = 20 bar. During cold testing, the integral leak rate will be measured before cool down, at cryogenic conditions and after warming up. Those tests will be performed with the unit installed in the testing cryostat.

4.2.1.5. Magnetic measurement

The magnetic field quality shall be evaluated.

- The main multipole component of the integral magnetic field ($T/m^{n-1} * m$).
- The main multipole component of the magnetic field at the centre of the magnet (T/m^{n-1}).
- The effective magnetic length (m) calculated from the above measurements.
- The Multipole (up to n = 12) magnetic field coefficients w.r.t the main field strength (B [T] at a reference radius of 40 mm.

The required magnetic field and quality will be realised if the Contractor produced the magnets in accordance to the GSI specified material and within the mechanical tolerances given. In case a large discrepancy between the measured magnetic field and the expected is observed, the Company and the Contractor will perform a root cause analysis and agree on the mitigation.

5. Related documents

Type	Mandatory/ Recommen-dation	Document ID	title	about	EDMS-ID
General in-formation	R	Unit-Produc-tion-CheckSizes	Check-size (Prüfmaße) of SIS100 unit production	general information	2913884