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Document Title:	<b>Solenoidsystem of GHIISI</b>
Description:	This document describes the detailed specifications of the solenoid system of the new ECR ion source GHIISI
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## Abstract

This document describes the detailed specifications of the solenoids of the new  
Electron Cyclotron Resonance Ion Source GHIISI at GSI


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## 1. Purpose and Classification of the Document

The GSI ion source group is designing a new ECR ion source, GHIISI, whose plasma will be heated by microwaves via the electron cyclotron resonance process. The heating of plasma will be realized by using an 18 GHz microwave frequency. The adequate plasma heating and confinement require a certain magnetic field configuration being a superposition of hexapole and solenoid magnetic fields to obtain a so-called minimum-B magnetic field configuration. The maximum magnetic field values and correct gradients at critical points of the ion source play a crucial role. The magnetic system to achieve the longitudinal magnetic confinement includes the injection solenoid (Solenoid 1), middle solenoid (Solenoid 2), extraction solenoid (Solenoid 3), low carbon steel yoke, low carbon steel blanks and terminals for solenoid currents and cooling water and three (3) high-current power supplies to produce the current needed by the coils to generate the solenoid magnetic field required by the plasma heating. In order to guarantee safe and stable plasma confinement at 18 GHz a proper mirror field with a magnetic flux density along the longitudinal axis of the solenoids of at least  $B=2.8$  T at injection (Solenoid 1) and at least  $B=1.5$  T at extraction (Solenoid 3) must be achieved. An optimal minimum-B configuration is obtained with a minimum magnetic flux density along the longitudinal axis of the solenoids lower than  $B=0.45$  T (Solenoid 2). This document describes the detailed specification for the solenoids belonging to the above-described system.

The contracting body for the equipment described in this document is "GSI Helmholtzzentrum für Schwerionenforschung GmbH (GSI)". So, all further references to the term 'the Customer' will refer to GSI.

## 2. Abbreviations, Terms and Definitions


ECR	Electron Cyclotron Resonance
ECRIS	Electron Cyclotron Resonance Ion Source
FAIR	Facility for Antiproton and Ion Research
FAT	Factory Acceptance Test
GSI	GSI Helmholtzzentrum für Schwerionenforschung GmbH
GHIISI	GSI Heavy-Ion Ion Source Injector
SAT	Site Acceptance Test
CDR	Conceptual Design Review
FDR	Final Design Review

**Table Fehler! Kein Text mit angegebener Formatvorlage im Dokument.-1: List of Abbreviations**

## 3. Scope of the supply

A new ECR ion source, GHIISI, is under development in GSI, whose plasma will be heated by microwaves via the electron cyclotron resonance process. The heating of plasma will be realized by using 18 GHz or/and 14 GHz microwave frequency depending on the ion beam requirements. An adequate plasma heating and confinement requires a certain magnetic field configuration being a superposition of hexapole and solenoid magnetic fields.

The scope of the supply is to assemble, test, and deliver the solenoid system for the longitudinal magnetic field for the plasma confinement based on built-to-print drawing. The parts of the solenoid assembly are summarized in the following table


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The overall solenoid and low carbon steel yoke geometry is presented in drawing IQU\_ISI PC1.160.000b\_solenoidsystem. It consists of injection solenoid (Solenoid 1: IQU\_ISI PC1.161.000\_solenoid 1), middle solenoid (Solenoid 2: IQU\_ISI PC1.162.000\_solenoid 2), extraction solenoid (Solenoid 3: IQU\_ISI PC1.163.000\_solenoid 3) and yoke parts together with the water and current feedthroughs. The offer has to include also blank steel material for in-house machining.

The offer has to include data showing the experimental BH curve of offered low carbon steel, in particular showing the value at  $H \approx 24$  kA/m (preferably up to 100 kA/m). If the data is not available at 24 kA/m the B value can be given at lower H-field. In this case, the minimum requirement has to be met at this lower data point.

Item №	PC Description	Drawing	№ of PCs
1	Solenoid Injection made of 7 double wound double Pancakes and iron yoke	IQU_ISI PC1.161.000_solenoid 1	1
1	Solenoid Middle made of 3 double wound double Pancakes	IQU_ISI PC1.162.000_solenoid 2	1
1	Solenoid Extraction made of 7 double wound double Pancakes and iron yoke	IQU_ISI PC1.163.000_ solenoid 3	1
1	Blank low carbon steel material	IQU_ISI PC1.127.001_BLANK_outer injection iron 1 (4) IQU_ISI PC1.127.005_BLANK_outer injection iron 5 (2) IQU_ISI PC1.142.001_BLANK_inner injection iron (3) IQU_ISI PC1.150.001_BLANK_iron flange (2) IQU_ISI PC1.152.001_BLANK_extraction electrode iron (3)	14
1	Coil current terminals	IQU_ISI PC1.161.010_coil current inlet terminal (6) IQU_ISI PC1.161.013_coil current connector terminal (3) IQU_ISI PC1.161.014_coil current connector terminal 2 (3) IQU_ISI PC1.161.012 current connector (2) IQU_ISI PC1.162.003 current connector short (1)	15
1	Cooling water terminals	IQU_ISI PC1.161.011_coil coupling	28
1	Middle Block	IQU_ISI PC1.162.001_middle block	6
1	Pressing Plate	IQU_ISI PC1.162.002_pressing plate	6

**Table 3-2: Scope of the supply**

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#### 4. Technical specification

Injection solenoid, middle solenoid and extraction solenoid consist of 7, 3 and 7 double wound, double pancakes, respectively, each pancake having 2 x 20 turns. The magnetic properties of low-carbon steel play an important role. The BH curve requirement of the offered low-carbon steel is presented in the section below. The dimensions and tolerances of each component are presented in the enclosed drawings. All requirements regarding the tolerances and dimensions defined in the drawings have to be met. The pancakes of the injection solenoid and the extraction solenoid have to be assembled into the yoke structure to form complete solenoids (see IQU\_ISI PC1.161.000\_solenoid 1 and IQU\_ISI PC1.163.000\_solenoid 3). The maximum dimensions reserved for pancakes in radial and axial directions are not allowed to exceed. In the application, the axis of the solenoids is in horizontal orientation and pancakes will be exposed to strong magnetic forces and consequently, the movement of pancakes inside the yoke has to be prevented.

Double-wound double pancakes are required to guarantee adequate cooling. The GSI infrastructure provides the cooling water pressure of 12 bars for inlet cooling water and 2 bars for outlet cooling water (i.e. pressure difference  $\Delta P$  of inlet-outlet water 8 bar). The temperature of the inlet water is 20°C and the cooling water temperature rise (T) of higher than 30 K is not allowed when the pancakes are excited using the current of 1000 A. The rectangular copper conductor of 11 x 11 mm having a water passage aperture of 5.5 mm (in diameter) was selected (rounding of corners:  $r = 1$  mm). Using the afore-mentioned values for the selected conductor the power consumption of complete injection and extraction solenoid is  $\leq 91$  kW each when the afore-mentioned current is used (and when temperature dependence of resistivity has been taken into account. An average  $\Delta T$  of 15 K has been assumed). In operation, a nominal current of 1100 A (1210 A maximum) for solenoid 1 and 3 and of 600 A (660 A maximum) for solenoid 2 is expected to go through each conductor. The pancakes have to form a series circuit (i.e. the current up to 1210 A from the power supply goes through each circuit.). The circuit/loop of solenoid 1 and solenoid 3 have the same current direction and the circuit/loop of solenoid 2 has an opposite one to achieve the minimum-B magnetic field configuration fundamental for the plasma stability of the ion source. The total current through the cross-section reserved for pancakes is not allowed to be lower than (1210A x 7 x 2 x 20) 339 kA-turns. At the same time the total power consumption of injection solenoid (Solenoid 1) and extraction solenoid (Solenoid 3) is not allowed to exceed 91 kW when the pancakes are excited using the current of 1000 A and the cooling water temperature rise is not allowed to exceed 30 K (temperature dependence of resistivity included).


The supplier will provide the built-to-print technical drawings of all pieces to be manufactured. The supplier guarantees that the solenoid system will meet the magnetic field requirements specified in Section 1 when operated at the nominal currents of the respective solenoids.

#### 4.1 Technical requirements for components of the solenoid assembly:

##### Pancakes:

The offer has to include double wound double pancakes defined as follows:

- 1) Total number of double wound double pancakes: 17 (sets 7, 3 and 7).
- 2) Copper conductor: Oxygen-free, high conductivity copper (conductivity at 20°C  $\geq 5.8 \times 10^{-7} (\Omega m)^{-1}$ ). Drawing IQU\_ISI PC1.161.001\_coil pancake 1 shows the dimension of the conductor.

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- 3) Geometry/dimensions of the double wound double pancake: The dimensions (thickness, inner/outer radius), tolerances, and number of turns (2 x 20 turns) are presented in Drawing IQU\_ISI PC1.161.001\_coil pancake 1.
- 4) Assembly of pancakes: Pancakes have to be divided into 3 sets: Solenoid 1 (7), Solenoid 2 (3) and Solenoid 3 (7) number of pancakes in the solenoid presented in the parenthesis.

The offer includes the assembly of the pancakes in the following way:

- Solenoid 1 and Solenoid 3 (IQU\_ISI PC1.161.000\_solenoid 1 and IQU\_ISI PC1.163.000\_solenoid 3): The pancakes (7) have to be assembled inside the low carbon steel yoke to form complete Solenoid 1 and Solenoid 3. The maximum dimensions reserved for pancakes are not allowed to exceed. The pancakes are not allowed to move inside the yoke structure (epoxy can be used to prevent the moving).
- Solenoid 2 (IQU\_ISI PC1.162.000\_solenoid 2): this solenoid includes 3 pancakes. Does not include a yoke structure. Radial dimensions are the same as for Solenoid 1 and Solenoid 3. The height of 3 pancakes, including the encasing epoxy, (forming Solenoid2) is not allowed to exceed 77 mm when assembled on a flat base.

NOTE: Parts IQU\_ISI PC1.161.005\_yoke part 3 (in Solenoid 1) and IQU\_ISI PC1.163.001\_yoke part 4 (in Solenoid 3) have to be removable for dimensional inspection and machining (if later B-grad optimization is needed).

### **Manufactured low-carbon yoke steel parts:**

The dimensions and tolerances of each part have been presented in the drawings. The offer has to include manufacturing of the following parts:


- 1) IQU\_ISI PC1.161.003\_yoke part 1: Minimum requirement for steel: 1.97 T at 24 kA/m.
- 2) IQU\_ISI PC1.161.004\_yoke part 2 (2 pieces): Minimum requirement for steel: 1.97 T at 24 kA/m (Note offered quality points).
- 3) IQU\_ISI PC1.161.005\_yoke part 3: Minimum requirement for steel: 1.97 T at 24 kA/m.
- 4) IQU\_ISI PC1.163.001\_yoke part 4: Minimum requirement for steel: 1.97 T at 24 kA/m.
- 5) IQU\_ISI PC1.163.002\_yoke part 5: Minimum requirement for steel: 1.97 T at 24 kA/m.
- 6) IQU\_ISI PC1.163.003\_inner yoke part 5: Minimum requirement for steel: 1.97 T at 24 kA/m.

Quality points will be given if low carbon yoke steel material with higher magnetic flux density at 24 kA/m will be used.

### **Blank low-carbon steel material for in-house machining:**

The offer has to include the following blank material parts:

- 1) IQU\_ISI PC1.127.001\_ BLANK\_outer injection iron 1 (4 pieces): Minimum requirement for steel: 1.97 T at 24 kA/m.
- 2) IQU\_ISI PC1.127.005\_ BLANK\_outer injection iron 5 (2 pieces): Minimum requirement for steel: 1.97 T at 24 kA/m.
- 3) IQU\_ISI PC1.142.001\_ BLANK\_inner injection iron (3 pieces): Minimum requirement for steel: 1.97 T at 24 kA/m.

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- 4) IQU\_ISI PC1.150.001\_ BLANK\_iron flange (2 pieces): Minimum requirement for steel: 1.97 T at 24 kA/m.
- 5) IQU\_ISI PC1.152.001\_ BLANK\_extraction electrode iron (3 pieces): Minimum requirement for steel: 1.97 T at 24 kA/m.

Quality points will be given if low carbon yoke steel material with higher magnetic flux density at 24 kA/m will be used.

### Painting of yoke parts:

- 1) The offer includes the painting according to the technical guidelines related to the colors of magnets at GSI (F-TG-S 5.2\_Farbgebung\_Magnete\_und\_Gestellte\_V1\_1):  
2 Times Epoxy Painting, glossy, color RAL5018.

### Terminals:


- 1) The offer has to include the terminals for the cooling water and current as follows:
  - Cooling water terminals with the specified threads for Solenoid 1, Solenoid 2 and Solenoid 3 have to be manufactured and soldered (one solution is presented in the drawing: IQU\_ISI PC1.161.011\_coil coupling Swageloks shown in the drawing are excluded).
  - Current terminals (soldered) for Solenoid 1, Solenoid 2 and Solenoid 3 (one solution is presented in the drawings: IQU\_ISI PC1.161.010\_coil current inlet terminal, IQU\_ISI PC1.161.013\_coil current connector terminal, IQU\_ISI PC1.161.014\_coil current connector terminal 2, IQU\_ISI PC1.161.012 current connector and IQU\_ISI PC1.162.003 current connector short).
- 2) The current inlet-outlet has to be realized through the outer yoke parts (IQU\_ISI PC1.161.004\_yoke part 2). The drawing represents the maximum volume of low-carbon steel that is allowed to be cut from parts IQU\_ISI PC1.161.004\_yoke part 2 (for feed-throughs of pancakes). Quality points will be given if smaller cutting (in volume) can be realized.
- 3) The pancakes have to form a series circuit (i.e. the current up to 1210 A from the power supply goes through each circuit.). The circuit/loop of solenoid 1 and solenoid 3 have the same current direction and the circuit/loop of solenoid 2 has an opposite one to achieve the minimum-B magnetic field configuration fundamental for the plasma stability of the ion source.

## 5. Realization process of the system, FAT und SAT

The realization process of the specified systems consists of the following phases:

- Design development and preparation of the production:
  - Design development;
  - Conceptual Design Review (CDR);
  - Creation of manufacturing documents;
  - Final Design Review (FDR).
- Production of the systems, FAT and shipping;
- Installation, commissioning and testing at the Company site (SAT).



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## 5.1 Test assembly and Factory Acceptance Test (FAT) at supplier:

- 1) Test assembly has to be performed as presented in IQU\_ISI PC1.160.000b\_solenoidsystem. The tube having outer diameter of 290 mm has to fit into the solenoid assembly as is presented in the drawing (when IQU\_ISI PC1.163.003\_inner yoke part 5 was dismantled).

**NOTE:** The test assembly (to test the adequate alignment of solenoids) can be realized with the axis of the solenoids in vertical orientation.

- 2) Insulation test of Solenoid 1 and Solenoid 3: conductor to the ground (complete yoke) using 2 kV DC. Current leak less than 20  $\mu$ A. Leak test of Solenoid 2 pancakes. Conductor to ground plate (both sides of pancake)
- 3) Hydraulic leak test for Solenoid 1, Solenoid 2 and Solenoid 3 using pressure of  $\geq 12$  bar (time  $\geq 10$  min).
- 4) Water flow measurement at  $\Delta P = 6$  bar. The water flow (at 20°C) through each double wound double pancake has to exceed 7,3 l/min.
- 5) Electrical resistance at 20°C for Solenoid 1, Solenoid 2 and Solenoid 3: The measured resistance value  $R_{mes}$  (at 20°C) has to confirm that the calculated electric power consumption  $P$  of complete Solenoid 1 and Solenoid 3 will not exceed 91 kW when the current of  $I = 1000$  A is used ( $P = R_{mes}I^2$ ). Solenoid 2 has to have an equivalent resistance value/double wound double pancake.
- 6) 3D Mapping (longitudinal axis included) of the magnetic system for three different combinations of current levels provided to solenoid1, solenoid2 and solenoid3, respectively: 1100A-660A-1100A, 90%-90%-90%, 80%-80%-80%
- 7) Thermography for three different combinations of current levels provided to solenoid1, solenoid2 and solenoid3, respectively: 1100A-660A-1100A, 90%-90%-90%, 80%-80%-80%

## 5.2 Site Acceptance Test (SAT):

- 1) 3D Mapping (longitudinal axis included) of the magnetic system for three different combinations of current levels provided to solenoid1, solenoid2 and solenoid3, respectively: 1100A-660A-1100A, 90%-90%-90%, 80%-80%-80%
- 2) Geometrical and technical inspection including tolerances verification
- 3) Thermography for three different combinations of current levels provided to solenoid1, solenoid2 and solenoid3, respectively: 1100A-660A-1100A, 90%-90%-90%, 80%-80%-80%