FIRST HIE-ISOLDE CRYO-MODULE ASSEMBLY AT CERN

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Abstract

The first phase of the HIE-ISOLDE project aims to increase the energy of the existing REX ISOLDE facilities from 3 MeV/m to 5 MeV/m. It involves the assembly of two superconducting cryo-modules based on quarter wave resonators made by niobium sputtered on copper. The first cryo-module was installed in the linac in May 2015 followed by the commissioning. The first beam is expected for September 2015. In parallel the second cryo-module assembly started. In this paper, we present the different aspects of these two cryo-modules including the assembly facilities and procedures, the quality assurance and the RF parameters (cavity performances, cavity tuning and coupling).

INTRODUCTION

The HIE-ISOLDE project consist in an increase of the beam energy and intensity of the existing ISOLDE and REX-ISOLDE. This upgrade requires the integration of the existing post acceleration system with a superconducting linac of four high-β (phase 1 and 2) and two low-β (phase 3) cryo-modules (CM) based on quarter wave SRF cavities. The cryo-modules will have to work at 4.5 K in a common vacuum (cavity vacuum and insulation vacuum are the same).

The first phase (CM1 and CM2) started in August 2014 with the assembly of the first HIE-ISOLDE cryo-module (CM1) which was completed in April 2015 and installed on the HIE-ISOLDE beam line in May 2015. CM1 is under full functional testing (vacuum, cool down, cavity alignment, RF conditioning and test) [1].

In parallel, for the second cryomodule, the production of cavities continued and the parts preparation was launched in early April. An upgrade of the tooling and assembly facilities was done. The assembly of the second cryo-module started in June 2015.

THE CRYOMODULE ASSEMBLY

The complete high-β cryo-module assembly (see Fig. 1) is done vertically, suspended to a mobile frame. The assembly process can be divided in 14 main steps:

1-Vacuum vessel- top plate separation and storage.
2-Vacuum vessel (VV) preparation.
3-Thermal shield (TS) assembly and insertion into VV.
4-Chimney assembly and installation on the frame.
5-Top plate assembly.
6-Chimney insertion in the top plate.
7-Support frame installation.
8-Solenoid and cryogenics instrumentation interfaces installation.
9-Cavity insertion test.
10-Intermediate vacuum testing.
11-Cavities installation.
12-RF ancillaries' installation and test.
13-Cryo-module vessel closure.
14-Final assembly and qualification tests.

This sequence is imposed by the cryo-module design and by the tooling characteristics. To minimize the risk of contamination, the RF cavities are installed at the latest possible step. All cryo-module technical specifications and required performance are presented in [2].

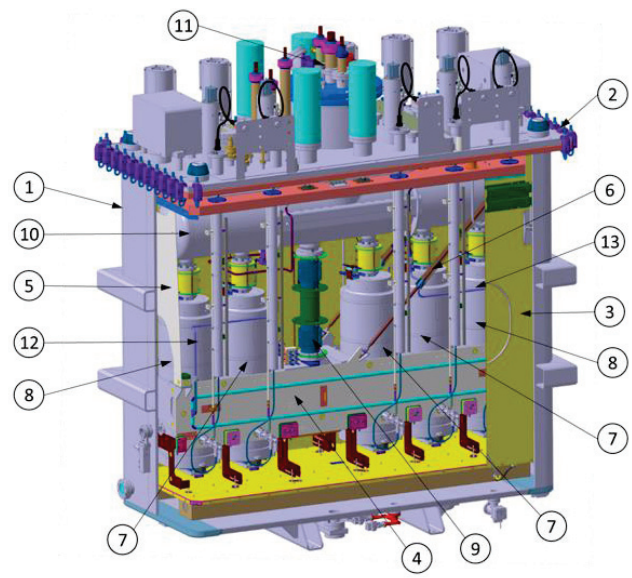

Figure 1: The complete HIE-ISOLDE high-β cryo-module; 1 Vacuum vessel lower box, 2 Vacuum vessel top plate assembly, 3 Thermal shield lower box, 4 Support frame, 5 Suspension end plate, 6 Tie-rod, 7 Inboard cavity, 8 Outboard cavity, 9 Down tube to solenoid, 10 Helium vessel, 11 Chimney assembly, 12 Support frame cooling supply, 13 Support frame cooling return, 14 Mathilde targets, 15 Mathilde viewport.

WORK ORGANIZATION

In order to reduce problems during the cleanroom assembly and to minimize the working time in the cleanroom, the work needs to be carefully organized.

One cryo-module contains more than 10000 parts under more than 500 references, going in size from sub-millimetre dimensions to four cubic meters, and weighing up to 2.5 tonnes. The assembly of CM1 showed that a full blank assembly of the complete cryo-module would have been necessary to identify problems at the earliest opportunity, but this was not entirely done because of time reasons. From the reception, all parts are controlled before cleaning and conditioning to ISO 5 standards. For CM1 assembly, a database was put in place and improved for CM2 in function of our needs. The database permits us to follow up the stock and the status of each part (reception, quantity, quality control, cleaning, and conditioning). To ensure a permanent activity in the cleanroom and plan the interventions of auxiliary experts (for vacuum, metrology survey, RF and quality checks) preparation with two week's advance is needed. For CM2, in order to maintain a smooth workflow, for each assembly step a list of parts needed is prepared with the corresponding drawings and assembly procedure. The work progress is followed directly on the worksite on a daily basis by an assembly coordinator, and reported at weekly meetings. The work flow was difficult to maintain during CM1 assembly due to the fact that all parts arrived day by day. Concerning the work organization, a core team was put in place composed of one engineer to organize and follow all assembly steps on the field, two technicians for the assembly operation, and four technicians dedicated to the reception, the preparation and the conditioning. For punctual actions and tests like leak detection and RGA or survey and alignment, one specialist was made available for each discipline.

The workflow and the organization of the assembly team is shown in Fig. 2.

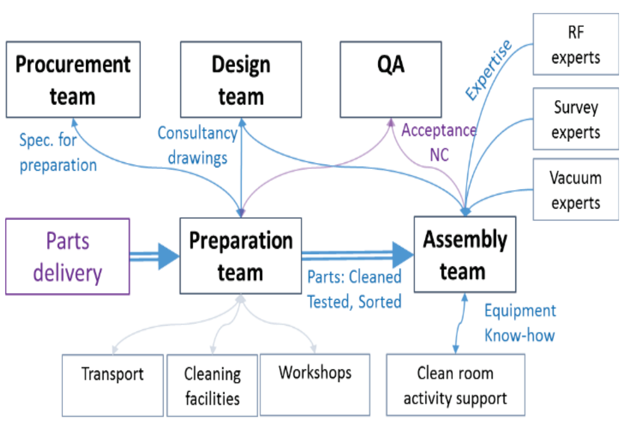

Figure 2: Workflow and teams organization.

PREPARATION AND ASSEMBLY FACILITIES

Parts Reception and Preparation Area

A logistics platform was set up to carry out the early preparations of each assembly steps as outlined above. A dedicated zone of floor area 190 m^2, situated in a building next to the main clean room, is dedicated for checking, cataloguing, cleaning, conditioning, storage and management of incoming and outgoing cryo-module components, sub-assemblies and elements of assembly tooling. This space was also used to make a blank assembly of the more complex sub-assemblies.

Cleanroom Facilities

The common vacuum design required a specific assembly environment, to avoid dust contamination and ensure cavity performances. The conditioning, the preparation of subassemblies, and the CM assembly proper are all done in ISO 5 soft wall cleanrooms.

Fig. 3 shows the CM assembly facility covering a floor area of 130 m^2. The box in the foreground is the ISO 5 vertical flux clean room of volume 4 × 4 × 2.5 m^3 used for component and sub-assembly preparation. In the rear ground an ISO5/ISO7 horizontal flux 10 × 5 × 5 m^3 clean room can be seen, equipped with specific tooling for the cryo-module assembly. The area between the cleanrooms is used to prepare pieces which can't be conditioned in the soft wall cleanroom due to their dimension and weight (Vacuum Vessel, top plate, He tank).

Figure 3: The HIE-Isolde cryo-module assembly facility.

Specific Assembly Tooling

Resources were invested in clean room compatible tooling designed to be easy to use and offering intrinsic precision, to unburden the assembly staff and allow them to focus fully on the assembly steps in hand. A schematic view of the specific assembly tooling in the main clean room is shown in Fig. 4. Stainless steel rails are set horizontally into the floor to within 0.5 mm over their 15 m length. Two rolling vehicles, one for general purpose use and one specifically designed for the transport and insertion of the RF cavities and the solenoid have been built in stainless steel conforming to clean room requirements. These vehicles permit the controlled transport of cryo-module components from the loading area to any station in the main clean room but in particular to final precise location under a 4-post tower frame installed in the rearmost ISO 5 part. Each post of the tower frame is fitted with an electrically motorised clean-room compatible linear movement. A mobile frame, installed inside the tower frame is linked at each of its corners to one of the linear movements. Electronic

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synchronisation of the 4 linear movements allows the mobile frame, while being maintained horizontal to within 0.5 mm to be displaced at pre-programmed speeds of 800 mm/min or 20 mm/min and inched to the required working height to within 0.6 mm anywhere over a range of 4.5 m while carrying a maximum load of 2.5 tonnes.

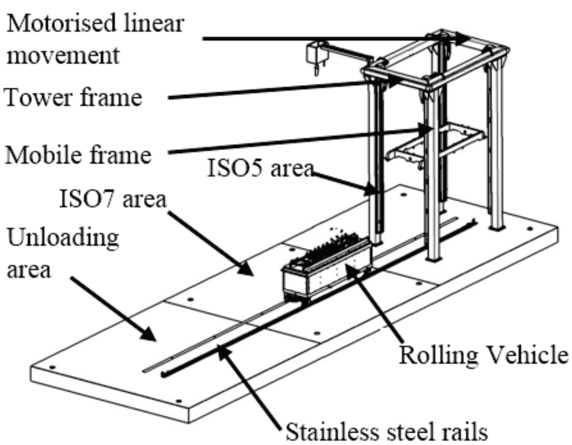

Figure 4: Cleanroom tooling.

QUALITY ASSURANCE

Assembly Procedures

The work to be achieved at each stage is detailed in assembly procedures whose writing started during CM1 assembly. From pictures, notes and knowledge acquired from the CM1 assembly, we started the CM2 assembly with good draft procedures that make reference to component and assembly drawings, measurement and test protocols. These procedures have been reviewed and refined through several iterations during the mounting of the second cryo-module.

Cleanroom Assembly Control

The difficulty with the HIE-ISOLDE cryo-module assembly results in the large variety in size and weight of the components to be assembled. The vertical assembly is not well adapted to cleanroom work due to the fact that some parts are hidden and not submitted to laminar flow. Standard cleanroom procedure for cleaning and conditioning cannot be applied. All parts of the cryo-module are degreased. Small components are conditioned in an adjacent ISO 5 area with ethylic alcohol, nitrogen blow and double plastic packaging). Bigger pieces are prepared in the unloading area with dust free tissue, alcohol and blown with nitrogen gas before entering in the cleanroom. The cryo-module top plate is suspended to the frame during long weeks with uninterrupted activities as more and more components are added. To maintain the clean room to the standards a weekly cleaning is done and the fan filter unit (FFU) pre-filters are changed every 3 months. Particle counting checks are realized in the cleanroom at different positions during assembly activities on the cryo-module. Measurements done during the cavity mounting on CM1 showed that the ISO 5 class range was maintained during this critical step.

Quality Assurance Tests and Results

Quality assurance tests were planned at key stages throughout the assembly. Leak tests and residual gas analyses allowed early stage identification of leaks and sources of contamination.

Staged electrical tests were performed on each set of instrumentation before and after installation.

Survey intervened on the clean room infrastructure, for geometrical follow-up, and validations, deformation tests, assembly follow-up, alignment and monitoring. Survey campaigns and intermediate adjustments ensured rapid final alignments with the RF cavities in place to reduce risk of particulate contamination.

RF ancillaries were tested at warm at the end of the assembly. Parameters are described later in this paper. Measurements confirmed the integrity of the installed equipment.

For CM1, at the pressure level given by the short pump down and water outgassing coming from the instrumentation (7.3×10^{-5} mbar after 20 hours) no contamination was observed. The leak tightness of the cryo-module 70 K circuits and 4.5 K circuits before cavities installation was measured below 2×10^{-10} mbar.l/s at room temperature.

The RF cavity apertures have been aligned horizontally and vertically to within 0.1 mm with respect to an axis coincident with the solenoid axis. After cryo-module installation and cool down, the active components aligned on this common axis may be monitored optically and if needed, repositioned with respect to the beam-line using the Mathilde [3] system.

Non Conformities

Related to the assembly, 64 non-conformities were raised, with 23.4 % related to instrumentation, 21.9 %, to the thermal shields, 10.9 %, to the support frame, 9.4 %, to the vacuum vessel and 34.4 % on others. Three further non-conformities were opened for leaks detected during tests, 2 were opened because of activity outside standard procedures and 22 defect reports detailed the need for tooling improvements.

Having available from the start, components and sub-assemblies for 2 cryo-modules together with a full set of spare fasteners, flanges, bellows etc. ready at an early stage has afforded precious flexibility for in-work problem solving when faced with non-conformities.

RF CAVITIES AND ANCILLARIES CARACTERISITCS

Cavity Specification

The HIE-ISOLDE specifications call for the intrinsic quality factor Q_0 value of $4.7\text{x}10^8$ at 6 MV/m corresponding to a dissipated power of 10W at resonant frequency of 101.28 MHz and 4.5 K. From the vertical test results, cavities installed in CM1 dissipate between

7.6 W and 13 W at 6 MV/m. The total dynamic load anticipated from the cavities is 53.7 W (Table 1).

Table 1: Quality Factor at Low Field and 6 MV/m with Corresponding Dissipated Power for each Cavity in CM1

	Q00 (Eacc ~ 0.2MV/m)	Q0 (Eacc=6MV/m)	Pcav (W)
QP2.1	1.59E+09	6.23E+08	7.6
QP3.2	1.93E+09	4.91E+08	9.7
QS1.1	1.33E+09	3.78E+08	12.5
QS3.1	9.96E+08	3.66E+08	13.0
QS4.1	1.12E+09	4.36E+08	10.9
Total			53.7 W

Before installation in the cryo-module, all cavities were rinsed and prepared (tuning plate, beam port support and shutter mounting) in ISO 5 cleanroom. In the assembly sequence, cavities and RF ancillaries (pick-up, the power coupler, the tuner mechanism, the RF cables and connectors) are mounted at the end of the assembly to minimize the contamination risk (Fig. 5). All tests of the RF parts are done room temperature in air atmosphere. Measurements are presented in the following paragraphs.

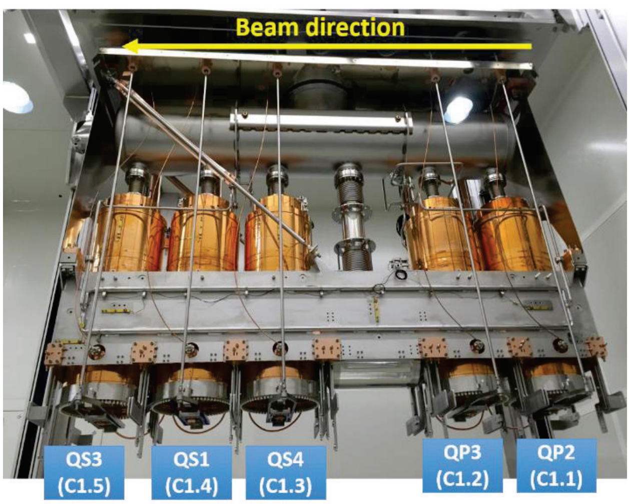

Figure 5: Cavities installed on CM1.

The Cable Losses

Table 2: CM1 RF Cable Losses

Cavity	Loss (coupler cable) [dB]	Loss (pickup cable) [dB]
QS3(C1.5)	-0.09	-0.29
QS1(C1.4)	-0.09	-0.29
QS4(C1.3)	-0.09	-0.29
QP3(C1.2)	-0.09	-0.27
QP2(C1.1)	-0.10	-0.30

Cables attenuation is checked after their installation to ensure that they were not damaged during the assembly. Table 2 presents pick-up and coupler cable losses whose are respectively in range of -0.29 dB and -0.09 dB as expected from the manufacturer specifications.

Frequency Perturbation of the Coupler

The total frequency perturbation (Δf) of the RF power couplers installed on CM1 at room temperature in air for each cavity is measured as a cross check of the variable coupler mechanism. The results are presented in Table 3. Values are in range of 133 kHz.

Table 3: CM1 Frequency Perturbation of Coupler at Room Temperature

Cavity	Δf (kHz)
QS3(C1.5)	-133
QS1(C1.4)	-133
QS4(C1.3)	-132
QP3(C1.2)	-129
QP2(C1.1)	-131

Tuning Plate Coarse Range

The tuning plates installed on each cavity are made in copper OFE and have a deformable part 0.3mm thick which can be elastically displaced up to 5mm from the flat position. The tuning plate is deformed by pulling on it with a lever arm mechanism connected to plate centre [4]. The working frequency of the QWR is 101.28 MHz at 4.5 K under vacuum with the tuning plate preferably pulled to its mid- range position. To reach this operating frequency at 4.5 K under vacuum, the frequency (unperturbed) required has to be close to 100.900 MHz at 20 °C with 50 % of humidity [5]. The tuning plate coarse range was measured at warm on CM1 cavities to check the integrity of the mechanism. Results are presented in Table 4. All the coarse range are in range of the 30 kHz, enough to cover the expected frequency error (≈ 10 kHz) [5].

To compensate an eventual laminating of the tuning plate with time which could prevent us to go back to the initial position, a recover range by pushing the plate of 4-5 kHz is set.

Table 4: Tuning Coarse Range of the CM1 Cavities and the Position to Reach the Operating Resonant Frequency

Cavity	Coarse range (kHz)	Target freq. consumption	Recover range (kHz)
QS3(C1.5)	27	59%	3
QS1(C1.4)	28	71%	3
QS4(C1.3)	30	33%	4
QP3(C1.2)	36	22%	4
QP2(C1.1)	33	33%	5

Qext of the Pickup Antenna

The pick-up Qext is measured before closing the cryomodule as a reference for future measurements. The pickup antennas installed on the CM1 cavities have the same length: Qext should be the same but, has shown in Table 5, the pick-up Qext changes from $2.1E^{+10}$ to $4.2E^{+10}$. This difference is linked to the chemical etch duration applied to the cavity (for the Nb coating preparation). Higher values correspond to the lower antenna penetration.

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Table 5: Pick-up Qext Measurement on CM1 Cavities

Cavity	Qext (pickup)	SUBU duration (min)
QS3(C1.5)	2.1E+10	160
QS1(C1.4)	2.7E+10	120
QS4(C1.3)	3.11E+10	100
QP3(C1.2)	2.02E+10	155
QP2(C1.1)	4.2E+10	65

RF Transmission at Warm

The transmission loss of all the RF line from the input to the output connector installed is measured using a network analyser. This is a sanity check to identify eventual mismatches or defective elements. The RF continuity measurement done on CM1 cavities showed losses in range of -64 dB (Table 6).

Table 6: RF Transmission at Room Temperature

Cavity	RF trans. (dB)
QS3(C1.5)	-63.716
QS1(C1.4)	-65.044
QS4(C1.3)	-65.642
QP3(C1.2)	-63.739
QP2(C1.1)	-67.021

Cavity Status for CM2

CM2 cryo-module assembly started last June 2015. At the moment, cavities needed for CM2 are not all produced. Only 3 cavities are accepted for installation. The last two would be produced by the end of September.

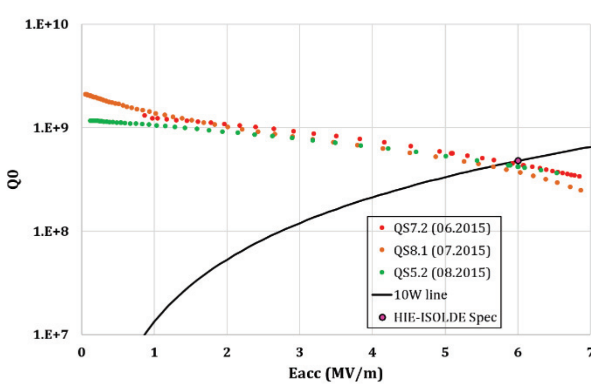

Figure 6: Q0 (Eacc) at 4.5K performance for the CM2 cavities.

As for CM1 cavities, the delivery time became shorter due to substrate production and delivery problems. CM2 cavity performances tested at CERN are presented in Fig. 6. The Q0(Eacc) measured at 4.5 K and at the resonant frequency 101.28 MHz shows performances in range of $5.10E^{+8}$ at 6 MV/m, corresponding to a dissipated power of ~12W.

CONCLUSION

After 32 weeks of intense work, the assembly of the first cryo-module was finished (April 2015) and the cryo-module was in installed on the beam line in May 2015. CM1 was delivered in time to start the commissioning and the RF test with the plan to be in operation in September 2015.

From this first assembly experience, a lot of debugging, design modifications and procedure modifications were done and used for the second cryo-module preparation and assembly.

The commissioning and the first RF tests of the cryomodule [1], confirmed the quality of the assembly, in terms of cleanliness and manufacturing. The cavity vacuum is in the range of 10^{-11} mbar at 4.5K and no field emission was observed at the nominal accelerating field (6 MV/m). These results comforted the assembly team to continue in the same way for CM2.

The procedures, the organization workflow (piece reception, blank assembly, cleaning and conditioning) are continuously improved in order to achieve a smooth workflow and keep the possibility to solve problems without delays.

The CM2 assembly started last June 2015 and had to be finished in October 2015. The last part missing for CM2 are cavities. Three cavities are available and the last two would be delivered by the end of September.

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