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Test Plan for Cryomodule testing at ESS Test Stand 2

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1. SCOPE

Scope of this document is to describe the tests to be done in Test Stand 2 to perform the Site Acceptance Test of elliptical cryomodules. In addition, the document lists the tasks to be done in order to prepare the cryomodule for the tests.

2. ISSUING ORGANISATION

European Spallation Source ERIC.

3. CONTEXT

The superconducting section of the ESS linear accelerator will include 30 elliptical cavity cryomodules and 13 spoke cavity cryomodules.

Prior to the installation of the cryomodules in the linac tunnel the series production cryomodules will be subjected to site acceptance tests. The elliptical cavity cryomodules will undergo their tests in a dedicated test stand at the ESS site, called Test Stand 2 (TS2). The test stand will also be used during operation of ESS to test cryomodules that have to undergo repair or maintenance outside the tunnel.

TS2 consists of a radiation shielding bunker, a test stand cryoplant and RF power sources. The test stand will provide facilities for testing the elliptical cavity cryomodules of both varieties: elliptical medium beta and elliptical high beta.

TS2 will allow the SAT of cryomodules with full cryogenic load at the final operating temperature and with full RF load on all cavities in parallel.

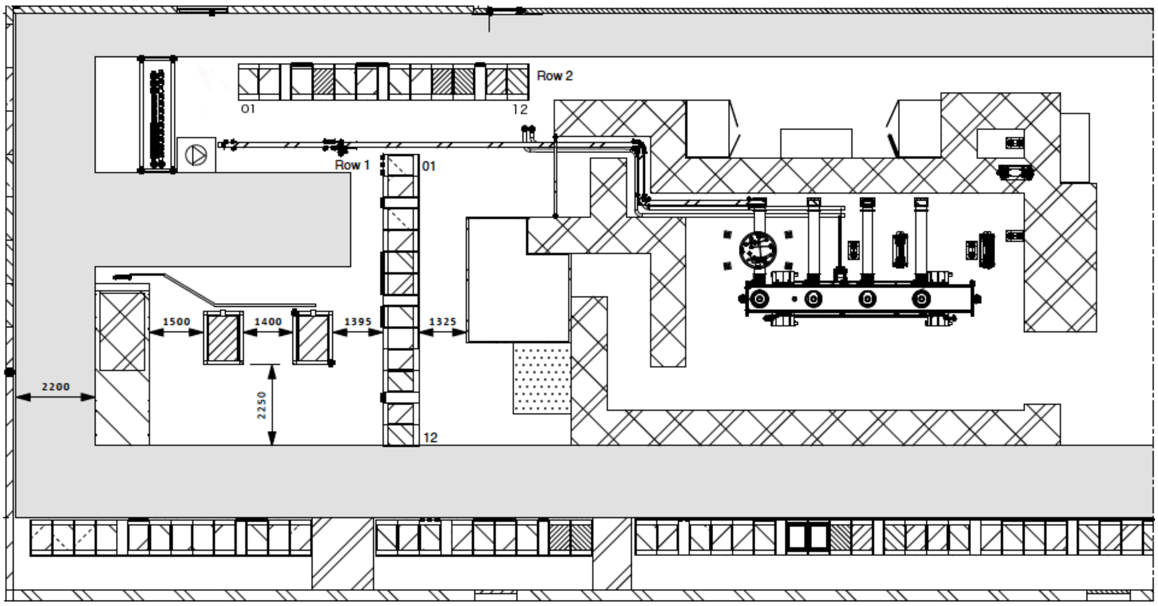

Figure 1: TS2 layout

3.1. Bunker

The bunker is one of the few components of TS2 to be procured and installed by WP10 itself.

The main function of the bunker is to protect the surrounding area from x-rays produced during the cryomodule tests. It consists of 1200 t of heavy concrete, arranged to form 1 m thick walls all around the cryomodule, while allowing services such as cryogenics, RF and cabling to enter through chicanes. The bunker is provided with a personnel safety system (PSS), oxygen deficiency hazard (ODH) monitors and radiation detectors. A personnel access chicane and a full width access door for the cryomodules are also part of the bunker.

3.2. Test Stand Cryoplant and Cryogenic Distribution System

The test stand cryoplant is named Test Stand and Instruments Cryoplant (TICP) and will serve the following tasks:

- Provide cooling at 2 K, 40-50 K and liquefaction for TS2
- Provide liquid helium for some neutron instruments and experimental environments
- Recover, purify and manage helium at the facility

Although the TICP will only be used for CM testing for the first few years, this operation will define the plant's design.

The cryogenic distribution system (CDS) for TS2 is dedicated to transferring cooling power from the TICP to the cryomodules during the SATs in the test stand bunker. The system includes a cryogenic transfer line (CTL), one valve box, four auxiliary process lines and a vent line.

3.3. RF system

The RF system converts the AC power from the electrical grid to the radio frequencies required to drive the superconducting cavities. Subsystems include the RF sources and conditioners (klystrons and modulators), the RF distribution system and the low-level RF controls.

TS2 will power two klystrons from one modulator, one klystron per two cavities. The modulator will convert electrical power from a standard low voltage distribution grid to an electrical pulse of 1 MW to the klystrons' cathodes. The klystrons will convert the pulsed power coming from the modulator to radiofrequency waves at 704.42 MHz.

3.4. The Technical Demonstrator Elliptical Cryomodule

The test stand will test cryomodules of medium beta and high beta, to be installed in the Linac. In order to finalise the commissioning of the test stand and to tune up all the involved systems, a prototype cryomodule called Technical Demonstrator (ECCTD) and containing more instrumentation than the series cryomodules will be placed in the test stand during its commissioning phase.

4. CRYOMODULE OPERATIONS

Testing of CMs includes a number of preparatory steps, the testing itself and a number of post-processing steps.

4.1. Preparatory Steps

4.1.1. Reception

Inspection for damage, obvious manufacturing errors and completeness of delivery. Some of the following tasks can be done in parallel, but they will <u>not take less than 1 full day</u>.

4.1.1.1. Pre-unloading actions

- Prepare reception checklist
- Check transportation documents
- Check seal on container, if applicable
- Open container doors
- Check if CM is still properly fixed, clamped and strapped
- Check utility boxes and their content
- Visual inspection for damages
- Read-out of shock logger
- Plug simple shock-logger for handling measurements
- Check that lifting brackets are still fixed and re-fix if needed
- Remove container roof
- Prepare spreader beam with 4 slings and trigger hooks accordingly
- Clear unloading area

4.1.1.2. Unloading of Cryomodule

- Block transportation cart (CART_1)
- Connect slings/trigger hooks with the lifting brackets on the CM (hazard: beam touches valves)
- Lift beam to a level right before forces are applied on the slings, make sure that it is centred
- Remove transport frame clamps from the CM feet, remove lashing straps
- Lift CM out of the transport frame
- Lower CM on CART_1
- Fix CM to CART_1
- Remove slings and spreader beam

4.1.1.3. Transport Cryomodule to preparation area

- Hook up pulling device
- Unblock CART_1
- Clear path
- Move CART_1

4.1.1.4. Transfer Cryomodule to support

- Check parallelism of CART_1 vs. cryomodule support (SUPPORT_1)
- Push up cart while checking height
- Turn wheels to allow movement to support
- Lower cart
- Jack up cart
- Connect cart with support and spacers
- Remove fixtures of CM on cart
- Move CM onto spacers on support
- Jack up CM to allow removal of spacers and positioning of alignment posts
- Remove spacers
- Place alignment posts and x-y tables
- Mount alignment posts and x-y tables
- Place full CM weight on the z-screws of the alignment posts
- Remove jacks and blocks

4.1.2. Preparation for test stand

Preparation for installation on test stand, including adjustments as well as mounting and dismounting of parts. Part of the incoming inspection can also be done during this step, as well as some RF measurements. The estimated time for the Cryomodule preparation is described at the end of the section.

4.1.2.1. Incoming Inspection

The incoming inspection is needed to accept the Cryomodule to be tested inside the bunker, it will include some RF checks and measurements defined in the next step. The definition of the Cryomodules acceptance criteria is critical to define which tests and measurements need to be part of the Incoming Inspection.

- Verify documentation from CEA
- Visual inspection for damages at valves and flanges
- Inspection for manufacturing errors
- Beam vacuum read-out through couplers gauges
- Vacuum leak checks
- Check electrical continuity
- Check nominal resistance values in temperature sensors
- Check proper functioning of gate valves
- Check proper functioning of cold tuning system

4.1.2.2. Mounting of parts

- Remove cavities supporting bar
- Mount door knobs in couplers
- Connect insulation vacuum pumping group
- Connect beam vacuum pumping group

Many of the tasks listed within the Incoming Inspection and the Mounting of parts can be done in parallel and for this reason there is no need to estimate the individual time consumption for each task in this document, further tables of tasks in parallel are being developed to estimate the manpower needed at each step. Nevertheless, it is necessary to present the estimated time for the mounting of the door knobs, with proper tooling, as this individual task can take up to 1 full day, needs to be performed without any task in parallel due to its delicacy and it is needed to perform the RF measurements in this step. The other tasks on the lists can take up to another 1 full day, where the connection of the beam vacuum pumping group is the most time consuming due to the need to keep low particle count clean room conditions during the process.

4.1.2.3. Initial RF measurements

Some RF measurements need to be done before installing the Cryomodule in the bunker, to verify the cavities response to injected frequencies, to perform functional and quality controls of the piezo tuners and to measure the inner RF cables. A series of software and hardware tools are being/need to be developed to perform these measurements, and these measurements will not take less than 1 full day.

- Measure piezo capacitance/Tuner functionality (on short range)
- Measure inner RF cabling (TDR), length and shorts
- Measure Warm spectrum, transmissions and dangerous HOM (WR1150-N transitions-PU flange)
- Compare results with CEA and cavity IKC
- Fill incoming inspection report

4.1.3. Installation on test stand

The installation on test stand includes the moving of the Cryomodule to the final support for the tests inside the bunker and the connection of every system (cryogenic pipes, RF waveguides, …), as well as the verification of these connections. The instrumentation inside the Cryomodule has to be connected to the Control System at this step, and therefore the verification of the cabling and function of the instruments needs to be performed after connection. Verification of the proper functioning of interlocks and control system needs to be performed after the instrumentation has been checked. All these connections are very time consuming, plus the verification and adjustment of the instrumentation will take no less than 3 days, being optimistic.

4.1.3.1. Transfer Cryomodule to cart

- Check parallelism of CART_1 vs. SUPPORT_1
- Turn wheels to allow movement to support
- Move cart to support
- Jack up cart
- Connect cart with support and spacers
- Remove fixtures of CM on support
- Move CM onto cart
- Fix CM on cart

- Remove connections to spacers and lower CART_1

4.1.3.2. Transport Cryomodule into bunker

- Hook up pulling device
- Unblock CART_1
- Move CART_1

4.1.3.3. Transfer Cryomodule to support

- Check parallelism of CART_1 vs. support inside bunker (SUPPORT_2)
- Push up cart while checking height
- Turn wheels to allow movement to support
- Lower cart
- Move cart to support, preserve clearance to jumper connection
- Jack up cart
- Connect cart with support and spacers
- Remove fixtures of CM on cart
- Move CM onto spacers on support
- Jack up CM to allow removal of spacers and positioning of alignment posts
- Remove spacers
- Place alignment posts and x-y tables
- Mount alignment posts and x-y tables
- Put full CM weight on the z-screws of the alignment posts
- Remove jacks and blocks
- Move cart outside bunker

4.1.3.4. Connections

- Alignment of the cryo jumper connection
- Perform and check interconnections
    - Waveguides
    - Cryolines
    - Cooling water pipes
    - Instrumentation
    - Compressed air

4.1.3.5. Checks

- Check proper functioning of valves
- Check proper functioning of sensors
- Check proper functioning of interlocks
- Check proper functioning of Control System and DAQ

4.2. Cryomodule Tests

In the second week of the Cryomodule at the TS2 area and if all the preparations, connections and verifications have been accomplished without problems, the Cryomodule can start undergoing tests. These tests include measurements and calibrations at warm temperature, the conditioning of the couplers, the cool down of the Cryomodule down to 2K and all the RF tests at low and high power, using a LLRF system for the former and klystrons for the latter. All the mentioned tests and processes need to be done in two weeks to keep the current schedule of 4 weeks/cryomodule without margin for retesting.

4.2.1. Warm RF tests

When the Cryomodule has been connected in the bunker and the instrumentation can be read, we need to perform RF measurements with the total length of cables to get valuable data for the calibrations, check the RF Distribution System (RFDS) and most important, perform the Spectra Measurements. For this test (Spectra Measurements) we have two options at TS2, or disconnect the waveguides at the doorknobs side and connect a WR1150-N to coaxial transition to read the pick-up signal from the module flange, or have a removable section in the RFDS outside the bunker to connect the WR1150-N transition and read the pick-up signal from a patch panel on the RF racks. We are aiming for the second solution but no official decision has been made yet.

- Spectra Measurements
- Static calibration
  - Dir. Couplers/Circulators: get calibration data
  - Calibrate RF power measurement cables with attenuators
  - Document: RF calibration summary table
- Klystron/LLRF check on the load
- WGs visual check
- System check / RF leak check at low power (not if waveguide is not yet reconnected)

4.2.2. Warm coupler conditioning

In order to prepare the couplers to work at expected frequencies, they must undergo a RF conditioning, also to ensure they capability. The power couplers would have already undergone their conditioning in a conditioning box at CEA, but they need to be reconditioned when connected to the cavities. Also, after long periods of inactivity.
Taking into account of 30% power overhead need for LLRF regulation, and full reflection at the beginning of cavity filling, significant high peak power handling is expected in elliptical cavity/coupler conditioning.
Without previous experience with these Cryomodules, we cannot estimate the amount of time needed for the coupler conditioning, CEA conditioning experience will offer valuable and particular high-power input to abstract high level logical schema. In order to have an estimated time schema, we can only mention that the power coupler conditioning will take no less than 1 day, but this time can be much higher in reality.

Parameters to be checked and have under control during the conditioning are:

- Vacuum levels
- Arc detection events on vacuum and air side (the most of these events are expected to happen on the air side)
- Multipacting events
- RF (f/r power to couplers)
- Temperature
- Water flowmeter
- Interlocks

4.2.3. Cool down to 2K

When the CM is installed in the test stand and after all the instrumentation has been checked and work properly, we can start to prepare the system for cryogenic operations as cool down, this means to purge and clean the circuits to ensure they are free of air particles and prevent the creation of ice inside the pipes (as well as condensation). These tasks can start in parallel with the warm RF tests and warm coupler conditioning as they will not affect significantly their results. Nevertheless, it is absolutely forbidden to enter the bunker when the klystrons are operating and the RFDS is connected to the Cryomodule doorknobs (PSS will ensure it).

The cool down of the thermal shield and the cavities is originally planned to be launched at the same time, where the thermal shield has to stabilize at 50 K and the cavities circuit needs to continue cooling down to 4.5 K. The CM will need to stabilize at 4.5 K before the operator launches the order to cool down to 2 K, done by starting vacuum pumps in the cryoplant's warm compressor system and filling the circuits with supercritical helium.

The CM needs to be thermally stable at 2 K to start with the RF tests. Cool down and thermalisation (can be done overnight) will take <u>at least two days</u>.

- System check to assure it is purged and clean
- Cool down following a predetermined ramp
- Maintain cold He flow to assure operating temperature of cavities
- Check cryogenic circuits for leaks
- Fill cool down report

4.2.4. Initial cold RF tests

When the CM has stabilized at 2 K, we need to repeat some of the measurements done at warm temperature, to know the cavities performance. It becomes more critical at this step to have the availability to remove a section of the waveguides outside the bunker to connect the WR1150-N transition and measure the frequencies from a patch panel. We estimate these tests to take <u>no less than 1 day</u>.

- Fundamental Bandwidth Measurement, check of proper frequency shift/Mean spectrum deviation (MSE) analysis

- Cold cable calibration
- Document RF Power calibration final table
- Cavity pretuning to operating frequency (VNA or dedicated tool using the LLRF)
- Piezo capacitance measurement

4.2.5. Cold LP cavity tests with LLRF

The WR1150-N transition is removed and the section of the waveguides are placed in place. The LLRF needs to have the capability to perform the series of tests designed at low power. We estimate these tests to take no less than 2 days.

- Microphonics measurement
- Piezo scans: cavity detuning transfer function
- Lowest bandwidth mode identification
- Fine tuning with LLRF
  - Drive LLRF in open loop FF pulsed mode (rectangular pulses ok) at low klystron power
  - Maximize level of transmitted power → approaching resonance
  - Use detuning information from LLRF server to perform last tuning steps
  - Record the tuning steps for the final tuning for future operation in Linac
- Calibrate RF pickup signals
  - Extract decay time from P_t at end of pulse, compute Q_L
  - Evaluate E_{acc} from $P_{forward}$ measurement
  - Measure Pt and determine Gradient calibration constant k_t
  - Store and document calibration data in report
  - Correlate with CEA and VT data
- Establish closed-loop, feedback operation
- Detune the cavities (for cold processing)

4.2.6. Cold couplers and cavities Conditioning

Same as in warm conditions: In order to prepare the couplers and cavities to work at expected frequencies, they must undergo a RF conditioning, also to ensure they capability. Again, we don’t have experience in these Cryomodules with this RF infrastructure, we can only estimate the conditioning to take no less than 1 day, but we won’t know the real timing until we gain experience with the technical demonstrator.

4.2.7. Cold HP RF tests

After the cold conditioning, we need to connect the klystrons to provide the cavities with high power. We will not operate with beam at TS2 and therefore two klystrons are enough for four cavities, as the non-existing beam will not absorb the injected power.
We will operate the klystrons using the software tools provided by the RF team, rise the power to nominal gradients and operate at different modes (open loop, closed loop).
The performance of the Cryomodule at this step will be part of the acceptance criteria and will determine if the cavities are good enough for the linac. Because the criticality of this step and due to the many tests to be performed, we estimate to operate with high power for at least 1 week.

Radiation levels will be measured during all HP RF tests, to ensure safety conditions for personnel and equipment.

- Power rise to nominal gradients (in-kind VT data)
- Open loop and closed loop operation
- Active piezo Lorentz force detuning compensation
- Cryomodule gradient performance assessment
- P_{for} power used to drive a cavity to the quench limit
- Identification of limiting mechanisms (power, X-ray, quench, ...) **[MV/m]**
- X-rays measurements
  - X_{rays} start – Value of gradient when radiation starts **[MV/m]**
  - X_{rays} quench – Value of radiation just before cavity quench **[mGy/min]**
- Data storage, correlation with VT data Power Rise to nominal gradients
- Optimization of the LLRF parameters
- Cavities to parking position
- Fill test report

4.2.8. Heat loads measurements

The heat loads measurements are done in order to calculate the thermal performance of the CM, as its design and insulation efficiency will affect the amount of helium that the cryoplant needs to provide in order to cool down the linac.

The original plan is to calculate the heat loads measuring the helium flow provided by the cryoplant, but no decision on the method or tests has been made yet. If we want to calculate the heat loads at 4.5 K and the static and dynamic modes for 2 K, we need to estimate these measurements to take approximately <u>1 day</u> in total.

- Measure heat loads at different operating conditions:
  - 4.5 K
  - 2 K without RF
  - 2 K with RF
- Add results to test report

4.2.9. Warm up

After all tests and measurements have been completed, or if the test leader decides to remove the CM from the bunker before the tests are completed, the CM needs to be taken back to 300 K room temperature and all interfaces disconnected. The warm up is foreseen to be launched manually by an operator after validation from the SRF specialists and tests operations leader and will be originally performed by circulating warm helium through the cryogenic circuits, this can be speeded up by heaters placed below the cavities helium tank and at the cold tuning system, but the use of heaters is not part of the original warm up operation process.

The warm up is planned to be done in two steps, from 2 K to 4.5 K and from 4.5 K to 300 K. An intermediate step during warm up can be operated if requested, this step would mean to warm up the CM up to 80 K and keep the system in standby to study this functionality for the linac, as it is foreseen to avoid the complete warm up of the linac but to keep it at 80 K during shut downs. Nevertheless, this intermediate step should be tested only once to validate the control system operating mode, and the TICP doesn't have the capability to provide 80 K so it would be done at 50 K instead. If not requested, the CM should warm up directly from 4.5 K to 300 K, preferably during night (1 day) to ensure the thermal stabilization of all circuits.

4.2.10. Disconnection

All the interfaces except vacuum need to be disconnected to extract the Cryomodule from the bunker, this task can be faster than in the installation step as there is no need to check the connections and proper functioning of equipment. We estimate that the disconnection step could be done in 1 full day.

- Perform disconnections
    - Waveguides
    - Cryolines
    - Cooling water pipes
    - Instrumentation
    - Compressed air
- Extract Cryomodule from the bunker
    - Check parallelism of CART_1 vs. SUPPORT_2
    - Turn wheels to allow movement to support
    - Move cart to support
    - Jack up cart
    - Connect cart with support and spacers
    - Remove fixtures of CM on support
    - Move CM onto cart
    - fix CM on cart
    - remove connections to spacers and lower CART_1
    - Move CART_1 outside bunker

4.2.11. Preparation for dispatch

Prepare Cryomodule to leave the test stand, to tunnel or storage. Can be done on the cart if available, if not, the cryomodule needs to be placed on a support outside the bunker. The cryogenic connections are done with flanges at TS2 which need to be cut after tests as the connection in the linac will be welded. As the preparation for the test stand, the beam vacuum needs to be disconnected in clean room conditions, therefore the full operation can take up to 2 days.
The current plan is to keep the door knobs mounted and secured in the CM during transportation to the accelerator tunnel, but the securing system has not been specified yet.

- Check frequencies with VNA
- Remove vacuum pumping groups

- Cut cryogenic connections
- Install blank flanges
- Fill outgoing report
- Dispatch

5. SUMMARY

TS2 in Lund shall perform the SAT of the elliptical cavity cryomodules. Testing shall include:

- Reception, Preparation and Installation
- RF measurements and calibrations
- Couplers conditioning
- Cooldown
- RF tests up to full power
- Heat Loads tests
- Warm up, Disconnection and Prepping for Dispatch
- Document processes and results

Detailed testing procedures are being written in collaboration between In-Kind partners, WP10 and SRF specialists.

The current schedule of 4 weeks/Cryomodule without shifts does not allow margin for retesting, equipment failures or personnel issues (estimated SAT time 24++ days).

- Coupler RF conditioning time has been estimated in 24 h, but there is no statistics in support of that.
- We need to gain experience with the ECCTD, also with the firsts series Cryomodules.

6. NOTATION FOR DESCRIPTION

Abbreviation	Definition
ESS	European Spallation Source ERIC
TS2	Test Stand 2
SAT	Site Acceptance Test
CDS	Cryogenics Distribution System
CTL	Cryogenic Transfer Line
TICP	Test Stand and Instruments Cryoplant
CM	Cryomodule
WP10	ACCSYS Work Package 10, Test Stands

Abbreviation	Definition
WP05	ACCSYS Work Package 5, Elliptical Cryomodules
CEA	Commissariat a l'Energie Atomique, Saclay France
LINAC	Linear Accelerator
PSS	Personal Safety Systems
ODH	Oxygen Deficiency Hazard
RF	Radiofrequency
RP	Radioprotection
RFDS	Radiofrequency Distribution System
SRF	Superconducting RF
ECCTD	Elliptical Cavities Cryomodule Technical Demonstrator
TDR	Time-Domain Reflectometry
VT	Cavity Vertical Tests
WG	Waveguide
LLRF	Low Level RF
VNA	Vector Network Analyser
CART_1	Transportation cart to move the CM at TS2
SUPPORT_1	Cryomodule support outside the bunker
SUPPORT_2	Cryomodule support inside the bunker

7. REFERENCES

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DOCUMENT REVISION HISTORY

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