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THE ESS DATABASE FOR ELLIPTICAL CAVITIES

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Abstract

The large in kind scope of the elliptical superconducting RF linac of the ESS implies the handling of the handover conditions between the cavities fabrication and testing phases performed at INFN and STFC, to the assembly of cryomodules at CEA, and later to ESS in Lund. The performance qualification at the module test stand, and later the commissioning and operation phases, require the availability of the cavity performance and frequency data under all environmental conditions during preparation (e.g. temperature, vacuum in beam line/He vessel/vacuum vessel, tuner state). Availability of the data needs to be guaranteed for the long term maintainability of the accelerator. For these reasons a cavity database has been set up at ESS, integrating the data contained in the handover documentation from the in kind partners and extending it during the activities at ESS after receiving the modules. The database was used to analyse the preparation steps of the prototype demonstrator cryomodule for the tests at ESS, by benchmarking with the data collected during the tests at CEA, and is currently used during the series cavities handover phases.

MOTIVATION FOR A DATABASE

Cavities for the ESS superconducting accelerator are provided by the project in kind partners. Cavities for the medium beta elliptical section are procured by INFN/LASA and those for the high beta section by STFC/Daresbury. Both partners rely on experienced industrial vendors for the fabrication and treatment processes. The medium beta series cavity production is well advanced [1, 2], and the high beta series is in its starting phase [3]. Cryomodule assembly is performed at CEA Saclay, which receives the RF resonators from the cavity in kind contributors after the successful qualification in near-critical RF coupling conditions in a vertical cryostat at 2 K.

ESS is responsible for the cavity acceptance according to the project specifications, after fabrication and testing, to supervise the handover conditions between partners, and to authorize the cavities for the installation into the module string. Conditions have been agreed between ESS, the cavity producers and CEA, documenting the mechanical interfaces and describing the shipment configurations and vacuum requirements during handover, and any discrepancy is addressed with Non Conformity Reports. (NCRs), discussed and resolved on a case-by-case base. In addition to the mechanical interfaces, the cavity frequency is controlled at several points in the lifecycle, and the measured data transferred to ESS, to be stored in the database.

Data transfer During Cavity/module Lifecycle

The main phases of the cavity and module lifecycle are resumed in Table 1, with the list of data required to provide for storage in the ESS Cavity DB.

Table 1: Data Required for the DB at Handover Phases

Phase	Data
Cavity fabrication	
Outgoing from cavity partners to CEA	• Reference cavity bandwidth at warm, in free conditions, in air • Field flatness profile • Warm HOM spectra • Cold bandwidth • Cold HOM spectra during vertical test • Q vs Eacc curve from vertical test • Cavity bandwidth before shipment to CEA, in vacuum and with tuner fixing clamps • Calibrated transmission of π mode
Incoming inspection at CEA	• Cavity bandwidth at reception • Calibrated transmission of π mode
Module assembly	
Module outgoing inspection from CEA	• Cavity bandwidth with tuner and coupler installed, in vacuum, warm
Module incoming inspection at ESS	• Cavity bandwidth at reception

Handover Frequency Related Criteria

Data produced in the first phase is used for the acceptance of the cavity before its installation in a module at CEA, in addition to the interface verification. In particular, the following conditions should be satisfied:

- the cavity π mode frequency needs to fulfil the agreed range at warm in free condition, in air, to guarantee the achievement of the correct minimal mechanical preload on the tuner and to avoid occurrence of plastic deformations during tuning,
- the performances shown by the Q vs E curve needs to exceed the gradient and Q requirements of the ESS design,

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- any dangerous trapped monopolar HOM mode lies at distances in excess of 5 MHz from integers of the beam frequency,
- the field flatness exceeds the agreed specifications.

As the cavity transport fixtures may induce an elastic frequency offset with respect to its natural frequency, the control performed during the transport from the in kind to CEA for assembly in the module is limited to verify that:

- the frequency of the operating π mode does not deviate more than an agreed maximal deviation between the outgoing and incoming inspections,
- the mean spectral error (mse) [4] between the outgoing and incoming inspection does not exceed the agreed specification,
- the calibrated transmission is within a nominal agreed range, indicating no detachment of the high Q antennas during transport.

The frequency and mean spectral error deviation controls are applied also to the verification of the cryomodule transports. Whenever a cavity (or module) fails to meet the agreed handover conditions, NCRs are raised, in order to proceed with the work or identify proper compensating actions (e.g. reprocess with HPR a cavity in case of strong field emission limitations).

Measurements at ESS

Once the module reaches ESS, all measurements of the cavity properties during the preparation stages for module testing (starting with the incoming reception) are performed with automated tools that directly store the data in the database. These measurements include bandwidth checks under different environmental conditions (as cavity temperature and pressure in the isolation vacuum or helium vessel circuit), fundamental mode tracking under transient condition (e.g. pumping or cooldown/warmup) and control of tuner/piezo functionality for subsystem verification. A set of applications allows to perform checks of the cavity behaviour with respect to the expected effect due to the change in the environmental condition (e.g. pressure sensitivity, temperature effects, tuning sensitivity).

ESS CAVITY DATABASE

The database is built on the Measurement&Calibration Database (M&CDB) offered by the ESS Integrated Control System services. The M&CDB is an owncloud service meant to store and index binary datafiles in the Hierarchical Data Format (HDF) [5]. The choice of this format allows the use of metadata tags to perform data aggregation. In particular, this allows the mandatory tagging of the measurement data to the ESS Enterprise Asset Management tool tracking the inventory of accelerator components installed in the linac. Helper applications allow to perform the transfer of the data received from the IK during the cavity and module handover stages in Table 1. The data is transferred into a staging area, then converted to HDF files.

The database applications, including most of the VNA based measurement tools, are available as a set of Python scripts publicly available on the ESS Gitlab [6].

Structure of the Database

The data flow and organization are graphically represented in Figure 1.

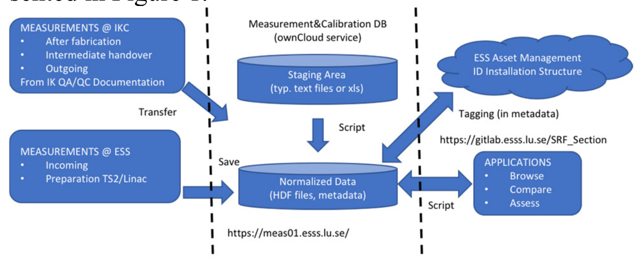

Figure 1: ESS Database data flow and structure.

Workflow for the Series Cavities

The lifecycle of the series cavities in the ESS Cavity Database starts when cavities are ready to be delivered for module installation, after the vertical testing and preparation for shipment, and is currently tracking the medium beta cavity production. Provisions for starting to track the high beta structures are in place and the activity will start with the delivery of the first series cavities.

At the cavity handover the institution responsible of the cavity delivery makes available, from their quality management system, the datasets listed in Table 1. ESS transfers the data, normalizes them as HDF datasets in the DB and perform the verification of the cavity handover (according to the procedure described above). Currently, the data handover is performed using the Alfresco system set up by INFN for the medium beta cavity production follow-up [1]. A similar mechanism will be available with STFC for the high beta cavities.

As the cavity reaches CEA, the data for the incoming inspection is again transferred to ESS and stored into the DB, using the same mechanism, and the handover conditions verified.

Cavity data according to the list in Table 1 will also be available in the documentation set provided at the module handover from CEA, and will be transferred to the DB and verified.

As soon as the module is received at ESS all data taken with the automatic measurement tools is immediately stored in the M&CDB in HDF native format, and is instantly available for the verification activities.

The component for the prototype medium beta cryomodule (M-ECCTD) did not follow the workflow foreseen for the series production and, as part of the DB deployment process, were made available by INFN and CEA and were used to populate, with an ad-hoc procedure, the cavity database, in order to have it available for the TS2 commissioning phase with this module.

DATABASE APPLICATIONS

A number of applications and modules have been developed to browse, compare and assess the data in the DB or to populate it directly at ESS with further measurement activities. All measurement data is incapsulated in a hierarchy of classes, for reusability across applications.

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All the applications are developed as Python scripts and are platform-independent, and are available on Gitlab at ESS [6].

Table 2 describes briefly the available applications in the DB framework, with a brief description of their scope.

Table 2: ESS Application Framework Components

Component	Scope
CavityReception	Transfers to the DB the cavity data downloaded from the cavity in kind quality management system. Performs checks of the completeness of the incoming data package. Data is transformed to HDF files and stored in the DB.
ModuleReception	Transfers the Cavity data provided from CEA with the module handover documentation. Data is transformed to HDF files and stored in the DB.
BWExplorer	Allows to browse, compare and analyse the cavity data available from the HDF files contained in the Measurement DB. Generate historical plots (e.g. frequency of π mode along lifecycle).
VTExplorer	Browses and analyses the vertical performance data available from the HDF contained in the Measurement DB, either one by one or in summary plots.
bwClasses	Measurement data encapsulation in object classes and serialization to and from files.
PyMeasure	VNA measurement of cavity transmission properties (S21) in the fundamental bandwidth, with mode identification and analysis. Stores HDF files into the Measurement DB.
PyMeasureHOM	VNA measurement of cavity transmission properties (S21) to detect HOM modes close to the integer beam lines.
PyTrack	VNA tracking of the cavity fundamental mode under changing environmental conditions (e.g. temperature, pressure).
VNAClasses	VNA management classes.

DATABASE IMPLEMENTATION STATUS

Series Cavities Frequency Analysis

As of writing, the first four medium beta series cavities have been handed over from INFN to CEA and are presently integrates into the first cryomodule, which will be delivered to ESS in fall 2019 after testing at CEA.

Figure 2 shows the BWExplorer application view of the available measurements of cavity M001. When one of the available measurements is selected from the listbox, the measured spectrum is shown in the bottom part of the application window, along with the metadata providing information on the measurement conditions.

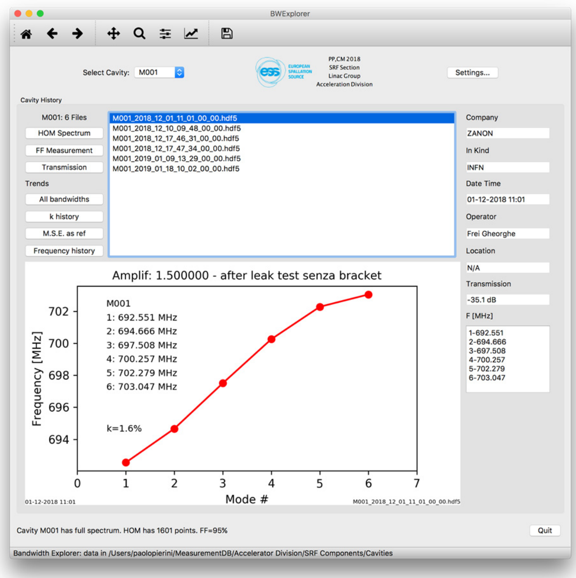

Figure 2: Explorer application to browse data for the first medium beta cavity of the series production.

The explorer application allows the access, whenever available, to extended datasets related to measurement of field flatness along the cavity after fabrication, transmission of all bandwidth modes and HOM spectra, and allows to show trends across the measurement present in the DB for the cavity, as shown in Figs. 3-5.

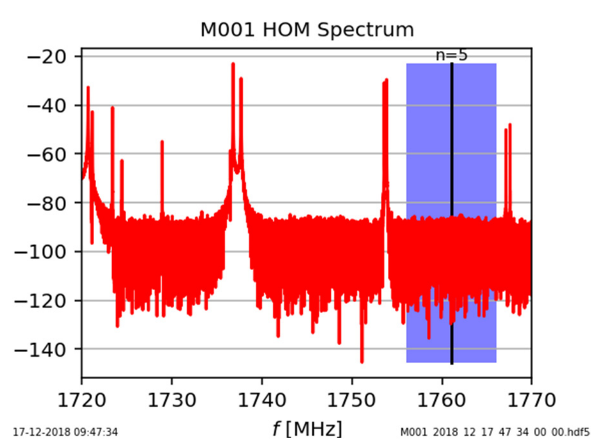

Figure 3: HOM spectrum at cold for M001, showing no mode within 5 MHz of the 5[th] beam harmonic.

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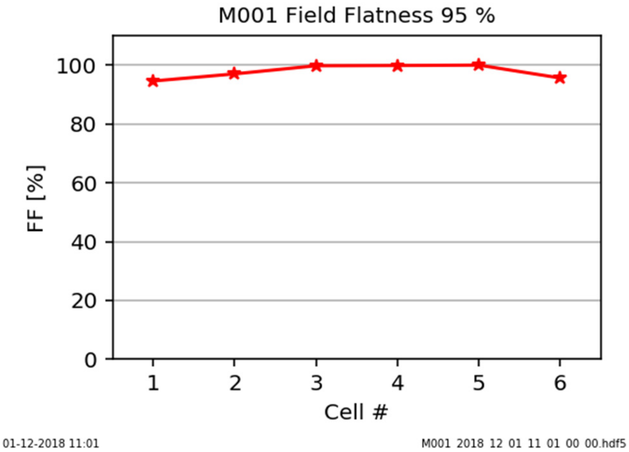

Figure 4: Field flatness of M001 after fabrication.

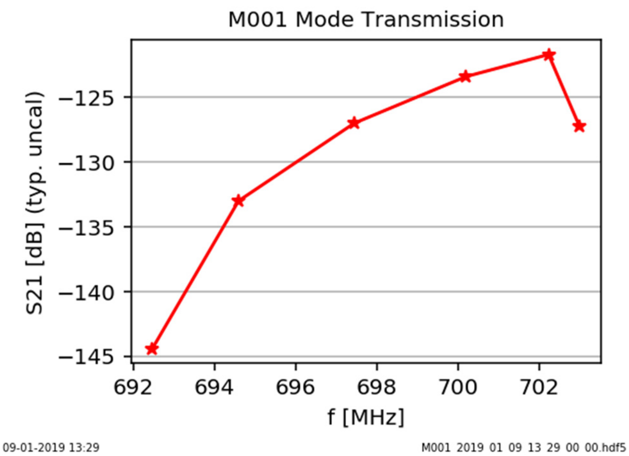

Figure 5: Calibrated transmission of M001 (outgoing measurement from INFN to CEA).

Figure 6 shows the mse value for all available measurements, taking the reference spectrum at cold. Measurement #1 is taken before the final BCP (when field flatness is measured), #2 is the reference warm spectrum, #3 is the spectrum during VT and #4 and #5 are the outgoing and incoming measurement between INFN and CEA, respectively. Compliance to handover condition is satisfied.

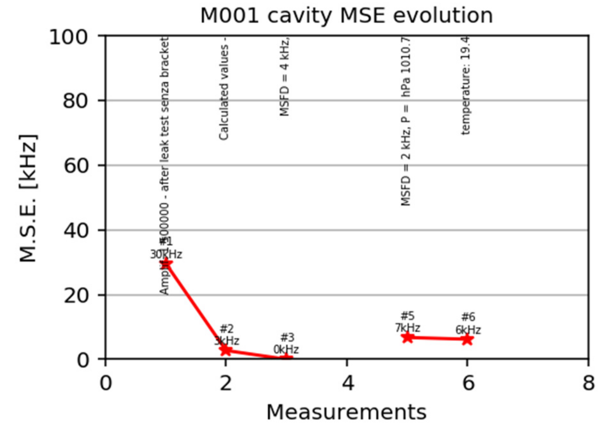

Figure 6: MSE with reference the spectrum at cold in VT.

M-ECCTD Prototype Data

The cavities assembled in the M-ECCTD prototype were provided by CEA and INFN as part of the development effort for the ESS components and did not follow the tracking procedures established for the series components. However, during the module preparation, a large amount of measurements were taken at INFN and CEA to supervise the string preparation and the module assembly procedures. This data has been made available from INFN and CEA for transfer into the ESS cavity database, so that the preparation and testing experience of this module can serve as an important benchmark during the testing phase at ESS, for the commissioning of the Test Stand 2 and the supervision of the testing procedures.

Figure 7 shows the fundamental mode frequency data for the LASA MB001 prototype which is installed in the M-ECCTD. It starts from the measurements at the end of the cavity production to the string assembly phases (with installation of the tuner components, vacuum pumpdown and venting in the cavity string and in the module isolation vacuum) and ending with the cold test operations, the incoming reception at ESS and the handling at the Test Stand 2 during isolation vacuum tests. Key phases are highlighted to explain the main observed variations in the cavity frequency during the module preparation and handling.

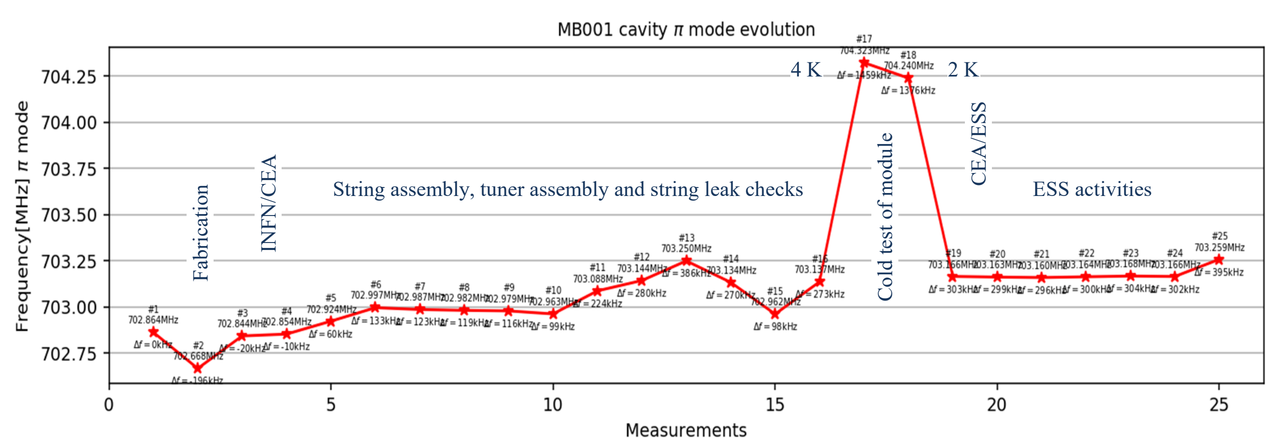

Figure 7: Frequency evolution of MB001 during cavity handover, module installation, test at CEA and handling at ESS.

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The analysis of the behaviour of the four cavities in the M-ECCTD module allows to derive the expected sensitivity of the cavity frequency with respect to the change in the environmental conditions during module preparation and handling. The main outcome of this analysis is presented in Table 3 and will be used during the ESS operations.

Table 3: Expected Frequency Variations for Environmental Conditions Changes during Module Handling

Condition	**Value [kHz]**
String:VAC, VV/Tank: PA, RT to 4.2 K	1172±18
String:VAC, VV/Tank: PA, RT to 2 K	1095±14
4.2 K to 2 K (1 bar to 30 mbar)	-76±7
String from PA to VAC (VV/Tank PA)	184±11
VV from PA to VAC (String VAC, Tank PA)	99±18

Series Cavities Qualification Data

The cavity qualification data during the vertical tests performed by the in kind partners is transferred and stored in the cavity DB during the handover for the installation in the module. Figure 8 shows the. VTExplorer application used for displaying the available measurements in the DB. The transferred data contains also important calibration constants determined during the cold test in near critical RF coupling conditions (the Q_{ext} of the transmitted antenna and the antenna calibration coefficient).

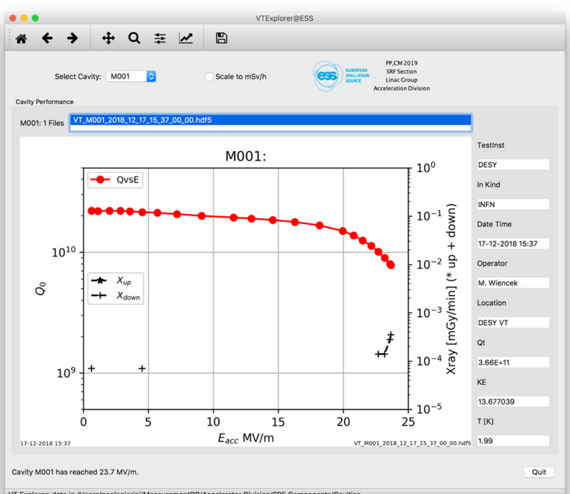

Figure 8: Explorer application to browse vertical test result data.

Measurement Dataset at ESS

A set of applications allows to automate VNA transmission measurement of the module cavities, once arrived in the incoming inspection area of the ESS Test Stand 2 and store directly the data in the Cavity DB. At ESS the full data read by the instrument during the mode identification is stored in the measurement files. Analysis of the individual VNA scans around the bandwidth modes allow to evaluate loaded Q measurement from the transmission curve, as shown in Fig. 9.

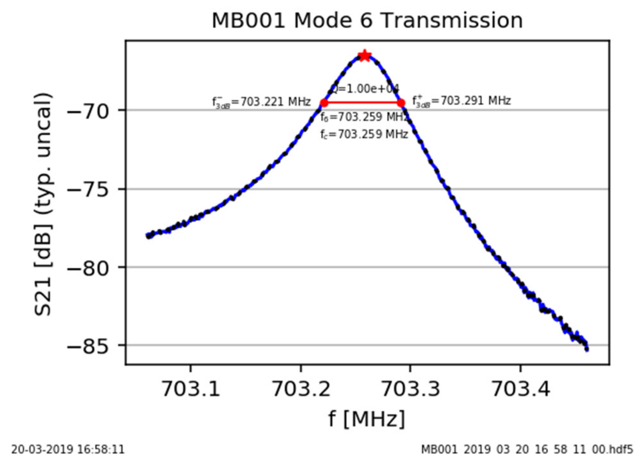

Figure 9: Bandwidth analysis of the fundamental mode, for loaded Q measurement.

CONCLUSION

A database has been set up for the assessment of the ESS elliptical cavities handover conditions between partners and will be an important asset for the testing, commissioning and operation of the ESS linac. A variety of browsing, comparison and assessment tools have been built to help during the module lifecycle phases and to monitor the component behaviour with respect to expectations during the preparation for the testing processes at ESS. The database is in place and is currently being populated with the series cavity production data. The large amount of data available from the prototype medium beta elliptical cryomodule, gathered during the INFN and CEA testing, has been fed to the database in order to assist in the testing operation that soon will start at the ESS Test Stand 2 in Lund. The database fulfils the ESS requirement to safely store important data on the accelerator component, that will be needed for fault finding, maintenance and operation of the facility.

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[6] The SRF Section Application Repository is Available on the ESS Gitlab. `https://gitlab.esss.lu.se/SRF_Section`