Status of IN2P3 contributions to ESS and MYRRHA

Introduction

IN2P3 is contributing for decades to the design and construction of superconducting accelerators such as ESS (European Spallation Source at Lund, Sweden) and MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications at Mol, Belgium). An up-to-date status of the on-going activities is presented for those two projects.

Contribution to MYRRHA

IN2P3 involvement for the development of an ADS facility at Mol started more than 20 years ago and has strengthened mainly through several R&D programs within the several Framework Programs supported by the EU: PDS-XADS, IP-EUROTRANS, CDT, MAX and MYRTE. In September 2018, an important step has been taken with the official agreement of the Belgium Council of Ministers to build the Phase 1 of MYRRHA (so-called MINERVA).

Before this official green light, since 2017, three laboratories of IN2P3 (IJCLab, LPSC and IPHC) are strongly involved within R&D programs and studies aiming at the construction of MYRRHA-Phase 1, so called Minerva. Indeed, three dedicated project agreements (PA), called NR1, NR2 and NR5 which are parts of the global Cooperation Agreement between SCK CEN and IN2P3, have been signed. The main objectives of those PAs are:

- For NR1 (2017-2020): perform specific studies to help bringing the design of the 100 MeV MYRRHA accelerator dedicated to construction phase
- For NR2 (2017-2020) and its addendum (2020-2022): design, manufacture and test a prototype accelerating module representative of the 15 to 100 MeV energy section of the MYRRHA accelerator.
- For NR5 (2020-2024): pursue the studies done in NR1 to help bringing the design of the MINERVA accelerator to the construction phase and a successful industrialisation with a dedicated support to the procurements of the series cryomodules and their installation.

One has to note that another PA (NR6), dedicated to the qualification tests of critical components such as cavities, couplers and cold tuning systems, is under discussion and would possibly involve IJCLab for a period of 3 years.

Contribution to ESS

For more than 15 years, IN2P3 is a major partner of the ESS project. Since 2013, IN2P3 contributes to the construction of the ESS linear accelerator (linac) especially through the laboratory IJCLab, which is strongly involved in the Spoke section construction. This contribution is done via two Work Packages (WP):

- WP4 (total cost of 17.5 M€): to design and provide 13 Spoke cryomodules

- For WP11 (total cost of 2.5 M€): to design, provide and install the cryodistribution line (13 valve boxes and cryogenic lines) of the Spoke section

NB: IN2P3 contributed also to the construction of the elliptical section of the linac through the WP5 (0.3 M€) which goal was to design and follow-up the fabrication of the elliptical cryomodules (excepted the cavities, couplers and cold tuning systems). This WP5 is finished and the status presented in this document will be done only on WP4 and WP11.

Status of IN2P3 contribution to MYRRHA

NR1 status

This PA has been signed in July 2017 for a period of 3 years.

The PA was composed of 4 tasks including studies on beam dynamics studies (Task 2), design of the fast switching magnet of the 17MeV MEBT3 (Task 3), design of the whole accelerator vacuum system (Task 4), development of beam position monitor diagnostics systems (Task 5). The PA also included the general coordination of all the CNRS contributions defined in the frame of the CNRS/SCK•CEN Project Agreements related to the development of the MYRRHA 100 MeV accelerator (Task 1).

90 men.months have been devoted to the studies listed before shared between IJCLab (44 m.m), LPSC (36 m.m) and IPHC (10 m.m) laboratories for a global cost of 447.7 k€ (283.7 k€ of manpower and 164k€ of equipment and consumables).

The PA is completed to 95%. Among all the work done within those 4 years, one can note that:

- **A detailed start-to-end design and beam simulation of the linac has been done with extensive error studies.**

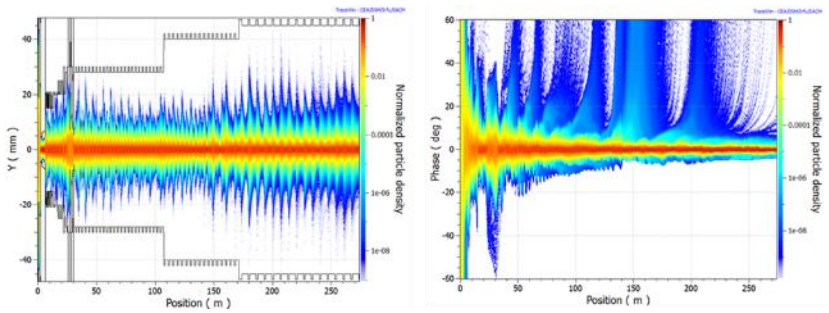


Figure 1 : Superposition of the beam distributions (3.106 particle per distribution) within 1000 linacs simulated for errors study [5]: vertical transverse densities (left), longitudinal transverse densities (right).

- **A complete magnetic and mechanical design of the fast switching magnet has been proposed**

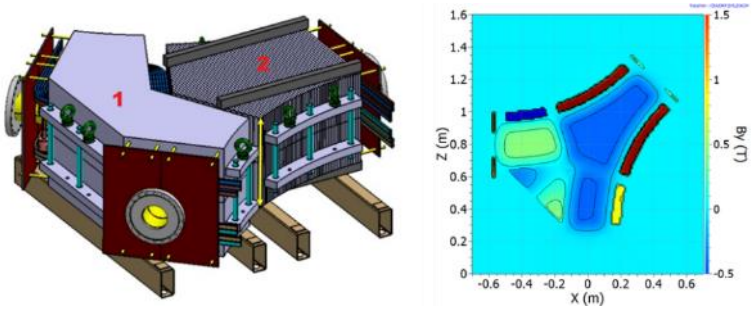


Figure 2 : Design of the switching magnet. The upstream part, labelled 1, produces a static dipolar field. The downstream part, labelled 2, represents a switching polarity dipole. The right panel shows a horizontal plane section with the vertical component of the

- **The vacuum system of the whole linac has been modelled and simulated.**

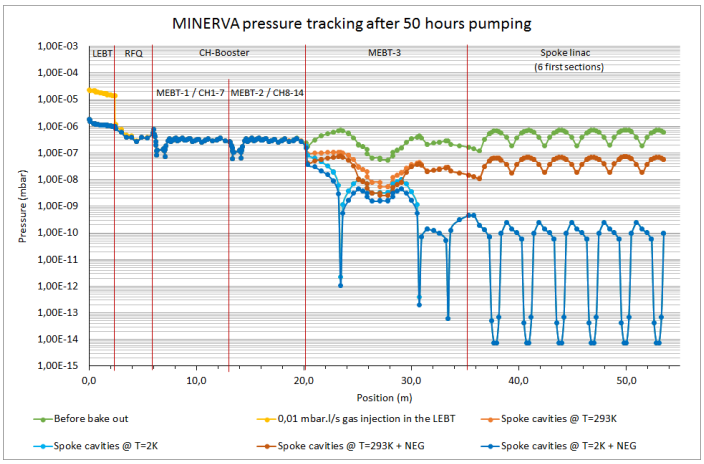


Figure 3 : Pressure from LEBT up to 6 first sections of the LINAC after 50 hours pumping.

- **An optimized BPM prototype has been designed and ordered**

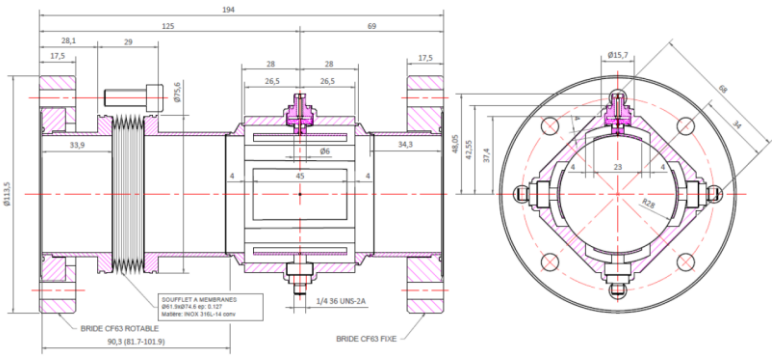


Figure 4 : BPM final prototype

The deliverable of Task 5 is missing due to the delivery delay of the BPM. The completion of this task is planned in February 2021 with the final test of the BPM that has been delivered end of December 2020.

NR2 status

This PA has been signed together with NR1 in July 2017 for also a period of 3 years. IJCLab and LPSC laboratories are the two laboratories involved in the project.

This PA aims at designing, manufacturing and testing a prototype accelerating module representative of the 17 to 100 MeV energy section of the MYRRHA accelerator. The test at 2K will be performed at IJCLab. Such a module contains two Spoke superconducting cavities (β=0.33) operating at 352.2 MHz with one cold tuning system and one power coupler each. This prototype cryomodule will be supplied by two RF power sources (20 kW CW amplifier per cavity) and associated controls in order to perform its full experimental validation under nominal operating conditions, including fault-recovery procedures – but without beam.

Because of delays mainly due to unexpected long lead time to publish and award two contracts (couplers and valve box) by the SCK CEN, the NR2 contract has been extended in 2020 for a period of 2 additional years (NR2 addendum). This extension will allow to complete the studies and perform the final test of the prototype cryomodule.

Initial plan included 211.5 men.months between IJCLab (176.5 m.m) and LPSC (35 m.m) for a global cost of 1840.6 k€ (919.6 k€ of manpower and 921 k€ of equipment and consumables). Extension of the contract leaded to additional 16 m.m for a global cost to 122 k€ (84.27 k€ of manpower and 38 k€ of equipment and consumables).

The NR2 project is divided in 11 tasks: coordination (Task 1), spoke cavities (Task 2), cold tuning systems (Task 3), power couplers (Task 4), cryogenic valve box (Task 5), cryomodule vessel (Task 6), RF amplifiers (Task 7), LLRF systems (Task 8), C&C systems (Task 9), cryomodule test (Task 10) and finally design update based on cryomodule test results (Task 11).

The status of today for each task is the following:

Task 2: the two cavities have been designed, manufactured and successfully tested in vertical cryostat well above the specifications. Those cavities are presently at manufacturer premises for minor modifications and will be back in mid-January. They are ready for cryomodule assembly operation.

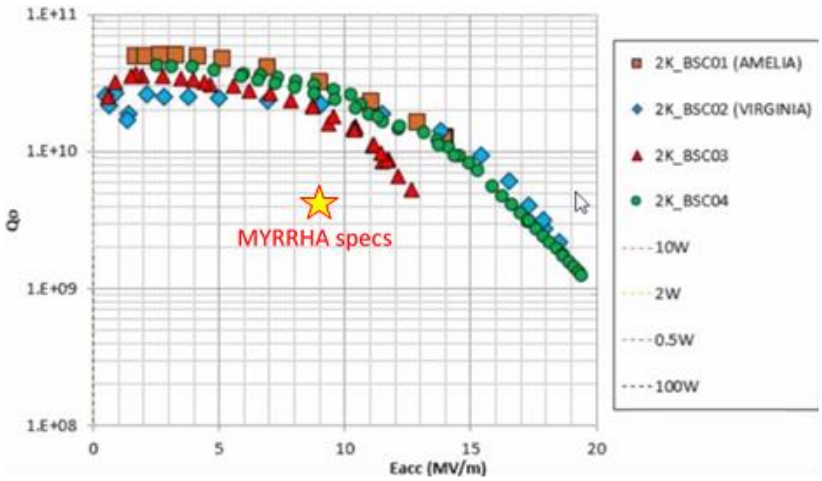


Figure 5 : Test results @ 2K at IJCLab of the the four prototype cavities: Qo factor vs. accelerating field.

Task 3: Four cold tuning systems (CTS) have been designed and manufactured. The first CTS has been successfully tested at room temperature with its piezo-actuators. A long term test (for 2 months) of two CTS @ 77K is planned in April 2021 before cryomodule assembly.

Figure 6 : Picture of the first CTS system developed for MYRRHA at IJCLab.

Task 4: six couplers, designed by the LPSC, have been manufactured and delivered in December 2020. Preparation for the RF conditioning test of the first two couplers is in progress at IJCLab and their RF conditioning is planned end of March 2021.

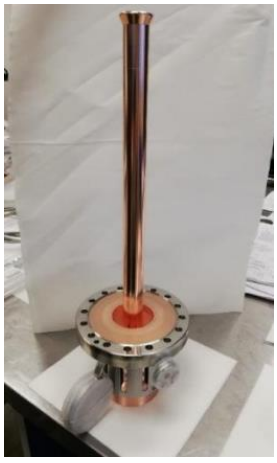


Figure 7 : Fabrication of the MYRRHA coupler designed at LPSC.

Task 5: the cryogenic valve box fabrication has been delayed and is still on going. It is close to completion and its delivery is planned end of January 2021. A cryogenic qualification test is planned in March 2021.

Task 6: the cryomodule vessel and its auxiliaries (thermal shield, cryogenic lines, magnetic shield…) has been delivered to IJCLab in December 2020.

Figure 8: Picture of the cryomodule vessel for MYRRHA.

Task 7: the 3 amplifiers (2 x 20kW for the cryomodule test and 1x 80kW for the RF conditioning test-stand of the couplers) have been delivered by IBA. Installation of the 2x20 kW amplifiers is almost completed and, installation of the 80kW amplifier is in progress and will be finished beginning of February.

Figure 9 : Pictures of the 2x20kW RF amplifier.

Task 8: RF front end of the LLRF systems has been designed, realized and the last firmware implementation and RF tests are under progress. Tests of qualification of RF interlocks prototypes (multipacting, arc detector) are also progressing well. Software/VHDL code development is ongoing and will be improved during the cryomodule qualification at 2K. The first complete LLRF system is expected to be tested beginning of April 2021.

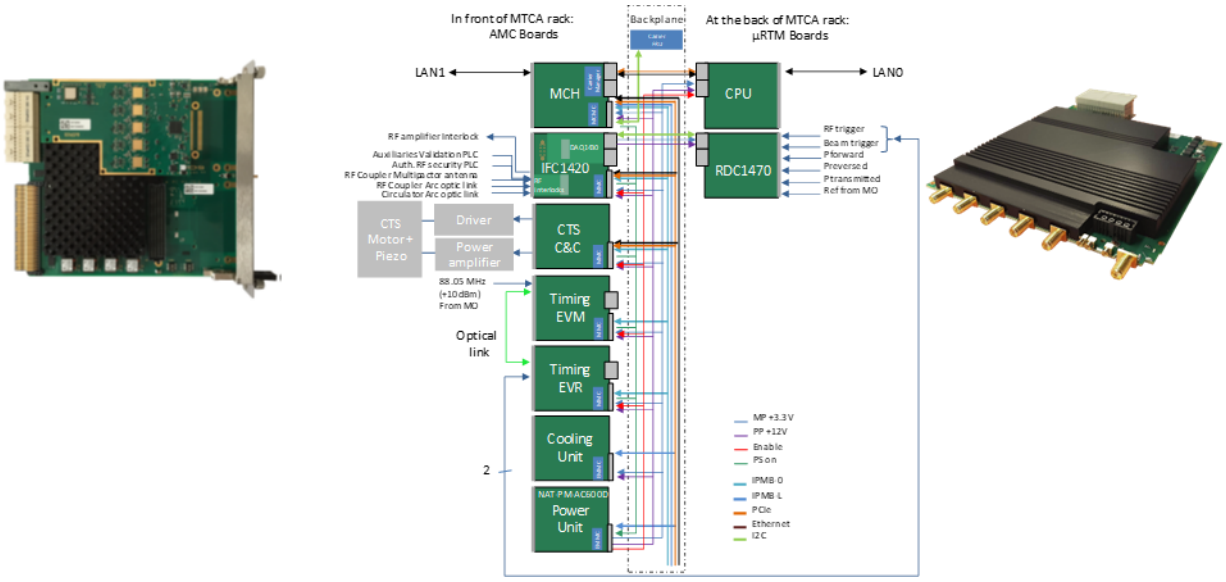


Figure 10 LLRF MTCAS based scheme with to the left side, main digital board called IFC_1420 (AMC format) and on the right side, the RF frond-end RDC_1470 board (µRTM format).

Task 9: Design and purchase of components are finished. The cabinet dedicated to cryogenic controls and interlocks has been assembled. Software/code development is progressing and a first commissioning test is planned next month in order to be ready for the valve box cryogenic qualification test in March 2021.

Figure 11 : Picture of the cabinet assembly at IJCLab dedicated to cryogenic controls and interlocks.

Task 10: The preparation of the cryomodule test area is still under progress. This is an important manpower consuming task. The two RF amplifiers have been installed. Auxiliaries utilities (cryogenics lines, instrumentation, cables…) have been ordered. The radiation protection system of the area is presently being updated and should be achieved in February. The preparation of the cavity string in clean room is planned in March 2021, followed by the completion of the cryomodule assembly in April 2021. Cryogenic and RF qualification test @ 2K of the prototype cryomodule with its valve box is planned in June this year.

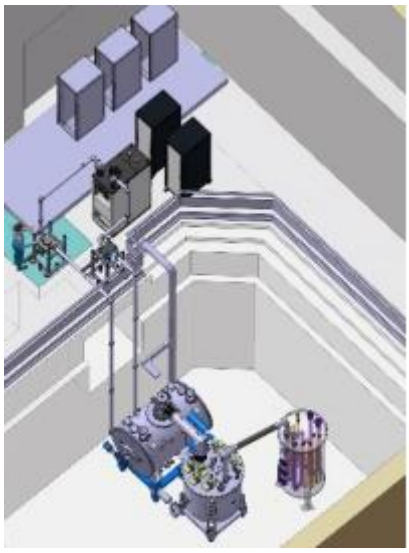


Figure 12 : 3D overview of the MYRRHA cryomodule test area at IJCLab.

Task 11: not yet started. Waiting for the test result of the prototype cryomodule.

NR5 status

This PA started in November 2020 for a period of 4 years.

NR5 is part of the pursuit of the NR1 contract in which a large R&D effort was done by IN2P3 laboratories (IJCLab, LPSC and IPHC). It ended-up to an important and extensive know-how which is a real key point for the construction phase of MYRRHA. This new project aims at gathering this know-how and strengthen the interactions between the critical tasks: beam dynamics, vacuum layout, HEBT beam position monitor, long term R&D beam profile monitor, injector commissioning. A specific task is dedicated to give an expertise support to SCK CEN during the call for tender period for purchasing the components of the series cryomodules. Other tasks were discussed like magnets design, BPM stripline, mechanical integration, cryomodule facility for tests and training. Some of them will can be added to this contract as addendum.

The contract is ready to be sign by IN2P3 and SCK CEN, delay occurs from the SCK CEN administration. The starting date of the NR5 contract is November 2020.

Initial plan includes 141 men.months between IJCLab (55 m.m), LPSC (78 m.m) and IPHC (8 m.m) for a global cost of 831 k€ (558 k€ of manpower and 237k€ of equipment and consumables).

NR5 is composed of 7 tasks: coordination (Task 1), beam dynamics studies (Task 2), vacuum system (Task 3), HEBT BPM (Task 4), beam diagnostics: Profile monitor (Task 5), injector RFQ commissioning (Task 6) and expertise support (Task 7).

Work has already started on task beam dynamic in order to fully freeze MEBT3 and HEBT layouts. Vacuum studies will start according updated specifications provided by SCK CEN. The long term R&D into a profile monitor task starts in September 2021 with a PhD already supported by IN2P3. The task

focus on expertise support on the procurement is already on the way due to SCK CEN needs in that field.

NR6 status

This project is under discussion between IN2P3 and SCK.CEN. It is related to the construction and industrialization phase of MYRRHA and would involve IJCLab for a period of 3 years. Ongoing discussions are on the qualification test of the critical components: 60 Spoke cavities, 60 cold tuning systems and 60 power couplers. It may involve almost 200 m.m.

Thesis

It is important to notice that three PhD students are working on the MYRRHA project.

The first PhD at LPSC is engaged on the potentiality of Neural Network to model the accelerator. This PhD was a CIFRE contract with ACS company, the defence is planned in March 2021.

The second PhD at IJCLab is engaged on the HEBT beam dynamic and BPM studies. This PhD is also CIFRE contract with Thales company. The defence is planned in April 2021.

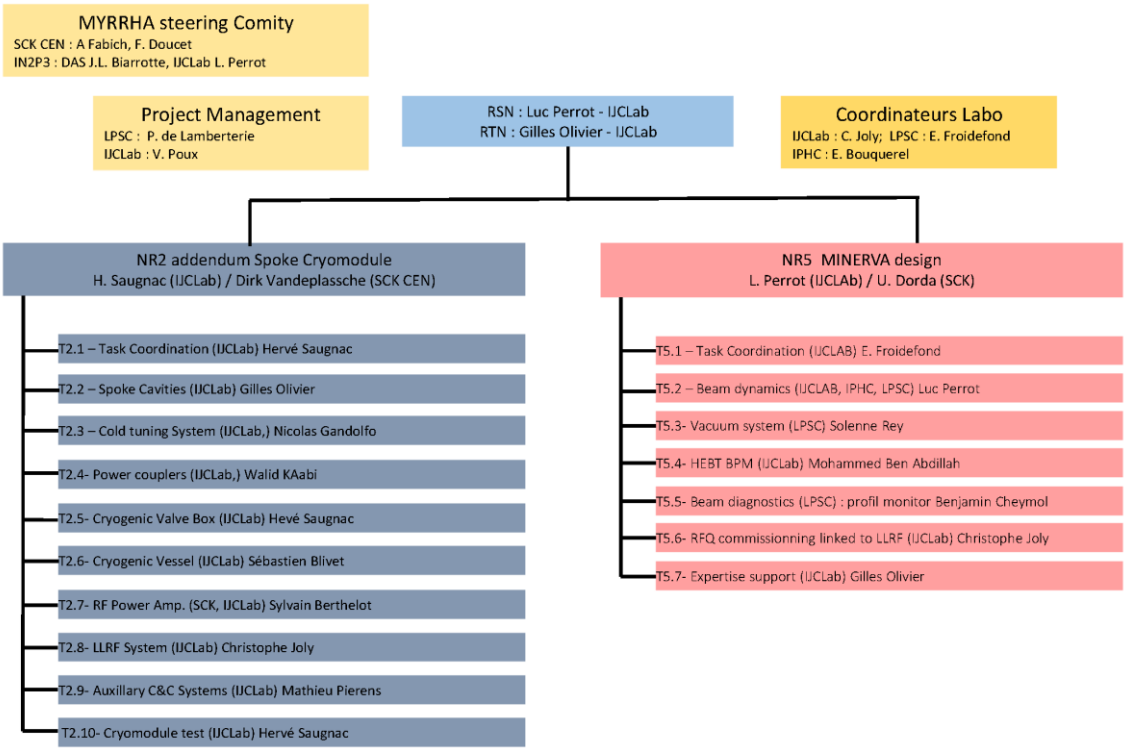
The third one just started at IJCLab in November 2020 in collaboration with ACS company (again a CIFRE contract) whose one of the main objective is the cryogenic modelling of the MYRRHA prototype cryomodule.

Finally, IN2P3 will also support a PhD from October 2021 at LPSC to work on the transverse beam profiler device for MYRRHA (NR5 project, task 5).

Organisation/coordination

IN2P3 engagements to MYRRHA is integrated in the master project MYRRHA (08-AT-115) with the two associated project: cryomodule spoke (08-AT-015-1105) and linac design (08-AT-015-1104).

IN2P3 organigram since end of 2020 is the following:



Communication

- F. Bouly et al., “Status of MYRRHA fault tolerant linac project”, LINAC2020
- M. Debongnie, “Training of a Neural Network to Model the MYRRHA LEBT for Reliability Improvements”, IN2P3/IRFU Machine Learning workshop, Janvier 2020, CC-IN2P3, https://indico.in2p3.fr/event/20187/overview
- M. Debongnie., “Entrainement de réseaux de neurones pour la modélisation d’injecteurs de particules et la fiabilisation des accélérateurs de haute puissance », séminaire Sept. 2020, IJCLab, https://indico.ijclab.in2p3.fr/event/6393/

Status of ESS

More than 93 FTE have been involved into the WP4, WP5 and WP11 activities since 2014 including, for instance, 19 FTE in 2020. Estimation for 2021 is 17 FTE and 4 FTE for 2022.

WP4 status

IN2P3 commitment to ESS is to deliver 13 Spoke cryomodules. IJCLab has designed every component of the Spoke cryomodules. All components have been ordered and most of them have been delivered to the laboratory. Every critical component (Spoke cavity, coupler and cold tuning system) is prepared

and tested individually at IJClab then assembled into the cryomodules. A cryomodule is composed of 2 cavities, 2 couplers and 2 cold tuning systems and auxiliaries such as thermal and magnetic shields, cryo piping, sensors… After their assembly at IJCLab, every cryomodule goes to Uppsala to be fully tested at high power and 2K before shipping to Lund site.

Status of the qualification phase of critical components:

Spoke cavities:

All cavities have been delivered (29 in total). 16 cavities have been successfully qualified within the ESS specifications. 10 more cavities will be tested until July 2021 (test rate of 2 cavities a month).

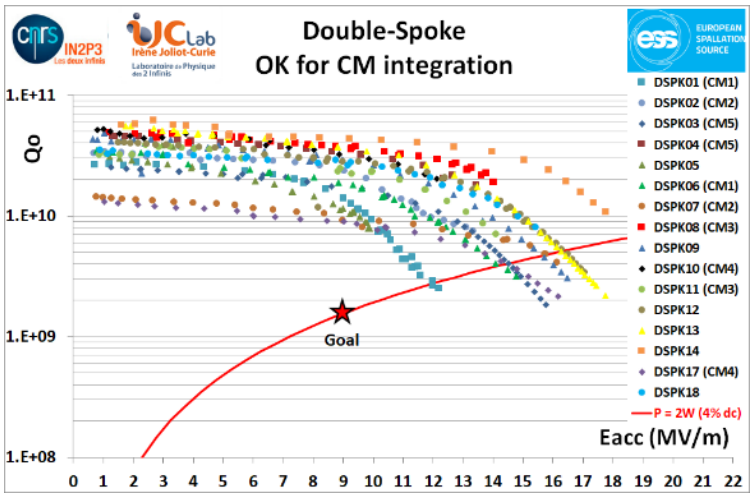


Figure 133 : Test results @ 2K at IJCLab of 16 qualified Spoke cavities: Qo factor vs. accelerating field.

Couplers:

26 couplers (over 30) have been delivered. Up to know, 14 couplers have been successfully conditioned. 6 additional couplers have been prepared and will be tested before the end of February 2021. A conditioning rate of at least 2 couplers a month is also planned to cope with the test planning of the cavities. All couplers should be tested before end of July.

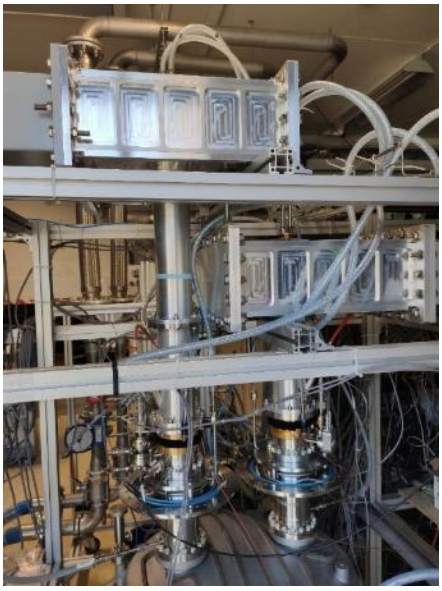


Figure 144 : Picture of 2 couplers during their RF conditioning at IJCLab.

Cold tuning systems (CTS):

30 CTS have been delivered. 23 CTS have been successfully qualified. The qualification phase is almost finished.

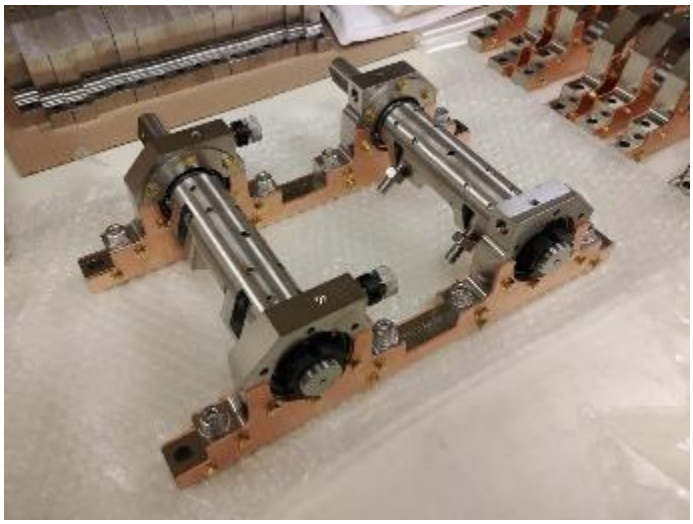


Figure 155 : Picture of a cold tuning system .

Status of the cryomodules assembly:

There is a delay in providing Uppsala and Lund with cryomodules due to the COVID19 situation and three events which led to major non-conformities. Status of today is that 2 cryomodules have been sent to Uppsala, 1 tested but not validated due to a technical issue with a cold tuning system. The second cryomodule has just arrived to Uppsala mid-January. Therefore, nowadays, there is no qualified series cryomodule on site at Lund ready for installation into the tunnel.

CM1:

IJCLab started the assembly of the first cryomodule (CM1) just before the lock-down due to COVID19 in March 2020. As a result, IJCLab was unable to deliver the cryomodule as expected in April. After the lock-down in June, IJCLab committed in delivering 3 cryomodules to Uppsala before end of 2020. A gradual resumption led to the completion of the assembly of CM1 end of August but, during the final checking operations, a major event occurred with the brake of one coupler. CM1 has been hold in quarantine and waits for repair actions.

Figure 166 : Picture of the cryomodule CM1 during the final leak tightness test before the coupler issue.

CM2:

Assembly of CM2 started right away after CM1 issue, beginning of September, and was delivered on October 19th to Uppsala.

Figure 177 : Picture of the cryomodule CM2 rigth after its arrival at Uppsala.

Despite very good results of the cavities (Eacc > 12 MV/m) and couplers and a validation from the cryogenic point of view, this cryomodule has been rejected due to a major non-conformity (cold tuning system stuck). It will be back to IJCLab for repair mid-January.

CM3:

The CM3 was assembled in duly time from mid-October till end of November and was ready to be shipped beginning of December when a leak was detected on the cavity vacuum. This major non-conformity forced IJCLab not to send the cryomodule to Uppsala.

CM4:

The CM4 assembly occurred in December and ended the first week of January. The dispatch has been done on January 6th and the cryomodule has been delivered on Monday 11 January. Two technicians from IJCLab will go to Uppsala for technical support (cryomodule connexion to the valve box).

CM5:

IJCLab started first week of January the assembly of CM5. It should be ready for transportation to Uppsala beginning of February.

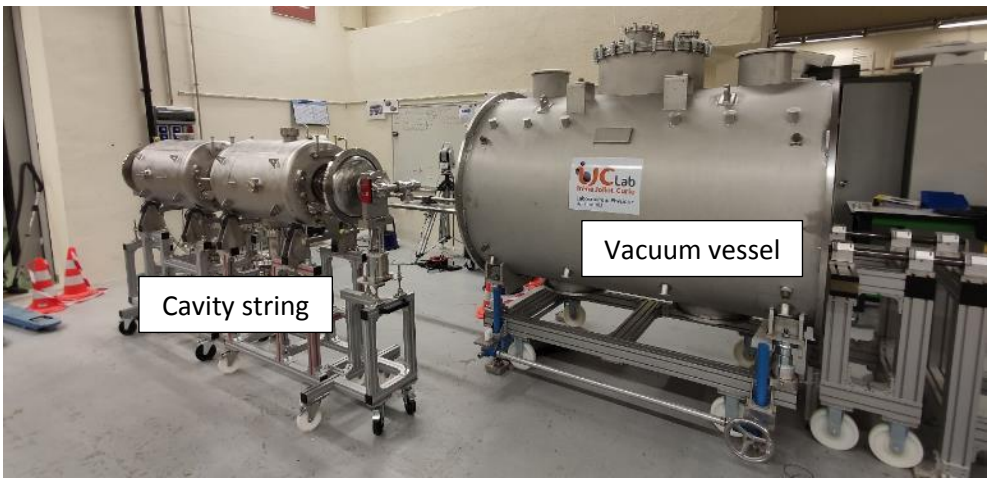


Figure 188 : Picture of the cryomodule CM5 assembly: cavity string before its intergation into the vacuum vessel.

CM6:

In parallel, the assembly of a new cavity string started into the Supratech clean room and will be used for the CM6 assembly. It should be available by the end of January.

Figure 199 : Picture of a cavity string (2 cavities + 2 couplers) assembled together into the clean room at IJCLab.

Cryomodules repairing:

In parallel, the repair operations will start on CM2 as soon as it will be delivered (most probably mid-January) and beginning of February on CM3 after the shipment of CM5 to Uppsala.

Planning for 2021-2022:

In addition to the CM4 already delivered to Uppsala, 9 more cryomodules are expected to be assembled at IJCLab in 2021 and 3 in 2022. The last of the 13 cryomodules should be delivered to Uppsala mid-April 2022.

WP11 status

IN2P3 commitment to ESS is to deliver and install the Cryogenic Distribution System (CDS) for the Spoke section of the linac, consisting in:

- 13 Valve Boxes (VB): producing superfluid helium and managing the distribution of the cryofluids to the cryomodules;
- 13 Headers Units (HU): being sections of a multichannel cryoline and linking the VBs together;
- 1 End Box (EB): a termination box looping the cryolines to send back the excess flow to the cryoplant and which is a source of superfluid helium for the cooling of the low pressure line and for the load regulation of the cryoplant;
- Auxiliary lines: a set of four circuits installed at the roof of the accelerator tunnel.

IJCLab, or its subcontractors, designed every component of this Spoke CDS and all components were ordered. Most of them were manufactured, prepared and tested individually by IJClab's staff at the manufacturer's workshop using specifically design tooling.

Status of the Valve Boxes (VBs):

Nine of the thirteen VBs were finalized (manufactured and fully tested) and 3 were sent to ESS. ESS requested piping modifications at the end of August 2020 and all VBs started to be refurbished. Currently, two refurbished VBs are nearly finalized and the others eleven will be ready by the end of March 2021.

Figure 20: Picture of BV5 (left) and BV6 (right) during FAT at Cryodiffusion's test area on December 17th.

Status of the Headers Units (HUs):

All of the thirteen HUs were finalized (manufactured and fully tested) and 3 were sent to ESS. ESS requested piping modifications at the end of August 2020 and all HUs started to be refurbished. Currently, 70% of the piping is refurbished. All HUs will be ready by the end of March 2021.

Figure 21: Picture of HU1 during assembly.

Status of the End Box (EB):

The End Box was manufactured and tested at the end of 2020. Decision of its delivery to IJCLab (and then to ESS) is now pending the visual inspection of the inner piping.

Figure 22: Picture of the End Box: Left: pressure test at SDMS – Right: He leak test after LN2 cool-down at SDMS.

Status of the auxiliary lines:

The auxiliary lines were manufactured and then fully installed in the ESS tunnel. During a pressure test in September 2020, a component failed on one line. This line was hence disassembled with dedicated designed tool and is now being repaired at the manufacturer's workshop before its re-installation scheduled to start at the end of February.

Figure 23: Picture of the auxiliary lines: installation of the auxiliary lines in the tunnel.

All mechanical supports for the VBs and HUs were procured, shipped to ESS and installed in the tunnel.