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CHALLENGES IN SUPERCONDUCTING ACCELERATING MODULE DESIGN AND CONSTRUCTION FOR HIGH POWER PROTON ACCELERATORS

C. Madec†, CEA, Saclay, France

Abstract

CEA is engaged in the construction of the Linear IFMIF-Prototype Accelerator (LIPAc), SARAF and ESS superconducting linacs and in particular in the design and production of their accelerating cryomodules: 1 for LIPAc composed of low-beta half-wave 175 MHz resonators, 4 half-wave 176 MHz resonators for SARAF and 32 medium and high-beta elliptical cavity resonators for ESS. The developments of these RF cryomodules, although at various stages, are led in parallel by the cryomodule team at CEA-Saclay, including all RF, mechanical, thermal, cryogenic, integration and QA-QC aspects in a global approach which attempts to optimise synergies and lessons learnt between these projects. A status report will be presented describing the common approaches and methods, and the systemic particularities of each project.

INTRODUCTION

CEA is designing, building, testing, installing and commissioning accelerator (or part of them) for others labs since 20 years : 352MHz cryomodule for SOLEIL, 88 MHz QWR cryomodules for SPIRAL2, 1.3 GHz cryomodules for XFEL, 175 MHz cryomodule for LIPAC [1] and SARAF [2], 704MHz cryomodules for ESS [3]. Among those cryomodules, SOLEIL and XFEL are operating; SPIRAL2 is under commissioning; LIPAC is under construction; ESS is under prototyping, SARAF is finishing its design. The development of last three cryomodules (CM) are led in parallel by the cryomodule CEA team. This talk will highlight the challenges faced and fruitfully used for the other next projects.

The LIPAC, SARAF and ESS will serve various applications (material study for fusion, nuclear science, production of radiopharmaceuticals, neutrons production for physics studies) and their overview is presented below.

PROJECTS OVERVIEW

The International Fusion Materials Irradiation Facility (LIPAC) aims at producing intense neutron fluxes so as to characterize materials envisioned for future fusion reactors. To this end, two identical Linacs, each accelerating a continuous-wave 125-mA deuteron beam at the final energy of 40 MeV, would be necessary to produce by break-up interactions of the D+ beam with the Li target the required 10^{17} neutrons per seconds with the appropriate energy. Because the accelerators have to reach unprecedented performances, the feasibility is being tested through the design, manufacturing, installation, commissioning and testing activities of a 1:1-scale prototype accelerator from the injector to the first cryomodule [4]. The cryomodule (Figure 1) is one of CEA Saclay's contribution, the others being the injector, the cryoplant and some beam diagnostics.

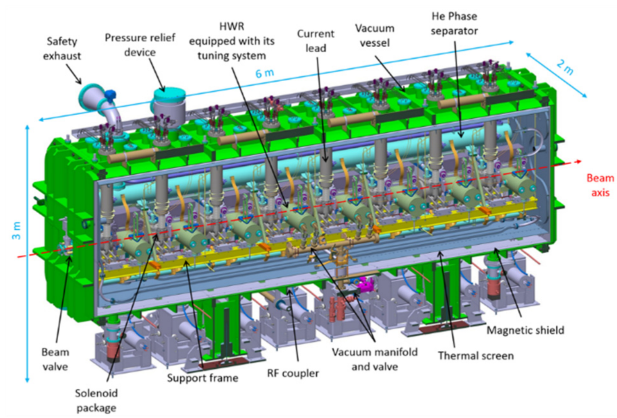

Figure 1 : LIPAC/IFMIF cryomodule.

The European Spallation Source (ESS) will bring new insights to the grand challenges of science and innovation in fields as diverse as material and life sciences, energy, environmental technology, cultural heritage, solid-state and fundamental physics. A 2GeV, long pulse proton accelerator is used to reach this goal. The pulsed length is 2.86 ms and the repetition frequency is 14 Hz (4 % duty cycle). The protons beam is accelerated in a superconducting linac [5] composed of one section of spoke cavity cryomodules and two sections of elliptical cavity cryomodules (Figure 2). These cryomodules, under CEA responsibility, contain elliptical cavities operating at 2 K.

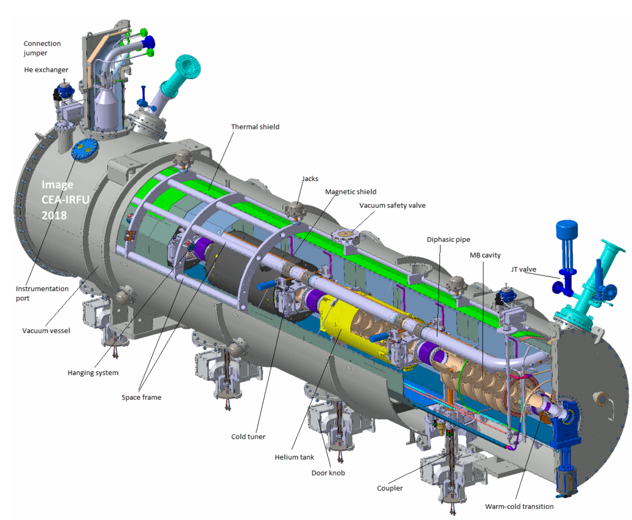

Figure 2 : ESS cryomodule.

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ESS is a collaboration project of 17 European countries and is under construction in Lund, Sweden.

Soreq Applied Research Accelerator Facility (SARAF) will be a multi-user and versatile particle accelerator facility. It is based on a proton/deuteron RF superconducting linear accelerator, with variable energy (5-40 MeV) and a continuous wave (CW) high ion current (0.04-5 mA). The high ion current generates an unprecedented amount of fast neutrons and radioactive nuclei, that may be used to explore rare nuclear reactions, produce new types of radiopharmaceuticals and more. Moderated neutrons can be used for non-destructive tests with similar resolution and contrast as performed in reactors. SNRC and CEA collaborate to upgrade the SARAF accelerator to 5 mA CW 40 MeV deuteron and proton beams by means of a four-vane 176 MHz RFQ, a MEBT and a superconducting linac [6] made of four five-meter cryomodules housing superconducting Half Waves Resonators (HWR), superconducting solenoids and Beam Position Monitor (BPM) (Figure 3).

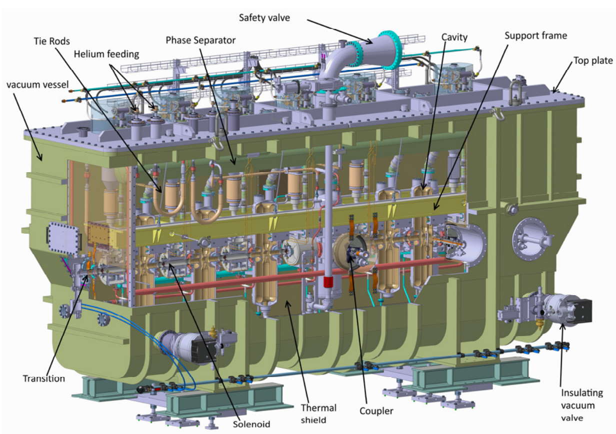

Figure 3 : SARAF Low beta cryomodule.

DEVELOPMENT PLAN

For each cryomodule, CEA cryomodule team is following a development plan including the definition of the requirements, the design of the components (cavities with tuning system, couplers, solenoids and cryomodules), the review of the design by a panel of international experts, the risk analysis and the implementation of a mitigation plan which mostly led to design optimization and critical components prototype manufacturing and validation, the tooling development, the mock-ups tests, the integration and validation with tests. For SARAF and LIPAc, CEA will participate in the installation of the cryomodules and the commissioning of the SRF Linac.

This generic description of the development is adapted for each project and detailed in Table 1. The "x" means that the study and work was not fully under CEA responsibility. As examples, the LIPAC solenoids are a contribution from Spain; ESS transport study output led to secure the cryomodule and the cold mass but the damping frame development and manufacturing is the responsibility of ESS; ESS components manufacturing refers to the manufacturing and qualification of the components but the cavities which are procured by INFN and STFC.

Table 1: Development Plan Steps for Each CEA Project

	SARAF	LIPAC	ESS
Requirements definition	X	X	X
Design	X	X	X
Review	X	X	X
Risk analysis and mitigation plan	X	X	X
Prototypes	X	X	X
Tooling design and Mock-up tests	X	x	X
Transport studies and tests	X	x	x
Manufacturing	X	x	x
Assembly	X		X
CM test at CEA	X		X
Transport	X		

As another example, from the table, one can read that LIPAc CM will not be assembled at CEA. It will be assembled under the responsibility of F4E, with the assistance of CEA. To insure the process, CEA has developed mock-ups and cavity-to-coupler tooling. LIPAc transport study examines whether the shipment would be by plane or sea.

THE REQUIREMENTS

CEA is implementing standard engineering method for the requirements which are defined with the collaborators. Table 2 is a summary of the requirements on the cavities.

Table 2: Cavities Parameters

	ESS	SARAF	LIPAc
Particules	P+	P+/D+	D+
Energy [MeV]	2000	40/35	5 à 9
Frequency [MHz]	704	176	175
Operating temp.	2K	4.45K	4.45K
Beta value	0.67/0.86	0.09/0.18	0.094
Eacc [MV/m]	16.7/19.9	7	4.5
Epk [MV/m]	45/45	34.6/35.9	21.6
Bpk [mT]	80/85.6	65.6/65.3	49.5
Beam pipe ID (mm)	94/120	40	40

The performance required for SARAF are 32% higher than for LIPAC and ESS is the most demanding one with 85.6mT at 2K compare to the 140mT Hc1 limit.

THE DESIGN

LIPAC first design consisted in a cryomodule to be as short as possible along the beam axis so as to meet the beam dynamics requirements. The cryomodule is made up with a rectangular section vacuum vessel, room temperature magnetic shield, MLI, thermal shield cooled down by GHe, and cold-mass wrapped in MLI. This is similar for SARAF [7]. ESS CM includes the same functionalities though the magnetic shield is around the cavity on top of the MLI, the CM section is round and the Helium circuit has to provide 2K to the cavities.

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LIPAC and SARAF cold mass is made up of the phase separator, cryogenic circuit, titanium cavity support frame, hanging from the top of the vacuum vessel thanks to TA6V rods plus rods ensuring lateral and horizontal positioning. Similarities are on the tie rods which are used in the 3 projects (antagonist tie rods for ESS). The number and type of cavities are 4 elliptical cavities for ESS, 6 or 7 HWR for SARAF and 8 HWR for LIPAC. The material of the space and support frame are different between the three projects. SARAF and LIPAC support frame are at temperatures between 70K and 4K and shall have low permeability since they are located close to the cavity torus. Therefore, Titanium, has been chosen. ESS space frame is at room temperature, it should hold the weight and cope with alignment constrains : aluminium meets those specifications and has been chosen for ESS. ESS tie rods are also able to take the shipping loads and maintain the cavities aligned during the transport between CEA and ESS (about 1300kms).

Both support and space frame allow easy access to the cavity string and permits intermediate alignment verification before insertion in the vacuum vessel and additional clamping for transportation.

Due to their size and weight, the ESS [8] and LIPAC [9] couplers are mounted vertically. The ESS coupler to cavity assembly tooling has been derived from LIPAC lessons learned on the mock-up test. On SARAF CM, the cavities are vertical thus the coupler is horizontal.

The support or space frame allow assembling the cold mass and adjusting the component for alignment outside the vacuum tank. The cryomodule is for that reason designed in two main sub-assemblies : the cold mass and a vacuum vessel fitted with magnetic and thermal shields. The vacuum tanks are also outfitted with traps and doors to allow the access to the cold mass and to carry out the necessary controls and possible maintenance after installation in the tunnels.

The SARAF tunnel width and the beam axis position are set by the already existing infrastructures. During installation and maintenance, two cryomodules should be rolled side by side. Therefore the cryomodule width can not exceed 1850 mmm. The cavity RF design has set its dimension to 1018 mm. Taking into account the vacuum vessel wall thickness, the magnetic and thermal shield thickness and the short coupler cavities have to stand vertically. Unlike the IFMIF cryomodule, a top loading solution have been chosen for the insertion of the cold mass in the vacuum vessel

LIPAC and SARAF CM are connected to a valve box thanks to transfer lines and operate at 4.45K. ESS cryomodule will operate at 2K. Each ESS cryomodule is linked to an individual valve box by a jumper connexion which provides the 4.5 K – 3 bars liquid helium (LHe) supply and return for the cavities and couplers cooling, as well as the 40 K – 19.5 bara helium cooling circuit of the thermal shield. The 2 K superfluid helium is produced inside the cryomodule by a Joule-Thomson valve.

In ESS CM, the spacing and location of the coupler port are the same on both type of cryomodules allowing capability to interchange modules in the tunnel. Thus most of the components are identical between 2 types of cryomodules but the number of cells per cavities and the intermediate beam line bellows. This standardisation has been implemented also on SARAF where a 7th cavity will assemble in the 2nd cryomodule. Instead of designing three different support frame, we have only 2, one for the low beta, one for the high beta. SARAF CM have been designed to use the same tie-rods, couplers and interfaces.

THE REVIEW AND MITIGATION PLAN

Cryomodule designs, including detailed technical analysis, are submitted to a panel of international experts (Detailed Design Review for LIPAC cryomodule, EDR for SARAF and CDR for ESS). The risks are addressed in a mitigation plan to prevent their occurrence. Mitigation plans have been implemented and led to the design optimization. For the three projects, it was decided to perform early testing on dedicated test bench and mock-ups to check critical components and operations before the beginning of the cryomodule assembly. To detect potential issues during operation of such complete set of components, SaTHoRI test stand [10] has been built and was used to test LIPAC jacketed cavity with coupler and tuner. SARAF is building a similar test. A Medium beta Elliptical Cavity Cryomodule Technical Demonstrator (MECCTD) ESS has been built [11].

For LIPAC, the risk of not meeting the Japanese regulatory requirements with regard to High Pressure Gas Safety Law (HPGSL) had been identified as a potential definite show-stopper for the cryomodule project. To meet the Japanese regulatory requirements with regard to HPGSL, it has been agreed in the collaboration to design, fabricate and test according to ASME standards all components containing helium gas or liquid during operation of the LIPAc. The cavity was the most complicated part to be licensed due to the use of non-referenced materials (Nb, NbTi) and the complicated geometry. It went through validating process with KHK, a Japanese Safety Institute. The first discussion took place in December 2011 at KHK in Tokyo. The application form of the cavity licensing was finally approved in March 2016. For ESS and SARAF, European Pressure Equipment Device regulation could be applied and pressure levels allow to comply with the state-of-the art follow-up.

PROTOTYPES

Meanwhile the cryomodule design is going on, the critical components namely solenoid, coupler, tuner and cavity are built in order to test and validate their design. The LIPAC superconducting HWR prototype, which was first equipped with a plunger for frequency tuning, was finally qualified after removing the plunger and associated flanges, and replacing these with a more conservative mechanical tuner including a disengagement system [12]. Such a solution based on the cavity wall led to a lengthening of the cryomodule in order to accommodate the tuner. The flange to flange length of the HWR was increased by

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100 mm. As a consequence, SARAF implemented a standard mechanical tuner. The cleaning of the LIPAC cavity through the 18mm HPR port, the orientation of the HPR ports with respect to the central stem and the oscillation of the HPR stem when under 100bars of water pressure were lessons learned [13] which led SARAF to increase as much as possible the HPR ports diameter and turn them by 30° so that the HPR water scanning could go over the beam axis and scan more thoughtfully the surface. Still, the cavity will have to be flipped to clean all areas.

Five ESS medium beta cavities were manufactured and vertically tested. The challenging specifications were met on the cavities [14]. As the INFN cavity was successfully tested and ready [15], it was integrated inside the prototype CM named M-ECCTD (Medium beta Elliptical Cavity Cryomodule Technical Demonstrator). 6 pairs of couplers have been manufactured and successfully conditioned up to 1.1MW. Among those, 4 couplers are assembled on the MECCTD.

TOOLING DESIGN AND MOCK-UP TESTS

The tooling designs were done in house. To lower the occurrence of critical events during cavity string assembly and to optimize and validate the assembly procedure and associated tools, test bench and mock-ups are built. LIPAC has developed mock-ups to test the assembly of the cavity-to-solenoid and coupler-to-cavity. This last assembly was validated during SATHORI assembly. The LIPAC mock-ups are now used by the company in charge of the cryomodule assembly at Rokkasho. ESS has used tooling principles from XFEL (clean room rails and vacuum groups). ESS built mock-ups for all the assembly steps to control the alignment preservation after integration in the cryomodule. During ESS mock-up assembly, the procedure were written and tests template drafted.

The LIPAC support frame enables to hold together all the cold mass components from the first assembly steps in clean room to the final assembly inside the vacuum tank. It aims to minimize the handling of a heavy cold mass (around 2.5 tons) and to avoid as much as possible to damage the components. The parts shall undergo a cleaning and the tooling shall hold the support frame at a working height with a good stability making the access to the beam port connection less practical. For SARAF, the cold mass is assembled on a clean room tooling, transferred outside and equipped with tuner, MLI. Then the support frame, hooked on the top plate, is lowered and the cold mass is attached.

PROTOTYPING

MECCTD has been built and prototyping was performed to validate all the assembly steps and toolings. After the qualifications of the cavities and couplers and the manufacturing of all the components and toolings, the MECCTD was assembled in the ISO4 clean room on a movable cart which was initially designed to be used in the ISO5 clean room. The procedure inherited from E-XFEL cryomodule such as venting procedure or pre-alignment in the clean room were implemented for the string assembly. The string composed 4 cavities with coupler, 4 bellows and 2 warm-to-cold transition has been leak tested and backfilled to atmospheric pressure with filtered dry nitrogen in the clean room. A carefull pre-alignment of the cavities occurs in the clean room and is checked with calipers. The string is then rolled outside of the clean room. The cavities are aligned to +/-1.5mm from the theoretical axis with a laser tracker. The string was equipped with tuners, MLI, magnetic shield and rolled in the space frame. The tie rods are mounted between the cavity titanium half rings and the space in order to transfer the cold mass from the cavity vertical clean room tooling to the space frame. The axial position of the cavities is fixed by transverse bars until the axial blocking of the couplers. Those bars used also for the cryomodule transportation are removed for pump down and operation. The alignment is checked again. The space frame was inserted in the vacuum vessel by means of wheels and in-situ rails. The jumper and doors were mounted and the cryomodule transferred to the test area where the doorknob assembly took place. All the steps were successfully passed. It led to tooling refurbishment.

TRANSPORT STUDIES AND TESTS

What makes CEA design unique is that the cryomodules are assembled at CEA and then transported to the accelerator site in Sweden or Israel. This led to transport study and development of structure that can handle the road transport and maintain the alignment over more than one thousand kilometer or airplane transport. ESS transport studies led to the clamping of the thermal shield and cavities on the space frame and the reinforcement of the feet of the cryomodule. SARAF transport studies are underway and benefit from ESS experiences. The mitigation of the transport risk for LIPAC has been to assemble the cryomodule on site at Rokkasho.

MANUFACTURING

For the manufacturing follow-up, the cryomodule team is supported by a dedicated group of engineers experienced in manufacturing. The dedicated group is writing the technical specifications using the cryomodule team expertise on specific themes, following the call for tender process. Once the contract are signed, they are following the contractual aspects, registering the non-conformities and validated them, traveling to the subcontractors for intermediate meetings and participating to factory acceptance tests. This support is off great value. To follow regulations (pressure equipment or seismic), the call for tender and contract follow-up could be tedious.

The ESS construction schedule imposed to anticipate the procurement of the long lead components and be prepared for the one month throughput. It has been agreed with ESS to launch the procurement before the qualification of the MECCTD. This excludes major redesign though hold points have been set to allow feedbacks and minor changes.

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The number of contracts to be signed is unpreceded for CEA.

ASSEMBLY

CEA has gained experience over the years in cryomodule assembly [16, 17]. It has developed an assembly "factory" in which an industrial operator assembled 100 cryomodules for 3 years for the E-XFEL project. The factory includes three assembly halls comprising a dedicated ISO-4 clean room 14 m long with two parallel integration rails (the clean room complex is 200m2 with the ISO4-5-7) and a 50m2 ISO5 clean room used for the individual components (cavities, couplers, solenoids). For ESS, the 30 cryomodules will assembled in the "cryomodule" factory by an industrial operator wheras the SARAF cryomodule will be assembled by a CEA team which was involved on SPIRAL2, E-XFEL and ESS prototyping phase. CEA ensures a close follow-up of the industrial operator with a CEA team always in the factory.

CM TEST AT CEA

A dedicated cryomodule test stand has been built for the different projects. It is fed with cryogenic fluid from the CEA facilities and RF power equipments are connected accordingly. The command control and test equipment are developed according to the projects needs and standardized allowing easy exchange of components.

The test conditions are different from the operation conditions. As a matter of fact, one out 4 1.1MW klystrons is installed in Saclay for ESS. The 4.5 K – 3 bars superfluid helium (SHe) supply is replaced by 4.64K -1.2 bara Gas helium supply and the 40 K – 19.5 bara helium cooling circuit of the thermal shield is fed with liquid nitrogen at 77K.

For SARAF, the thermal shield will be supplied by liquid nitrogen at 77K instead of 14.5Bar, 60K GHe.

TRANSPORT

CEA has transported cryomodule from CEA to GANIL (200kms) by road on a damping frame maintaining the alignment of the cavities [18]. The one hundred cryomodules assembled at CEA have been transported to DESY on a damping frame [19] under DESY responsibility. More recently, ESS cryomodule transport test of the vacuum vessel have been conducted.

CONCLUSION

CEA is working on three projects and uses lessons learned from one project to the other ones. Methods are shared and singularities are individually treated. The cryomodules will be assembled in a close future : LIPAc CM assembly will start at the end of year and the CM will be operating by the end of 2019. ESS cryomodules assembly production will start by January 2019 and should last 1.5 years. SARAF CM assembly will start January 2020. ESS and SARAF will start operating by 2022.

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