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DEVELOPMENTS AND PROGRESS WITH ESS ELLIPTICAL CRYOMODULES AT CEA-SACLAY AND IPN-ORSAY

F. Peauger†, C. Arcambal, F. Ardellier, S. Berry, P. Bosland, A. Bouygues, E. Cenni, JP. Charrier, G. Devanz, F. Eozénou, A. Gaget, D. Gevaert, A. Gomes, T. Hamelin, X. Hanus, P. Hardy, V. Hennion, T. Joannem, C. Marchand, O. Piquet, J.P. Poupeau, B. Renard, P. Sahuquet, T. Trublet, Irfu, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
G. Olivier, IPN Orsay, France
C. Darve, ESS, Lund, Sweden

Abstract

CEA Saclay in collaboration with IPN Orsay is in charge of the ESS elliptical cavities cryomodule design, prototyping and series production. Two cryomodule prototypes are being developed and will be tested at CEA Saclay before starting the series production. The main cryomodule design features are first reminded. We present the cavities and couplers test results and the achieved assembly sequences of the first medium beta cavities cryomodule demonstrator M-ECCTD. The progress on the preparation of the CEA cryomodule test station is given. The procurement status and development plan of the second high beta demonstrator H-ECCTD are also reported. Finally we give the components procurement progress and the assembly strategy of the 30 series cryomodules to be integrated at CEA before delivery to ESS at Lund.

INTRODUCTION

The European Spallation Source ESS is under construction in Lund, Sweden [1]. It is composed of a 62.5 mA - 2 GeV proton LINAC operating in long pulsed mode 2.86 ms – 14 Hz. The high energy section consists in 352 MHz spoke and 704 MHz elliptical superconducting cavities working at 2 K [2]. The elliptical section is made of 36 medium beta (β=0.67) 6-cell cavities which accelerate the beam from 200 MeV to 570 MeV and 84 high beta (β=0.86) 5-cell cavities up to the final energy. The elliptical cavities are grouped four by four in a 6.6 meter long cryomodule which has a common design for medium beta and high beta cavities. A total of 30 elliptical cryomodules will be integrated in the next 3 years with a delivery rate of one cryomodule per month.

An international collaboration has been established to develop and construct the 30 elliptical cryomodules. CEA Saclay and IPN Orsay collaborate to design, build and test a first Medium beta Elliptical Cavities Cryomodule Demonstrator (M-ECCTD). A second demonstrator with high beta cavities (H-ECCTD) is being developed by CEA before starting the series cryomodule activities. The 36 β=0.67 cavities will be delivered by INFN LASA (Italy) and the 84 β=0.86 cavities by STFC (UK). CEA will provide all the other components, including the power couplers and their RF processing. All cryomodules assembled in CEA Saclay will be shipped to Lund. The qualification tests at high power will be performed in the ESS test stand before the integration in the tunnel.

This paper describes the developments and progress done at CEA Saclay and IPN Orsay. The prototyping phase will be detailed as well as the preparation for the series. This work has also been reported recently in [3].

CRYOMODULE DESCRIPTION

The design of the ESS elliptical cryomodule is shown in Figure 1. It hosts four high gradient cavities specified at Eacc = 16.7 MV/m (β=0.67) and 19.9 MV/m (β=0.86). Each cavity is equipped with a single window high power coupler able to transmit 1.1 MW peak power, a 600 kHz range 1 Hz resolution cold tuning system equipped with two piezo-actuators for fast tuning, and a 2 mm thick magnetic shield made of Cryophy material.

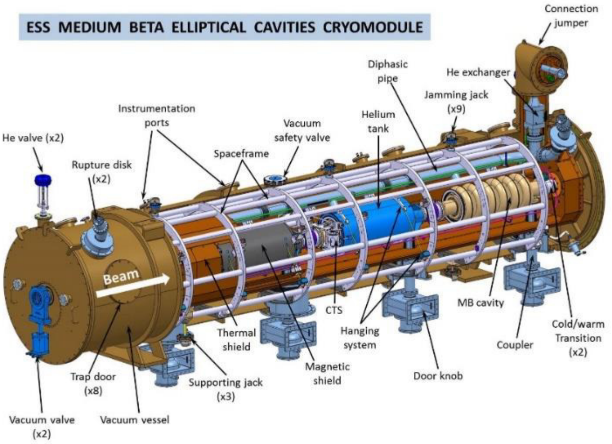

Figure 1: Elliptical cryomodule 3D view equipped with medium beta cavities.

The mechanical design of the cryomodule is based on the SNS cryomodule principle [4] where a rigid structure named spaceframe holds the four cavities and a 2 mm thick aluminium thermal shield. The spaceframe allows easy access to the cavity string and permits intermediate steps of mechanical alignment before integration inside the vacuum vessel. The segmented approach has been adopted so that independent cryomodule cool down, warm-up and replacement can be performed. Thus each 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. The cryomodule includes also a heat exchanger to enhance the Joule-Thomson expansion efficiency. Medium and high beta cryomodule components are identical except the cavity number of cells, the cavity length, the double wall external conductor length and the intercavity bellows and cold warm transitions length.

The first M-ECCTD cryomodule tests aim at demonstrating the medium beta cavities, cold tuner, magnetic shield and power coupler performances in the cryomodule configuration. It also validates the basic design and operation of the cryogenic cooling circuits.

MEDIUM BETA CRYOMODULE DEMONSTRATOR M-ECCTD

Medium Beta Cavity Performances in Vertical Tests

The fabrication and vertical tests results of the four medium beta cavities (Figure 2) integrated inside the M-ECCTD cryomodule are detailed in [5] and [6], and are reminded in Figure 3.

Figure 2: Medium beta cavity.

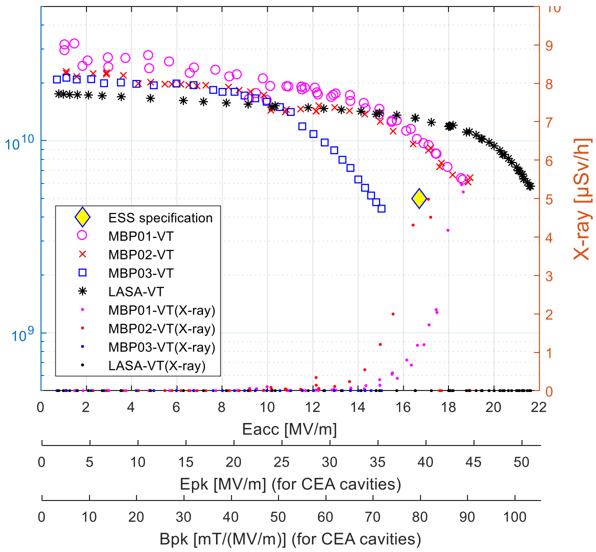

Figure 3: Vertical tests result of M-ECCTD cavities.

Three cavities reach the ESS specification of Q0 = 5e9 at Eacc = 16.7 MV/m whereas one cavity has a Q-drop starting from 11 MV/m. Two cavities shows high X-ray radiation level measured at the top of the cryostat. The origin of this Q drop is not fully understood. Multipactor simulations have shown that field emission starting from the end cells iris could produce electron trajectories hitting the inner cells for accelerating gradients between 12 and 15 MV/m. The surface quality of the iris and the cell walls obtained after chemical polishing could trigger or not this phenomena, and thus lead to a Q-drop or not.

Power Coupler Performances After RF Conditioning

Two pairs of power couplers were mounted on stainless steel air cooled coupling boxes (Figure 4) in clean room. After baking at 170 °C, three pairs were successfully conditioned in travelling and standing wave conditions at 1 Hz first and 14 Hz. Three multipactor regions were found at 100, 300 and 900 kW during the power ramping but were easily conditioned without the use of the DC bias system. The couplers were tested up to 1.1 MW peak power at the nominal ESS duty cycle [7].

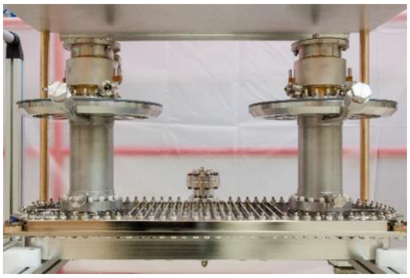

Figure 4: Power coupler pair assembled on a coupling box.

Cavity and Coupler Assembly in Clean Room

The coupler pair mounted on the coupling boxes and the cavities are carefully cleaned and introduced into the ISO4 clean room. The coupler is disassembled from the coupling box, rotated by 180° before being put on the assembly tooling with the cavity. After the pre-alignment of the coupler axis to the cavity flange, the coupler is connected to the cavity (Figure 5). Slow pumping followed by leak check and RGA ensures that this first assembly is satisfactory.

Figure 5: Coupler integration on cavity.

Cavity String Clean Room Assembly

For this first prototype cryomodule the cavity string assembly is done on movable cart equipped with a double rail system. Cavities and heavy components are handled with a lifter dedicated to ISO4 clean room environment. Nitrogen venting was successfully experienced at CEA for the XFEL cyomodules assembly and has been also applied on this first ESS prototype cryomodule. The flanges of the cavities are designed for aluminium gaskets similar to the XFEL cavities. The cavity string is finalized with the assembly of the second cold-warm transition and gate valve (Figure 6). The distance of 1500 mm between each coupler is adjusted. For the assembly of this first cryomodule, it has been chosen to put the cavities under high vacuum with gate valves opened during the assembly process. The second prototype H-ECCTD will be assembled with cavity vacuum at the atmospheric pressure, refilled with filtered dry nitrogen.

Figure 6: Cavity string assembly in clean room.

Cryomodule Assembly

Once the cavity string is leak checked inside the clean room, it is rolled out of the clean room on a second cart equipped with similar rail system. The string is lifted with a crane and transported in a dedicated assembly hall.

The cavity alignment is checked with a laser tracker at different steps of the assembly process. The orbital welding of the helium tank titanium diphasic line is then performed. All the welds have been controlled by visual check, leak tests and radiography. Since the article 4.3 of the PED is applied for the ESS cryomodules, there is no requirement in terms of pores size and number. However the welding parameters were adjusted to obtain the best possible welding quality.

The multi-layer insulation (MLI) blankets (10 layers) are assembled on the cavities and the diphasic line, and the different parts of the magnetic shield are mounted. The cold tuning systems are assembled following special procedures and dedicated toolings. Frequency change of only 60 kHz maximum has been measured after the assembly of the tuners. The assembly of the instrumentation and the cryogenic circuit inlets are performed. Alignment verifications are done at this stage. The cavities are located at +/- 1.5 mm from the theoretical positions. The cavity string configuration before insertion into the spaceframe is shown in Figure 7.

Figure 7: Cavity string dressing outside clean room.

In parallel, the thermal shield is equipped with a 30 layers thick MLI blanket and fixed to the spaceframe. The cavity string is then introduced carefully in the equipped spaceframe (Figure 8).

Figure 8: Cavity string insertion in the spaceframe.

The mass transfer of the cavity string from the vertical handling posts used in clean room to the tie rods fixed on the spaceframe can start. This operation is illustrated in Figure 9. It consists in mounting TA6V 6 mm diameter rods on two titanium half rings fastened to the cavity helium tank under the magnetic shield. The rods are positioned in a crossed configuration. They are pre-stressed (about 3000 N) and locked by a nut (in red on Figure 9) after a cavity string alignment procedure. The thermal shield is also fixed on the tie rods for thermalization via flexible boxes allowing the thermal shrinkage of the shield while the rods stay fixed. Axial positioning of the cavities is made by transverse bars (in green on Figure 9) fixed on spaceframe rings. These bars are kept until axial blocking of the couplers, removed during cryomodule pumping and operation, and re-installed for cryomodule transportation.

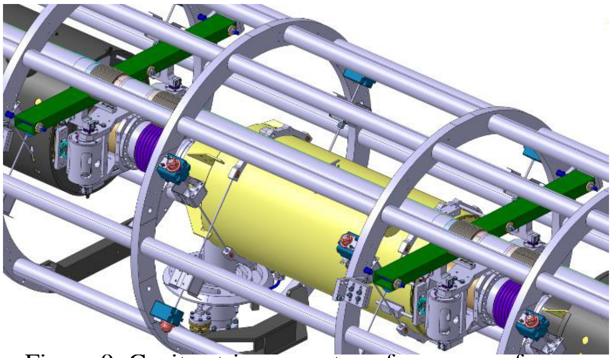

Figure 9: Cavity string mass transfer on spaceframe.

The spaceframe equipped with the cavity string is then inserted inside the vacuum vessel using an in-situ rail system. The assembly of the jumper equipment (heat exchanger, cryogenic piping, and thermal shield), the diphasic line outputs (rupture disks, pressure sensor) and the coupler cooling outlet (with heaters) are performed. The cryogenic connections at the cryomodule extremities are done, including the two cryogenic valves (Figure 10).

Figure 10: Cryomodule assembly after spaceframe insertion.

The vacuum vessel doors are assembled with the help of special tooling supporting the cold-warm transitions and gate valves. The cryomodule is lifted with a crane and transferred to the testing bunker located close to the assembly hall (Figure 11). Final assembly of the cryomodule is now on-going. The coupler flanges equipped with atmospheric pressure compensation, the doorknob transitions, the waveguide system and the cryogenic lines can be installed. The coupler area will be equipped with displacement sensors to measure the coupler and cavity movement during pumping and cooldown. These sensors can be controlled remotely in the control room and have been successfully tested.

Figure 11: Cryomodule final assembly.

Cryomodule High Power Tests Preparation at CEA

The cryomodule test stand is described in [8].

The RF power signal coming from the klystron and circulator is split into two lines by a RF switch and divided by two with variable attenuators installed vertically inside the bunker. This waveguide configuration allows powering each cavity one by one or two adjacent cavities at the same time without dismounting any waveguide. The RF distribution has been tested in short circuit configuration up to 500 kW peak power at 704 MHz with only 5% RF losses.

The EPICS control system is operational. The fast signal acquisition in the control room has been tested. Calibrations of RF signal attenuations coming from bidirectional couplers were performed. The cryomodule tests will start with a basic RF regulation system producing P-P/4 type RF pulses. Arbitrary waveform generator (Tektronik AFG3022) driven by EPICS and NOLIAC NDR6220 amplifiers will control the piezo-actuators of the cold tuning systems. This control architecture will give enough to flexibility to test different kind of pulses to compensate the Lorentz force detuning (single pulse or burst of trapezoidal type pulses), with adjustable pre-trigger relative to the RF pulses. The Phytron motors are controlled with a PLC where the direction and the number of turns are monitored. The PLC includes a home position and is powered via a UPS for safe operation in case of electrical shutdown.

The cryogenic connections between the cryomodule and the two Dewars (2000 l helium for cavities and couplers, 1000 l nitrogen for thermal shield) are nearly completed. It is made of independent cryogenic circuits composed of rigid and flexible lines. The 2 K low pressure line is connected to a 14 kW heater installed at the top of the bunker and linked to the Supratech very low pressure pumping system.

The cryogenic system controlled by MUSCADE® Embedded SCADA system is also operational. The different cryogenic operating modes are being established with grafcets. Input/output tests will be performed when all instrumentation will be connected.

In order to validate the cryogenic design of the module first, it is foreseen to start with a cool down test at 2 K and warm-up before warm conditioning of the power couplers. Accelerating gradient measurements and cold tuner operations results are expected in September 2017.

HIGH BETA CRYOMODULE DEMONSTRATOR H-ECCTD

A second cryomodule prototype H-ECCTD with high beta cavities is being constructed by CEA. This cryomodule will demonstrate the challenging performances of the cavities and couplers and will give a second iteration to the cryomodule design and assembly procedures after the M-ECCTD accomplishments described in the previous section.

H-ECCTD Cryomodule Construction Status

Five new high beta cavities have been ordered at Research Instrument GmbH (Germany) and are under manufacturing. Deep drawing process of half cells and RF controls are in progress. A first bare cavity is expected for October 2017. Chemical treatment and vertical tests will be performed at CEA. Heat treatment for hydrogen degassing is planned at IPNO where a new vacuum furnace is available for ESS Spoke cavities.

Concerning the power couplers, four RF windows and antenna are already available and need to be conditioned. New external conductors (copper plated) have been recently manufactured. Clean room integration on coupling boxes and RF power conditioning up to 1.1 MW are planned for August (1st pair) and October 2017 (2nd pair).

The magnetic shields, cold tuners, motors, piezo-actuators, internal RF cables and titanium bellows were ordered during the M-ECCTD procurements and are already available.

All the other cryomodule components are procured as pre-series of the series cryomodule contracts. The vacuum vessel, spaceframe and thermal shield have been ordered, with deliveries expected for the first quarter of 2018.

Titanium diphasic tubes were difficult to manufacture for the M-ECCTD, and so have been anticipated. Delivery is expected for September 2017.

The inter-cavities bellows and cold warm transitions, the 2K heat exchanger, the cryogenic piping and the internal instrumentation are the next important procurements to be launched.

Cryomodule Design Updates

Continuous return of experience from the M-ECCTD assembly is applied to the H-ECCTD cryomodule design in order to improve the assembly process and solve the assembly issues met during the M-ECCTD integration. The main design changes are the following:

- Diphasic line sections delivered without titanium bellows and adding of a stainless steel section on the jumper side
- Adding of an Invar bar to block the diphasic line at a pressure of 2 bar
- Adding of blocking rods on the diphasic line extremities (to operate under 2 bar pressure)
- Adding of a diphasic tube support on the cavity helium tank (on the jumper side)
- Replacement of DN16 flanges to bimetallic stainless steel / titanium transitions on the diphasic line (cavity filling circuit and helium level circuit)
- Replacement of DN 16 flange by bimetallic stainless steel / titanium transitions on the cavities (cooling circuit)
- Standardisation of the tie rods hanging system on the on the spaceframe
- Widening of the thermal shield openings to easier the access to the tuning system area
- Modification of the thermal shield design in the jumper area to easier the access to the diphasic line extremities
- New design of thermal shield cooling pipes supports and thermal shield closing system at the bottom part (in the coupler area)
- Improvement of the spaceframe / vacuum vessel rail system
- Modification of the cryogenic piping spacer in the jumper connection

SERIES CRYOMODULE PROCUREMENT AND ASSEMBLY PREPARATION

The present ESS Linac construction schedule imposes to start the first series medium beta cryomodule assembly in mid-2018. The procurement of long lead components need to be anticipated and the cryomodule assembly activity with a production rate of one module per month must be prepared.

Series Cryomodule Procurement Plan

It has been agreed with ESS to launch the main component procurements before fully qualifying the first cryomodule demonstrator. This approach excludes major redesign of the module. However, contractual hold points are implemented to allow feedbacks and minor design changes.

The procurement progress is reported in Table 1.

Table 1: Series Cryomodule Procurement Status

Components	Status
Vacuum vessels	Contract awarded
Power couplers	Contract awarded
Coupling boxes	Contract awarded
Thermal shields	Contract awarded
Spaceframes	Contract awarded
Cold tuners	Candidate chosen
Motors	Contract awarded
Piezo-actuators	In stand-by
Magnetic shields	Candidate chosen
MLI	Offers received
2 K Heat exchangers	Published
Instrumentation	Offers received
Thermal sensors	Published
Inter-cavity bellows	Offers received
Cryogenic pipings	In stand-by
Cavity supports	In stand-by
Cryogenic valves	Published
RF cables	Offers received
Safety valves	Technical specification
Clean room screws set	Technical specification
Aluminium gaskets	Technical specification

The components procurement plan is fully linked to the 6-level Product Breakdown Structure of the module and is decomposed according to the skills of existing companies. Call for tenders are mandatories to respect the CEA procurement procedure. Depending on the complexity of the component and the confidentiality of their design, either market survey followed closed tender or open tenders are launched. During the call for tender, obligatory visits of the candidates are organized for critical contracts. Technical analyses of the received offers often lead to additional questions to finalize the choice of the candidates. The procurement starts when the contracts are signed by both parts and a kick off meeting is organized. Table 1 shows that some procurements are in stand-by and wait either for the M-ECCTD cryomodule test results or interface requirement finalization with the ESS cryomodule test stand and LINAC tunnel.

Series Power Couplers Production

After manufacturing, the power couplers must be RF conditioned at high power at a production rate of four couplers per months. To achieve this rate a new klystron type 704 MHz 1.6 MW RF source has been ordered. It will be installed near the actual 1.1 MW klystron so that, thanks to a modular waveguide distribution system, either two couplers pairs can be conditioned at the same time or one of the two klystrons can power a cryomodule under test (Figure 12). A clean area will be built in front of the two klystrons, surrounding the two coupler conditioning stands. This room will include a baking furnace and three vacuum pumping station.

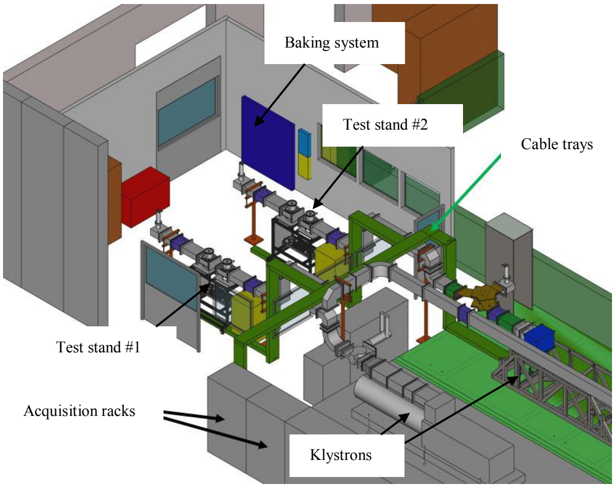

Figure 12: Layout of the power coupler RF conditioning stands.

Series Cryomodule Assembly Strategy

The strategic decision to assemble the 30 elliptical cryomodules with an industrial partner in the CEA infrastructures has been taken. This approach has been successfully implemented on the XFEL project [9] [10]. An industrialization process has to be considered between the first M-ECCTD assembly experience and the series assembly phase at nominal production rate. This industrialization development includes:

- An engineering phase (1 month) where a production and quality plan will be provided, as well as a detailed planning and a risk analysis.
- An observatory phase (4 months) during the H-ECCTD integration. The H-ECCTD assembly will be managed and performed by CEA team with the assistance of the two assembly technicians and a welding team from industrial partner. The industrial will deliver the logistic management process, the assembly procedures (based on the CEA preliminary procedures), the list of controls and the list of toolings (in addition to the one developed and provided by CEA). The manpower skills have also to be studied as well as non-conformities and modification management procedures.
- A training phase (6 months) during the assembly of the two first series medium beta cryomodules CM1 and CM2. The assembly tasks are performed by the industrial partner but CEA team trains the industrial staff.

The nominal cryomodule assembly cycle of three months and the deliver rate of one cryomodule per month are achieved from the third series cryomodule CM3 and maintained until the last cryomodule CM30.

The current definition of the different workstations is shown in Figure 13. Before launching the assembly contract, CEA is continuously improving the assembly procedure and toolings. Figure 14 shows an example of an assembly tooling update and concerns the clean room cavity handling posts which will be adapted to the clean room railing system.

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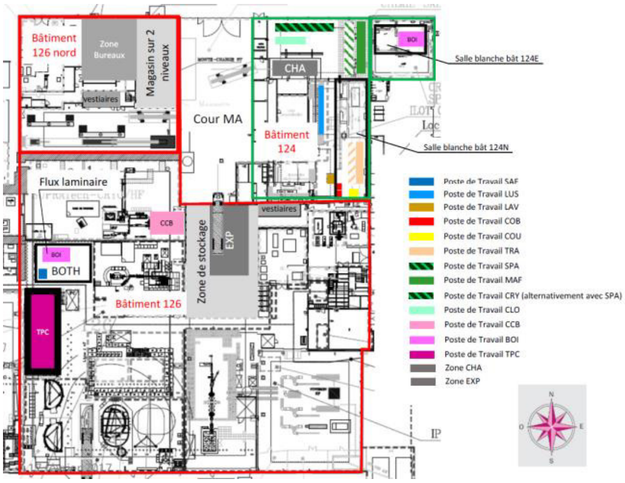

Figure 13: Assembly workstations in CEA infrastructures.

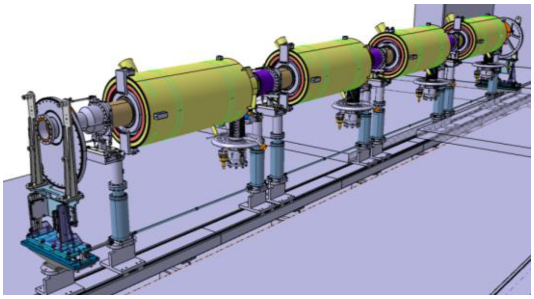

Figure 14: Clean room assembly toolings update.

CONCLUSION

Four activities are conducted in parallel by CEA Saclay and IPN Orsay to deliver the ESS elliptical cavity cryomodules: the first prototyping phase where the final assembly and RF tests of the medium beta demonstrator will occur this summer 2017, the fabrication of a second high beta cryomodule demonstrator, the anticipation of the series component procurement with more than 60% of contracts launched, and the preparation of the industrialization phase of the 30 cryomodules assembly with an industrial partner which will start at the end of 2017 and continue over the entire year of 2018.

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