RECENT PROGRESS OF ESS SPOKE AND ELLIPTICAL CRYOMODULES*

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on behalf of the ESS collaboration

Abstract

The ESS accelerator high level requirements are to provide a 2.86 ms long proton pulse at 2 GeV at repetition rate of 14 Hz. This represents 5 MW of average beam power with a 4% duty cycle on target. In a framework of collaboration between IPN Orsay, CEA Saclay and ESS, prototype spoke and medium and high beta elliptical cavities and cryomodules have been studied, constructed and tested. After a description of the ESS project and the accelerator layout, this paper will focus on the recent progress towards realization of the detailed design, the manufacturing of the first components of the prototype cryomodules and the first test results of some of the main critical elements such as SRF cavities and cold tuning systems.

ESS PROJECT

The European Spallation Source (ESS) project is a neutron-scattering facility, currently under construction by a partnership of at least 17 European countries, with Sweden and Denmark as host nations [1,2]. Construction started in July 2014, aiming at the source producing first neutrons around 2020. The ESS was designated a European Research Infrastructure Consortium (ERIC) by the European Commission in October of 2015.

The ESS is an accelerator-based facility producing neutrons for a large array of advanced instruments. Once constructed, in Lund, Sweden, it will provide new opportunities for researchers in a broad range of scientific areas including life sciences, energy, environmental technology, cultural heritage and fundamental physics.

The ESS accelerator will deliver to the target a time averaged proton beam power of 5 MW at the completion with a nominal current of 62.5 mA.

The superconducting linear accelerator lattice redesign [3] has permitted to optimize the layout of the linear accelerator using transition energy of 90 MeV with the normal conducting linac and reaching 2 GeV at the target.

The Superconducting Radio-Frequency (SRF) linear accelerator is composed of one section of Spoke-type cryomodules (352.21 MHz) and two sections of elliptical cavity cryomodules (704.42 MHz) [4]. Figure 1 shows the layout of the ESS linac, Optimus +, with emphasize on the SRF sections. The spoke section is being designed by and tested in IPN Orsay before being tested at high power in Uppsala University [5]. The design and test of the elliptical section is led by CEA Saclay and distributed in a SRF collaboration composed of CEA Saclay, INFN-LASA and STFC-Daresbury. LASA and STFC are providing the medium-beta and high-beta elliptical cavities, respectively. The elliptical cavities will be installed in their cryomodules in Saclay, using the experience learned from the X-FEL project.

COLLABORATION OF FRANCE TO THE ESS LINAC CONSTRUCTION

France is one of the major partners of the ESS collaboration, in particular with an important involvement in the accelerator construction under the form of in-kind contributions. Thru the two research organizations CEA and CNRS, France will provide key parts of the ESS accelerator, and is the major contributor to the SRF linac. The IRFU Institute of CEA-Saclay will provide the RFQ, beam diagnostics for the LEBT, all medium and high beta cryomodules (except for the SC cavities), and also controls for the proton source and LEBT. The IPN-Orsay Institute of CNRS has the responsibility to deliver all spoke cryomodules with their associated cryogenic valve boxes and cryogenic lines, and the cryogenic controls for all cryomodules (elliptical and spoke).

Both laboratories are participating to the ESS accelerator design since the early hours of ESS in 2009, and their contribution was reinforced with the signature in 2010 of a French-Swedish cooperation agreement, giving the framework for the design and development of prototype components such as spoke, medium beta and high beta elliptical cavities and cryomodules which are currently under fabrication and tests.

SPOKE CRYOMODULE

Since 2009, IPN Orsay is intensively involved in ESS project by leading the design of the whole Spoke section of the linac. The final aim is to deliver to Lund, 13 Spoke cryomodules, their associated valve boxes and cryogenic transfer lines. This chapter will described the status of the cryomodule, spoke cavities, cold tuning systems and power couplers prototypes developments.

As presented before, the Spoke section will be composed of cryomodules housing two Double-Spoke, beta 0.50, 352.21 MHz resonators with their cold tuning systems and capacitive power couplers (Fig. 2). IPN Orsay has designed a fully equipped prototype cryomodule and its valve box which are intended first to be validated cryogenically at IPN Orsay, then to be fully qualified, at high power, at Uppsala University.

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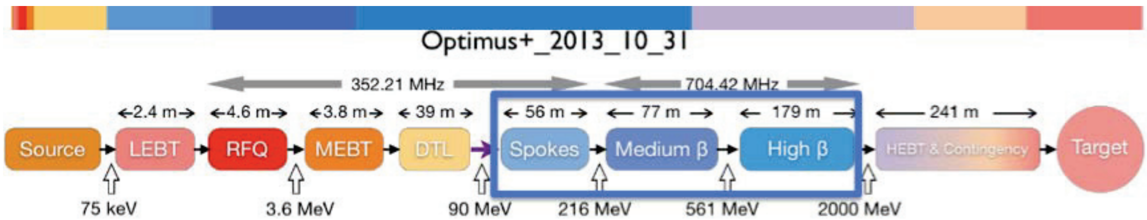

Figure 1: Block diagram of the ESS linear accelerator.

Cryomodule and Valve Box

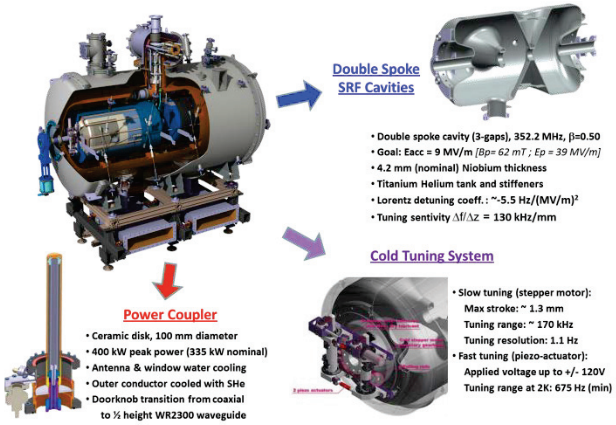

Figure 2: 3D model of the prototype cryomodule and the main components.

The design of the cryomodule has been presented in [6]. Additional information and an up-to-date status of the fabrication of the cryomodule and valve box prototypes can be found in [7].

As a summary, up to now, all components have been ordered and some of them have been received such as the vacuum vessel, the aluminium thermal shield, the mechanical supports, the cold-to-warm transitions, the gate-valve (see Fig. 3). After the reception of the components, in addition to the required geometrical controls and leak checks, a blank assembly is done to check the assembly procedures.

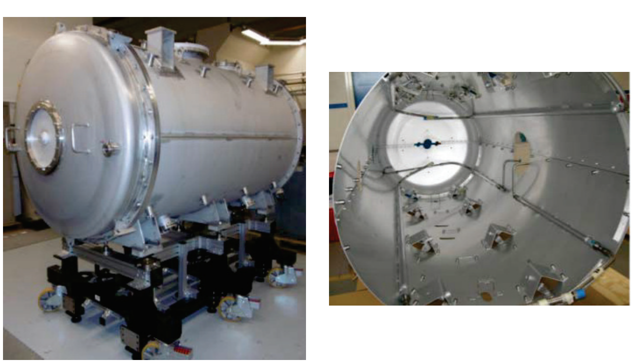

Figure 3: Vacuum vessel set on its mechanical support (left) and the thermal shield (right).

The complete assembly of the cryomodule (with the cavities, couplers, tuning systems, magnetic shield…) is planned by the end of 2015.

The valve box fabrication has started in July this year and the delivery is planned for end of November 2015.

Double-Spoke Resonators

Details about RF and mechanical designs have been presented in [8]. Three beta 0.50 Double-Spoke prototypes have been fabricated and delivered at the end of 2014: two prototypes (ZA-01 and ZA-02) by E. Zanon and one prototype (SD-01) by SDMS.

From the same detailed technical drawings provided by IPN Orsay, the two companies have developed different techniques for the forming of the end-cups and the spoke bars (Fig. 4). E. Zanon did the spoke bars into 2 pieces while SDMS chose to split the bars into 4 parts (Fig. 4). For the end-cup fabrication, E. Zanon spun this cavity part from one sheet whereas SDMS spun two discs and welded them together. Likewise, for the frequency tuning phase (before completion of the bare cavity with the welding of the two end-cups), the two companies chose not to trim the same part: the cavity body for E. Zanon and the end-cups for SDMS.

All cavities were delivered fully jacketed with their 4 mm thick titanium helium vessel. The integration of the helium vessel around the bare cavity was of the most critical steps of the fabrication and had a non-negligible impact on the frequency cavity (between 200 and 500 kHz). This particular point will be carefully checked during the series production of the cavities.

Figure 4: Spoke bar and end-cup fabrication from E. Zanon (left) and SDMS (right).

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All three cavities have been etched by BCP. The goal was set to 200 µm minimum removal. The Double-Spoke cavities have been etched in 3 phases (Fig. 5):

- Phase 1 (120 min): horizontal position
- Phase 2 (120 min): horizontal position, cavity turned 180°
- Phase 3 (240 min): vertical position

These three positions gave us a better homogeneity of the chemical etching and led to nearly cancel the frequency shift caused by the BCP process; respectively -11, -13 and -17 kHz for the 3 cavities instead of +260 kHz (calculated value).

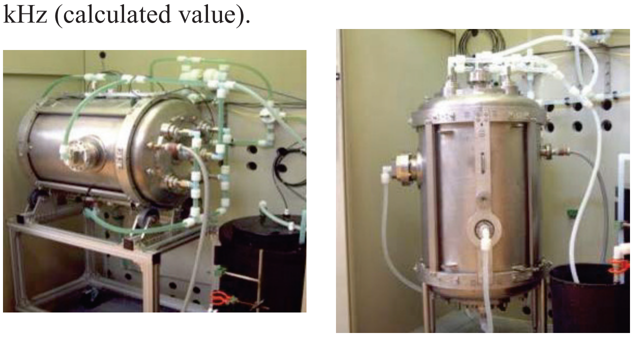

Figure 5: BCP set-up: horizontal (left) and vertical (right).

Then, the cavities have been high-pressure rinsed 4 times at 100 bar, through all ports in vertical position. Each HPR pass has lasted 3 hours. A total of 6000 litres of ultra-pure water was necessary for the whole process. We let the cavities dried for a minimum of 48 hours.

The cavities have been tested at 2K in vertical position inside our vertical cryostat because of lack of space (radially). No 120°C baking nor 600°C heat treatment have been done before those tests. As shown on Figure 6, all cavities exceeded the ESS requirements (i.e. $Q_o > 1.5\ 10^9$ at 9 MV/m). Multipacting barriers have been observed at 1 MV/m (narrow and soft) and between 6 and 8.5 MV/m (wide and harder). Processing time for the hardest barriers lasted about one hour. For the 3 first tests, the limitation came from the cooling capacity and we saw instabilities when the cavity losses were above few tens of Watts due to the "bad cryogenic" conditions with the cavity in vertical position.

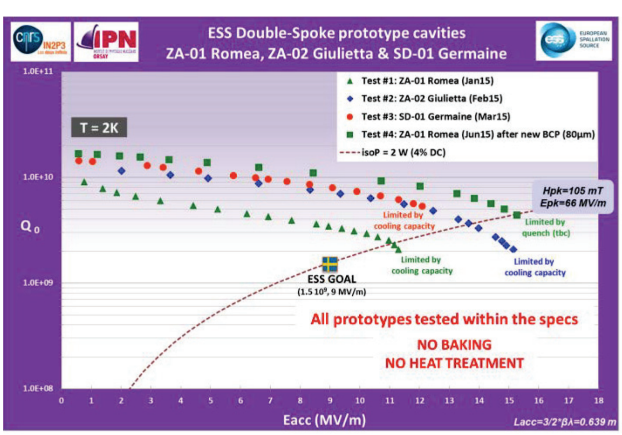

Figure 6: Q-curves vs. Eacc of the 3 cavities.

ZA-01 has been tested twice after a new BCP treatment (80 µm). Indeed, we observed at the end of the phase 3 of the first BCP etching of the ZA-01 cavity that the temperature of the acid bath was exceeding 30°C because of an improper setting of the chiller used to maintain the acid bath temperature below 20°C. We improved the chiller operation point after each BCP treatment and we saw, as illustrated on Figure 6, an improvement of the quality factors for ZA-02, SD-01 and, of course, ZA-01 during its second test (with respect to test #1). The final temperature was 25°C for ZA-02 and SD-01 and 18°C for ZA-01 (second BCP).

A maximum gradient of 15.3 MV/m with cavity losses of 50 W (equivalent to 2 W with 4% duty cycle) was reached with ZA-01 during test #2. The cavity limitation is not clearly established between a quench and the cooling capacity.

After its first vertical test, SD-01 was sent to Uppsala University to be tested in horizontal position inside. Description of the test can be found in [9].

In the coming weeks, studies on 120°C baking will be performed. The cavities will be equipped with a dedicated 6 kW heated jacket designed for an operational temperature of 140°C maximum. Finally, the heat treatments for Q-disease cure at 600°C will also be done, beginning of 2016, in the new furnace which was delivered in September at IPN. This furnace is intended to be used for both ESS Spoke and Elliptical cavities treatments.

Cold Tuning Systems (CTS)

Each Double-Spoke cavity will be tuned with a "double-level arm" type tuner with eccentric shaft actuated by a cold motor and equipped with 2 piezo stacks (Fig. 7). The coarse tuning range is about +130 kHz and the fast tuning range shall be +675 Hz minimum to compensate the dynamic Lorentz force detuning. The detailed design and the first measurements performed at room temperature can be found in [10-11].

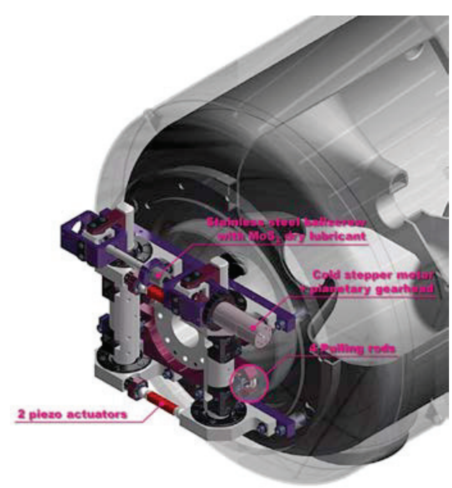

Figure 7: 3D model of the Cold Tuning System for spoke cavities.

Two versions of CTS have been designed in order to test three different lengths of piezos and two sets of each version have been fabricated. The CTS version 1 (nominal configuration) can host 36 mm and 50 mm long piezos whereas the version 2 (optional design) can host 50 mm and 90 mm long ones. We took benefit of the vertical tests of the cavities to test, at the same time, several configurations of CTS version 1 and 2. As shown Figure 8, we reached the specifications for the Lorentz force detuning compensation with the CTS version 1 with 50 mm long piezos but we experienced problems with the CTS version 2. At the present time, there is still no explanation but we highly suspect that the pre-load was too much. New measurements and tests are planned, first at room temperature then again at 2K.

Cavity ID		ZA01 Romea	ZA02 Giulietta	SD01 Germaine	ZA01 Romea
VT date		janv-15	feb-15	apr-15	juin-15
Piezo #1		Noliac 50 mm	Noliac 50 mm	PI 36 mm	PiezoMec. 90 mm
Piezo #2		Noliac 50 mm	Noliac 50 mm	Noliac 50 mm	PI 90 mm
Tuner sensitivity @2K	kHz/mm	78	88	68	-
Tuner sensitivity @4K	kHz/mm	79	92	73	82
Tuner sensitivity @300K	kHz/mm	-	-	67	-
Cavity sensitivity @300K	kHz/mm	-	-	144	-
Detuning range Piezo #1 @2K	Hz	930	953	542	306 (+/- 120V)
Detuning range Piezo #2 @2K	Hz	680	717	791	0 (issue)
Frequency @4K (w/o tuner)	MHz	352.453	352.123	352.038	352.409
Frequency @2K (w/ tuner)	MHz	352.429	352.100	352.032	352.419
Pressure sensitivity (w/o tuner)	Hz/mbar	25.5	23.3	5.5	-
Pressure sensitivity (w/ tuner)	Hz/mbar	28.8	28.8	14.5	-
Static Lorentz coefficient	Hz/(MV/m²)	-8.5	-6.8	-8.1	-

Figure 8: Test results of CTS version 1 (Jan-15, Feb-15 and Apr-15) and version 2 (June-15). Green squares show fast detuning range within the specifications, red square shows problems.

Figure 9: Prototype couplers from SCT (upper) and PBM (lower).

Fundamental Power Couplers

The design of the RF power coupler for the ESS spoke cavities has been presented in [12]. Four prototype power couplers have been fabricated by two French companies (a pair for each) and delivered in 2015 (Fig. 9). The antenna is electro polished and the RF window is coated with TiN. Both antenna and window will be cooled with water.

The first pair of couplers has been assembled on the RF conditioning cavity (see Fig. 10) in an ISO4 clean room at IPN. Then, the RF conditioning test bench has been baked up to 155°C for 24 hours after a ramp-up period of 24 hours.

The test bench will be transported by end of September to CEA Saclay to be conditioned up to 400 kW peak power (4% d.c.).

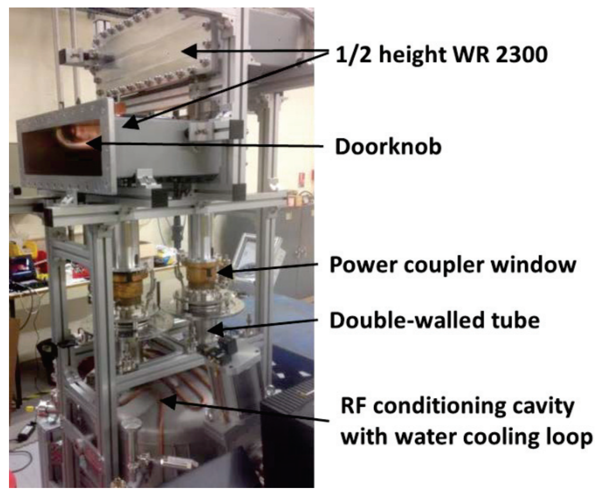

Figure 10: RF conditioning test bench.

The second pair of couplers will be tested afterwards and we will try to condition them up to 1 MW (or to the break-up limit).

Series Production

IPN is nowadays preparing the calls for tender for the high-RRR Niobium material (~3.5 tons of sheets, rods and tubes) and the 26 series cavities. The start of both contracts is planned for the beginning of 2016. A risk mitigation strategy has been adopted by including, within both contracts, the possibly for ordering extra Niobium and cavities throughout the contract period in case of bad performances of few cavities.

Mid-2016, the call for tender of the 13 cryomodules and valve boxes will be published.

ELLIPTICAL CRYOMODULES

Two prototype cryomodules are being developed in order to qualify the technology before launching the production of the series of "elliptical cryomodules". These two prototypes are named M-ECCTD (for the medium beta section at β=0.67) and H-ECCTD (for the high section at β=0.86). The status of the prototype M-

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ECCTD cryomodule is presented at this conference [13], the status of manufacturing of the 6 medium beta prototype cavities is presented in [14] and the status of the prototype coupler production is presented in [15]. The following chapter summaries these 3 papers and gives a short overview of the cryomodules for the two sections of medium and high beta elliptical cavities with a special focus on the status of the prototype cavities and couplers.

General Layout

The medium beta section of the ESS accelerator is based on β=0.67 6-cell cavities and the high beta section on β=0.86 5-cell cavities. Thanks to the small difference in the cavities length (56 mm) the medium and high beta cryomodules have the same vacuum vessels.

The design of the cryomodule (Fig. 11) is based on the SNS/CEBAF concept with an aluminium space frame and titanium rods holding the cavity string and the thermal shield inside the vacuum tank. Each cryomodule houses 4 cavities working at 2K and there is no focusing magnet coil inside the vacuum tank.

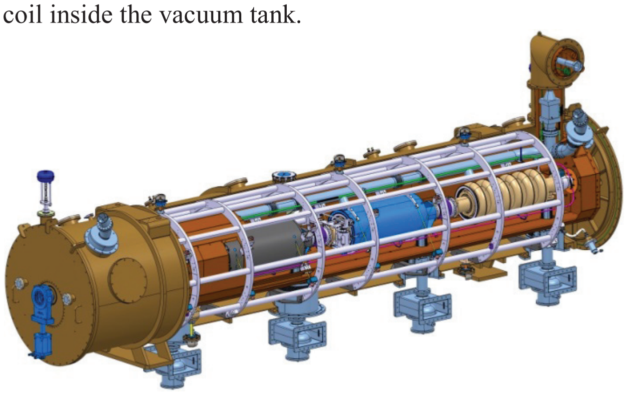

Figure 11: Cryomodule cross section.

Main characteristics:

- Overall length: 6.6 m
- Beam axis height: 1500 mm
- Overall height: 2826mm from the ground
- Weight: 5.8 tons
- Distance between couplers: 1500mm

The cryomodule is ended at each extremity by two warm gate valves connected to the WLU (Warm Linac Units).

The power couplers are fixed longitudinally and the thermal shrinkage of the external conductors of about 0.6 mm is kept free allowing the cavity axis to be kept fixed during cool down cycles. A bellow insures the tightness between the coupler and the vacuum tank while limiting the atmospheric pressure strength applied thanks to a pressure compensation system based on springs. Flexible wave guides are thus required to allow the doorknob displacement during the thermal cycles. Inter-cavity bellows provide the necessary flexibility for the cavity thermal shrinkage (of about 2 mm per cavity) and for the frequency tuning deformation. Two cold to warm transition bellows at each extremity limit the heat load to the cold mass at 2K (see following Table 1).

Table 1: Static Heat Loads Values for One High Beta Cryomodule

Component	**50K (W)**	**5K (W)**	**2K (W)**
Thermal radiation	19		0.7
Supporting system with thermalization at 50K	8		0.23
Interface between the spaceframe and the thermal shield	20		
Warm to cold transition (2 items)	6		0.4
Safety relief valves	6.8		0.42
Control valves	3		1.5
Power coupler double wall from 5K flange			4
Instrumentation, heaters and actuators	13	1.5	0.2
TOTAL	75.8	1.5	7.5

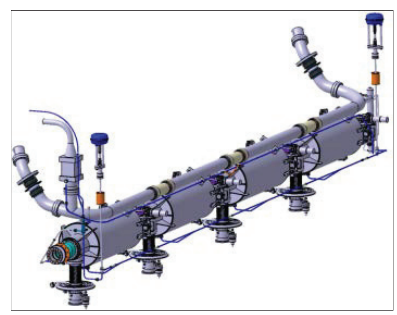

Figure 12: The cavity string equipped with the cryogenic pipes.

The thermal shield in aluminium is cooled by helium gas at 50 K and 19 bars. It is fixed on the titanium rods holding also the cavities string. Eight movable panels in front of the Cold Tuning System allow the access for replacement in case of failure on the motors or other fragile parts like piezo stacks.

The cryogenic heat exchanger is inside the cryomodule vacuum (Fig. 12) and two cryogenic valves are placed on the cryomodule, one for the cooling down and one for the helium level regulation.

The other cryogenic valves are located on the cryogenic valve box. The 100 mm diameter bi-phase cryogenic pipe above the cavities is made out of titanium. It is welded and three bellows in Titanium along this pipe compensate the cavity misalignments and allow the thermal shrinkage. This bi- phase tube ends at its two extremities by 2 burst discs (diameter 100 mm), ensuring the security against accidental events. The geometry of the bi-phase tube has been optimized to limit the pressure increase in the worst case of a beam vacuum rupture accident. The maximum pressure is then determined by the burst disks value which has been chosen at 0.99 ± 0.05 barg. This value fixes the service pressure of the cryomodule at Ps=1.04

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barg allowing these cryomodules to be compliant with the article 3.3 of European Pressure Equipment Directive (PED 97/23/EC).

Elliptical Cavities

The cavities at 704.42 MHz presented in more details in papers [13-14] are made out of standard high purity niobium (RRR>250) and are equipped with a titanium tank. The requirements are presented in the Table 2. One important characteristic of these cavities is that they are not equipped with any HOM coupler. As a consequence a requirement has been established on the cavities HOM frequency and all HOMs shall be at least 5 MHz away from any multiples of the beam-bunching frequency 352.21 MHz.

Table 2: RF Requirements for Elliptical Cavities

	Medium	High
Geometrical β	0.67	0.86
Frequency (MHz)	704.42	704.42
Number of cells	6	5
Operating temperature (K)	2	2
Maximum surface field in operation (MV/m)	40	44
Nominal Accelerating gradient (MV/m)	< 16.7	< 19.9
Q0 at nominal gradient	$> 5\ 10^9$	$> 5\ 10^9$
Qext	$7.5\ 10^5$	$7.6\ 10^5$

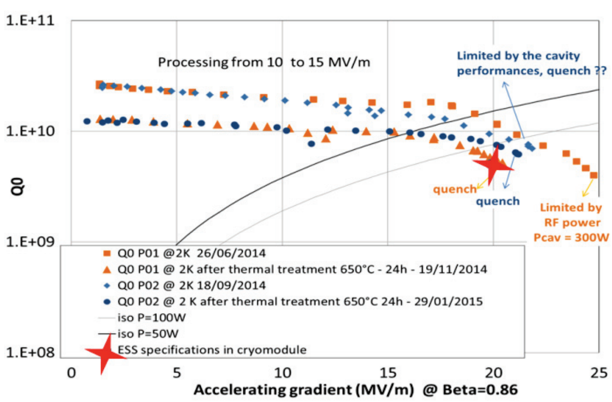

Figure 13: Q-curves of the two high beta prototype cavities before and after heat treatment for hydrogen degassing.

Two prototype high beta cavities have been fabricated by two different European companies. Two series of RF tests in vertical cryostat have been performed for each cavity before and after heat treatment for hydrogen removing. Results are presented on Fig. 13.

The heat treatment caused a degradation of the performances probably due to a surface pollution that was not totally removed by the second light BCP (~20 µm) done after the heat treatment. The cavities will be tested again after a deeper BCP treatment.

For these two cavities, the accelerating π–mode frequency is very close the target value but HOMs with frequencies close to the 4th harmonic of the beam have been found whereas the design of the cavity predicts this HOM frequency at 12 MHz away. The analysis of the external cell shape of the fabricated cavities showed a deviation of the external cells shape of more than 1 mm. Calculation of the cavity reconstructed with this defect confirmed the measured frequency.

As a consequence of this HOM issue on the two high beta prototype cavities, the six medium beta cavities are presently being fabricated for the M-ECCTD prototype cryomodule with a particular attention on the cavity shape that is checked at each step of the production. At present, all dumbbells are completed (Fig. 14) with stiffening rings welded. 3D and RF measurements have been performed on ½ cells and on the dumbbells. Cells reshaping has been done and the final shapes of the series pieces showed a good reproducibility.

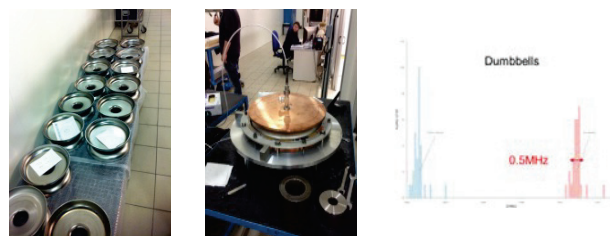

Figure 14: Dumbbells of the medium beta cavities prototype (left) and frequency measurements (right).

The first bare cavity should be delivered to CEA before the end of October. Once CEA releases the production of the 5 other cavities the delivery rate of the bare cavities can be one cavity every two weeks.

For this first small series of 6 prototype cavities, CEA is in charge of the field flatness, heat treatment, 200 µm BCP before sending back the cavities to the manufacturer for helium tank welding. Tests in vertical cryostat of the dressed cavities are done at CEA.

Power Couplers

The power coupler is presented with more details in [15]. It is an adaptation of the 704 MHz, 1.2 MW peak power FPC developed in the framework of the European program CARE/HIPPI. The ceramic windows and antennas are the same for both types of cavities and their Q_{ext} is adjusted by using external conductors with 2 different lengths, one for the medium and one for the high beta cavities.

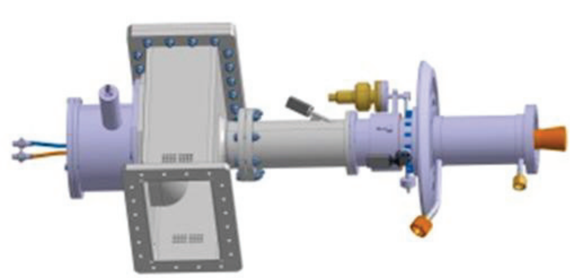

Figure 15: 3D model of the power coupler.

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The antenna is cooled by a water flow and the external conductor is a double wall with an inner chicane cooled by supercritical helium gas entering the tube at the cavity side flange at 3 bar and 4.5 K. The doorknob transition is equipped with a bias system. Three diagnostics are used for protection of the ceramic window: a pressure gauge, an electron pickup antenna and an arc detector.

The production of the power couplers for the M-ECCTD is in progress and the first pair of couplers should be ready for RF power conditioning at warm temperature in January 2016.

Cold Tuning Systems

The cold tuning system (CTS) is based on the proven mechanical design principles of Saclay tuners (Fig. 16). It is described in more details in [13]. It combines a slow and a fast tuner. The slow tuner is a double lever system with eccentric shafts actuated by a motor gear box and a screw. This mechanism is running under vacuum at cryogenic temperatures. The fast tuner is made by two piezo actuators that can act simultaneously or not to compensate the Lorentz force detuning.

The manufacturing of the tuners for the M-ECCTD is in progress.

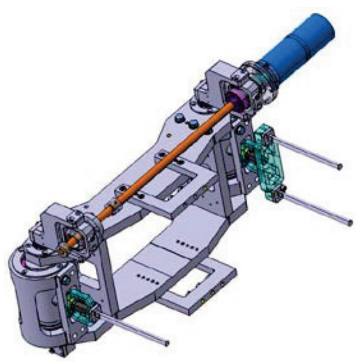

Figure 16: 3D model of the CTS.

Production of the Series of Cryomodules

The production of the cryomodules with elliptical cavities will be made within the collaboration of several contributions:

The medium beta cavities: INFN Milano
The high beta cavities: STFC Daresbury
Cryomodules components: CEA Saclay
Cryomodules assembly: CEA Saclay
RF power tests: ESS Lund

The organization of the collaboration started with the objective to be ready to launch the production of the serial components immediately after the tests of the two prototype cryomodules at Saclay.

The M-ECCTD will be tested in December 2016 while the H-ECTTD will be tested in October 2017.

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