19th Int. Conf. on RF Superconductivity SRF2019, Dresden, Germany JACoW Publishing
ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP096

ESS PROTOTYPE CAVITIES DEVELOPED AT CEA SACLAY

Enrico Cenni†, Matthieu Baudrier, Pol Carbonnier, Guillaume Devanz, Xavier Hanus, Luc Maurice, Juliette Plouin, Dominique Roudier, Patrick Sahuquet, CEA Université Paris-Saclay, Gif-sur-Yvette, France.

Abstract

CEA-Saclay has developed and manufactured 11 elliptical cavities for the European Spallation Source (ESS). A reliable manufacturing and preparation sequence (bulk buffer chemical polishing, heat treatment, flash buffer chemical polishing) has been developed. Latest results on the high beta model are reported and compared to the one of other cavities that have followed the same preparation. The five cavities presented here overpass the target perfor-mance values set by ESS.

INTRODUCTION

The European Spallation Source (ESS) elliptical superconducting Linac consists of two types of 704.42 MHz cavities, medium and high beta, to accelerate the beam from 216 MeV up to the final energy at 2 GeV. The me-dium and high-beta parts of the Linac are composed of 36 and 84 elliptical cavities, with geometrical beta values of 0.67 and 0.86 respectively. CEA Saclay is in charge of the cavity prototypes that is designing, manufacturing, testing and integrating them into demonstrator cryomodules. 6 medium beta and 5 high beta cavities have been manufac-tured. Herein, our latest results especially on high beta cav-ities are reported.

CAVITIES REQUIREMENTS

In this section, some relevant RF parameters and requirements for medium and high beta elliptical cavity section will be presented. More details are available elsewhere [1–5]. Two types of elliptical cavities were developed in CEA-Saclay, one called medium beta has a geometrical beta of 0.67 while the second, a high beta has a geometrical beta of 0.86. Some relevant parameters concerning cavity design and expected performance are listed in Table 1.

The two cavity models integrated with the helium tank are shown in Fig. 1. A mid-section view is used to appreciate the inner geometry.

One of the concern during design was to avoid higher order modes (HOMs) to be closer than 5 MHz to the main accelerator harmonics (“machine lines”). Both design proved to be reliable with respect to this potential issue. In Fig. 2 are shown a family of TM HOMs close to the 4th main harmonic for the 5 high beta cavity prototypes. Ac-cording to the design, an offset of 11 MHz is expected. The manufacturing process ensures their correct position on the spectrum. It shall be pointed out that Fig. 2 presents the cavities spectrum just after welding, that is no other plastic deformation was applied to the cavity (tuning) at this stage.

† enrico.cenni@cea.fr

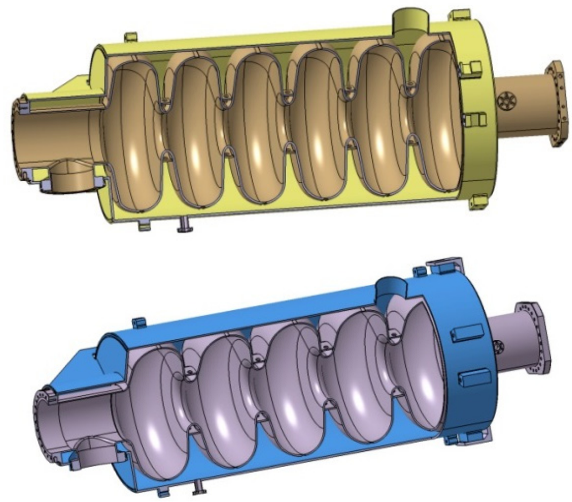

Figure 1: High beta (top) and medium beta (bottom) mid cross section.

Table 1: Design Parameters and Expected Performance

Design parameters	Medium beta	High beta
Geometrical beta - β_{geom}	0.67	0.86
Nominal gradient E_{acc} [MV/m]	16.7	19.9
Q_0 at nominal gradient	> 5 x10^9	
Cavity dynamic RF heat load [W]	4.9	6.5
E_{pk}/E_{acc}	2.36	2.2
B_{pk}/E_{acc} [mT/(MV/m)]	4.79	4.3
E_{pk}@nominal E_{acc} [MV/m]	39	44
B_{pk}@nominal E_{acc} [mT]	80	85
R/Q [Ω]	367	435
G [Ω]	196.6	241
TM HOMs[6]	>5 MHz from machine line	

MANUFACTURING AND PREPARATION

To achieve these results, a careful analysis on half cell shape was carried out and a shape tolerance of 0.4 mm (±0.2 mm with respect to ideal shape) was applied on all the RF surfaces. Finally, in agreement with the manufacturer, a straightforward acceptance criteria for each end cell and dumbbell was applied. Taking into account that for the high beta the closest HOMs have the strongest field in the end cell, a stricter criteria was chosen for the end group cell in comparison to the central one. The cell measurements were performed by means of coordinates-measuring machine (CMM), 400 contact points were

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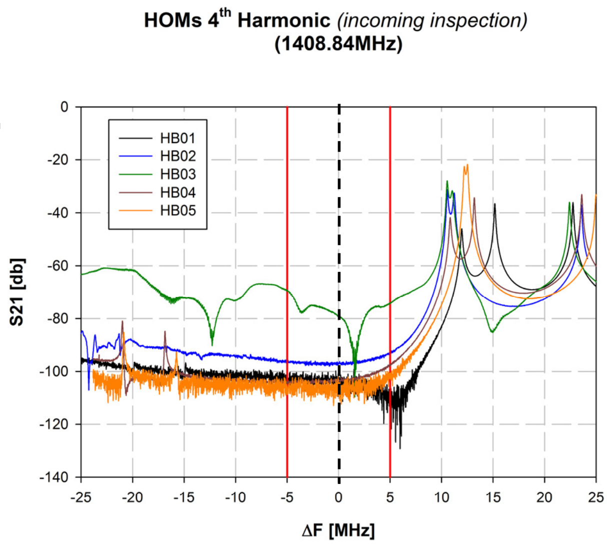

Figure 2: High beta prototypes HOMs spectra close the 4th machine harmonic (1408.84 MHz black dashed line), S21 [dB] parameter with respect to the frequency shift distance to the machine line. According to the design, an offset more than 10 MHz to the closest mode respect to the main harmonic is expected. Requirements impose to have them at least 5 MHz away (red lines).

inspected on each cell. An end cell was considered acceptable if more than 90% of the points were within tolerance, while for central cells this limit was lowered to 85%. Similar procedures were applied for medium beta prototypes.

The workflow for high beta is summarized in Table 2.

Table 2: Manufacturing and Preparation Workflow for High Beta Cavities

Phase	Parameters
End cell/central cell forming and measure (CMM)	90%/85% (points within 0.2 mm)
Bulk BCP	(100+100) µm etching
Heat treatment	650 °Cx10 h
Tuning and field flatness	>95%
Flash BCP	15-20 µm (T<1 5°C)
Vertical test	Q_0>5x10^9@19.9 MV/m
Tank integration	Ar filled cavity
Flash BCP	15-20 µm (T<15 °C)
Vertical test	Q_0>5x10^9@19.9 MV/m

Bulk BCP

After cavity electron beam welding and leak checking, a bulk etching by means of buffer chemical polishing (BCP) was performed. BCP was applied twice on each cavity and removed on average 100µm of Niobium. Due to the highly asymmetrical nature of this chemical polishing the cavity orientation was flipped at each step. The bulk BCP was per-formed with a mixture of $HF:HNO_3:H_3PO_4$ with volume proportion of 1:1:2.4.

From this first set of BCP, it was possible to establish the frequency shift induced by material removal (Table 3) and use it to deduce the frequency tuning before tank integra-tion and final BCP.

Final BCP are of paramount importance in order to ob-tain cavities with good performance. One of the challenge encountered with high and medium beta prototypes was re-lated to the volume of acid needed to treat the cavity with respect to quantity contained in the acid tank. Both cavity type can contain about 70 L of acid, and the chemical reac-tion develop about 2 kW of heat, so keeping the acid at low temperature during the treatment could be demanding. A well-designed acid cooling system and a high-capacity acid tank are mandatory to obtain reliable etching rate and good quality surface finishing.

Table 3: π-mode frequency sensitivity to BCP

Cavity number	Sensitivity [kHz/µm]
HB01	-3.82
HB02	-3.75
HB03	-4.43
HB04	-4.04
HB05	-4.77*
Average	***-4.16***
Simulation with uniform removal	-3.99

*Acid feeding issue lead to slow down and circulation stop.

It should be noted that the HB05 sensitivity is an outlier with respect to the others. The reason could be linked to an issue occurred on the acid pumping system, the pump re-duced the acid flow and then stopped for about 10 minutes leading to an uneven etching profile, this can justify the extra frequency shift, if HB05 is excluded from statistics the average sensitivity is closer to the computed (-4.01 kHz/µm). Similar data were collected for the six me-dium beta prototypes giving an average frequency sensitiv-ity about -3 kHz/µm. This compares to -2.97 kHz/µm sim-ulated assuming uniform removal.

Heat Treatment

After bulk BCP, high temperature heat treatment (HT) was performed to remove hydrogen and relax mechanical stress induced by electron beam welding. Cavities were kept at 650 °C for 10 hours. The cavity support was made of In-conel® and high purity alumina for the part in direct con-tact with the cavity external surface. The first heat treat-ment was performed with the cavity supported on all 5 cells and with the support jigs fixed on the oven frame. This set up proved to be not the optimal one due the over con-strained configuration. Hence, for the remaining four cavi-ties we decide to support only 3 cells and to not fix the sup-port jigs. A summary of the heat treatment parameters can be found in Table 4 and in reference [7].

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Table 4: High Temperature Heat Treatment Parameters

Parameter	Value
Base pressure [mbar]	$5x10^{-7}$
Heating rate [°C/min]	3
Dwell temperature [°C]	650
Dwell time [h]	10
Max pressure [mbar]	$5x10^{-5}$

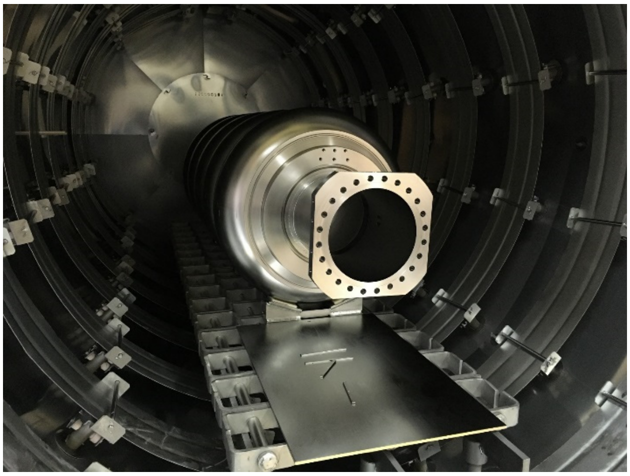

Figure 3: High beta cavity installed into the IPNO oven for heat treatment, on the foreground some niobium sample used for SIMS and RRR analysis.

During heat treatment, the total pressure and the partial pressures of residual gasses were monitored. Hydrogen partial pressure drops about two order of magnitude during heat treatment, Fig. 3 shows a high beta cavity in the heat treatment oven along with niobium samples.

After heat treatment, π-mode frequency was measured for each cavity and compared to its previous value. The re-sults are summarized in Table 5. It should be noted that HB01 have a different frequency shift with respect to oth-ers probably due to the different support set up in the oven.

Table 5: π-mode Frequency Shift After Heat Treatment

Cavity number	π-mode shift [kHz]
HB01*	-162
HB02	123
HB03	145
HB04	118
HB05	143

*Oven supports set up were different with respect to the others HT.

Flash BCP

After heat treatment and tank welding, two small BCPs were performed and followed by a test in the vertical cry-ostat. For these, a different mixture of acid was used: 1:1:2 ($HF:HNO_3:H_3PO_4$) and kept around 5 °C before starting the chemical polishing. During the chemical etching, it was maintained between 5-6 °C, while the outlet temperature was below 15°C. This last BCPs were performed with fresh acid or with a dissolved niobium concentration below 4 g/L.

VERTICAL TESTS

Two vertical tests are usually planned for each cavity, one with the cavity without helium tank and a second after the tank integration. During this second test, the field probe, which will be used in the cryomodule, is installed on the cavity to measure its specific quality factor (Q_t). During the first test, a field probe less coupled to the cavity was used to avoid extra power losses during the cavity per-formance assessment. A typical order of magnitude for Q_t is 1/100 with respect to unloaded Q (Q_0) for the first test and 1/10 for the final one.

The vertical cryostat is protected from earth magnetic field by a μ-metal magnetic shield and 3 set of solenoid coils, allowing a remnant magnetic field at the cavity equa-tors less than 1 μT.

The cooldown rate from room temperature to 4.2 K is about 4 K/min to minimize the effect of hydride formation on cavity quality factor. RF measurements were performed by means of phase locked loop (PLL) and the power rise measurements performed at 2 K.

In Fig. 4 are shown the latest results concerning the high beta cavities integrated in the helium tank, the meas-ured performance are above ESS requirements, $Q_0>5x10^9$ with an accelerating field of 19.9 MV/m.

Cavity HB02T was affected by strong field emission, nevertheless the Q_0 below 18MV/m was about the same as the other 2 cavities and we started to observe a significant Q_0 slope between 18 MV/m and 23 MV/m. A more detailed analysis concerning field emission will be presented in the following reference [8].

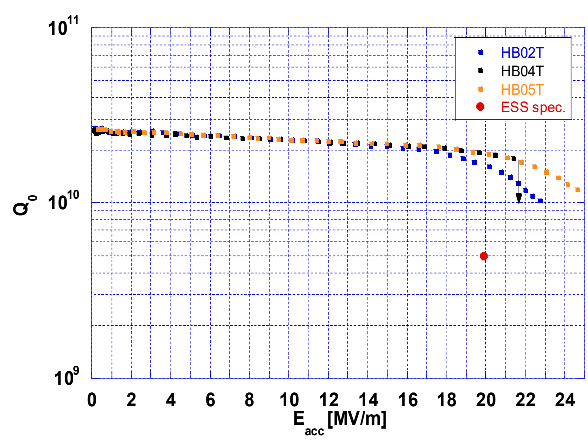

Figure 4: Q0 with respect to accelerating gradient for the first 3 high beta prototypes integrated in the helium tank.

The cavities were cooled down from 4.2 K to 1.6 K by reducing the cryostat pressure down to about 8 mbar. Dur-ing this phase it was possible to obtain the cavity surface resistance by means of decay time measurements, while starting form an the accelerating field at about 1 MV/m.

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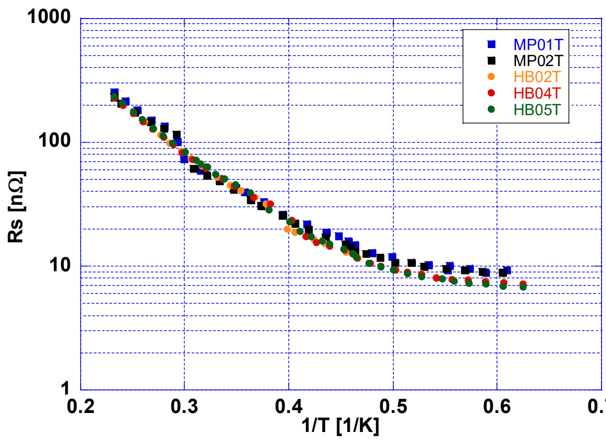

Figure 5: Surface resistance at 1MV/m for high and medium beta prototypes.

In Fig. 5 are shown the results from the first 3 high beta prototypes (HB02T, HB03T, HB05T) along with the first 2 medium beta prototypes (MP01T, MP02T). Such comparison are necessary since the two set of cavities had the same kind of surface treatment. Data were fitted with equation (1) in order to extrapolate niobium gap energy and residual resistance, results are summarized in Table 6.

$$R_S = \frac{A}{T} \times e^{-\frac{\Delta}{T}} + R_0 \qquad (1)$$

Table 6: Surface Resistance Fitting Parameters

Cavity number	**R_0 [nΩ]**	**Gap ($\Delta \cdot k_b$) [meV]**
MP01T	9.2	1.70
MP02T	8.9	1.71
HB02T	7.0	1.66
HB04T	7.4	1.68
HB05T	6.7	1.65

Finally, in Fig. 6 are shown the Q_0 measurements with respect to the peak magnetic field for each type of cavity.

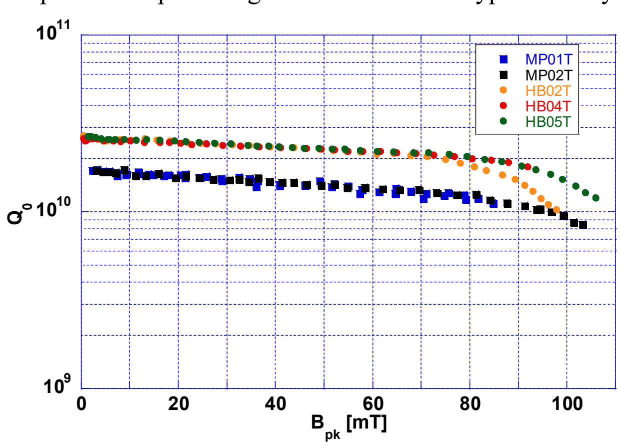

Figure 6: Q_0 with respect to surface peak magnetic field B_{pk}[mT].

SUMMARY

CEA-Saclay developed and manufactured 11 elliptical cavities for ESS. One of our main goal was to find a reliable manufacturing and preparation sequence to meet the cavity performance target set by ESS. It consists of bulk buffered chemical polishing, heat treatment and flash buffered chemical polishing. Here, latest results concerning the high beta model were presented. These results were compared to the ones of other cavities that have followed the same preparation. Table 7 shows the unloaded Q at low field (1 MV/m), the Q0 at nominal field (ESS requirements), the maximum accelerating field achieved along with the origin of the limit (Power limited, administrative limit or quench) and finally the Q0 at the maximum accelerating field. Administrative limit was imposed in order to limit the possibility of damage due field emitter bursts.

The five cavities presented here overpass the ESS requirements.

Table 7: Vertical Cryostat Tests Summary

Cavity number	**$Q_0/10^{10}$** [1MV/m]	**$Q_0/10^{10}$** [nom.E_{acc}]	**Max E_{acc}** [MV/m]	**$Q_0/10^{10}$** Max E_{acc}
MP01T	1.7	1.2	17.7 (Admin)	1.12
MP02T	1.7	1.2	21.5 (Power)	0.84
HB02T	2.5	1.6	22.7 (Power)	1.03
HB04T	2.5	1.9	21.4 (Quench)	1.8
HB05T	2.57	1.9	24.6 (Power)	1.2

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