# STATUS AND FIRST TEST RESULTS OF TWO HIGH BETA PROTOTYPE ELLIPTICAL CAVITIES FOR ESS

F. Peauger, P. Bosland, P. Carbonnier, G. Devanz, F. Eozenou, X. Hanus, P. Hardy, V. Hennion, L. Maurice, J. Plouin, D. Roudier, C. Servouin, CEA Saclay, Gif-sur-Yvette, France
G. Olivier, IPN, Orsay, France
C. Darve, S. Molloy, ESS, Lund, Sweden

*Abstract*

Two prototypes of elliptical superconducting cavities have been designed and manufactured for ESS. These 704.42 MHz. 5-cell cavities have a beta value of 0.86 and the nominal accelerating gradient on the ESS accelerator is 19.9 MV/m at 2 K.

We present the manufacturing status of the cavities by two different vendors. We emphasis the activities performed on the first bare cavities recently received at CEA such as the RF measurement and tuning operations, the cleaning and chemical treatments and the clean room assembly including high pressure rinsing. Finally, first test results at 2 K in vertical cryostat are reported.

## INTRODUCTION

The European Spallation Source (ESS) is a 5 MW – 2 GeV – 62.5 mA superconducting proton linac project under construction in Lund, Sweden. Two families of 704.42 MHz elliptical cavities are considered for the high energy section of the linac. In the last accelerator design called "Optimus+" [1], a total of 36 cavities with a geometric $\beta$ of 0.67 will first accelerate the beam from 220 to 570 MeV and 84 cavities with a geometric $\beta$ of 0.86 will increase the beam energy up to 2 GeV.

In the frame of the French-Swedish agreement, CEA Saclay and IPN Orsay are developing in collaboration with ESS the cryomodule for elliptical cavities where a prototype (ECCTD) is being constructed [2].

The accelerating gradient have been respectively specified to 16.8 and 19.9 MV/m for the medium and high beta elliptical cavities, with a $Q_0$ of 5e9 in the cryomodule configuration. Details on RF and mechanical design have been presented in [3]. The construction and qualification of two high beta prototype cavities have been anticipated with the objective to demonstrate the required accelerating gradient and evaluate the possible margins.

This paper describes the fabrication status and the first experimental results obtained during this prototyping phase.

## CAVITY MANUFACTURING

The manufacturing contract of the two cavities has been awarded by two different European vendors: E. ZANON in Italy for cavity n°1 and RI in Germany for cavity n°2. The two contracts started in September 2012. The fine grain Niobium material has been provided by CEA. It has been manufactured by Tokyo Denkai in Japan from a single order. The Nb sheet thickness is 4.5 mm average and the RRR measured value is between 300 and 360.

### *Shaping the Half Cells*

The deep drawing process has been chosen by the two vendors. Dimensional measurements have been performed on few niobium cells after iris and stiffeners welding. The internal shape accuracy is specified at ± 0.3 mm.

For the cavity n°1, the measured shape of the inner cell is within the specification in the equator region but deviates significantly in the iris area. For the cavity n°2, the internal shape achieved after deep drawing was in agreement with the specification except in the equator region. The diameter of the equator welding interlocking was too large and additional spinning operation had to be applied on few cells to allow the correct assembly of the cavity.

### *RF Measurement of Dumbbells and Endgroups*

Intermediate RF controls have been organized at factory on the elementary parts of the cavity. This measurement is done after each trimming step in order to reach a target resonant frequency and satisfactory field flatness. It has been done in collaboration with the company, using dedicated manufacturer equipment. In both cases the same principle is used. It consists in closing the cavity volume by metallic plates, coupling it by two capacitive antennas and measuring the RF transmission parameters. The accuracy is about ± 0.02 MHz when a good electrical contact is reached ($Q_0$ > 6000). This process benefits from previous experience on SPL 704.4 MHz $\beta$ = 1 elliptical cavities where the importance of the flatness of the metallic plates and the applied pressure was highlighted [4].

### *Cavity Composition Optimization Before Final Equator Welding*

Geometrical 3D models of all dumbbells and endgroups have been reconstructed in HFSS. The modelled internal shape fits with the dimensional measurements and takes into account the cavity over length obtained after the last trimming operation. The measured resonant frequency is achieved by a fine final adjustment of the internal geometry. All the dumbbells and endgroups combinations are simulated. The theoretical field flatness values

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deduced from the optimal configuration are 89.6% and 82% for cavity n°1 and n°2.

Figure 1 shows the two prototype cavities after final welding. Leak tests and internal visual inspection have been successfully performed at factory and after delivery at CEA.

Figure 1: ESS high beta prototype cavity n°1 (up) and n°2 (down) at factory before shipment.

The main cavity parameters have been measured at CEA after delivery and are given in Table 1.

Table 1: Cavity Parameters Measured in Air, at Room Temperature and Before Chemical Etching

| | Design | Cavity n°1 | Cavity n°2 |
|---|---|---|---|
| $F_\pi$ (MHz) | 703.822 | 703.553 | 703.704 |
| Cavity length (mm) | 1316.3 | 1321.7 | 1322.9 |
| Field flatness | 99 % | 86.8 % | 39 % |

In both case the π–mode frequency is very close to the target value. A significant cavity over length is noticed on the two cavities and would be corrected if the cavity should be integrated in a cryomodule. The field flatness ratio is satisfactory and near the expected value for cavity n°1 whereas a strong discordance is observed on cavity n°2 and is not yet understood. As preliminary conclusion of the manufacturing phase of the bare cavity, these two prototypes present rather good results but also demonstrate that the manufacturers and processes have to be specifically qualified, even for very experienced companies. Improvement shall be applied for the series cavities.

## FIELD FLATNESS TUNING

The field flatness of cavity n°1 has been tuned at CEA using the newly developed set-up which allows deforming each cell independently. After a total of 10 iterations, the field flatness ratio has been increased from 86.3 % to 92.7 % (Fig. 2). The resonant frequency has been slightly shifted to 703.596 MHz. After tuning, a mechanical elastic deformation of ± 1 mm has been applied on the beam flanges. The measured frequency sensitivity to elongation is + 118 kHz/mm.

Cavity n°2 has been recently installed on the tuning set-up and the tuning procedure will start in June 2014.

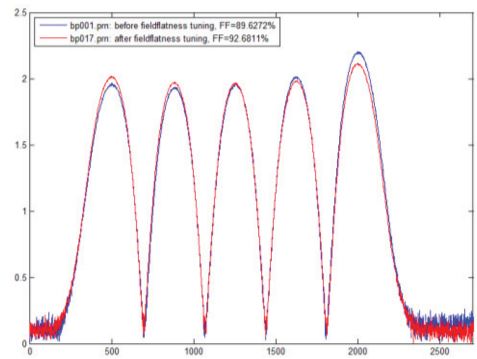


Figure 2: On-axis E-field profile of cavity n°1 before (blue) and after (red) tuning (arbitrary units in both axis).

## CHEMICAL TREATMENT AND CLEAN ROOM ASSEMBLY

Cavity n°1 has been etched with a buffered chemical solution ('BCP' polishing using Hydrofluoric-Nitric-Phosphoric acids with ratio, 1:1:2.4) in three steps. The acid temperature was kept below 15 °C to avoid any hydrogen contamination of the niobium. The measured removal speed is 0.5 µm/min and the average niobium thickness removed is 200 µm. Bead-pull measurements have been performed after the first two etching operations and did not show any field flatness modification. The last BCP treatment was followed by a filling of the cavity with pure water and a transfer to the CEA clean room. Four steps of High Pressure Rinsing (HPR) have been applied. For each step, the cavity was turned up and down and rotated by 180° with respect to the cavity axis. The cavity has been dried overnight in the class 100 area. The incident antenna has been mounted in the power coupler port with an external coupling factor $Q_x$ of 6e9. Two stainless steel cups (140 mm diameter, 100 mm long) were added on the beam ports in order to move away the end-plates of the cut-off tubes and avoid any additional rf losses. The transmitted antenna was assembled on the tuner-side cup along the cavity axis and coupled to the vacuum valve by a tee connector. The aluminium gaskets were assembled and tightened under specific torque. No leak was detected after two days of pumping.

During the integration of the cavity on the vertical insert, an accidental manipulation of the cavity supporting plate produced a vacuum leakage on the valve flange. After a complete disassembly and a cleaning in ultra-sonic bath, the same clean room procedure was applied for HPR, drying and assembling. No leak was finally detected after the second assembly on the vertical insert.

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## PRELIMINARY TEST RESULTS IN VERTICAL CRYOSTAT

Cavity n°1 has been tested at 4.2 K and 2 K in vertical cryostat at CEA Saclay in May 2014. A fast cool down has been performed (30 minutes between 150 K and 50 K). The π-mode resonant frequency at 4.2 K and 2 K is respectively 704.100 MHz and 704.296 MHz, which stays within the tuner range and fulfils the specification.

At 4.2 K, the accelerating field was only pushed up to 2.9 MV/m, limiting the RF power level to 33 W.

The cavity has been cooled down to superfluid helium temperatures. The surface resistance measured at low field (1.3 MV/m) as a function of the helium bath temperature is shown in Fig. 3.

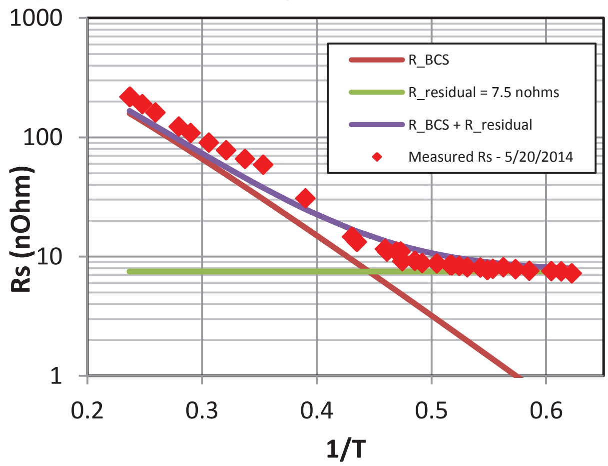


Figure 3: Surface resistance measurement as a function of the temperature for ESS high beta prototype cavity n°1.

The measurement fit using Eq. (1) [5] leads to an estimated residual resistance value of $R_{res} = 7.5\ n\Omega$.

$$R_S = 2\cdot 10^{-4}\frac{1}{T}\left(\frac{f}{1.5}\right)^2 e^{-17.67/T} + R_{res} \qquad (1)$$

Fig. 4 shows the result of the $Q_0$ = f(Eacc) curves measured at 1.6 K and 2 K and plot for β = 0.86, $L_{acc}$ = 0.92 m and R/Q = 435.35 Ω.

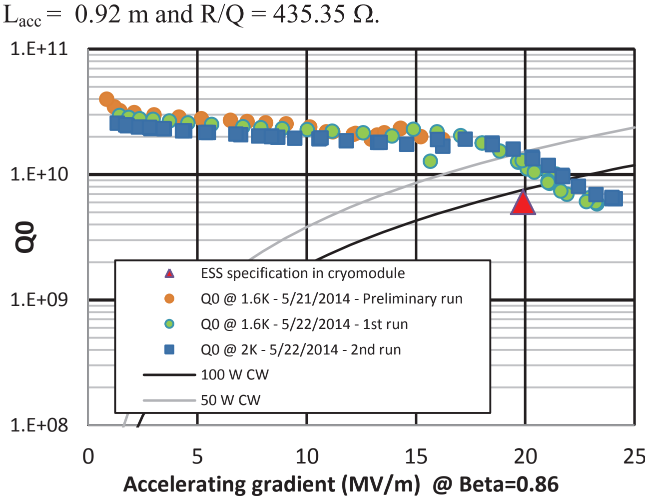


Figure 4: First test results at 1.6 K and 2 K of ESS high beta prototype cavity n°1 in vertical cryostat.

During the preliminary run at 1.6 K (orange dots), the test was limited at $E_{acc}$ = 16.2 MV/m by the admissible radiation level in public area (0.5 µSv/h). The first and second runs (green and blue dots) were performed under a special authorization to increase the radiation limit up to 5 µSv/h. A soft multipacting barrier occurred between 13 and 16 MV/m and was easily processed after few minutes of conditioning. At low field the curve stayed relatively flat whereas a high field Q-drop was observed above 18.4 MV/m.

At 20 MV/m and 2 K, the measured quality factor $Q_0$ was 1.3e10. Although the cavity is in early stage of its preparation, this result is already above the ESS requirement of 5e9 in cryomodule configuration.

The highest gradient achieved was $E_{acc}$ = 24 MV/m at 2 K corresponding to $E_{peak}$ = 52.8 MV/m and $B_{peak}$ = 103.2 mT. No quench was observed and the measurement was limited by the maximum available RF power of the amplifier (170 W). The measured static Lorentz detuning factor is estimated at $|K_L| = 6.5 \pm 1$ Hz/(MV/m)$^2$ in free ends conditions.

The cavity has been kept at cold temperature and additional tests are foreseen with a new 1 kW RF amplifier. HOM frequency measurements at cold temperature will also be performed.

## CONCLUSION

Two prototypes of ESS high beta elliptical cavities have been manufactured by two different European vendors. Each cavity element has been finely tuned to optimize the field flatness and resonant frequency parameters. The two cavities have been delivered at CEA without its helium vessel. The first cavity has been successfully tuned using a newly developed tuning set-up. It has been chemically etched with a standard BCP mixture and assembled in clean room including high pressure rinsing. The preliminary vertical test results have shown very good performances in term of losses and maximum accelerating gradient achieved. The second cavity will follow the same preparation and testing plan while the first cavity will be high temperature treated under vacuum before the next high gradient test.

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