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VERTICAL ELECTRO-POLISHING OF 704 MHz RESONATORS USING NINJA CATHODE: GRADIENT OVER 40 MV/m ACHIEVED ON SINGLE-CELL ESS CAVITY

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Abstract

CEA, KEK and Marui Galvanizing Company have been collaborating to apply the Vertical Electropolishing (VEP) process of elliptical SRF cavities to a 704.4 MHz single-cell β=0.86 ESS-type cavity, using a rotating so called and patented 'Ninja' cathode. First presented results were promising with a gradient of 27 MV/m achieved, without any heat treatment applied. The performance has been pushed further since. The cavity has undergone a heat treatment at 650 °C during 10 h, followed by a final VEP sequence and a baking at 120 °C during 48 hours. The achieved gradient at 2 K was 44 MV/m (power limitation), and the quality factor Q_0 exceeding 5E10 up to 10 MV/m. The superiority of VEP compared to standard 'BCP' chemical treatment is demonstrated and we intend now to scale the process to a 5-cell β=0.86 ESS cavity. We also intend to push further the performance by applying the "2-step baking" (75 °C and 120 °C) proposed by FNAL, which was successfully applied at CEA Saclay on 1300 MHz single-cell resonators with gradients above 50 MV/m achieved after VEP bulk treatment.

INTRODUCTION

In 2014, CEA Saclay has started studying vertical electropolishing of 704 MHz elliptical niobium cavities within Eucard project for Super Proton Linac (SPL) [1] beta=1 cavity application. The involved 5-cell cavity was electropolished in a mixture made of hydrofluoric and sulphuric acids HF(40%)-H_2SO_4(96%) (volume ratio 1-9) with a fixed rod cathode and it appeared that efficient hydrogen removal was the key for a successful treatment. In fact, inefficient stirring of the acid generates topological features at the surface of the cavity, especially in upper cells, and results in a strong asymmetric removal between upper and lower half cells [2]. Furthermore, it is likely to generate so-called Q-disease [3] phenomenon, which can be efficiently cured by a heat treatment. The SPL cavity, which suffered from strong Q-disease reached 19 MV/m after heat treatment at 650 °C (test limited by field emission) [2].

In order to optimize the vertical electropolishing treatment, KEK, Marui Galvanizing Company Ltd and CEA Saclay have started a collaboration to improve the performance of 1300 MHz ILC type resonators, and more recently, 704.4 MHz ESS type elliptical resonators. The later goal is to improve the performance of ESS type cavities routinely treated by standard 'Buffer Chemical Polishing' (BCP). The Marui technology involves a rotating cathode with wings nearing the surface of the cell. Extensive parameter investigation is presented in [4, 5]. A β=0.86 704.4 MHz cavity has been purchased for the study (EH101 cavity). Bulk (200 µm removal) VEP treatment was carried out and achieved performance was promising [6]. The experiments have been updated: the cavity was tested after heat treatments at 650 °C and 120 °C while 15 µm were removed from the cavity ('flash' VEP) in between. The EH101 cavity on the VEP set-up is shown in Fig. 1.

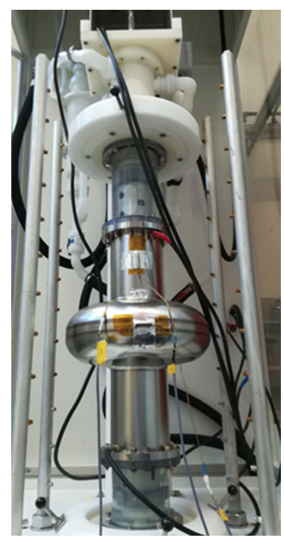

Figure 1: EH101 single-cell cavity installed on the VEP set-up.

BULK TREATMENT

The VEP set-up designed at Saclay is described in [7]. Experimental details (cavity, cathode, treatment parameters) used for the bulk treatment have been discussed in [6] and summarized in Table 1 below. The preliminary results were promising. First hints for a very efficient cavity treatment were achieved since no Q-disease was observed before any heat treatment. The corresponding RF test results are presented later in the graph in Fig. 3 which compiles all the tests carried out on the cavity. The performance achieved on the single-cell cavity before heat treatments matches ESS cavity performance specifications [8], with a gradient of 27 MV/m achieved at a Q_0 of 6E9.

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Table 1: Experimental Parameters

EH101 Cavity Parameters	**Value**
R/Q [Ω] @β=0.86	113
G [Ω]	250
E_{pk}/E_{acc}	1.88
B_{pk}/E_{acc} [mT/(MV/m)]	3.86
Inner surface [m^2]	0.55
Supplier	Zanon RI
Nb RRR	>300
Nb Supplier	Tokyo Denkai
Treatments Parameters	**Value**
Acid temperature (in tank)	15 °C
External cool down water	12 °C
Acid flowrate	15-20 L/min
Voltage	19-20 V
Current	25 A
Removal rate	0.1 µm/min
Electrolyte	HF-H_2SO_4
HF acid mass concentration	0.5%
Ethanol rinsing (static)	60 h
Ninja Cathode Parameters	**Value**
Number of wings	4
Al cylinder diameter	70 mm
Cathode rotation speed	20 rpm
PVC ext cylinder diameter	114 mm
Cathode/cavity surface ratio	0.2

RESULTS AFTER HEAT TREATMENTS

The cavity was then heated under vacuum at 650 °C during 10 h. The treatment was carried out at IJCLab Orsay. The temperature and pressure evolution during treatment is shown in Fig. 2.

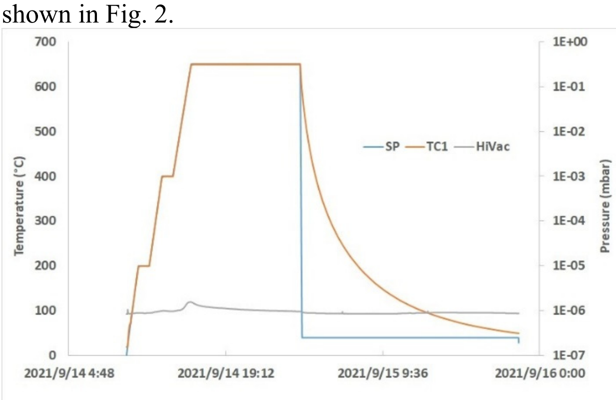

Figure 2: Temperature (orange curve) and pressure (grey) evolution during the heat treatment.

An additional 'flash' (~15 µm removal) VEP sequence was carried out. The set of parameters used for the bulk treatment (Table 1) was maintained except for the HF concentration in the electrolyte: the HF content was increased since a batch of acid from a different supplier was used.

The cavity was rinsed by High Pressure Rinsing and assembled in ISO5 clean room prior to RF test in vertical cryostat at 2 K and 1.4 K. The performance was increased significantly both in terms of accelerating gradient E_{acc} and quality factor Q_0.The Q_0 at low Eacc at 1.4 K is over 1E11 and 5E10 at 2 K (please refer to Fig. 3). E_{acc} is increased significantly around 35 MV/m. A Q-slope is observed with an onset around 30 MV/m. Additional mild baking under vacuum at 120 °C during 48 h was carried out as a final step, with the possible removal of the Q-slope in mind. The baking was successful since the gradient was further increased up to 45 MV/m. A residual Q-slope is observed for gradients above 40 MV/m, due to some field emission. The gradient is limited by the power available. The temperature dependence of the surface resistance Rs is represented in Fig. 4 for the different tests. The achieved residual resistance R_0 is lower than 2 nΩ after the heat treatment at 650 °C followed by the flash VEP. The cavity behaves similarly to the 1300 MHz resonators treated by electropolishing: the mild baking is responsible for a decrease in the BCS resistance while the residual resistance R_0 is increased.

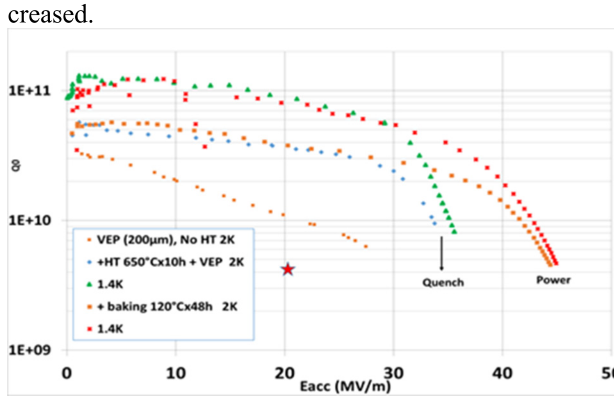

Figure 3: Q_0 = f(Eacc) measured at 2 K and 1.4 K for the different treatments.

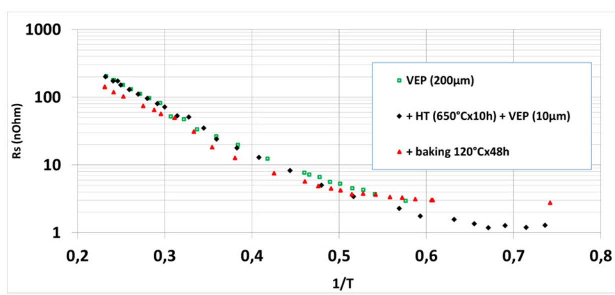

Figure 4: Surface resistance Rs as a function of 1/T measured at 1.1 MV/m before/after heat treatments.

DISCUSSION AND OUTLOOK

As shown with the former treatment of the SPL cavity, efficient removal of the hydrogen bubbles generated at the cathode is of paramount importance for an efficient electropolishing treatment since they might be responsible for features at the niobium surface and for a Q-disease phenomenon. The presented experiments were carried out with parameters chosen towards an optimized control of the hydrogen production for the 704.4 MHz cavity:

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- Large area of the cathode
- Efficient swiping of the cell thanks to the cathode wings
- High rotation speed of the wings
- Low temperature of the acid and external cooling
- Acid with low HF concentration.

The efficient hydrogen removal makes it also possible to improve the homogeneity of the removal [6] compared to the BCP in vertical position [9, 10]. The drawback of this protocol is a low removal rate (0.1 µm/min), compared to standard BCP chemical polishing (0.5 µm/min) [10]. However, the achieved RF performance is excellent and the superiority of VEP compared to standard BCP treatment, routinely used for ESS cavity series production [8, 11], demonstrated. We intend now to investigate the possible benefit of the '2-step baking' proposed by FERMILAB [12] which makes it possible to push further the performance of 1300 MHz Tesla shape resonators compared to the standard baking at 120 °C. This recipe which includes an intermediate step at 75 °C, was successfully applied at CEA after VEP on a 1300 MHz single-cell cavity with Eacc>50 MV/m achieved (Fig. 5). We intend now to apply this baking recipe to EH101 after additional 10 µm removal by flash VEP to evaluate the possible benefits to 704.4 MHz resonators.

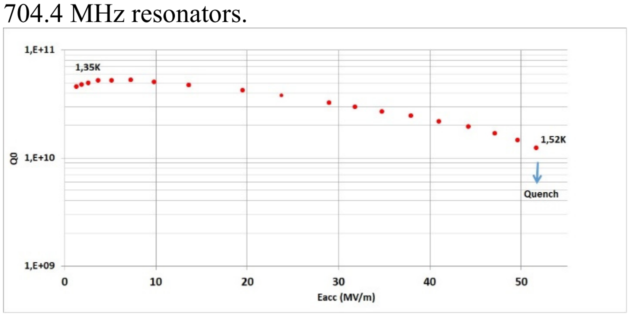

Figure 5: Gradient >50 MV/m achieved at CEA after VEP + '2-step baking' (FERMILAB recipe) at 75 °C-120 °C on 1AC3 Tesla shape 1300 MHz single-cell cavity.

The process will finally be transposed to a 5-cell geometry configuration like the ESS 5-cell β=0.86 cavity (HB03, see Fig. 6). The cavity has been treated by BCP for the baseline test. Once the RF-test done, bulk VEP will be carried out with a dedicated cathode designed and fabricated by Marui Galvanizing Company Ltd, which is already available for the experiment. The schematic of the treatment is shown in Fig. 7.

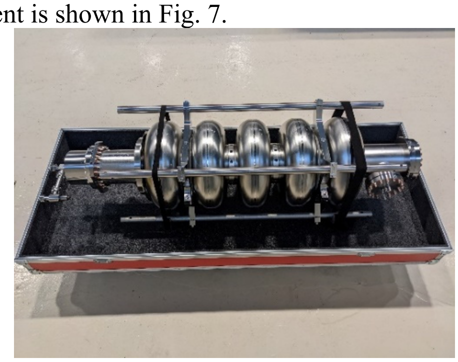

Figure 6: HB03 ESS-prototype cavity (β=0.86) to be treated by VEP with dedicated cathode after RF test.

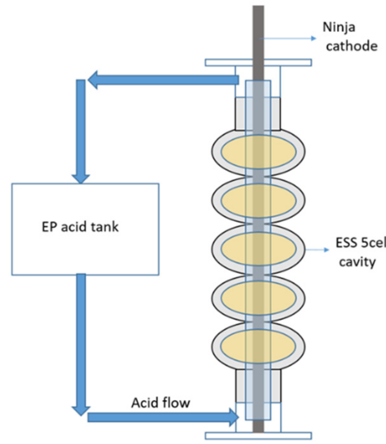

Figure 7: Schematic of the treatment of the 5-cell β=0.86 ESS cavity.

It will also be interesting to compare achieved results with these obtained by horizontal electropolishing treatment for 650 MHz elliptical resonators (see for example [13]) for the Proton Improvement Plan-II (PIPII) accelerator [14].

CONCLUSION

Promising results have been achieved after vertical electropolishing of a 704.4 MHz, β = 0.86 single-cell ESS cavity. Heat treatment at 650 °C and final baking at 120 °C after flash VEP make it possible to reach gradients over 40 MV/m on a single-cell cavity. The 2-step baking recipe could provide additional benefits and will be tested on EH101 cavity. We intend now to transpose the process on a 5-cell cavity with a dedicated cathode which has been purchased, and thus finalize a cavity treatment protocol that might be applied for future machines using this type of cavities, such as MYRRHA [15].

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