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ELECTROPOLISHING OF PIP-II LOW BETA CAVITY PROTOTYPES

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Abstract

We present the upgrade of the EP facility for the surface treatment of PIP-II low beta cavities. The main process parameters, such as voltage, treatment time, acid throughput and cathode geometry, already optimized on the previous experience of 1.3 GHz Tesla-shape cavities, are discussed taking into account the different cavity size and geometry. The first surface treatments have been performed at Ettore Zanon SpA on single cell cavity prototypes in order to reach good final surface finishing and the required thickness removal. In the meantime, the upgrade of the system for the treatment of multicell PIP-II prototype cavities is presented.

INTRODUCTION

INFN-LASA joined the international effort for the PIP-II project in Fermilab and it is expected to build the 650 MHz superconducting cavities required by the low β section of the 800 MeV front-end proton linac.

PIP-II specifications for the low-beta linac section are $E_{acc} = 16.9\,\mathrm{MV\,m^{-1}}$ with a $Q_0 \geq 2.15 \cdot 10^{10}$ (that may be extended to $3 \cdot 10^{10}$) [1]. This ambitious target for Q-value is unlikely to be reached with a BCP treatment, given the characteristic medium field Q-slope of BCP-treated cavities. For this reason, the Electropolishing treatment has been chosen as baseline. Such treatment has been routinely employed in the past as the main surface treatment for 1.3 GHz cavities. The great experience acquired during the series production of E-XFEL and LCLS-II allowed a full optimization of the process on the traditional geometry of Tesla-shaped 1.3 GHz cavities, so that it is nowadays commonly considered as the most effective surface treatment for the achievement of higher cavity performances.

Now, facing the upcoming PIP-II series production of low-beta cavities, no equivalent experience on electropolishing is available, due to the different cavity shape and size. Many process features are expected to change due to the different cavity geometry. It is therefore important to develop a tailored electropolishing process by a clever optimization of treatment parameters, along the same lines of the efforts done by FNAL and ANL in the adaption of the Argonne EP plant for the treatment of $\beta = 0.91$ multicell prototype cavities [2].

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EP DEVELOPMENT STRATEGY: FROM SINGLE TO MULTICELL PROTOTYPES

Besides two dressable multicell cavity prototypes, which are currently under fabrication, 3 single-cell cavities have been already manufactured and 2 more are under production. These prototype resonators are made by two end cells from the multicell cavity end-groups and already allowed at first the qualification of the deep-drawing die for this specific design and thickness [3].

The EP plant currently operating in Zanon S.p.A, developed for the treatment of E-XFEL 1.3 GHz cavities [4], would require a subtantial refurbishment to allow the processing of a multicell PIP-II low beta cavity. Conversely, the plant is able to host the single cell cavities through the introduction of minimal modifications of the structure. Figure 1 shows the EP facility adapted for the processing of PIP-II single cell cavities.

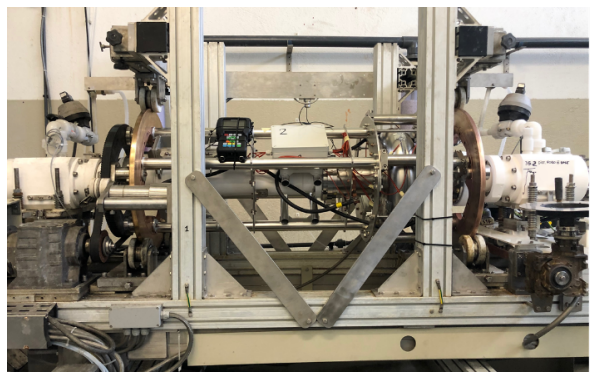

Figure 1: The EP plant at Zanon S.p.A, adapted to host a single cell low beta PIP-II cavity

The main modifications introduced are:

- cavity length (0.506 m) is adapted to the EP rotating frame - previously developed for 1 m long XFEL cavities - by employing 2 polypropylene cylinders
- the cathode (30 mm diameter) is completely shielded by a PTFE tape in correspondence of cylindrical adapters. The holes on cathode at beam tube position are closed, so that the acid enters inside the cavity volume only trough the hole at equator position.
- Aiming to obtain a more uniform temperature distribution, an external water cooling system is installed on the beam tubes.
- An ultrasound (US) probe for online thickness measurement is installed on cavity surface. In the future, the system will be upgraded so to allow a multi-probe thick-

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ness reading (by a proper multiplexing of signal readout and sensors) in different points of cavity surface.
- In order to increase the cathode surface in correspondence of cavity inner volume, a cylindrical enlargement made of ultra-pure Al is now under fabrication. As rule of thumb a 10:1 cavity:electrode surface ratio is needed to achieve the best polishing conditions [5].

Besides structural modifications in the infrastructure, a proper optimization of electropolishing for low β 650 MHz resonators requires a careful review of all treatment parameters (current, voltage, chatode geometry, acid troughput, temperature). The bigger cavity size and more squeezed cell length are expected to significantly change the process behavior. The goal is to find the right balance among the many process parameters, so to obtain a good smoothing (sub µm roughness) on all inner surface and achieve at least 1:2 of equator/iris removal ratio. Given the complexity of the task, we decided to exploit a single cell PIP-II prototype cavity made in fine grain niobium (FG001) for experimentally optimize the procedure. Once the recipe will be ready on single cell cavities, we will discuss the strategy for the refurbishment of the EP plant for the treatment of multicell prototype PIP-II cavities.

OPTIMIZATION OF THE EP PARAMETERS

In order to achieve the best polishing conditions, the anode voltage must be set so to place all the cavity surface in the limiting current plateau. This means that no significant current increase must be noticed by increasing the anode voltage. As preliminary measurement, the voltage has been ramped from 0 V to 20 V continuously acquiring the current. Acid inlet and outlet temperature (respectively 12 °C and 15 °C) and the thermocouple readings during the treatment remain constant during the ramp so that one can assume no change in reaction rate due to heating. Figure 2 shows the polarization curve. The three typical regimes of etching, current oscillation and polishing can be clearly identified. A modest increase of current with voltage can be noticed even in the polishing region.

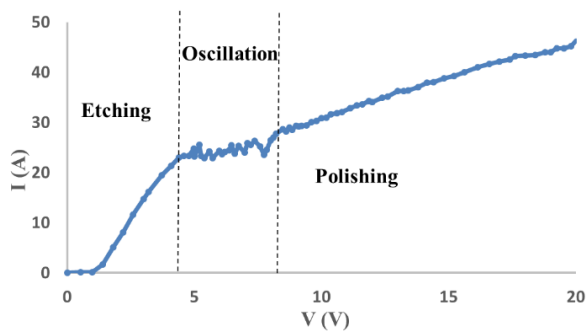

Figure 2: The polarization curve for cavity FG001 in the 0-20 V interval

According to the polarization curve, the polishing zone starts at about 8 V. In order to stay not too close to current oscillation zone, we restrict the usable voltage in the 13 V to 20 V interval. This region is expected to yied the best surface finishing after the treatment [6]. Given the process total current, one can calculate the removal rate from equation:

$$r[\mu\mathrm{m\,min^{-1}}] = 0.123\frac{i[\mathrm{A}]}{S[\mathrm{dm^2}]} \quad (1)$$

where i is the current and S is cavity inner surface [4]. Employing the PIP-II single cell value of 43 $\mathrm{dm^2}$, one obtains a removal rate of 0.127 $\mu\mathrm{m\,min^{-1}}$ for an average current of 40 A. A 200 µm removal would therefore require approx. 27 hours of treatment. The removal rate will be increased by the foreseen installation of the Al cylindrical enlargement that is expected to extend the cathode active surface .

Moreover, one has to consider the temperature dependence of removal rate. The EP reaction is exothermic so that the circulating acid gets warmer as the treatment goes forward. Within certain limits, one can benefit of this reaction enhancement to shorten the treatment duration, but it is necessary to control the temperatures on beam tubes so to locally limit the reaction, which would risk to be too aggressive if compared to the cell inner surface. The external water cooling system does this task very effectively. Figure 3 show the temperature and current registration for a short treatment trial (2 h at 15 V). The temperature on beam tube dramatically increases in the first 30 minutes, reaching 25 °C, while at equators temperature remains stable at around 17 °C. Once the external water cooling is turned on, the temperature on beam tubes immediately decreases, and a more uniform temperature distribution on cavity surface is established. The modest reduction of current is caused by the partial inhibition of EP reaction at beam tubes.

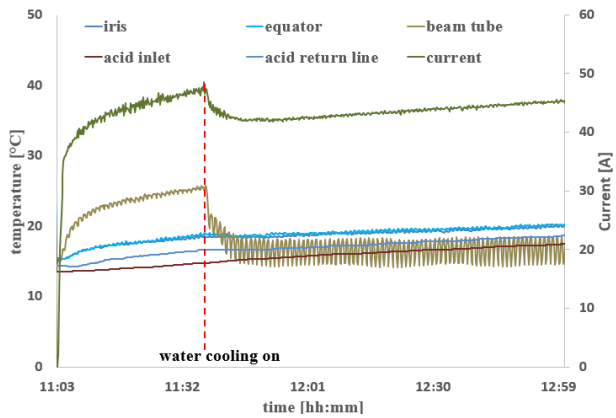

Figure 3: Temperatures and current during 2h, $V = 15$ V treatment, with and without external water cooling.

FIRST TREATMENT TRIAL

The previous experimental data, obtained thanks to a series of short EP treatments, represented a starting point for attempting a longer electropolishing on cavity FG001. This treatment has been then performed employing a 15 V voltage for a 1200 kC total charge removal, which correponds

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to a 60 µm removal in approximately 8 hours if an average current of 40 A is assumed. Set point for acid cooling is 25 °C as maximum temperature on cavity surface.

The US probe is installed on cavity walls, as shown in Fig. 4, so to be as near as possible to the equator zone. The external water cooling has been activated during the whole EP treatment.

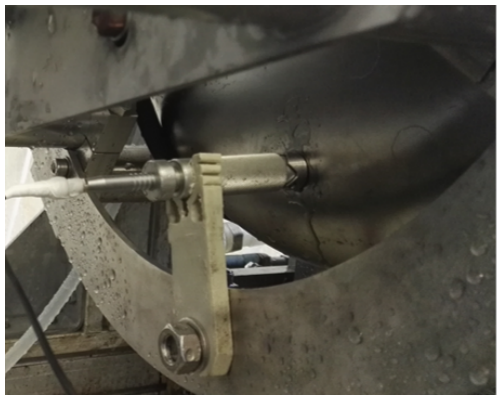

Figure 4: The US probe during the treatment.

The temperature and current readout for the whole treatment is shown in Fig. 5. The action of external cooling induced a very slow drift of temperatures and current towards the equilibrium value (approx. 48 A with 22 °C on cavity surface). There is a very small temperature difference between equator and beam tubes, meaning that the reaction has been enhanced in correspondence of equator. After 300 minutes, the acid chiller has been automatically turned on because the maximum temperature of inlet acid was reached. As a consequence, temperature and current slightly decreased.

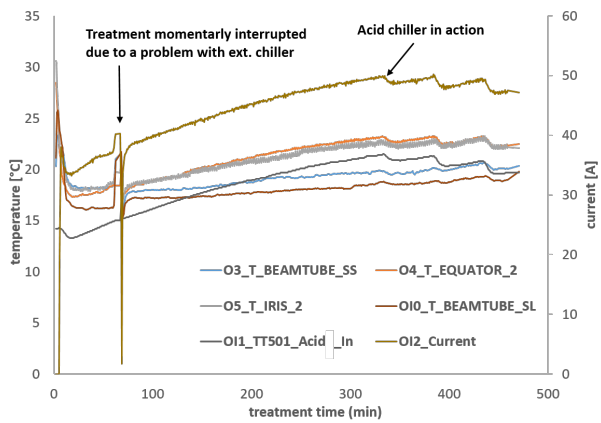

Figure 5: temperature and current readout during the 480 min. treatment

The consequence of the acid cooling becomes more dramatic when looking to the US thickness probe readout, which is shown if Fig. 6. In the first 330 minutes the removal is linear with time, and a removal rate of 0.136 µm min^{-1} is obtained by linear fitting. This value is in line with what expected from equation (1) assuming an average current of 45 A. Immediately after the water cooling turning on, the removal rate suddenly dropped down to 0.06 µm min^{-1}. Basically, the EP process has been almost completely inhibited at the inner cell position. This is probably due to the lowest temperature of acid, but a simple explanation is still not available because the mechanism is probably influenced also by other process parameters, like the acid velocity and the thickness of the diffusion layer [7].

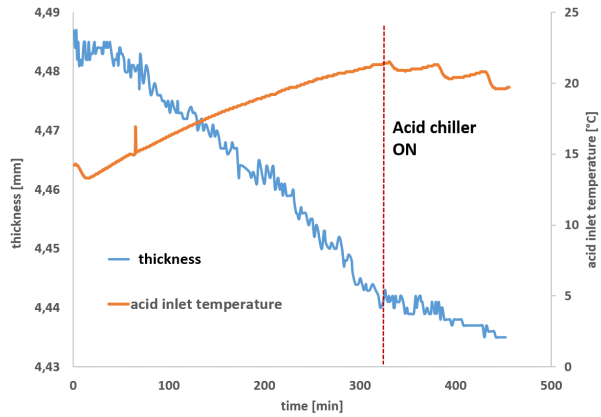

Figure 6: Thickness (in blue) and inlet acid temperature (in red) vs treatment time

At the end of treatment, the following parameters are measured:

- the average removed thickness is 63 µm, as evaluated from the difference of cavity weight before and after the treatment. This corresponds to a 0.13 µm min^{-1} average removal rate.
- the measured frequency shift is 51 kHz. This corresponds to a 0.81 kHz µm^{-1} sensitivity.
- the local thickness removal is measured by means of US probe on several points of cavity surface and compared with the values before treatment. The results are shown in Fig. 7.
- surface roughness (R_a and R_z) is measured inside cavity volume with a compact roughness tester. The evolution of R_a in some significant points of cavity inner surface are reported in Table 1. The last row is the treatment here discussed.

Table 1: Evolution of R_a [µm] After Some EP Treatments in Three Characteristic Cavity Points

Step	Beam tube	Iris	Near equator
Not treated	0.74	0.95	0.99
After 2h @ 13 V	0.51	0.51	1.39
After 4h @ 15 V	0.24	0.49	1.39
After 8h @ 15 V	0.26	0.40	1.12

These experimental results deserve some comment. The average 63 µm corresponds to about 40 µm removed near the equator and 80 µm removed on average from beam tubes and irises, as it is evident from Fig. 7. The iris/equator removal

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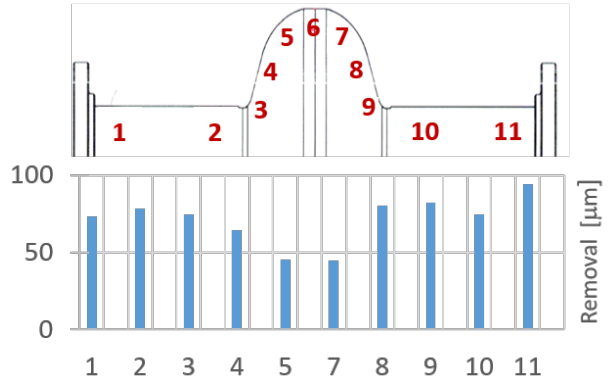

Figure 7: average removal as measured by US probe. On top side, the position of measured points.

ratio must be therefore larger than 2. This is the cause of the low frequency sensitivity value - 0.81 kHz µm^{-1} - which is remarkably less than the one measured for BCP-treated low beta cavities [8]. There is an apparent asymmetry in the removal on the two cavity sides, probably due to the different fluid-dynamical conditions experienced by the two cavity sides, which can be also noticed by the slightly different temperatures on beam tubes.

Surface smoothness on beam tubes and irises improves with material removal, in line with the experimental observations reported in [9]. There is almost no change in roughness near the equator for the first treatments, and only a modest decrease after the last treatment, in spite of a 40 µm removal, as also witnessed by the cavity frequency change.

According to these observations, the choice of 15 V grants a good surface smoothening on irises and beam tubes, but not on equator. This is in line with the observation that electrolyte resistance R_{el} is locally increased because of the longer anode-cathode distance at equator. Assuming at first order constant anode (V_a) and cathode (V_c) potentials, from the expression of voltage drop $V = V_a - V_c + R_{el} \cdot i$ one can evaluate the current as $i = \frac{V-(V_a-V_c)}{R_{el}}$. Hence, the higher electrolyte resistance results in a lower current. The foreseen installation of a cathode enlargement will therefore raise the removal at equator both by increasing the active cathode surface and by locally reducing the cathode-anode distance Besides the cathode enlargement, a further increase of voltage to 17 V is also planned, and also an higher setpoint of inlet acid temperature that will also favor a quicker reaction.

ELECTROPOLISHING REMOVAL MODEL

The experimental data of frequency shift, average removal and local removal by US probe allowed to have a first evaluation of the removal dynamics. In order to check the autoconsistency of the measured values, we developed a simple model to simulate the removal during an Electropolishing treatment on the PIP-II single cell.

First of all, the local thickness variations measured by the US thickness gage reported in Fig. 7 (Δ_i for i=1,2...) are assumed as true local values for the process removal. As first approximation, a symmetrical removal rate with respect to the cavity equator is considered. For that reason we averaged the final thickness of the corresponding symmetric points.

Then, starting from the control points defined by Δ_i for i=1,2..., we calculated the removal all over the cavity walls by means of a b-spline interpolation , so that the local $\Delta(z)$) function is built, where z is the axial coordinate. The resulting removal function is plotted in Fig. 8, compared with the cavity profile.

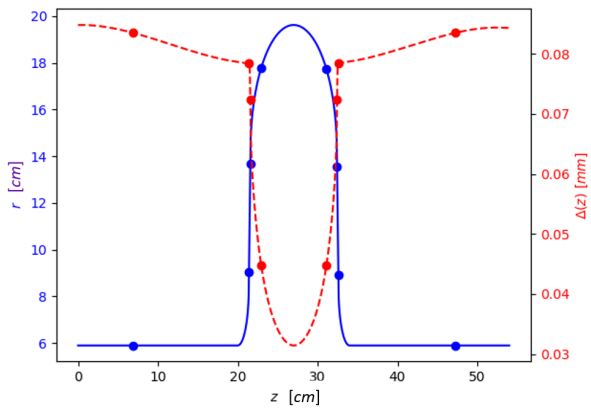

Figure 8: removal profile $\Delta(z)$ as obtained by b-spline interpolation (in red) and cavity profile (in blue). The control points Δ_i obtained by US measurements are marked.

The averaged removal is defined as the ratio of cavity volume variation and inner surface. It can be then obtained analytically from the interpolation as:

$$\overline{\Delta} = \frac{1}{S_{int}} \int dv \approx \frac{2\pi}{S_{int}} \int f(z)\Delta(z)dz \qquad (2)$$

where S_{int} is cavity inner surface, $\Delta(z)$ is the removal profile, $f(z)$ is the cavity profile function.

Since the variation in the geometry shape is small with respect to the overall geometry, the frequency shift can be evaluated by Slater Theorem:

$$\frac{\Delta f}{f} = \int_{\Delta V} \frac{(\mu_0 H^2 - \varepsilon_0 E^2)}{4U} dv \qquad (3)$$

where E and H are the electric and magnetic electric field on cavity wall, U is the stored energy, f is cavity nominal frequency and ΔV is the deformation volume.

Average thickness can be numerically calculated from Eq. (2) and frequency shift can be calculated from Eq. (3) by means of a 2D axially simmetric electromagnetic model of the single cell developed in SuperFish. Table 2 shows the reconstructed and measured values of frequency shift, average removal and frequency sensitivity.

The calculated values match very well the experimental results, meaning that the model here proposed is autoconsistent and that the experimental strategy so far adopted

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Table 2: Comparison of Experimental and Calculated Parameters for the 8h 15 V EP on Cavity FG001

Item	Exp.	Calc.
Frequency variation [kHz]	-51	-53
Average removal [µm]	63	67
Sensitivity [kHz µm^{-1}]	0.80	0.79
Iris/equator removal ratio	>2	≈ 2.6

allows with a good accuracy to predict the real behavior of cavity during the treatment. The removal at equator position is difficult to be measured by US thickness gage because of the irregularity of inner surface nearby the welding. The calculation gives in this case a 30 µm removal value, which is consistent with the modest gain in surface roughness reported in Table 1.

CONCLUSIONS

The LASA-INFN activities on the optimization of the Electropolishing process for low-beta PIP-II 650 MHz cavities are well underway. A first trial adopting conservative parameters (15 V, 25 °C temperature max. set point, 8 hours treatment) has been performed. Results are promising, but a further effort has to be done in order to maximize the removal on cavity equator and then improve the surface smoothness. In the next future, the cathode surface will be increased by the introduction of the Al enlargement.

In the mean time, the process control strategy has been fully optimized and checked. The online measurements (thickness and temperatures) allows a continuous monitoring of treatment conditions. The set of post-treatment measurements (weighing, frequency shift, thickness removal by US probe) is enough to analytically reconstruct the evolution of cavity inner profile and therefore evaluate many important process parameters.

A new treatment trial is foreseen in the next month. The goal is to achieve a full process optimization with no more than 2 further treatment trials. By the end of the Year, cavity FG001 will undergo a full bulk EP treatment and will be then tested a both LASA and FNAL vertical test facilities. The results will serve as a starting point for the joint FNAL-INFN effort in defining the full cavity surface processing strategy.

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