VERTICAL ELECTRO-POLISHING AT CEA SACLAY: COMMISSIONING OF A NEW SET-UP AND MODELING OF THE PROCESS APPLIED TO DIFFERENT CAVITIES

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Abstract

Reproducible operation at high performances of sc cavities is required for superconducting linacs, at least in their high energy section in the case of accelerators for proton beams. High beta elliptical cavities are thus of concern, and, to achieve required performances for such cavities, surface preparation including electro-polishing (EP) is recommended.

Moreover, for large dimension cavities we consider the EP treatment in vertical configuration (abbreviated as VEP) to be more appropriate. For this reasons, a VEP set-up has been designed at Saclay for the electro-polishing of muticells elliptical cavities.

Chosen equipment will make it possible to use a wide range of parameters (voltage, flowrate, temperature, nitrogen inerting) with R&D purpose in mind. Optimization will be done using modeling with COMSOL software for different cavities. As examples, we present some results for the 704 MHz high-beta SPL cavity and the 1300 MHz ILC cavity and show the influence of cathode shape on both acid flow and electric field distribution during the process. At last, importance of the size of the cavity will be commented.

INTRODUCTION

Electro-polishing (abbreviated as EP) is believed to be the most desirable treatment for SRF cavities [1]. EP is an anodic electrochemical treatment carried out in concentrated hydrofluoric - sulphuric (HF-H_2SO_4) acids. Generally, the cavity is electro-polished following a process developed by KEK [1]: A voltage is applied between the cavity and a cylindrical aluminium cathode (set in its centre) while it is placed in horizontal position, rotating, and half-filled with the circulating acid. This process makes it possible to reach high gradients on 9cell Tesla shape cavities and has been chosen for the surface treatment of cavities for the XFEL linac. However, it induces some drawbacks: the rotating seals are more easily prone to leaks, the cavity must be switched full of acid for draining and the footprint of the set-up is rather large. Furthermore, the removal rate in the cavity depends on the location of the cell [2]. To overcome these drawbacks, some laboratories are investigating an alternate process where the cavity is electro-polished in vertical position [3]. Cornell University has proved that VEP with static acid could make it possible to reach high gradients [4], and as VEP is suitable to the treatment of large elliptical cavities, we have developed at CEA-Saclay a VEP set-up sized for surface treatment of the largest high beta and high gradient cavity we have designed, that is to say a 704 MHz cavity for the Superconducting Proton Linac. All other “smaller” cavities, as ILC cavities, fit into the set-up too.

In this paper, this VEP set-up is described as well as results concerning the modeling of VEP for both high beta SPL [5] and ILC cavities. The acid flow and electrical field distribution expected during VEP will be discussed.

CHARACTERISTICS OF THE SET-UP

Generalities

This set-up is designed to electro-polish a cavity in presence of circulating acid electrolyte. The expected flowrate range is between 5L/min and 40L/min. A constant voltage EP process has been chosen for the treatment of the cavities. The available electric power for the electro-polishing is 30kW (20V – 1500A). The set-up is divided into two distinct ventilated cabinets: The acid storage area and the main treatment cabinet (Figure 1). Insertion of the cathode into the cavity and assembly of connecting pieces are done on a dedicated table close to the set up. The cavity is then transferred in the main cabinet with a specific handling tool.

The acid storage tank is located in a pit connected to the liquid exhaust storage area of the laboratory. The storage capacity is 300L. This capacity has been calculated in order to maintain a niobium concentration in the electrolyte below 10g/L after a bulk EP for SPL cavities.

The cavity is filled up from the bottom by a membrane pump located in the pit. Once the acid reaches the connection tube on the top of the cavity, the acid flows to

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the tank by gravity. The circulation of acid is uninterrupted when voltage is on. Temperature of the acid bath is stabilized thanks to circulation of cold water through a Teflon heat exchanger inserted inside the acid tank, as shown on the flowsheet of the process on Figure 2.

At the end of an electro-polishing sequence, the acid is drained back to the tank and the cavity is rinsed with Ultra-Pure water. A predetermined sequence of filling (from the bottom)/draining of the cavities is followed by a continuous circulating sequence. Rinsing stops automatically as soon as water conductivity is low enough.

All the process is automated and run through a touchscreen (See Figure 2).

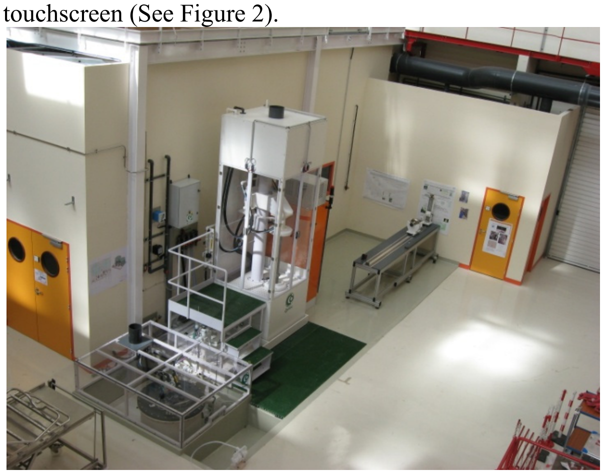

Figure 1: VEP set-up at CEA Saclay. 1: Main cabinet for cavity treatment. 2: Acid tank located in a pit. 3: Table for assembly prior to VEP.

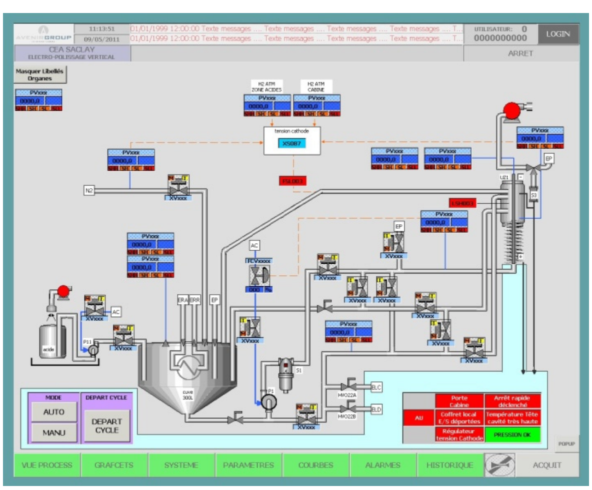

Figure 2: Flowsheet of the process displayed on the touchscreen.

Safety

Safety aspects have been carefully taken into consideration to design the set-up. Nitrogen is blown on the top of the cavity and on the top of the acid tank to dilute the hydrogen generated during the process and prevent any risk of explosion. Furthermore, the program of the automat includes specific procedures if sensors (temperature, pressure, hydrogen, flows, acid level) should detect any failure:

- high temperature detected: the process is stopped and acid is drained,
- insufficient nitrogen flowrate: the current is stopped,
- extraction failure: The nitrogen flowrate is stopped as well as the generator,
- high level of acid detected on the top of the cavity: the pump stops.

Fundamental parameters (temperature, flowrate, voltage) evolution is monitored on the touchscreen of the automat, as well as failure occurrence. A USB port allows an easy exportation of data.

Materials

The acid tank is coated with Teflon and piping/valves are made of PFA. PVDF has been chosen for some pieces requiring higher mechanical resistance (connections for the cavity, inserts for sensors).

MODELING OF VERTICAL EP

2D Axi-symmetry Model with COMSOL Multiphysics

The described set-up makes it possible to use a wide range for operating parameters. (acid flowrate between 5 and 40L/min, voltage between 0 and 20V, nitrogen flowrate between 0 and 50L/min, etc.). It was designed with R&D purpose in mind, with the view of tracking the optimal parameters for VEP process. A complementary approach consists in modeling the process using, COMSOL Multiphysics software which allows evaluating some parameters not easily accessible by experiments. Previously, studies (fluids, electric field, concentrations, thermal properties) have been carried out with different softwares. [6,7,8] In this paper, fluid distribution and electric field have been modeled for SPL and ILC cavities with a cylindrical cathode (30 mm diameter) shape. In a second step, alternative cathode shapes have been numerically investigated for possible improvement of the process.

Contrarily to horizontal EP, VEP is a symmetrical process. Gravity force, represented by Fz on Figure 3. does not depend on radial component. It is thus possible to create a 2D model with symmetry according to the cavity z-axis (see Figure 3) which makes the calculation easier compared to a 3D model.

Fluid Dynamics Modeling

For the considered set-up, acid is introduced in the cavity through eight holes equidistant from the cathode. To simplify the model, a crown of acid, with parabolic profile, has been considered, as described in Figure 3. The velocity in the center of the crown is called vmax.

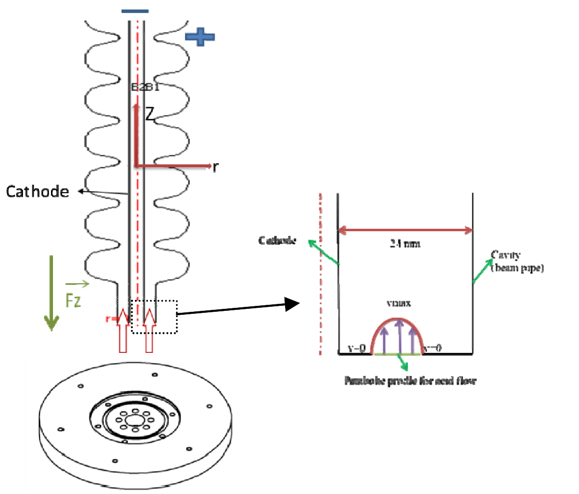

Figure 3: 2D axi-symmetry used for modeling of VEP. We have considered a crown of fluid entering the cavity with a parabolic profile.

Low fluid velocities (<0.8m/s) were used in the model. As a consequence, Navier-Stockes equations, related to laminar flow of incompressible fluid were chosen to model the fluid dynamics in the cavity:

$$\rho \frac{\partial u}{\partial t} - \eta \nabla^2 u + \rho(u.\nabla)u + \nabla p = G \qquad (1)$$

$$\nabla.u = 0 \qquad (2)$$

η is the dynamic viscosity (Pa.s) ; u the fluid velocity (m/s) ; p the pressure (N/m^2) ; G (N/m^3), the resultant force, only the gravity is considered here.
Boundary conditions chosen: the fluid neither slips at the cathode nor at the cavity surface.

Electric Field Modeling

For the electric field modeling, a potential equal to zero has been chosen for the cathode and a 15V potential has been applied to the cavity. Only primary current distribution is considered there. To improve homogeneity, some parts of the cathodes have been insulated as explained in following paragraphs.

FLUID DYNAMICS: VEP VS HORIZONTAL EP

Contrarily to the process investigated in the present paper, a hollowed cathode is used for horizontal EP. It enables to inject the acid into the cavity through holes located in front of equators. Previous models [6] have shown that such a configuration is inappropriate for homogenous fluid distribution. In fact, fluid velocity increases from the center of the cavity to extremities. This inhomogeneity might be responsible for the degradation of field flatness observed after horizontal EP of 9cell cavities [2]. Similar investigation has been carried out for the VEP of 9cell cavities with a cylindrical cathode.
Results obtained with a rod cathode and vmax=0.2 m/s are shown on Figure 4. Along each line 1-5 considered in the central cell, the fluid profile is similar to the shape shown in 4c).

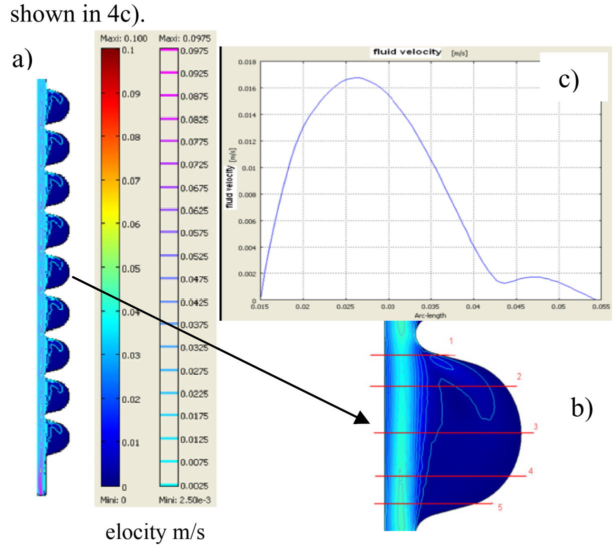

Figure 4: a) Fluid modeling in the ILC cavity for vmax=0.2m/s. b) Zoom of the central cell. c) For each line (1 to 5), the distribution profile between the cathode and the cavity is similar.

This simulation highlights that in VEP case, fluid distribution does not depend on the position of the cell in the cavity. The graph highlights a fluid profile in two distinct parts: the fluid flows principally in the continuation of the beam pipe (see Figure 4c.) and the second bump characteristic of the flow in the cell is lower (10% of the maximum flow). It is then necessary to modify the geometry to improve the expected removal rate of niobium. It has been proved that shaped cathode make it possible to improve the process [7, 9].With this purpose in mind, different cathode shapes were modeled in our configuration. They are aimed at generating obstacles to guide the acid flow towards the cavity surface,

Four alternative cathode shapes were investigated for more homogeneous fluid velocity in cells (Figure 5). In each case, fluid velocity was studied at five different locations of the central cell of the cavity.

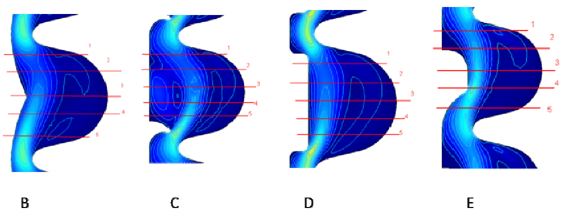

Figure 5: Shapes tested to improve fluid distribution inside the cells.

From the analysis of related data, we have concluded:

- The shape D allows a 39% increase of fluid velocity close to the cell.
- Uniformity of fluid velocity is improved by 33% using shape C.

These two shapes are promising candidates to be tested during VEP.

INFLUENCE OF THE SIZE OF THE CAVITY

The experiments have highlighted fluid distribution for the Tesla-shape 9cell cavities. As the set-up is mainly dedicated to two types of cavity, it is vital to anticipate effect of polishing parameters on the larger 5Cell SPL cavity whose drawing, including characteristic dimensions, is shown in Figure 6.

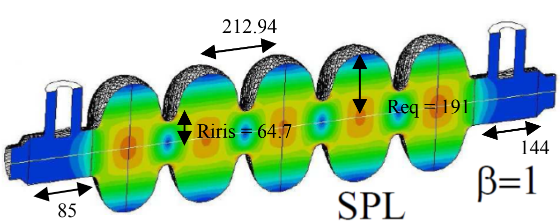

Figure 6: 704 MHz SPL cavity to be electro-polished in VEP set-up.

Similar equations and boundary conditions have been chosen to model fluid dynamics with a cylindrical cathode. Fluid distribution in such configuration is represented in Figure 7, with vmax=0.8m/s. The shorter beam pipe is located on top.

We notice that fluid velocity at the cavity surface is very low. The fluid distribution along the red line shows that the velocity in the cell is negligible compared to the velocity at the cathode surface.

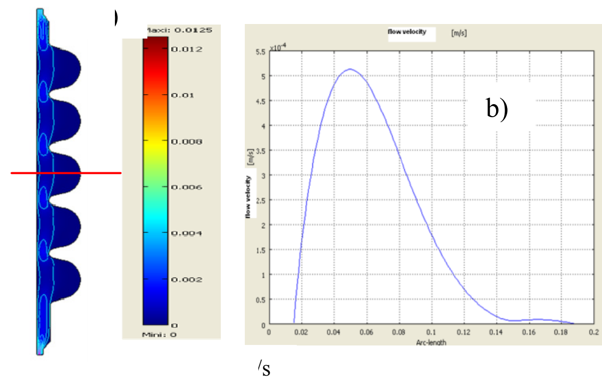

Figure 7: a) Fluid distribution in the 5cell SPL cavity and b) fluid velocity profile along the red line.

These results show that EP is less adapted for larger cavities. In fact, stagnant acid in the cell is undesirable because of:

- low convection at the cathode surface
- local saturation of the acid in niobium.

It is then vital to anticipate more adapted cathode geometries. Similarly to the ILC cavity case, an alternative shape was also designed for the SPL cavity (Figure 8). We have considered a beam pipe without taper at the extremities to allow the use of the cathode with large protuberances.

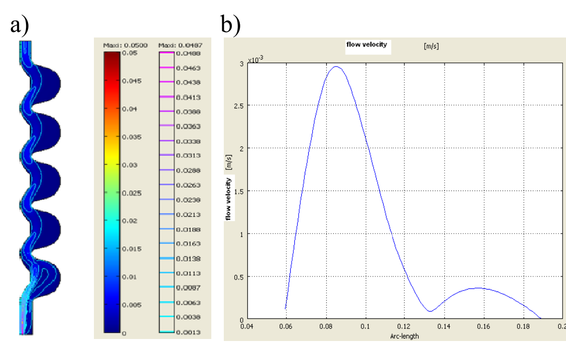

Figure 8: a) Fluid distribution in the 5cell SPL cavity and b) fluid velocity profile along the red line. Shaped cathode makes it possible to increase fluid velocity in the cell.

The fluid distribution achieved with this cathode (called F) is shown on Figure 8. The narrowed section available for the fluid circulation increases the fluid velocity in the proximity to the cathode (flow roughly multiplied by 5.5) and in cells (multiplied by 5).

In that way, shaped cavities are desirable for VEP treatment. We also have to keep in mind that presented models do not take into account the forming of gases during process. Hydrogen forming at the cathode, and potentially, oxygen at the cavity surface might have a great impact on fluid mixing.

STUDY OF THE ELECTRIC FIELD

Models described in previous paragraphs show that uniformity of the acid flow inside cells might be improved by using a shaped cathode. Furthermore, removal rate during EP also depends on electro-migration of ions. Thus, a uniform electric field during EP along the cells is desirable for uniform removal of the surface.

The electric field during EP with a cylindrical cathode has been modeled in the cells of ILC cavities. A voltage of 15V between the cavity and the cathode has been used in the model. Figure 9 below shows the isopotential curves in a cell. Close to the iris, short intervals are observed between the lines, generating a high electric field E_i: 825V/m. At the equator, the field E_e is divided by more than forty: 20V/m.

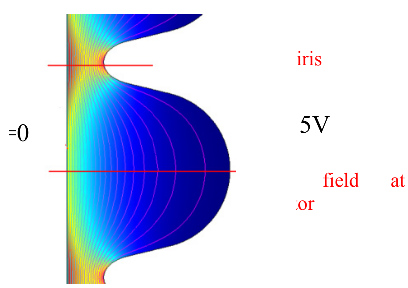

Figure 9: Potential distribution in a Tesla shape cell using a cylindrical cathode. At the Cathode, V=0 and at the anode, V=15V.

Benefits of shaped cathodes have already been studied [7, 9]. Thanks to the protuberances investigated in the previous paragraphs, the average cavity-cathode distance is more homogenous, favorable for a more uniform removal rate along the cell. In a second step, insulation of the parts of the cathode in front of the iris allows additional improvement of the uniformity.

In order to evaluate quantitatively the benefits of the investigated cathodes, the electric field has been modeled for both 9cell and 5cell cavities, in different configurations (as an example, Figure 10 shows configurations used for the 9cell cavity):

- cylindrical cathode (shape A), without insulation
- cylindrical cathode with insulation at the iris
- shaped cathodes (shapes B, C, D, E, F) without insulation
- shaped cathode with insulation

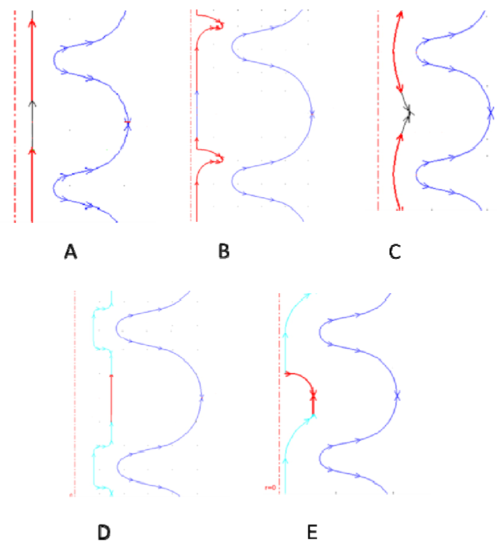

Figure 10: Alternative insulated cathode shapes numerically tested for the Tesla cavity. At the cavity: V=15V, at the cathode. V=0. Insulated parts of the cathode are in red (A, B, C) and in light blue (D and E).

Results (Voltage of 15V between the cavity and the cathode) are summed up in the recapitulative Table1.

Table 1: Electric field at the iris and at the equator of the ILC cavity for different cathode configurations

Shape	Insulation	E_i (V/m)	E_e (V/m)	E_i/E_e
A	No	825	20	41.2
B	No	816	18	45.3
C	No	913	33	27.7
D	No	1138	43	26.5
E	No	600	35	17.1
A	Yes	200	50	4.0
B	Yes	96	15	6.4
C	Yes	225	30	7.5
D	Yes	128	35	**3.7**
E	Yes	240	32	7.5

Similar investigation has been carried out for the SPL 5cell cavity with a cylindrical cathode and the shape F. Tested cathodes are shown below (Figure 11.).

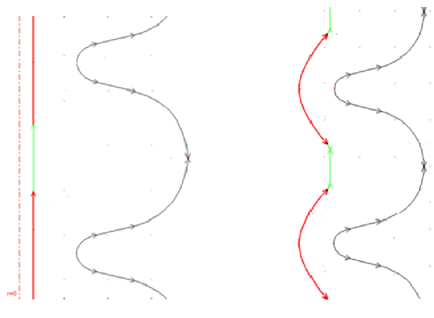

Figure 11: Alternative insulated cathode shapes numerically tested for the SPL cavity. At the cavity: V=15V, at the cathode. V=0. Insulated parts of the cathode are in red.

The obtained results are presented in Table2 below.

Table 2: Electric field at the iris and at the equator of the SPL cavity for different cathode configurations.

Shape	Insulation	E_i (V/m)	E_e (V/m)	E_i/E_e
A	No	292.7	8.1	36.1
F	No	409.5	21.7	18.9
A	Yes	80	5.7	14.1
F	Yes	111.7	19.0	**5.9**

For both ILC and SPL cavities, designed cathodes make it possible to improve electric field uniformity in the cells. However, we have to keep in mind that an insulated cathode will be responsible for a decreased removal rate.

OUTLOOK AND CONCLUSION

The Electro-Polishing in Vertical configuration is well adapted for large elliptical cavities. A dedicated set-up has been commissioned at Saclay. The VEP will be achieved with circulating acid through an automated process. However, proper parameters might be carefully chosen in order to achieve satisfactory treatment. Modeling with COMSOL allows investigating appropriate cathodes designs. The studied cases did not take into account parameters such as gas forming at the cathode and the cavity surface. Once the first cavities electro-polished, results will be compared with models, for full understanding of the process.

ACKNOWLEDGEMENTS

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP7 programme (EuCARD, contract number 227579). This work has been carried out with the financial support of the "Conseil General de l'Essone" in the frame of the ASTRE program.

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