Modeling, Fabrication, and Optimization of Niobium Cavities Final Phase: Final Report

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Modeling, Fabrication, and Optimization of Niobium Cavities – Final Phase
Final Report

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AAA Research Area: Accelerators / Transmuter
Introduction

This final report provides the activities and accomplishments of Modeling, Fabrication, and Optimization of Niobium Cavities – Final Phase. The fluid flow experiments for the etching of the superconducting cavity walls and baffle designs of phase II of the three phases has been completed leading to a MS thesis in December of 2003. Designing the experimental setup of secondary electron emission was well underway in early summer of 2003 when funding was made available for this portion of the study. By March 2004, many of the components of the experimental study reached UNLV with some assembly accomplished. The first secondary electron emission (SEE) measurement was made from the surface of a Faraday cup in September 2004. In December of 2005, the software for the particle positioning detector was finally up and running. The integrity of the code and detector were fine-tuned and initial experiments were completed by April 2005. Experiments on the surface cleaned samples were completed in May of 2005 culminating in a thesis at the end of June 2005. Results were disseminated at the International Conference of Plasma Science in June 2005. The accomplishments are presented below.

Experimental Set-up for the SEE from a Niobium Test Piece:

Two different surface polished samples have been provided from LANL for study; a buffered chemically polished (BCP) niobium sample and a electro-polished (EP) niobium sample. Prior to polishing, the surfaces of the samples were beveled allowing for at least three different primary electron beam angles of incidence to be studied. Figures 1a and 1b display the two different surface cleaned samples. Two EP and five BCP were supplied for study.

With the aid of Transfer Engineering Inc. located in Fremont California, a secondary electron emission test stand was designed and built. Refer to Fig. 2a and 2b below. To save money, the cryostat is the inner cooling system of a cryopump able to achieve temperatures as low as 8.5° to 9° K. With good surface contact between the sample and cryostat head being an issue, a thermal conductive grease was used as an interface between the two surfaces. A temperature diode was mounted on the cryo-head in the same manner as the sample on the surface. Stable 23°K were
recorded. Such temperatures exceed the superconducting temperatures of LANL’s last stage in their proton accelerator. Vacuum pressures on the order of $9 \times 10^{-10}$ Torr to $3 \times 10^{-9}$ have been achieved throughout experimentation. The working end of the machine is labeled in Fig. 2b. The distance between the grid (lower most part of the detector) and the sample top is 2.54 cm.

![Image of machine components](image1.jpg) ![Image of machine components](image2.jpg)

Fig. 2a,b. A full profile of the secondary electron emission test stand is presented in (a) whereas (b) displays the inside of the machine showing the gun-detector-grid(just below detector)-sample-cryostat assembly.

**Secondary Electron Emission Studies:**

The samples of Fig. 1 were interrogated with a primary electron beam with energies between 100 eV to 3 keV where a major focus of the tests occurred at 1 keV. The electron beam diameter was set at 150 mm. Typically, the pulse duration was 100 ms. The beam current ranged between 80 pA to 3.7 nA where 2.2 nA was typical in most experiments. The grid potential was set to 100 V for normal and 15° incidence runs and 150 V for 30° incidence experiments. Typical vacuum pressures and sample temperature are $9 \times 10^{-10}$ to $5 \times 10^{-9}$ Torr and 23°K. Except for the surface conditioning experiments, all each recorded shot was performed on a virgin cleaned surface. No one surface was illuminated more than once.

Figures 3a-c illustrate typical experimental results measured from the particle position detector after subtracting one count from each bin to enhance the backscattered secondary electron effect.
Fig. 3a-c. Secondary electron emission resulting from a primary beam impinging on the target at (a) normal incidence, (b) 15° incidence and (c) 30° incidence for the buffered chemically polished niobium sample. The central region of each plot displays a circular aperture which is due to the presence of the beam aperture opening for the primary electron beam. The major contribution of the distribution of secondary electrons in (a) and (b) have been lost to the aperture opening. For (c), the distribution is clearly positioned on the detector surface. The black cross on (c) shows the center of gravity and the standard deviation of the distribution of the secondary electrons detected.

It has been shown that the buffered chemically polished sample had a much lower secondary electron emission count as compared to the electro-polished sample.\textsuperscript{2,3} This is in agreement with literature. Physically, secondary electrons generated in a microscopic valley of the rough surface are collected by the walls of that surface and do not escape the sample proper. As observed in Fig. 1, the BCP surface is much rougher than the EP surface.

It has been demonstrated that if the grid potential is changed, the center of gravity of the distribution of secondary electrons in Fig. 3b, may be positioned on the detector surface proper.\textsuperscript{2} Detailed modeling of the field structure taking into consideration the presence of the detector allows for the determination of a family of initial trajectory conditions at the sample surface. Such conditions have been examined and compared to numerical simulations to be established in the next section.\textsuperscript{2,3} Figure 4 is a close-up view of typical experimental data with an inset illustrating particle trajectory paths (black lines) and potential contours (colored lines). It is observed that the white spaces illustrating a grid-like white pattern is due to a void of electrons. This is a consequence of the presence of the wire mesh grid in front of the detector. The aperture opening and edge effects of the whole cut into the grid are identified as well.

Surface conditioning has also been examined. The results in Fig. 5 indicate that initially the secondary electron emission decreases with low current short pulse widths and then increase. Future follow-up experiments will be conducted to determine if this effect is real but consistency has been observed.
Fig. 4. Blow-up view of typical data with an associated potential and particle trajectory inset plot. The colors of the bin indicate the number of electrons that have been detected at a particular position on the detector surface.

Fig. 5. Conditioning experiment where a continuously pulsed electron beam illuminates a single location on the niobium surface. It appears that the secondary electron yield initially decreases, reaches a minimum and then increases. Different pulse durations were examined. These results are from the buffered chemical polished niobium sample. Similar results have been observed from the electro-polished samples as well.
Simulation Results with Comparison to Experiment:

A Monte Carlo Back Scattering and Secondary Electron Scattering code developed by Dr. David Joy (ORNL and University of Tennessee Knoxville) has been substantially modified to study secondary electron emission from material mediums. At present, the model the code is developed around is limited. Tracking and the collision process is terminated for electrons having energies less than 50 eV. If the 50 eV or lower energy particle is within a mean free path from the material surface, a random generator decides if the electron escapes the surface of the material. Figure 6 illustrates a scatter plot of the initial trajectory (conical angle and energy) of the secondary electrons (backscattered electrons) generated based on the Monte Carlo code. The population density illustrates the more favorable trajectories of the emitted electrons. The circled regions on the plots identify the more populated regions. Here, 0.1 keV and 1 keV primaries with 30° incidence are displayed. Each plot was generated based on 100,000 initial primary electrons incident upon the surface.

Fig. 6. Monte Carlo scatter plots for 0.1 and 1 keV primary electrons with 30° incidence on a pure niobium surface.
The results of the Monte Carlo code was compared to experimental results. With the aid of particle tracking codes, families of initial secondary electron trajectories were obtained from the detected final particle position data. The minimum and maximum trajectory conditions based on the standard deviation about the center of gravity of the measured distribution are plotted. The mean and standard deviation of initial conditions as obtained from the Monte Carlo code was superimposed on the plot in the form of an error bar in energy and trajectory angle. Figure 7 displays typical results showing good agreement between theory and experiment.  

![30° Beveled Surf.](image)

**Mean and Standard Deviation as obtained from Monte Carlo code**

Fig. 7. Comparison between experimental and simulation results.

**Experimental Visualization of the Verification of the Etching Process:**

When the CFD results were presented to LANL personnel, they strongly recommended experimental flow visualization of etching process inside the cavity, to help verify FEA simulations and to get better insight into the problem. They also agreed to loan a transparent plastic cavity that will be used at UNLV to simulate etching conditions.

Verification procedure:

a. Compare the CFD results of the LANL baffle under axial exit conditions to the experimental flow under same conditions.

b. The result is then analyzed to verify whether if the CFD and experimental results agree.

c. Design the optimized baffle in such a way so that it could be properly placed inside the cavity.

d. The experiment is repeated using the optimized baffle is then visualized. It is then compared with the CFD results of the optimized baffle.
**Experimental setup:**

The Setup consists of:

- Arrangement of the cavity and baffle inside the Plexiglas box.
- Traversing mechanism for positioning the camera.
- High-speed high resolution CCD camera for capturing images.
- Workstation for controlling the traversing mechanism and the camera.

**Experimental Configuration:**

The initial idea was to have the cavity mounted vertically supported inside the Plexiglas tank. This arrangement would however make it difficult to reach the base of tank from inside for connecting the cavity to the exit pipe. The only difference between the horizontal and vertical configurations is the gravity effects. CFD modeling of both configurations indicated that the gravity effect is negligible. So, it is decided to use the horizontal configuration, Figure 8, to better access the cavity. The only problem with the horizontal configuration is the possibility of having a free surface within the cavity during fluid flow. This problem is eventually solved by properly controlling the valves.

![Fig. 8. Horizontal configuration](image)

In this configuration the cavity is supported by a Plexiglas box, which is filled with water to reduce refraction. The baffle, is placed inside the cavity. Fluid enters the inlet section of the cavity.
from the tank and exits to reach the bottom tank. Valves are used to control the flow inside the cavity to achieve the required flow rate.

*Etching fluid:*

Verification of the predicted velocity distributions in a prototype niobium cavity using acid etchant can be hazardous. Fortunately, laminar and turbulent flow distributions can be verified experimentally through dynamic similitude by choosing a fluid flow that has the same Reynolds number for the desired flow rate. Reynolds number is a dimensionless quantity that relates the inertial forces in a fluid to viscous forces. By matching the Reynolds number of the flow in a model to the prototype cavity, the resulting flow patterns will be the same. The velocity of the “model” fluid must be adjusted for differences in fluid density and viscosity. Calculation for velocity for water as model fluid is shown below.

\[
\frac{\rho_e V_e}{\mu_e} = \frac{\rho_w V_w}{\mu_w}
\]

The data for the original setup and the experiment are:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of etching fluid ($\rho_e$)</td>
<td>1532 kg/m³</td>
</tr>
<tr>
<td>Dynamic viscosity of etching fluid ($\mu_e$)</td>
<td>0.02 kg/m-s</td>
</tr>
<tr>
<td>Velocity of etching fluid ($v_e$)</td>
<td>0.047 m/s</td>
</tr>
<tr>
<td>Density of water ($\rho_w$)</td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>Dynamic viscosity of water ($\mu_w$)</td>
<td>0.001 kg/m-s</td>
</tr>
</tbody>
</table>

Table (1)

Substituting in Eq. (1), the velocity of water is equal to, 0.0036 m/s in the inlet pipe compared to 0.047 m/s (velocity of etching fluid). This corresponds to a flow rate of 43.4 GPH.

*Inlet pipe length:*

For fully developed laminar flow to occur, the length of inlet pipe or the laminar entrance length is given by

\[
L_e = 10D
\]

Where $L_e$ =laminar entrance length.

D=hydraulic diameter (5 inches)

Which gives $L_e = 50$ inches (4 foot 2 inches) approximated to 5 foot long.

*Traverse mechanism:*

A computer controlled traversing mechanism is used for positioning the camera in the X-Y plane, which is shown below. The controller uses Basic programming language for its operation.
The specifications of the controller are:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>5 lb</td>
</tr>
<tr>
<td>Horizontal Travel</td>
<td>48 inches</td>
</tr>
<tr>
<td>Vertical Travel</td>
<td>24 inches</td>
</tr>
<tr>
<td>Straightness</td>
<td>0.0005 in/in</td>
</tr>
<tr>
<td>Positional Accuracy</td>
<td>0.0005 in/in</td>
</tr>
<tr>
<td>Drive Type</td>
<td>Screw</td>
</tr>
<tr>
<td>Motor Type</td>
<td>Stepper</td>
</tr>
<tr>
<td>Controller</td>
<td>Controller should be able to control two motors with RS-232 ports</td>
</tr>
</tbody>
</table>

**CCD Camera:**

The flow is photographed using a high-speed high resolution CCD camera.
The specifications of the camera are given by,

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>2.0” H X 2.7” W X 6.0” L</td>
</tr>
<tr>
<td>Lens</td>
<td>C-Mount</td>
</tr>
<tr>
<td>Weight</td>
<td>1.5 pounds</td>
</tr>
<tr>
<td>Scanning</td>
<td>Non-interlaced, progressive</td>
</tr>
<tr>
<td>Synchronization</td>
<td>Pixel clock internal</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>48 db 8-bit, &gt;58 db 10-bit</td>
</tr>
<tr>
<td>Pixel clock rate</td>
<td>20 MHZ</td>
</tr>
<tr>
<td>Frame rate</td>
<td>30 fps in dual channel mode</td>
</tr>
<tr>
<td></td>
<td>15 fps in single channel mode</td>
</tr>
</tbody>
</table>

Exit arrangement:

The CFD results proved that the performance is better when the flow exit is axial to the flow inlet, but it is not practically feasible to create a larger single circular segment for flow exit as it removes the support for the baffle. Instead small circular holes are drilled to achieve the required condition. The effect of replacing the four holes arrangement instead of a single circular segment is also analyzed using the CFD.

![Fig. 11. Baffle hole replacement (a) axial exit and (b) exit through holes](image)
Fig. 12. CFD plot for axial (a) exit with single circular segment and (b) exit through four holes.

Quantitative comparison:

<table>
<thead>
<tr>
<th>System</th>
<th>Average velocity</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single circular segment</td>
<td>0.0015154</td>
<td>0.23823</td>
</tr>
<tr>
<td>Four holes arrangement</td>
<td>0.0015155</td>
<td>0.2382</td>
</tr>
</tbody>
</table>

Both the graphical plots and the numerical values prove that four holes arrangement for exit can be substituted for a single circular segment without affecting the results.

*Experimental procedure:*

The pump is switched on, to circulate the water in the system. Valves are properly controlled to make sure the water runs full inside the cavity without any free surface. The discharge is then measured using a measuring jar and a stopwatch. Depending on the discharge obtained the valves are then re-adjusted to maintain the required discharge rate of 0.7238 GPM, once the required discharge rate is obtained, the system is monitored for steady state conditions. If steady state doesn’t maintain the process is repeated again until steady flow condition is achieved. The camera is positioned at the required region by the traversing mechanism. The dye is injected (refer to Fig. 13) in the inlet pipe upstream of the inlet section of the cavity and then the flow is photographed with regular time intervals. Using the time difference between the frames and the displacement of the particles the velocity of the fluid is determined.
Figure 14a and b shows the position of the dye marked by tiny circles at times 153.781 s and 161.765 s shown in time window. Other subsequent times may be found elsewhere. The displacement of the particle in the subsequent frames is shown below.

In the quantitative calculations a scaling factor of 0.976 has to be considered to convert the displacement in the images to their actual displacement in the real cavity. Accordingly the average velocity at points 30.744mm and 23.248 from the axis of the cavity are calculated by \( \frac{\Delta x}{\Delta t} \).
Table 4.2 velocity values at different time frames

<table>
<thead>
<tr>
<th>Frame1-2</th>
<th>Frame2-3</th>
<th>Frame3-4</th>
<th>Frame4-5</th>
<th>Average velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity at 30.744 mm from axis mm/s</td>
<td>3.1975</td>
<td>3.416</td>
<td>2.928</td>
<td>3.239</td>
</tr>
<tr>
<td>Velocity at 23.428mm from axis. Mm/s</td>
<td>2.9516</td>
<td>2.928</td>
<td>2.44</td>
<td>2.8729</td>
</tr>
</tbody>
</table>

These velocity values are used to interpolate a quadratic function, which is used to approximate the velocity value at any point from the center line to the end. The section is then divided into finite annular elements. Each finite area is then multiplied with the corresponding velocity values to get individual discharge for that annular segment, which on summation gives the total discharge, which is equal to 7.63ml/sec. The result is then compared with the discharge measured using measuring jar and stopwatch, which is 9.5ml/sec, close to the experimental result.

**LANL Baffle:**

Based on the drawings from the LANL the baffle was fabricated using Plexiglas Fig. 15a. It is then fixed into the cavity, which is inside the Plexiglas box and analyzed for flow pattern. Figure 15b shows the LANL baffle inside the cavity.

Comparison of CFD versus Experimental results for the LANL baffle:

In the CFD results the streamlines with relatively high velocity values are concentrated in the region 0.08m from the centerline of the cavity, which corresponds to 0.03 from the baffle tip. This high velocity region in the experimental image is identified by band of streamlines, which displace the dye more rapidly, and occurs at a distance of 0.0224 from the baffle tip Fig. 16. This value is
comparable to 0.03m in CFD model. Both results show less penetration inside the cavity cells, with more circulation only near the iris regions.

![CFD velocity plot for LANL baffle](image)

**Fig. 16. CFD velocity plot for LANL baffle**

**Dissemination or Results:**

All results have been offered and appropriately disseminated to Dr. Tajima our DOE collaborator.

**References:**