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Fluid Flow and Current Distribution during Pulse-Reverse Electropolishing of Niobium Superconducting RF Cavities

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Background: SRF Niobium Cavity Electropolishing (EP)

Nb Superconducting Radio Frequency (SRF) are required for the International Linear Collider as well as other high energy physics projects. To achieve required particle acceleration gradients, electropolishing is the final surface finishing operation;

**9:1 H₂SO₄ (98%) : HF(48%)
electrolyte (DC)
“High Viscosity”**

HF → Safety/Cost Burden

Personal Protective Equipment (PPE) for
“conventional” SRF niobium cavity electropolishing
using sulfuric acid – hydrofluoric acid mixture.

John Mammoser, Instructor
“Chemical Safety for SRF Work”
U.S. Particle Accelerator School
January 2015

T. Dote, K. Kono (2004), “An Acute Lethal Case of Exposure During A Washing Down Operation of A Hydrogen Fluoride Liquefying Tank”, *Japanese Journal of Occupational Medicine and Traumatology*, **52**, 3, pp189-192.

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Corrosive

Pulse Reverse EP Process

Anodic Pulse “Tuned” to:

- Focus current distribution

→ Eliminate need for viscous electrolytes

Cathodic Pulse “Tuned” to:

- De-passivate surface/remove oxide

→ Eliminate need for HF, and/or low water content electrolytes

Off-Time “Tuned” to:

- Dissipate heat
- Replenish reacting species
- Remove reaction products

Pulse-Reverse Cavity EP

Pulse-Reverse EP Studies

- Vertical Orientation
 - 5-10 gal/min upward flow
 - 100% Volume Fill
 - No Rotation
 - 5-10 wt% H_2SO_4 in H_2O
-
- ➔ Analogous to, e.g., Cr plating of tube inner diameters
 - ➔ Simpler & industry-compatible
 - ➔ *Enabled by low viscosity electrolyte!*
No gas bubbles trapped on bell i.d.

Modeling of Cavity EP Physics & Electrochemistry

- Fluid Dynamics
 - Dye tracer test
 - Laminar flow modeling
- Primary Current Distribution
 - Effect of counter-electrode masking
- Surface Oxide Growth
 - Preliminary modeling of oxide growth during anodic pulses

Generation of Cavity Model

Dye Tracer Flow Study

Dye Tracer Flow Study

- Flow in beam tube above injection point
- 0.25x playback speed
- Laminar/turbulent transition flow

$$Re = \frac{LQ\rho}{A\mu}$$

- 1.0 gal/min $\rightarrow Re = 418$
- 2.5 gal/min $\rightarrow Re = 1050$

Dye Tracer Flow Study

1.0 gal/min

No Baffle

“Low” Baffle

2.5 gal/min

Dye Tracer Flow Study

COMSOL Flow Profile Simulation

- Axisymmetric, laminar flow
- Flow rate ramped step-wise to 5 gal/min
 - Time-dependent simulations with “settling periods” typically more stable than stationary models

COMSOL Flow Profile Simulation

Axisymmetric
Laminar
Flow

1.0 gal/min

No Baffle

“Low” Baffle

“Mid” Baffle

5.0 gal/min

Counter-Electrode Masking – 1° CD Effects

- Control current distribution on cavity surfaces via masking of counter-electrode
 - Porous PTFE → Partial Masking
 - Plater's Tape → Complete Masking

Counter-Electrode Masking – 1° CD Effects

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Counter-Electrode Masking – 1° CD Effects

Surface Oxide Modeling

- Surface oxide growth significantly affects current dynamics
 - Partial consumption of current
 - Local impedance $\propto$ Local film thickness
- Preliminary simplified parallel-resistance polarization model
 - Empirical
 - Fundamental representation of Nb oxide kinetic polarization and film properties is challenging

$$R_{OER}(\vec{r}, t) = A + B \cdot j_{OER}(\vec{r}, t)$$

$$R_{ox}(\vec{r}, t) = \rho_{ox} s_{ox}(\vec{r}, t)$$

- Oxide film thickness modeled as a 2-D surface field variable across cavity interior

Oxide Modeling Results

Parameter	Value
$t_{\text{on,anodic}}$	140 ms
T	1.25 s
d_{ox}	5.9 g/cm ³
M_{ox}	124.9 g/mol
κ	500 mS/cm
ρ_{ox}	7 G Ω -cm
A	10 k Ω -cm ²
B	80 Ω -cm ⁴ /mA

No Oxide

With Oxide, at End of Anodic Pulse

Material Removal Rate ($\mu\text{m/h}$)	Experiment	Model
Beamtube	1.79	11.7
Equator	1.25	6.20
Ratio	1.43	1.89

Summary

- Multiphysics modeling can provide key insights into flow, current distribution, and other phenomena relevant to electrochemical apparatus/processes
- Rigorous modeling of all physics is often not required to gain useful insight
- For Nb cavity processing, modeling can guide improvements in:
 - Flow profile, via baffle geometry/placement
 - Current distribution, via masking
 - Polishing performance, via waveform selection

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Thank You!