Study high pressure hydrogen gas filled RF cell

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Breakdown field with Cu electrode

\[ E_{N2} = 0.0941 \times \text{Pressure} + 8.606 \]
\[ E_{SF6} = 0.0919 \times \text{Pressure} + 7.060 \]
\[ E_{H2} = 0.0634 \times \text{Pressure} + 5.672 \]

- Procedure: N2 run → H2 run → SF6 run
- Maximum field in 2008 run is ~20 % increased
- Good agreement of the Paschen slope between both ('08 & '04) runs
- Knee pressure (red arrow in upper plot) in 2008 run is 900 psi while that in past run (red arrow in lower plot) is 700 psi
- Increment of field in 2008 run can be real
- Plateau is different with different gas
- SF6 has big ambiguity

N2 (taken at 9/18/08)
N2 (taken at 9/17/08)
H2
SF6 (Δp = 0.01 %)
SF6 (Δp = 0.2 %)

Took after SF6 run
Other electrodes

\[ E_{SF6} = 0.1076 \times \text{Pressure} + 4.378 \]

\[ E_{H2} = 0.0497 \times \text{Pressure} + 9.406 \]

\[ E_{H2} = 0.0452 \times \text{Pressure} + 6.002 \]

\[ E_{SF6+He} = 0.01282 \times \text{Pressure} + 4.935 \]

\[ E_{He} = 0.00937 \times \text{Pressure} + 3.704 \]
What changed for the copper electrode?
• Change in gas mixture and/or change in the copper surface
• Spots appear independent of locations where there are arc marks.

• This can occur when machine oils are used, and thin films of copper are smeared over the oils, trapping them, to be leached out later during subsequent processes.

• Where discoloration is present around an arc, it represents regions where contaminants may have been “released” as shown, with a “splatter” footprint.
In H₂, if there are oxides or other contaminants on the surface, they may be reduced during the arc forming CHₓ or H₂O in the closed system. Adding to the gas mixture.

Perhaps that is the “shadow” of apparently clean copper surrounding the melted regions.

May change the dielectric constant of the gas mixture in the closed system.
Mahzad Photos #3 In center of electrode

- We need to verify the chemistry of this discoloration.
- It may be carbonaceous, or if there is a heavy residue of sulfur, it would be from the SF$_6$ (with our luck it will probably be both).
- If it were carbonaceous, it might again suggest machine oils that were not cleaned off.
Small Section of last photo

Mahzad & Mike

- Notice the apparent thickness
- If it were carbonaceous, it may increase the breakdown limit for copper based on the melting point theory.
From SEM study

With regards to the copper electrode, copper sulfate was found, carbon, and some oxide. These compositions most likely increased the work function over pure copper and contributed to higher breakdown gradients.

With regards to the aluminum electrode, there appears to be ample evidence of Al2O3, with a thickness TBD that may have contributed to a higher work function and higher breakdown gradients than pure aluminum.
Summary

• Data during September run followed a straight line as a function of melting point, but had a different slope from the 2004 data.
  – Sn being the “pivot point”

• The copper surface may have “improved” as the result of contamination
  – Need SEM analysis of residue

• A model is presented for how the dielectric constant may not be the ideal, if there is breakdown in $H_2$ with contamination on the electrode in a closed system.
Breakdown Plasma Physics

Alvin & Mohammad

This cavity designs to enhance an electric field between two electrodes.
It generates a relatively large inductance.
Equivalent resonance circuit after breakdown

L & C can be estimated from field distribution

\[ L = \frac{\mu_0}{2\pi} h \log\left(\frac{r_1}{r_2}\right) = 2.45 \times 10^{-8} = 0.245 \text{ nH} \]

\[ r_1 = 4.5”, \quad r_2 = 1”, \quad h = 3.2” \]

\[ C = \frac{1}{(2\pi\nu_0)^2} \times \frac{1}{L} = 1.62 \times 10^{-12} = 1.62 \text{ pF} \]

\[ \nu_0 = 800 \text{ MHz} \]

Plasma current generates additional inductance

Assume current radius is 50 μm (h=1.773 cm)

\[ L_w = 2.98 \times 10^{-8} = 0.298 \text{ nH} \]

This number is close to the inductance of cavity
Q-values in HPRF after breakdown

Impedance of HPRF after breakdown

\[ z(p) = \left( \frac{1}{pL} + pC + \frac{1}{fLp + r} \right)^{-1} \]

If we know resonant frequency and resistivity in HPRF after breakdown we can extract the Q-value.

Upper plot shows the relation between resonant frequency vs RF cycles to damp the stored energy.

Observed resonant frequency after breakdown is always higher than the frequency in stable condition.

This model predicts well this trend.

The current density in plasma will be determined from this model!
Physics in HPRF with beam

What is breakdown??

Thermal energy of electron with time evolution

\[
\frac{d\epsilon}{dt} = \left[ \frac{P_c}{n_e \nu_m} - \delta \epsilon \right] \nu_m
\]

- \( \nu_m \): electron-neutral collision frequency
- \( \delta \epsilon \): fractional energy loss
- \( P_c \): average power transferred from external RF
- \( n_e \): number density of electron

Rate equation of electron

\[
\frac{dn_e}{dt} = S + \left( k_i - k_{DA} \right) n_{H2} n_e - \beta_r n_e^2 - \frac{D}{\Lambda^2} n_e
\]

- \( S \): Electron Source
- \( k_i - k_{DA} \): ionization rate - dissociation rate
- \( \beta_r \): Recombination
- \( D/\Lambda^2 \): Diffusion

- \( k_i < k_{DA} \): Stable
- \( k_i > k_{DA} \): Breakdown
Q-value with beam

**FIG. 6**: Dissociative recombination rate coefficient as a function of average electron energy [19, 20].

**FIG. 7**: Examples of electron density evolution over many micropulses without (red) and with (blue) recombination process. Here, we pick the parameters to $\beta_r \sim 10^{-8}$ cm$^3$s$^{-1}$, $r_b \sim$ 1 cm, $p = 500$ psi.

**FIG. 8**: Decrease in the loaded $Q$, $Q_L$, over many micropulses without (red) and with (blue) considering recombination process. Initially, we assume $Q_L = 6000$.

Expected Q-value shift caused by plasma

$$\Delta \left( \frac{1}{Q} \right) = \frac{(\nu_m/\omega_0)}{1 + (\nu_m/\omega_0)^2} \langle n_e \rangle / n_c$$

$\langle n_e \rangle$: expectation of electron density with respect to the distribution of electric field

$n_c = \epsilon_0 m_e \omega_0^2 / e^2$: critical electron density
Dopant gas effect

At equilibrium condition

\[ n_e \sim S(\tau_\epsilon + \tau_a) \]

\( \tau_\epsilon \): time constant to thermal equilibrium condition
\( \tau_a \): time constant to capture electron

C4F8 looks better than SF6 for electrons with T~1 eV
Collaborators

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Conclusion

• Observed higher Breakdown than past
• Chemical analysis shows contamination on electrode surface
• Made very primitive optical measurement
• Investigate physics under breakdown
• Investigate physics with beam