Ion Current from Breakdowns in RF Structures

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Outline

- Set-up
- Measurements
  General observations
- Results
  Analytical calculations: results and limitations
  Estimations of breakdown site size
- Surface analysis of FC
  Results, comparison with ion current measurements
- Conclusion
30 GHz test-stand
Setup

Accelerating structure

RF in

RF out

Upstream signal (to scope)

'Downstream' FC

'Downstream' FC

Downstream signal (to scope)
Faraday-Cup

Signal to ADC

Reflected light

Aluminum Faraday-Cup

Breakdown electrons and ions from acc. structure (~20 cm from FC)
Measurements

• Data acquired in 2007:
  – August 20\textsuperscript{th} – October 8\textsuperscript{th} (HDSt\textsubscript{thick})
  – November 1\textsuperscript{st} – December 14\textsuperscript{th} (NDSt\textsubscript{thick})

• 6700 ion current events recorded
  – Significant ion currents detected after 40\% of breakdown events (overall).
Sample ion currents

- Triggered on e- signal
- 5 μs delay
- Ion currents detected on 30-70% of all breakdown events.
- No obvious dependence on RF, conditioning time etc....
Sample ion currents

- "Fast" signal
- "Medium" signal
- "Slow signal"

Multiple ionization states?
Multiple ion species?
Multiple breakdown sites?
Arrival time spectrum from hot Coulomb explosion:

\[ \frac{dN}{dt} = f \left( N_0, \alpha, t_s, t \right) \]

(Ziemann NIM. A 575 (2007))

- \( N_0 \) = number of particles in sphere.
- \( \alpha \) = relative importance Coulomb forces vs thermal motion, allows for calculation of temperature \( T \)
- \( t_s \) = arrival time of fastest ions from cold distribution. Determine time of peak.
- \( t \) = time
How does this fit measured ion currents?

Fit of events with one peak works well.

Events with several peaks can be fit with a simple sum.

Theory *does not* work for different masses/charge states....

....which we maybe see in the measurements....

....thus need

*Simulations

*Experimental means to measure charge-mass ratio (e.g dipole magnet)
Theory - Fit

N₀ = 1.32 * 10^{10}
α = 0.4128 → T = 900 000 K
tₜ = 5.2 μs

N₀₁ = 1.61 * 10^{10}  
α₁ = 0.52 → T = 115 000 K

N₀₂ = 0.75 * 10^{10}  
α₂ = 0.27 → T = 312 000 K

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Results – breakdown site size

• Average number of particles reaching FC per ion current event $\sim 10^{10}$.

• $10^{13}$ ions in each breakdown site (FC covers 1/1000 of total solid angle).

• This is equivalent of a copper cube with 5 $\mu$m side.
"Where is the copper?"

Visual inspection of FC: no copper.

Bulk sensitive analysis: no copper.

Surface sensitive analysis, XPS: copper! (thanks Mauro, Delphine and Luigi!)
Comparison XPS – number of particles

**XPS analysis:**

We still see some of the bulk material

Assume a nm thick layer of copper (could be 0.3 – 3 nm), homogeneously distributed on FC surface

→ $8 \times 10^{-12}$ kg copper / mm$^2$

(Again: Thanks Mauro!)

**Ion current measurements:**

Mean number of ions per ion current event

$\approx 10^{10}$ ions (assuming singular ionized)

Assume $10^6$ ion current events (total for all copper structures)

→ $1.38 \times 10^{-12}$ kg copper / mm$^2$
Conclusions

Ion current events have 3 components
  “Fast”, “Medium” and “Slow”
  Multiple breakdown sites?
  Multiple ion spices?
  Multiple ionization states?

Hot Coulomb explosion theory gives nice fits...
  ...but does not describe multiple ion spices or ionization states
    -Simulations needed (*work in progress*).
    -Add spectrometer to 30 GHz test stand?

Amount of copper seen on FC with XPS is consistent with estimations from ion current measurements
Fin
Arrival time spectrum –
hot Coulomb explosion

Arrival-time spectrum \( \frac{dN}{dt} \) given by:

\[
\frac{dN}{dt} = \frac{3 N_0 \alpha^2}{\sqrt{\pi} t_s} \left( \frac{t_s}{t} \right)^2 V_2 \left( \frac{1}{\alpha}, \frac{1}{\alpha} \frac{t_s}{t} \right),
\]

where the function \( V_2 \) with input arguments \( w \) and \( s \) is given by:

\[
V_2(w, s) = \frac{s}{2} e^{-s^2} - \frac{s + w}{2} e^{-(s-w)^2} + \frac{\sqrt{\pi}}{2} \left( s^2 + \frac{1}{2} \right) (\text{erf}(s) - \text{erf}(s-w)).
\]

3 free parameters:

\[
N_0 = \frac{4\pi \rho R^3}{3}, \quad \alpha = \frac{\sqrt{2} \sigma}{v_s}, \quad \sigma = \sqrt{\frac{kT}{m}}, \quad t_s = \frac{L}{v_s}
\]

- \( N_0 \): Number of particles in initial sphere,
- \( \rho \): the number density of initial sphere,
- \( R \): the radius of initial sphere.
- \( \alpha \): RMS width of thermal velocity distribution divided by \( v_s \),
- \( k \): Boltzmanns constant,
- \( T \): the temperature of the initial charge distribution,
- \( m \): the mass of the ions.
- \( t_s \): arrival time of the fastest ions from cold distribution,
- \( L \) is the distance from the detector to the Coulomb explosion,
- \( v_s \) is the velocity of the fastest ions from a cold Coulomb explosion.
HV bias box

**FC** (left) sees a high-pass filter with cut-off frequency of 1.5 Hz

**HV** (bottom) sees a low-pass filter with cut-off frequency of 1.5 Hz

**Signal out** (right) is decoupled by a capacitance, and has 0 bias voltage.
Cu and Mo properties

• Boiling point
  – Cu: 2855 [K]
  – Mo: 5830 [K]

• Heat of vaporization
  – Cu: 4.75 [MJ/kg]
  – Mo: 6.83 [MJ/kg]

• Energy per RF pulse
  ~ 1 [J]
  – enough to vaporize order of 1 mg material
  – 1 mg copper corresponds to a sphere with radius R=0.3 [mm]

• Ionization energy
  – Cu: $E_{\text{ion}} = 7.478$ [eV]
  – Mo: $E_{\text{ion}} = 7.099$ [eV]

• Temperature needed to ionize Cu:
  $E_{\text{ion}} = (3/2)*k_B*T_{\text{ion}}$
  $\rightarrow T_{\text{ion}} = 2*E_{\text{ion}}/(3*k_B)$
  $\approx 100$ [kK]
Signal Schematic