DC Aging And Damage.

By

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Aging Studies Overview

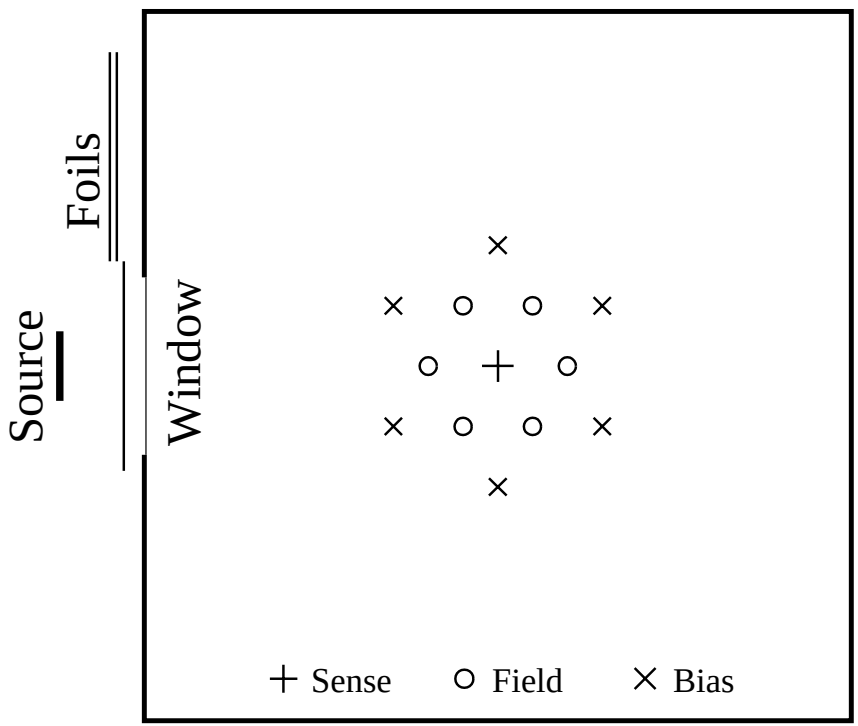
- BaBar saw high current spikes and steadily increasing chamber currents during commissioning.
- A familiar problem - known solutions:
  - Add alcohol (Charpak et. al. 1972, Atac 1977), or
  - Add water (Argus expt ~1985).
- BaBar added 3500 ppm water vapor – spikes gone.

- The spike problem prompted a study at even higher ionization rates and various additives in a test cell.
  - Results published in
    - NIM A515 (2003) 190-195, for the additive study.
    - NIM A535 (2004) 632-643, for the modeling study.
- This talk is based on these publications as well as other information.

Test Chamber Requirements

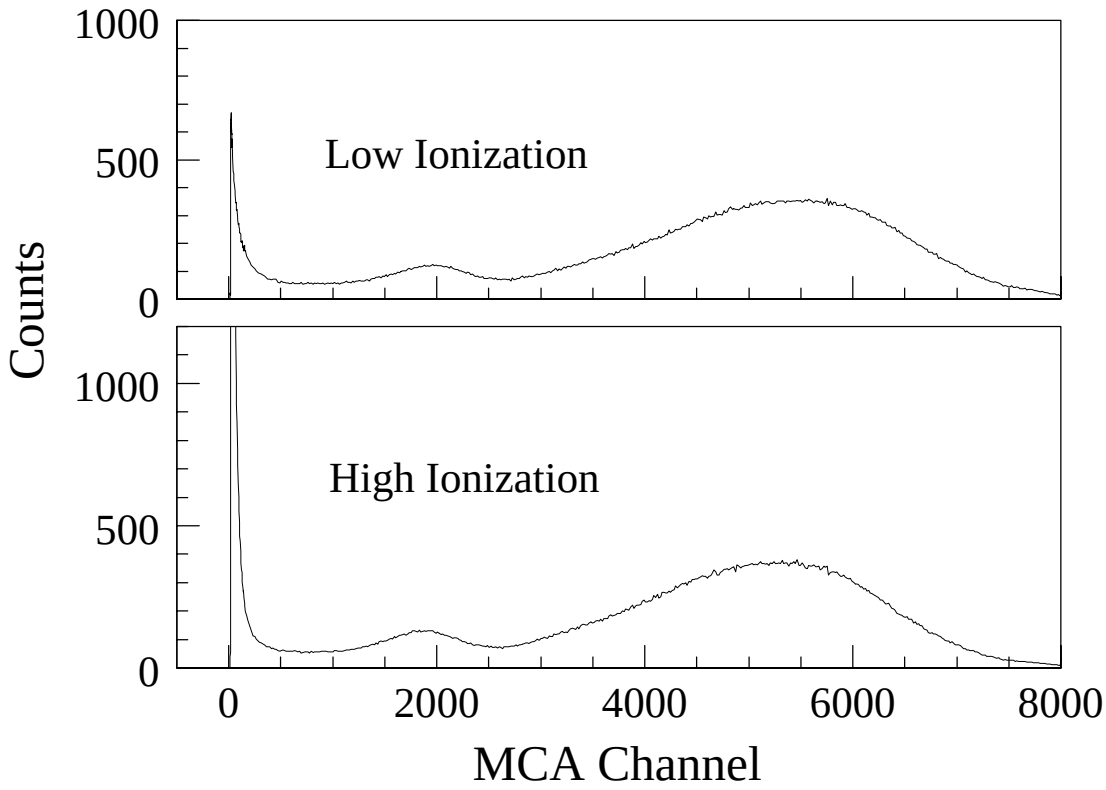
- Use a cell design similar to that in BaBar.
  - Hexagonal cell, ~1cm wire spacing.
- Use BaBar gas - helium(80%) isobutane(20%) but without additives to allow aging effects to proceed.
- Use a ^{55}Fe source for ionizing the gas.
- Pico-ammeter to measure chamber current.
- Multi channel analyzer to measure the pulse spectrum shape.
- Ability to add water, alcohol, oxygen or CO_2.

Test Chamber



- Box 10x10x30(L) cm.
- One hexagonal cell.
- 1 cm wire spacing.
- 1-Sense wire, 20 um, gold coated, 2050 V.
- 6-Field wires, 120 um, gold coated, 0 V.
- 6-Bias wires, 120 um, gold coated, 1300 V.
  - Same fields as BaBar.
- ^{55}Fe source, mylar window, atten. foils.

Spectra at Low & High Ionizations.



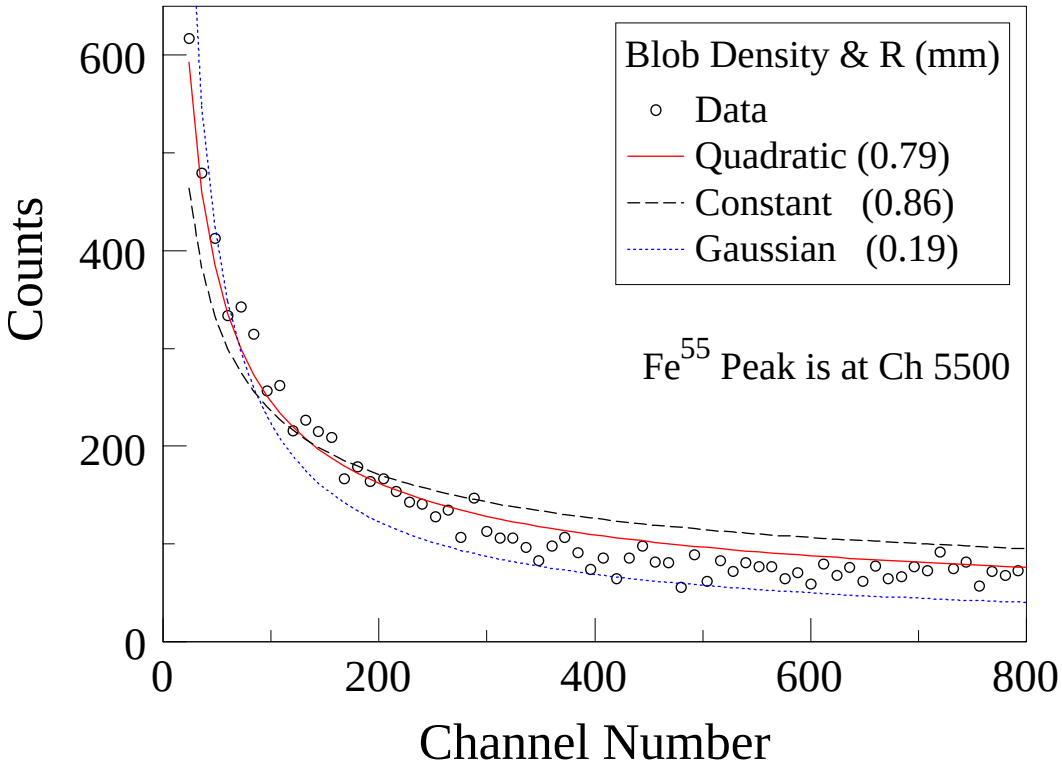
The number of small pulses per ^{55}Fe conversion is larger at higher ionization levels in an aged chamber.

Understanding small pulses from ^{55}Fe

Small pulses may be a useful tool.

- Need to understand the small pulse spectrum.
- Small pulses are due to conversions at the cell boundary, where ions are shared between adjacent cells.
  - Of the ~170 ions per conversion, it is possible to collect only 1-, or 2-, or more ions in one cell while the rest go to a neighbor cell.
  - A model is shown in next plot.

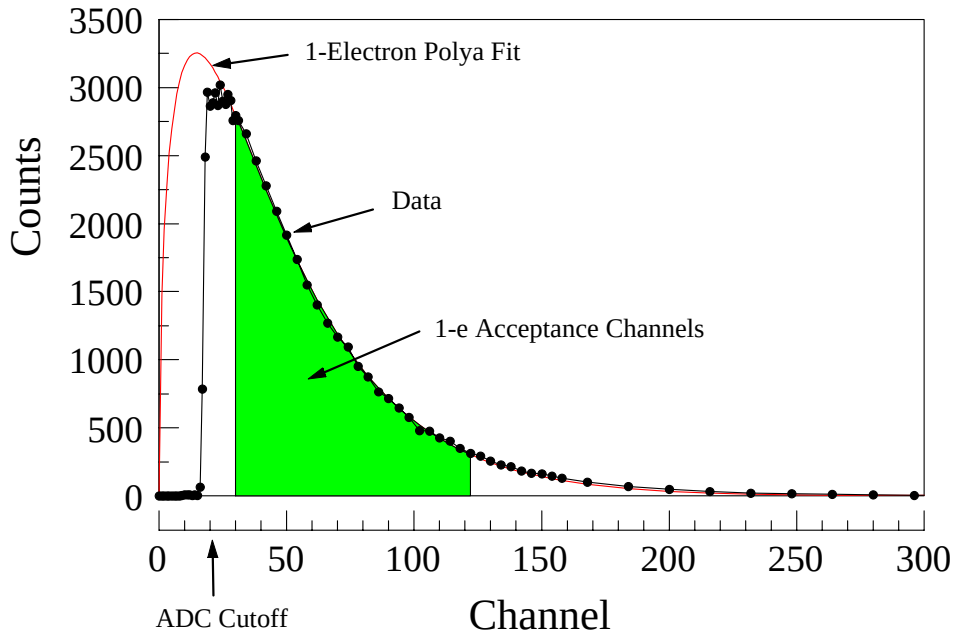
Small Pulse ^{55}Fe Spectrum
And Conversion Blob model



- Best fit is with a quadratic density, (max at center to zero at radius R).
  - R=0.79 mm (1.6 mm diam.)
  - Consistent with the 2.5 mm range of a 5.9 KeV electron in the (80:20) gas.
- Constant density, R=0.86 mm, is too flat.
- Gaussian density, sigma=0.19 mm, gives too much of a peak.

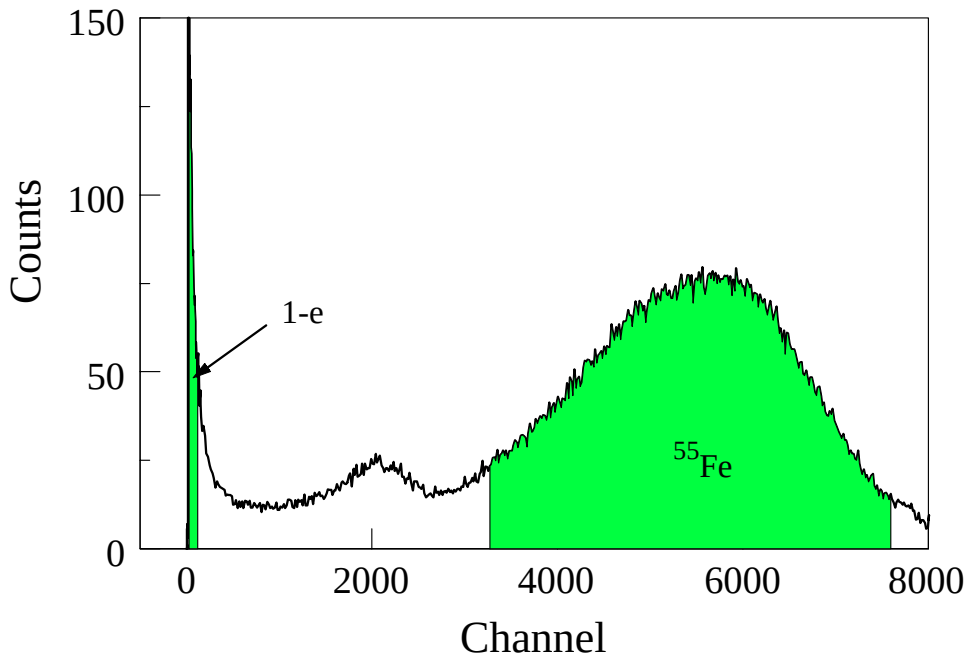
Single Photoelectrons & 1-e Cuts

- Establish channel cuts for single electrons.
- Shine light through a window to measure a photo-electron spectrum.
  - A Polya function fits the photo-electron spectrum well.
  - Channels 30-120 see approximately 50% of the 1-e avalanches.



The Spectrum and N_1/N_{Fe} Ratio

- Channel cuts for ^{55}Fe pulses
  - Amplifier gain adjusted for peak at Ch ~5500. Used channels 3280-7590 to count ^{55}Fe.
- The ratio of single-electrons per ^{55}Fe in a new chamber is
  - 0.022 at low rates.
  - 0.033 at high rates (larger due to pileup, base line shifts).
  - Any higher values observed must be from aging effects.
- Quiz – What's at ch 2000?



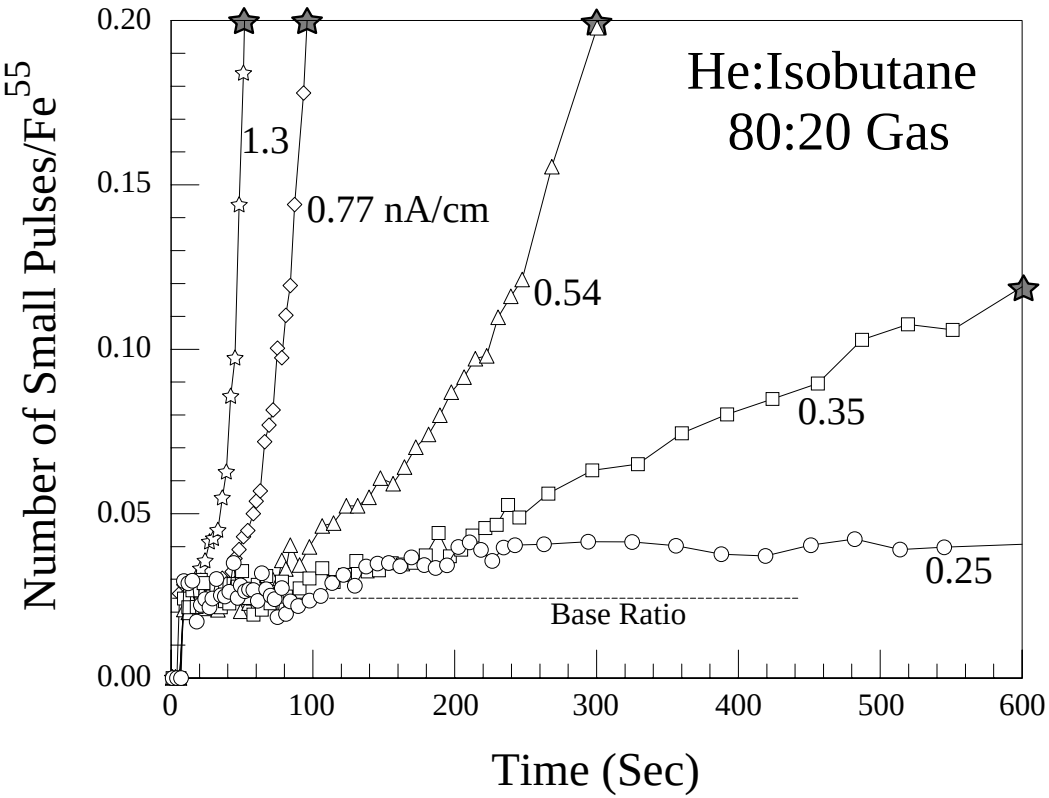
Measurements in an Aged Cell.

- Transient single electron rates were measured in an aged cell.
  - Starting with a resting chamber (source off, HV on),
  - Source was suddenly opened.
  - Data was recorded until a steady single electron rate was reached or a breakdown occurred.
  - Repeated for various source strengths.

  - In each case, the N_1/N_{Fe} ratio starts at the base-line value, then increases with time – very rapidly at the higher source strengths. Plot.

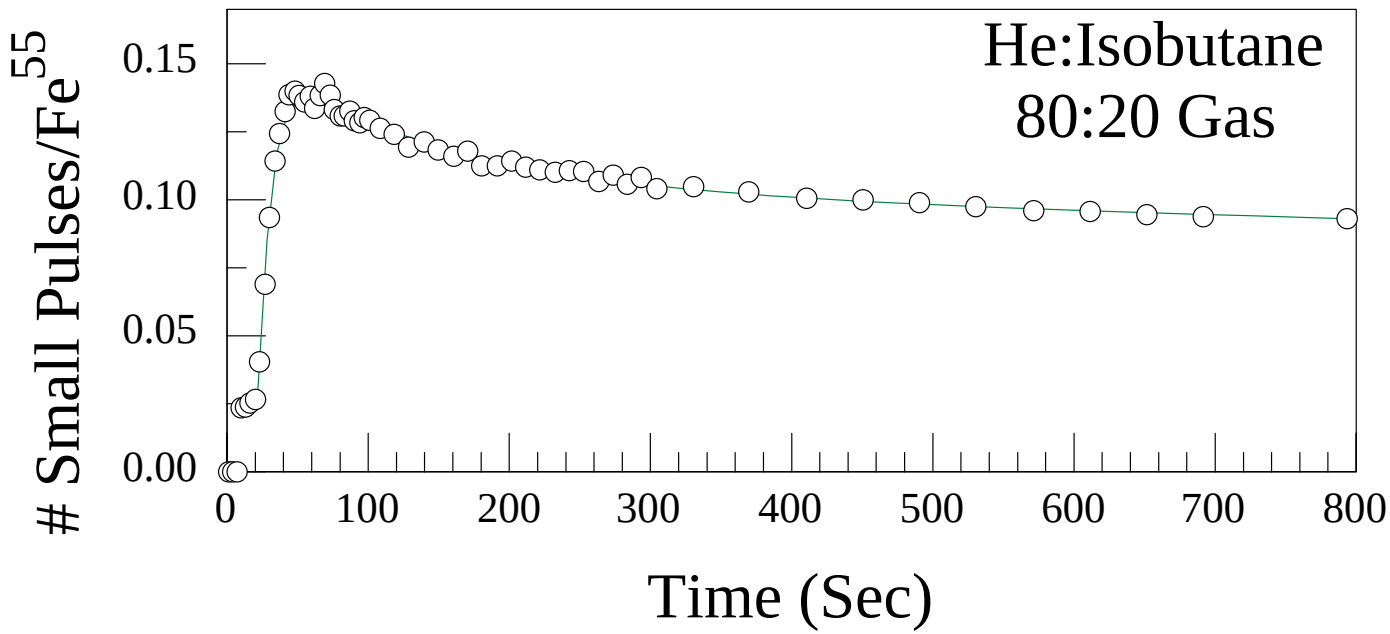
Single Electron Rates in Aged Cell.

- At various ionization levels (in nA/cm on SW).
- "Star" indicates high-current jump occurs, eventually.



Transient Spikes

- For ionization levels below the breakdown level, when the source is opened the single electron ratio increases rapidly and then decreases slowly - a transient spike is seen.



Spike Height

- The spike height was found to depend on the length of quiescent time (settling time) prior to source turn on, shown in the table.
- For HV on & source off, the E field clears out ions in the film in ~0.5 h.
- For HV off, only the self field from stored charge pushes charges outward.
  - Charge pushed to the metal side are neutralized there.
  - Charge at the gas side of the film is neutralized by ions in the gas.
  - Settling time depends on the ionization level in the chamber.
  - With source off, the low cosmic ionization gives a long 70 hr settling time.
- The charged film behaves like a storage capacitor.

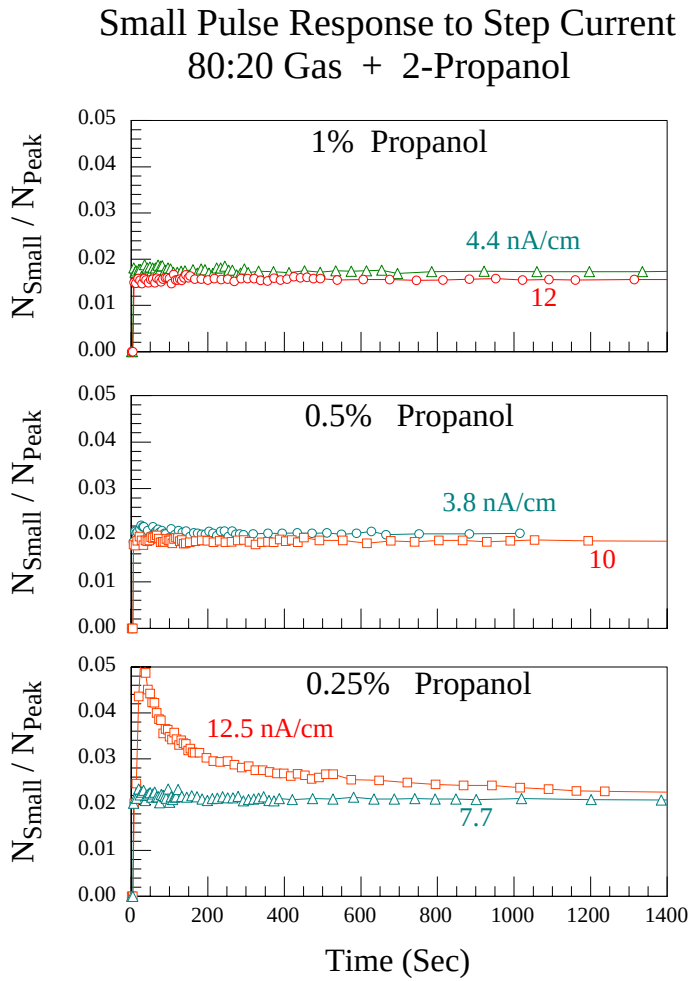
High Voltage	Source	Settling Time (h)
ON	OFF	0.5
OFF	ON	2
OFF	OFF	70

Additive Study.

- Using an already aged chamber,
  - Chamber breaks down at low currents when no additive is present.
  - Add additive (alcohol or water),
  - Measure transient spikes while running at high ionization levels,
    - Restricted to less than 10nA/cm of current on SW to allow reliable detection of single electrons.
    - BaBar runs at approximately 0.3nA/cm so the test chamber is at 30 times the level of BaBar.

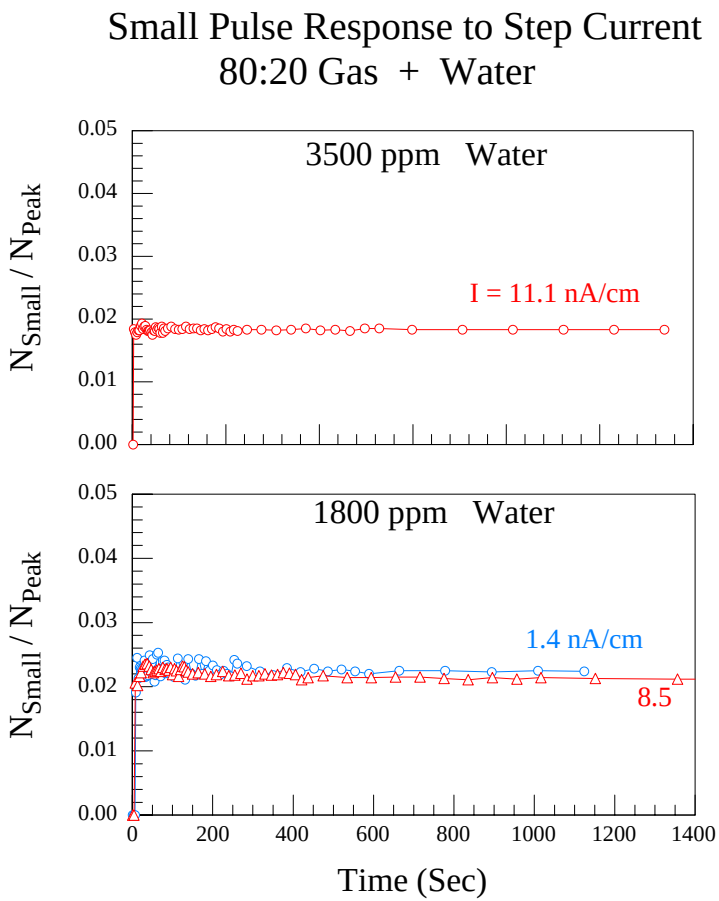
Additive: 2-Propanol

- Concentrations above 0.5% propanol show no small pulse activity.
- At 0.25%, a spike is seen at the highest chamber current, 12.5nA/cm.
- 2-Propanol at 1% is a good additive.



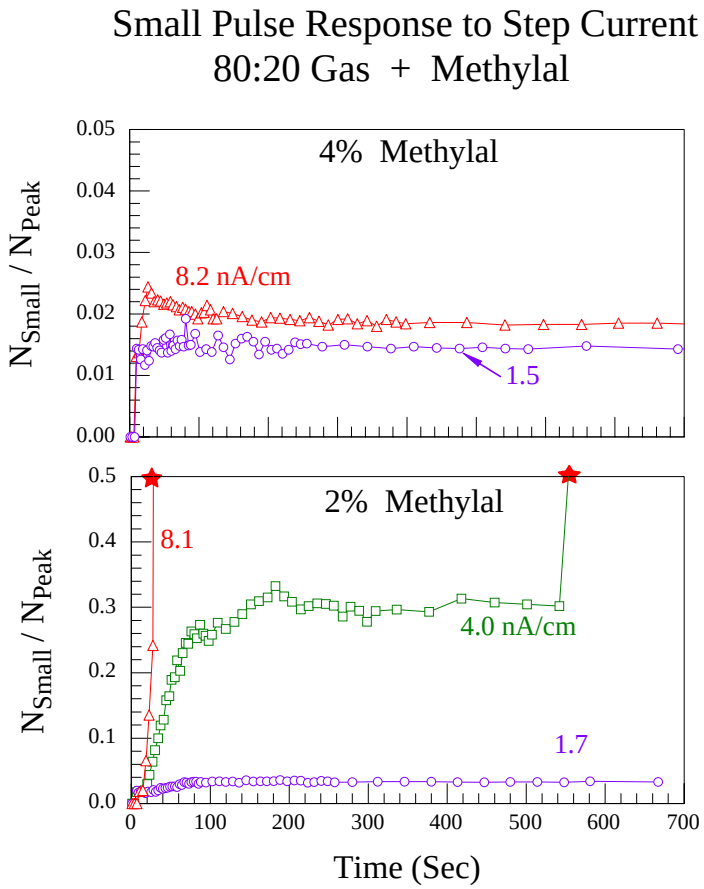
Additive: Water

- No spikes seen at highest currents for concentrations of 0.35% (the BaBar value) or half that.
- Water at >0.2% is a good additive.



Additive: Methylal

- Some spiking seen at the 4% concentration.
- Huge spikes and chamber breakdown at the 2% level.
- Methylal is not good even at 4%.



Alcohol and Water Summary

- These additives immediately improve a damaged chamber.
- When the additives are removed, then the small pulses return.
- These additives prevent high dark currents and breakdown, but they do not clean or cure the chamber.

Long Term Running With Water

- The test cell was run with 0.35% water
  - Use a very high current (40nA/cm on SW, 130×BaBar)
  - For a month duration.
  - Charge collected = 80mC/cm of SW,
    - about that expected in BaBar over 10 years.
- Changguo Lu at Princeton did a similar run to 230mC/cm.
- No small pulse activities were measured during these runs.
- Conclusion - the water additive should keep BaBar safe over its lifetime. No aging seen at 100× its present current.

Adding Oxygen in Aged Chamber

- Different behavior than water or alcohol. Training needed.
- Could only operate at low currents at first without breakdown, but the current level could slowly be increased to the maximum source level in ~2 hours.
- But when oxygen was removed, the chamber could still run at max level. The chamber was cleaned! (Although not to the level of a new chamber).
- First such observation of cleansing with O_2. Etching was previously seen with a CF_4 additive.

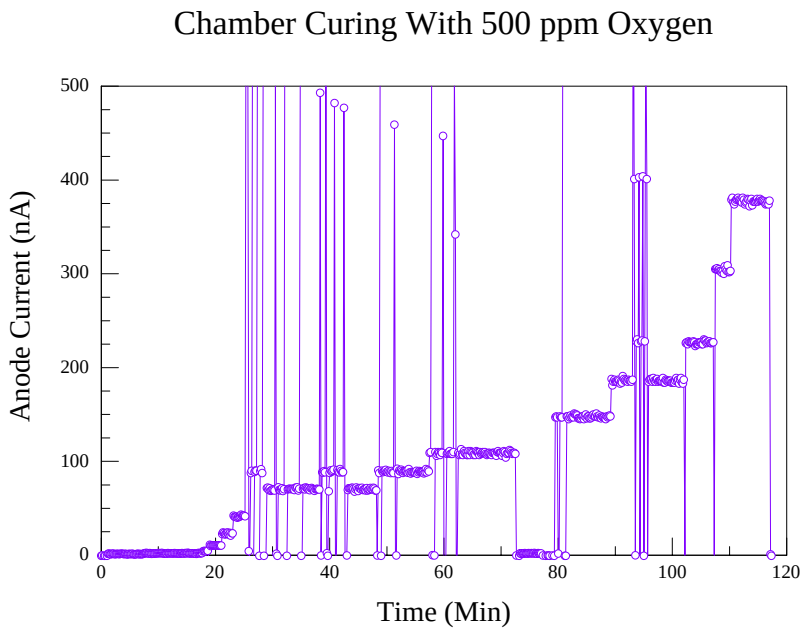


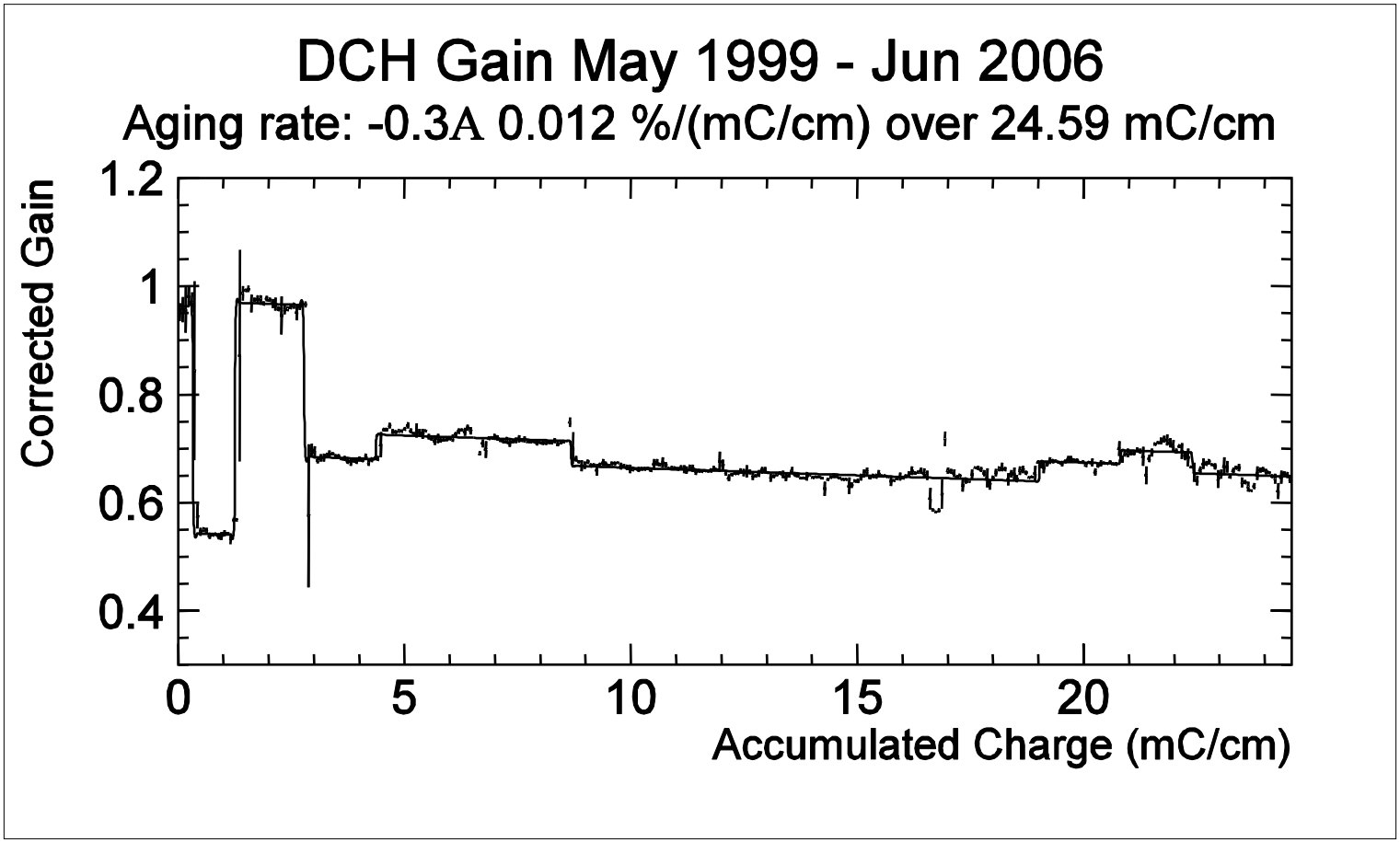
Table 1. Summary of Additives. The maximum stable current I_{max}(nA/cm) in a damaged chamber with Helium:Isobutane (80:20) gas is shown before the additive, then with the additive, and then after the additive is removed. Cases that did not reach break down at the maximum attempted current are marked with a ">" sign. T is the training time to reach I_{max}. Some additives cure a damaged chamber, as indicated in the last column.

Additive	(%)	Before	With Additive		After	Cure?
		I_{max}	T(hr)	I_{max}	I_{max}	
Methylal	4 2	0.3	~0 ~0	>8 3	0.4	No
Propanol	1.0 0.5 0.25	0.7	~0 ~0 ~0	>12 >10 >13	0.2	No
H_2O	0.35 0.18	0.4	~0 ~0	>27 >9	0.5	No
O_2	0.10	0.5	1.5	>32	>40	Yes
	0.05	0.4	2	>29	>16	Yes
	0.02	0.9	10	>35	>14	Yes
CO_2	5	0.4	35	>40	>27	Yes
O_2 + H_2O (0.05%+0.35%)		0.4	40	10	3	Partly

Fermilab Experience

- Oxygen also can restore sagging gain.
  - The CDF central outer tracker (COT) showed a gain loss of ~50% after 2 years using a 50/50 argon/ethane mixture with 1.7% alcohol.
    - ICFA Instrumentation Bulletin, Vol. 27, Spring 2005
  - When air (O_2) was added inadvertently, there was an improvement in gain.
  - They now use ~100 ppm O_2, and the gain is back up to normal after only 10 days of operation.

Gain Droop in BaBar (Mike Kelsey)



BaBar runs with ≤100 ppm of O_2.

- The small droop, only ~8%, may be due to the presence of O_2 - based on the Fermilab experience.
- It would be interesting to see if more O_2 in BaBar would reverse the droop.

Understanding Cathode Aging.

- What is the mechanism for those large single electron rates?
- Need a model.
  - Could wire chamber breakdown be related to breakdown seen in accelerator structures?

Starting Point

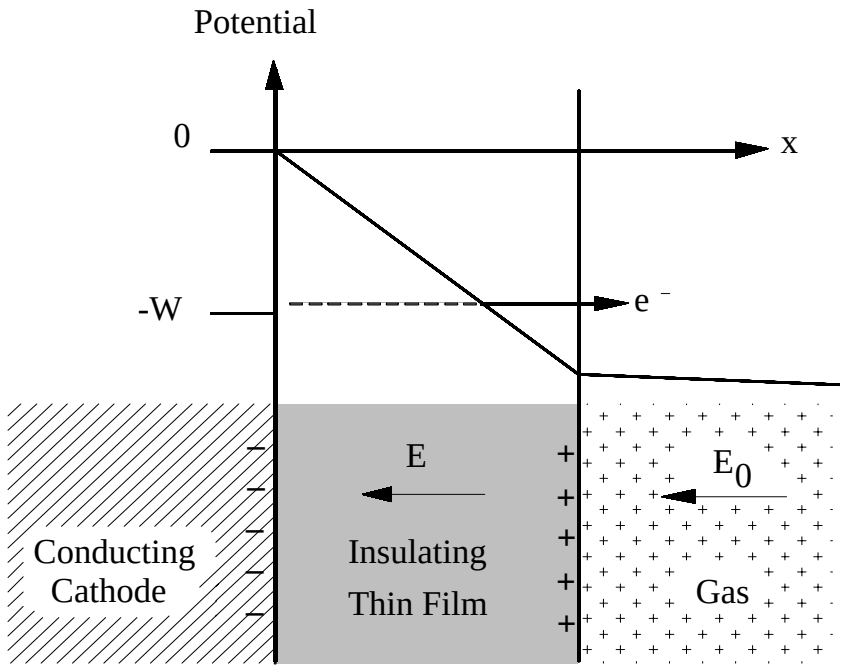
Two known phenomena.

1. Malter (1936) showed that a thin insulating film on a cathode, charged positively, produces a high electron current from the cathode due to a high E-field in film.
2. Fowler-Nordheim (1928) used quantum mechanics to derive the field emission current from a metal surface in the presence of a high external E-field.

- Link the two together to try to explain the observed single electron rates.
  - Assume +ions neutralize and accumulate on cathode and grow a thin polymer (insulating) film over a period of time.
  - New +ions continually charge up the thin film and establish a high E-field before the charge dissipates.

Thin Film Field Emission

- Cell field E_0 in gas.
- Positive ion current I (A/m^2)
- +ions collect on film, -ve induced charge opposite.
- High E field in thin film.
- Triangular potential barrier for Fermi electrons in cathode (work function W).
- Fermi electrons tunnel through barrier (field emission), through film to gas and avalanche at SW, producing 1-e avalanches.



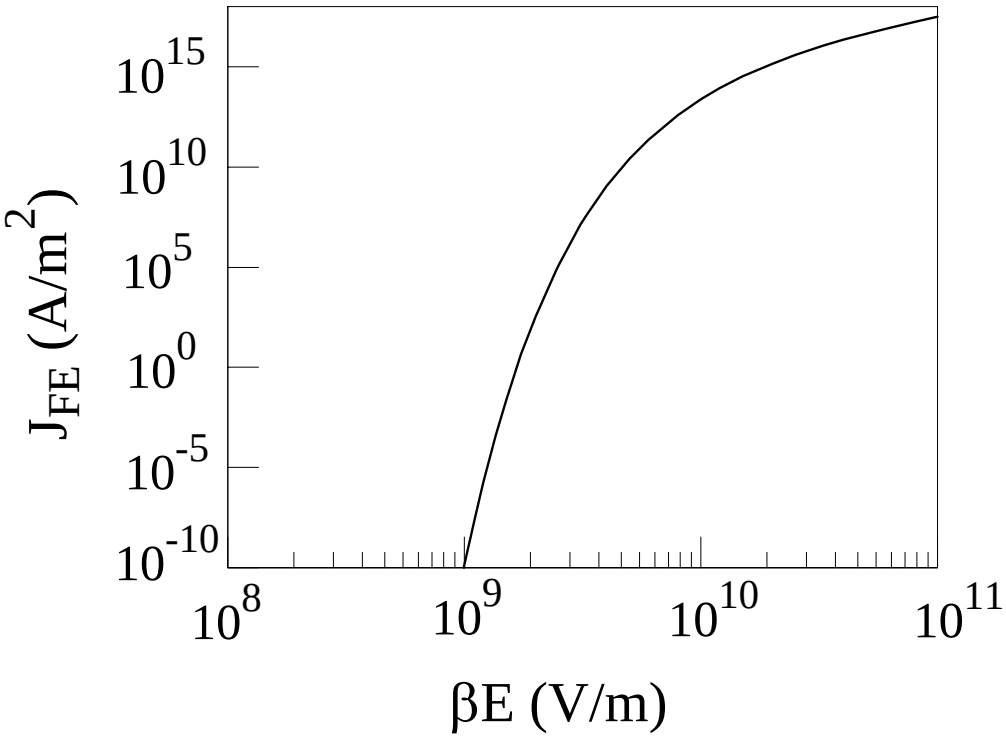
Field Emission Current J_{FE}

- Use the Good-Muller version of a modified Fowler-Nordheim equation for $J_{FE}(E)$.
- J_{FE} depends on work function W (4.3eV for gold).
- Modify $E \rightarrow \beta E$ ($\beta > 1$) to account for the increases in E due to localized surface bumps – as experienced in RF accelerating cavities.
- J_{FE} (in A/m^2) is:

$$J_{FE} = 5.4\times10^{-5}\left(\beta E\right)^2 e^{\frac{-5.43\times10^{10}}{\beta E}}$$

J_{FE} Graph As Function of βE

- A very rapid rise in J with βE.



Field On Cathode Wire

If βE known, can calculate J. But what is E?

- E depends on the (known) charge-up rate from ionization and the (unknown) discharge rate.
- Assume a resistive leaking-capacitor model,
  - Thin film behaves like a parallel plate capacitor,
  - Dielectric const ε ($=k\varepsilon_0$),
  - resistivity ρ,
  - thickness d, area A.
  - Time constant is $\rho\varepsilon$ ($=\rho d/A \times \varepsilon A/d = RC$).
- Any charge Q on or in the film produces a field $E=Q/\varepsilon$ at the wire surface (Gauss law).

E(t) For Resistive Model

- Field *E(t)* on the wire surface for a step increase *I* in current density on the film at *t = 0*, is

$$E(t) = \frac{E_0}{k} + I\rho\left(1 - e^{-t/\rho\varepsilon}\right) \qquad t > 0$$

- Now can calculate $J_{FE}(E)$ *vs t*.
- Note – no dependence on the film thickness *d*.

More Parameters – Area, Feedback, Absorption

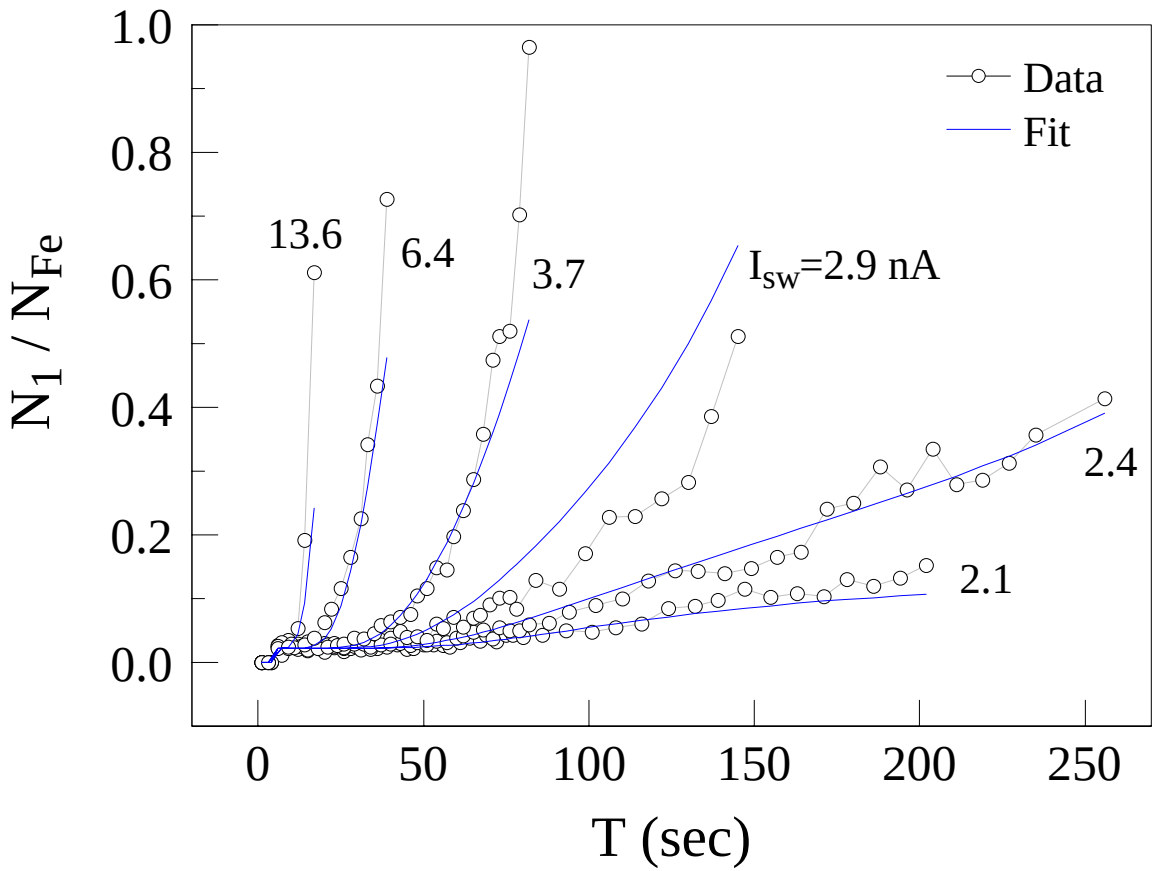
- Area – η, the surface area on the cathode producing field emission.
- Feedback – A field emitted electron that reaches the anode will avalanche and produce additional G~10^5 positive ions.
- Absorption – σ, field emitted electrons passing through the film can recombine with positive ions on the film.
- The feedback and absorption parameters make an analytical solution difficult. Use a numerical solution.

Resistive Model Fitting

- Loop in small *dt* steps (0.2 sec).
  - Increment surface *Q* by
    - $+I_{55} * dt$ (source ionization current density)
    - $-I_{\rho} * dt$ (resistive leakage current density)
    - $+G\eta J_{FE} * dt$ (feedback)
    - $-\sigma I_{55} J_{FE} * dt$ (recombination).
  - Record R_1 (= 0.022 + $G\eta J/I_{55}$) vs *t*,
  - Loop over the duration of the measured data.
- Repeat for each measured ionization level.
- Fit all data to a common set of parameters

  $\rho, \varepsilon, \beta, \eta, \sigma$. (Next plot).

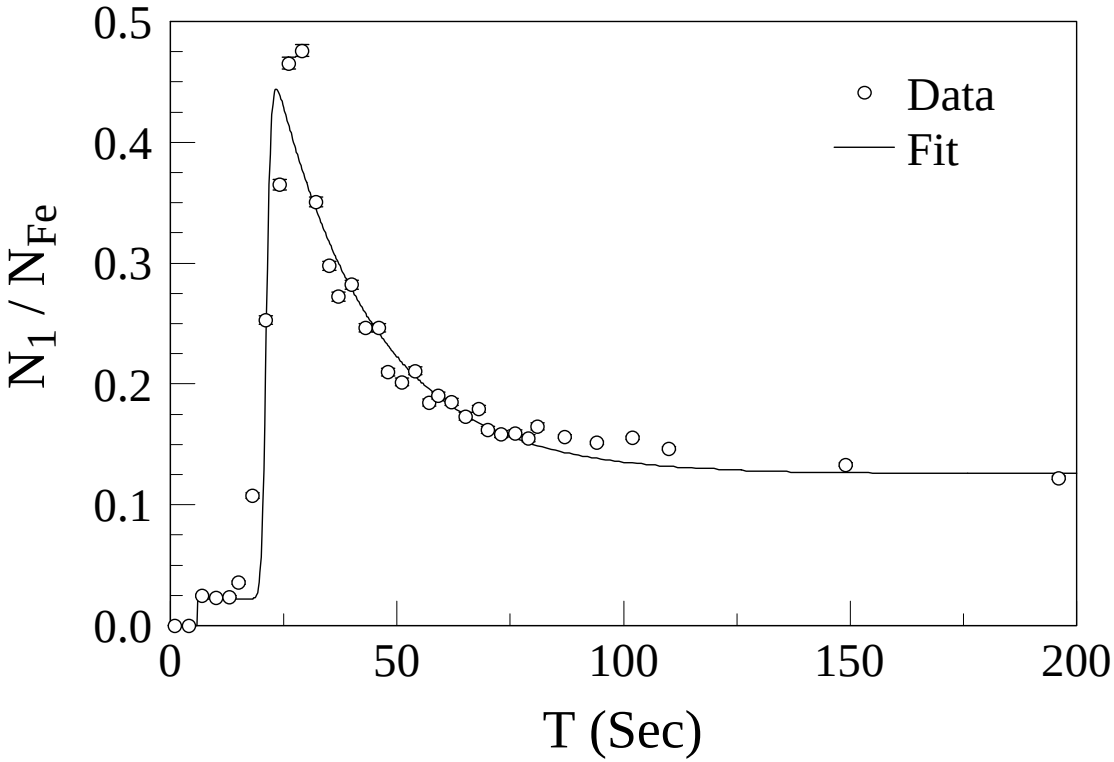
Resistive Model Fit For A Very Aged Cell.



Spike Modeling.

- Resistive model does not give a spike, i.e. rise and fall in *E*.
- Need a method that holds a burst of charge and bleeds it away slowly,
- Can do so by limiting discharge/passage of *J* current through film with second resistive parameter ρ_J for these electrons.
- As *E* increases and an *E* threshold is reached, there is a burst of electrons which then discharge slowly. This negative electron charge reduces the *E* field at the cathode surface, thus limiting further *J* production and settling to some equilibrium value eventually.

Spike Fit – Both ρ_I & ρ_J Model



Problem With Resistive Model

- Although the resistive model fits transient data for an aged chamber fairly well, it has a problem.
  - Model is not a function of film thickness.
  - It predicts that a new chamber ($d \approx 0$) should look like an aged one, which is incorrect.
- Need to add another discharge mechanism that removes charge only when the film is thin.
- Mobility of holes provides such a mechanism.
  - For thin films the transport time through the film is shorter than the resistive $\rho\varepsilon$ time constant, so mobility dominates in the discharge process.
  - For thick films, the transport time is longer than the resistive time, so the resistive mechanism dominates.

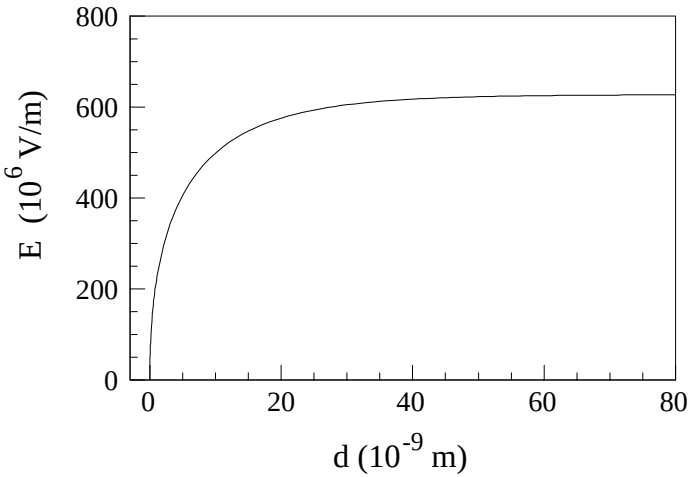
Resistivity + Mobility ($\rho\mu$) Model

- For field *E(x)* within the film material at depth *x,* and a current density *i(x)* flowing over time *dt* with velocity $v=\mu E$ (mobility constant μ), two coupled differential equations,
  - The increase in *E* due to *i* is $dE = idt/\varepsilon = -idx/(\varepsilon\mu E)$.
  - The resistive decrease in *i* is $di = -dE/\rho = idx/(\rho\varepsilon\mu E)$.
  - These can be solved to give *E(x)* as

$$E - \frac{E_0}{k} + \left(\frac{E_0}{k} + I\rho\right)\ln\left(1 - \frac{E - E_0/k}{I\rho}\right) = \frac{x-d}{\rho\varepsilon\mu}$$

- *I* is the external ionization current density hitting the film. Setting *x=0* gives the steady state E field on the wire.
- In this model *E* does depend on *d.*

$E(d)$ From $\rho\mu$ Model

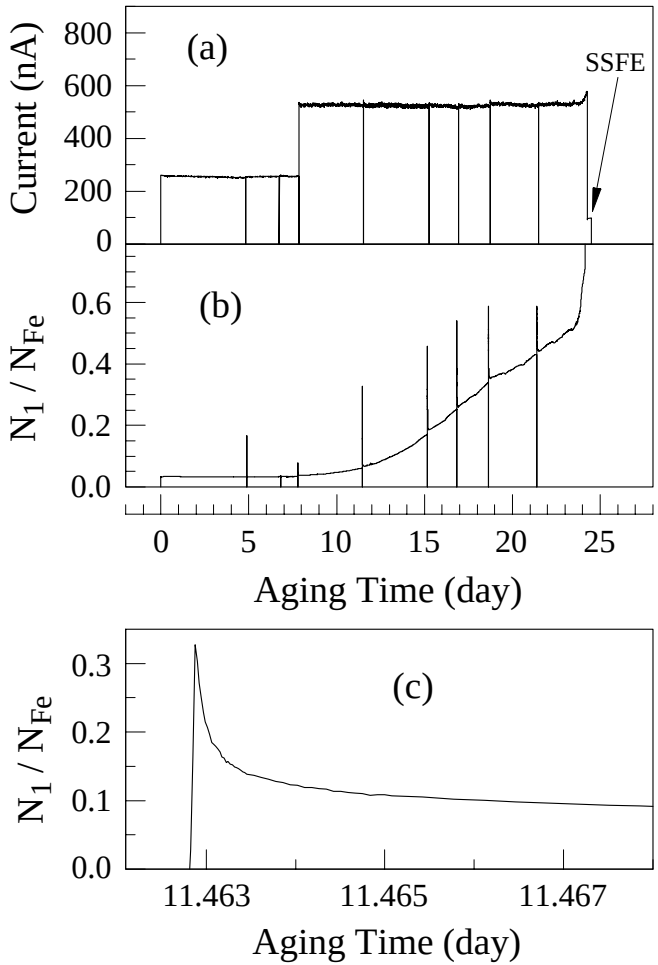


- The parameter values (ρ,ε,μ,I) used in the plot are shown later (from a fit).
- E reaches a plateau of 0.6×10^9V/m at large thickness values (βE is 1.2×10^9V/m, with $\beta=2$ in the fit)

- Need data over a wide range of d's to test this model.

Aging Data – From New to SSFE

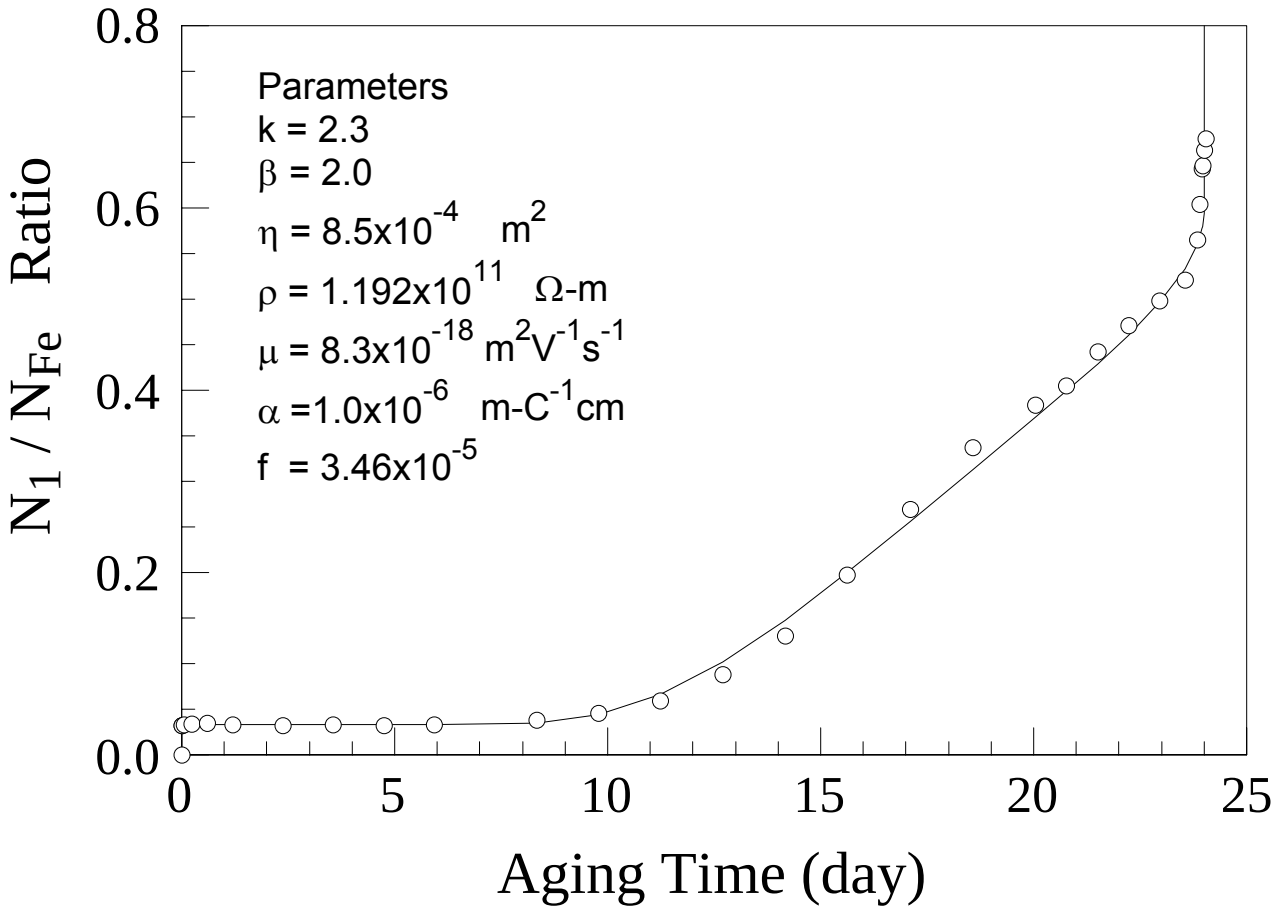
- Use a newly wired chamber.
- Run with a high source level.
- Monitor the current (a) and the single electrons (b).
- HV was increased in day 7.
- Pause periodically for checks, 1-e spike on restart (c).
- Self sustaining current in day 24 (Q_{SW}=70mC/cm).
- Single e^- seen much earlier, in day ~10 (Q_{SW}=20mC/cm) with rapid rise in day 24.



Fitting Parameters

- In addition to ρ, ε, β, η, σ, need
- α - relates d to the accumulated charge Q_{SW}, $d = \alpha Q_{SW}$
- f - *feedback*, fraction of +ions fed back from avalanches.
- The previous σ parameter was dropped (it didn't help).
- Total parameters are ε, ρ, β, η, μ, α, and f. Too many to fit, so fix some parameters.
  - Set $\varepsilon = 2.3\varepsilon_0$, the value for polyethylene.
  - Set $\beta = 2$, and $\alpha = 1.0 \times 10\text{-}6$ (1 μm for 1 C/cm^{-1} on SW).
- Do a *dt* stepping fit for remaining parameters, using the *E(d)* equation. Next plot.

Fit of $\rho\mu$ Model To Aging Data



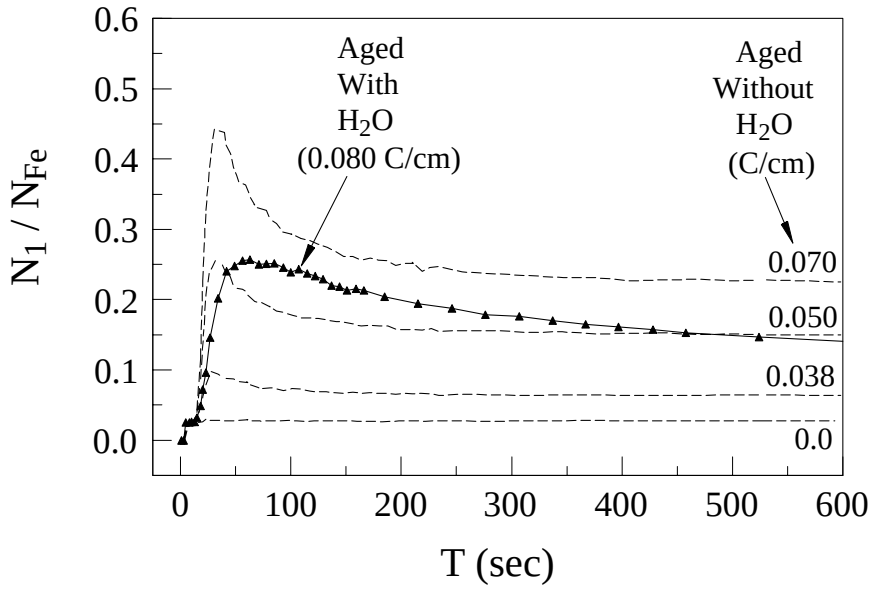
Aging With Water

- Does water prevent film growth?

- Measurement -
  - Start with newly wired chamber.
  - Age with water for a month at high ionization.
  - Dry it out thoroughly (flush for a month).
  - Compare with chamber aged for a month with no water. (plot)

Water & No-Water Comparison

- Spike height for “Aged with H_2O” is approx. the same as “Aged without H_2O” at half the accumulated charge.
- Suggests that H_2O does not prevent film growth, but maybe slows the rate down.



Summary

1. A water additive can keep a drift chamber alive at very high rates, but water does not prevent film growth.
2. Oxygen can clean cathodes and anodes.
3. The breakdown mechanism in chambers with no additives is due to high E-fields from charge accumulation in thin films on cathodes and Fowler-Nordheim field emission.
4. Cathode aging can be modeled.