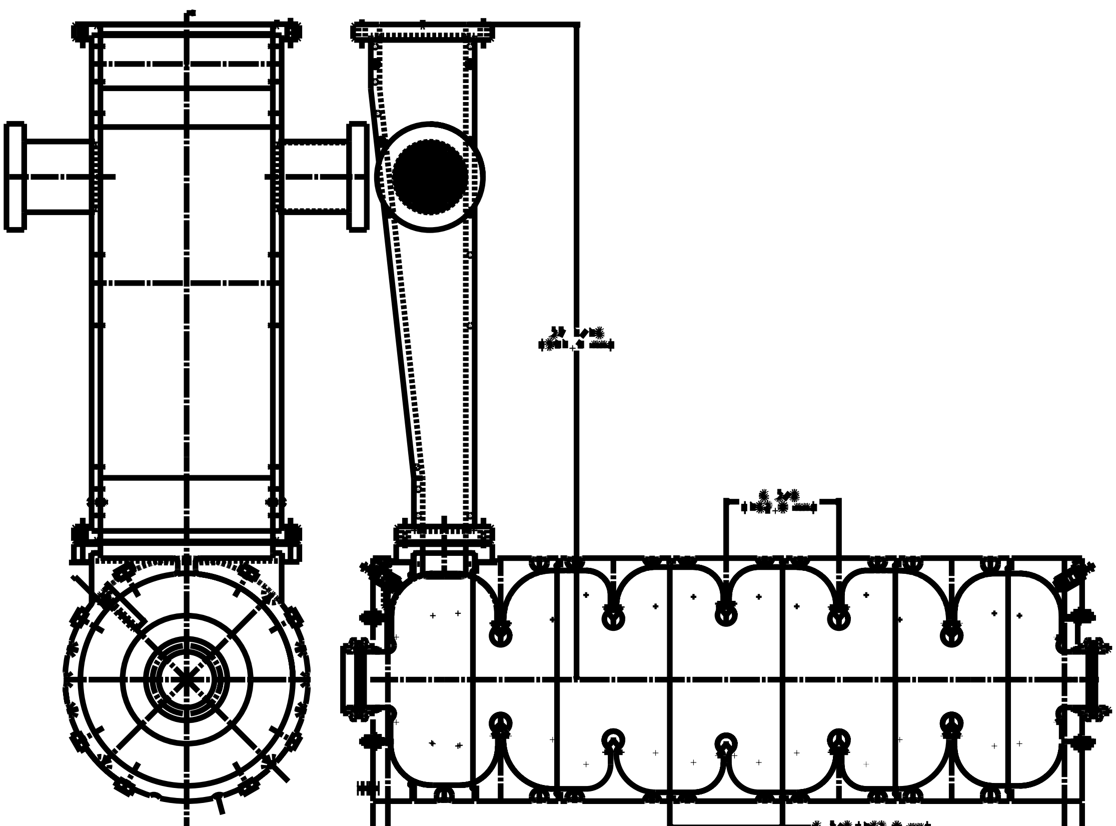
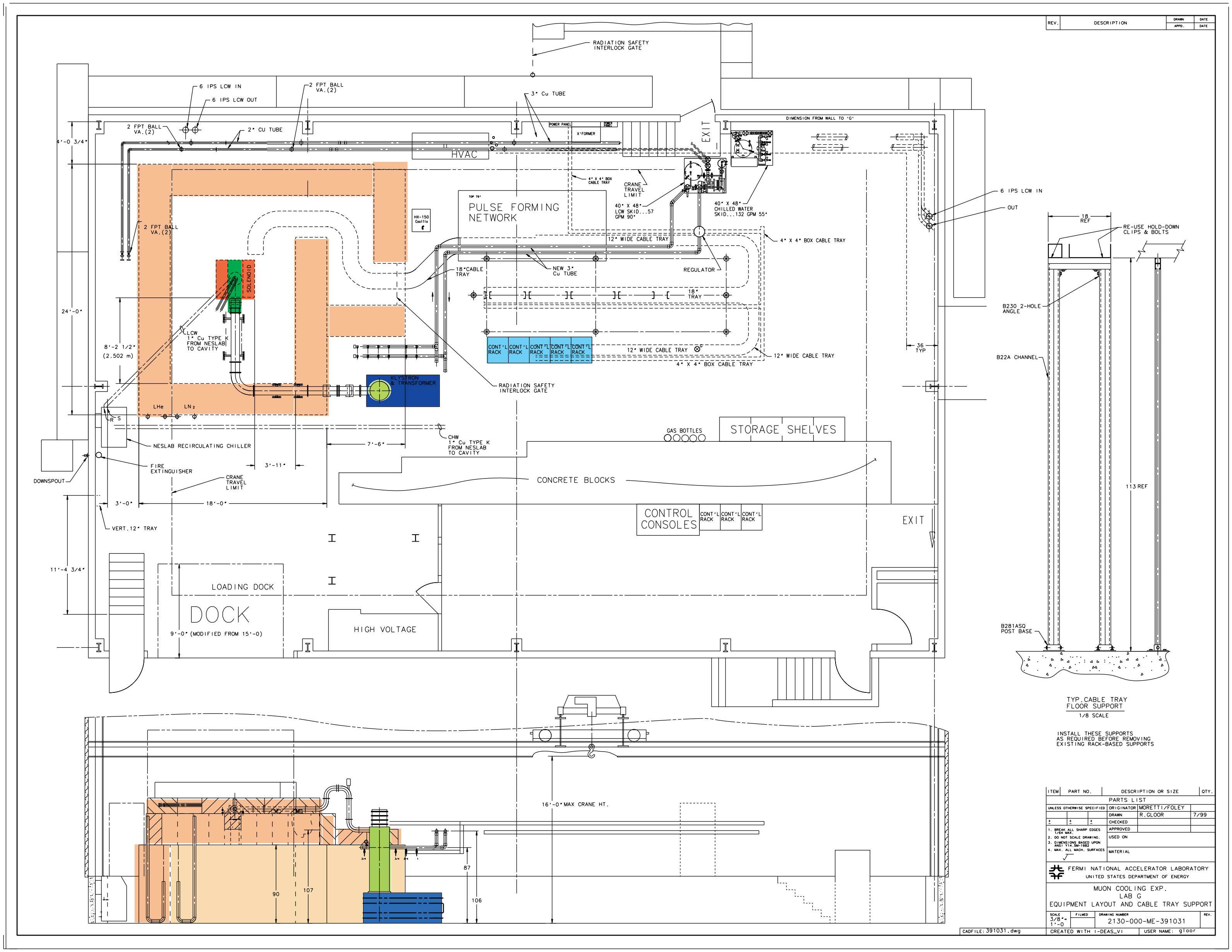
# Preliminary Lab G Dark Current Results

J. Norem ANL
S. Geer, A. Moretti, M. Popovic, Z. Qian, V. Wu  Fermilab
L. Ducas, D. Errede  U of IL.
N. Solomey, Y. Torun  IIT

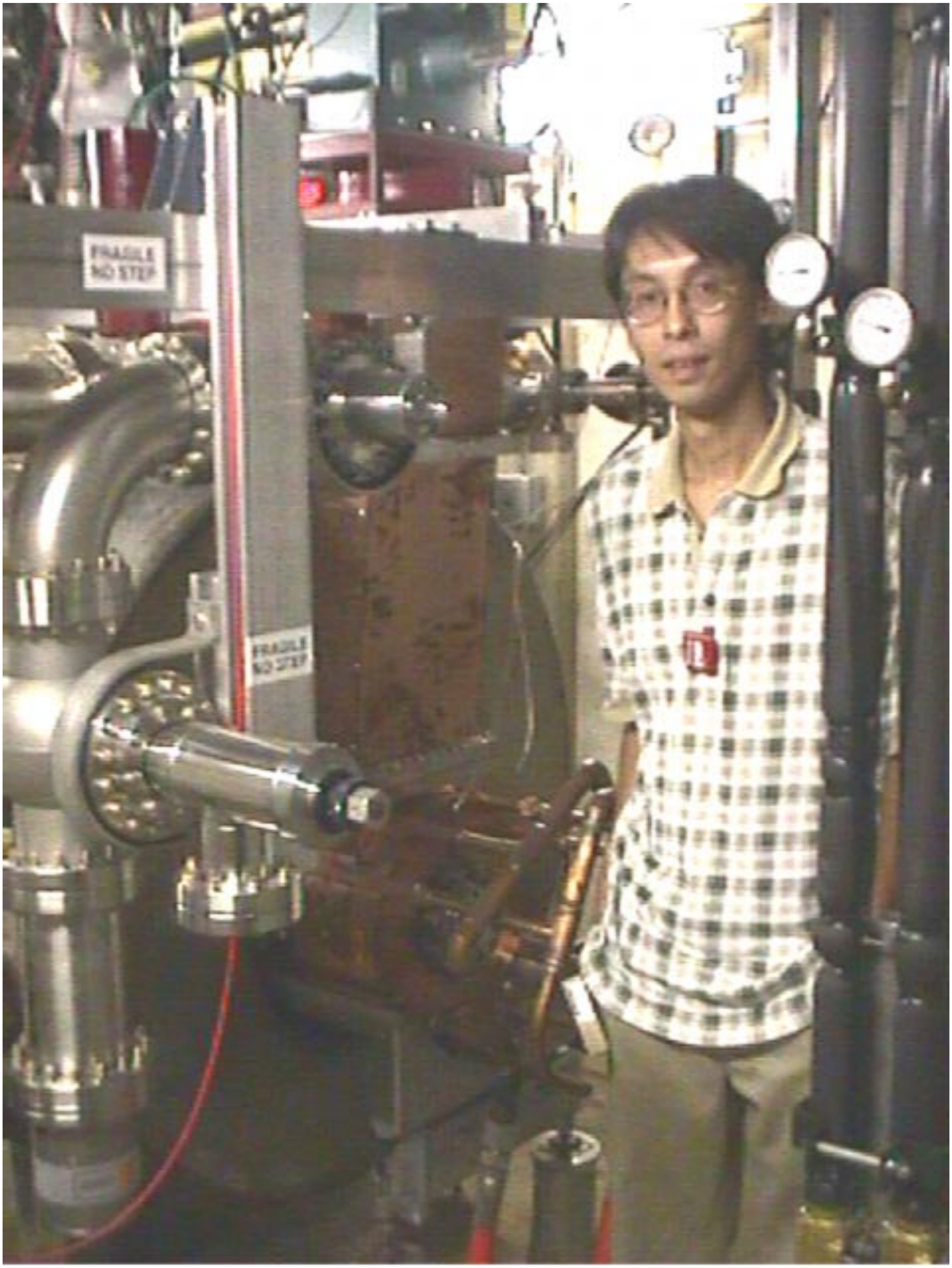
10/11/01

We are studying an open cell cavity which operates at 805 MHz.





RADIATION SAFETY INTERLOCK GATE
6 IPS LCW IN
6 IPS LCW OUT
2 FPT BALL VA.(2)
3" Cu TUBE
2 FPT BALL VA.(2)
2" CU TUBE
HVAC
POWER PANEL
X-FORMER
EXIT
DIMENSION FROM WALL TO "G"
4'-0 3/4"
2 FPT BALL VA.(2)
PULSE FORMING NETWORK
4" X 4" BOX CABLE TRAY
CRANE TRAVEL LIMIT
40" X 48" LCW SKID...57 GPM 90°
40" X 48" CHILLED WATER SKID...132 GPM 55°
6 IPS LCW IN
OUT
12" WIDE CABLE TRAY
4" X 4" BOX CABLE TRAY
SOLENOID
18"CABLE TRAY
NEW 3" Cu TUBE
REGULATOR
18" TRAY
24'-0"
LCW 1" Cu TYPE K FROM NESLAB TO CAVITY
8'-2 1/2" (2.502 m)
CONT'L RACK
CONT'L RACK
CONT'L RACK
CONT'L RACK
CONT'L RACK
12" WIDE CABLE TRAY
12" WIDE CABLE TRAY
4" X 4" BOX CABLE TRAY
36 TYP
KLYSTRON & TRANSFORMER
RADIATION SAFETY INTERLOCK GATE
LHe
LN2
NESLAB RECIRCULATING CHILLER
7'-6"
CHW 1" Cu TYPE K FROM NESLAB TO CAVITY
GAS BOTTLES
STORAGE SHELVES
DOWNSPOUT
FIRE EXTINGUISHER
3'-11"
CRANE TRAVEL LIMIT
CONCRETE BLOCKS
3'-0"
18'-0"
VERT. 12" TRAY
CONTROL CONSOLES
CONT'L RACK
CONT'L RACK
CONT'L RACK
EXIT
11'-4 3/4"
LOADING DOCK
DOCK
9'-0" (MODIFIED FROM 15'-0)
HIGH VOLTAGE
16'-0" MAX CRANE HT.
90
107
87
106
18 REF
RE-USE HOLD-DOWN CLIPS & BOLTS
B230 2-HOLE ANGLE
B22A CHANNEL
113 REF
B281ASQ POST BASE
TYP. CABLE TRAY FLOOR SUPPORT
1/8 SCALE
INSTALL THESE SUPPORTS AS REQUIRED BEFORE REMOVING EXISTING RACK-BASED SUPPORTS
REV. DESCRIPTION DRAWN DATE APPD. DATE
ITEM PART NO. DESCRIPTION OR SIZE QTY.
PARTS LIST
UNLESS OTHERWISE SPECIFIED
ORIGINATOR MORETTI/FOLEY
DRAWN R.GLOOR 7/99
CHECKED
APPROVED
USED ON
MATERIAL
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
MUON COOLING EXP.
LAB G
EQUIPMENT LAYOUT AND CABLE TRAY SUPPORT
SCALE 3/8"=1'-0
2130-000-ME-391031
CADFILE: 391031.dwg
CREATED WITH I-DEAS_VI
USER NAME: gloor


FRAGILE
NO STEP
FRAGILE
NO STEP

Measurements use a variety of traditional instrumentation to look at dark currents and X rays.

Beam Transformer

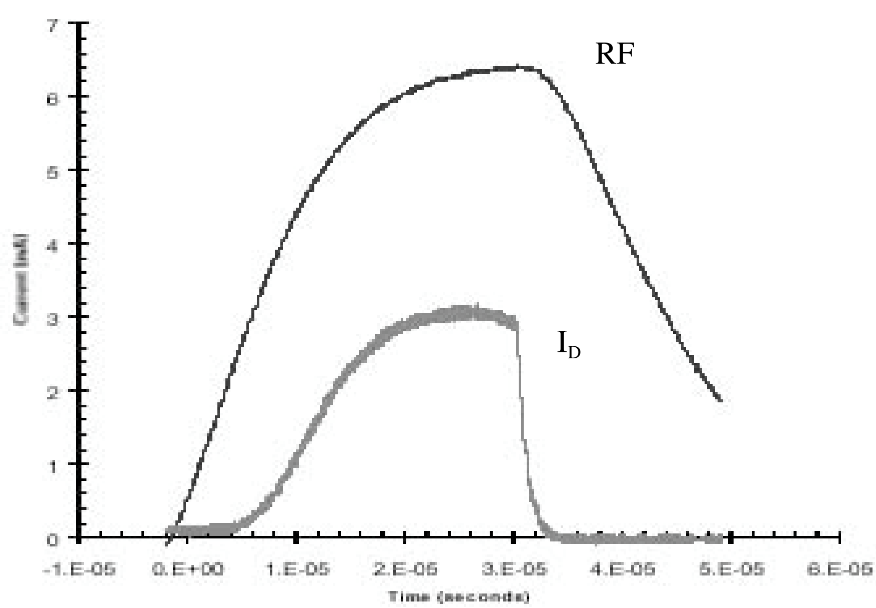
Thermoluminescent detectors

Scintillator / Photomultiplier tubes

Polaroid sheet film

A permanent magnet spectrometer

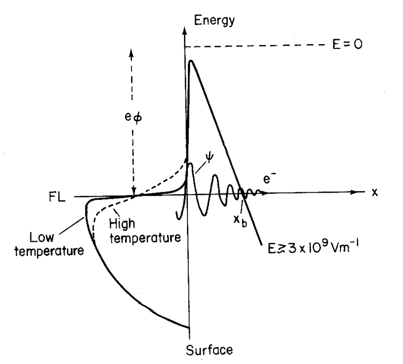
At low power, the pulse is triangular, rising until the rf shuts off.  With longer pulses, or higher powers the current seems to saturate.  This rf pulse was longer than usual.



The performance of rf cavities at high power is determined primarily by field emission from cavity surfaces. This field emission creates currents which:

- Produce x-ray doses which limit the accelerating field
- produce backgrounds for our $\mu$ cooling exp.

The currents seem to be generated by **Fowler-Nordheim field emission** from localized sources on the cavity surface. These currents are the result of tunneling thru the surface potential with the help of an external field. The picture is,



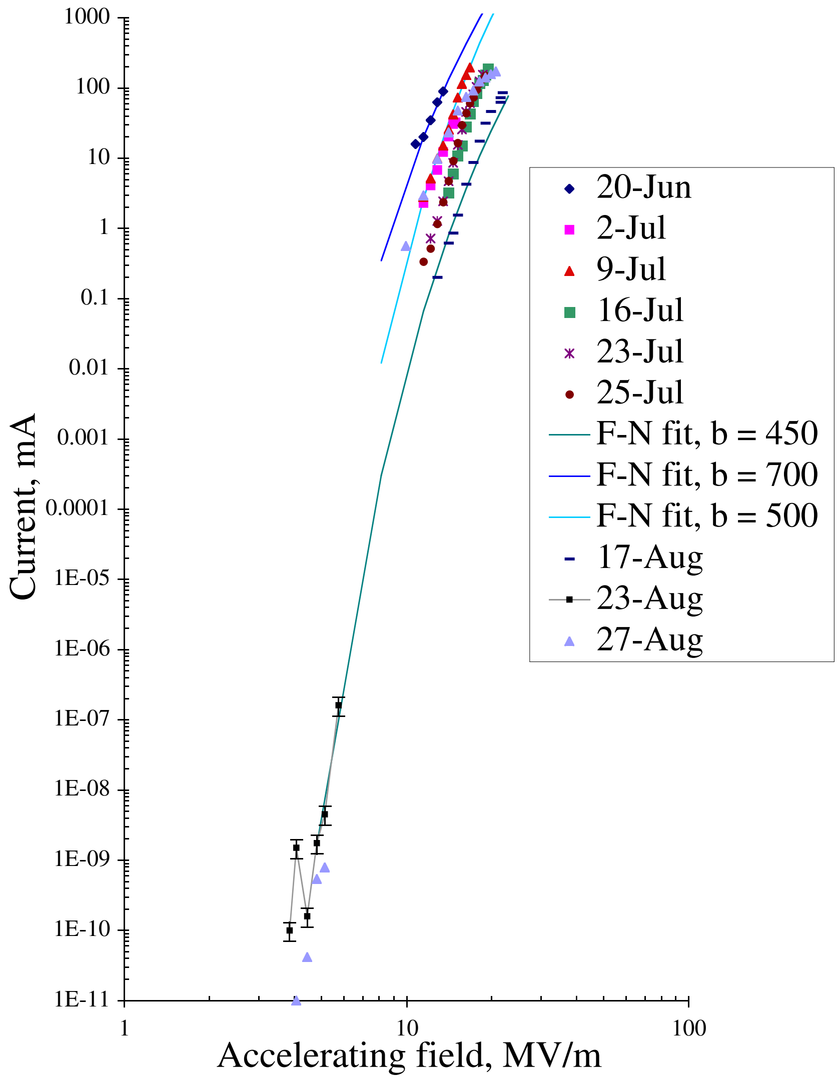

The equation that describes this is,

$$I(E) = \frac{A_{FN} A_e (\beta_{FN} E)^2}{\phi} \exp\left( \frac{B_{FN} \phi^{3/2}}{\beta_{FN} E} \right)$$

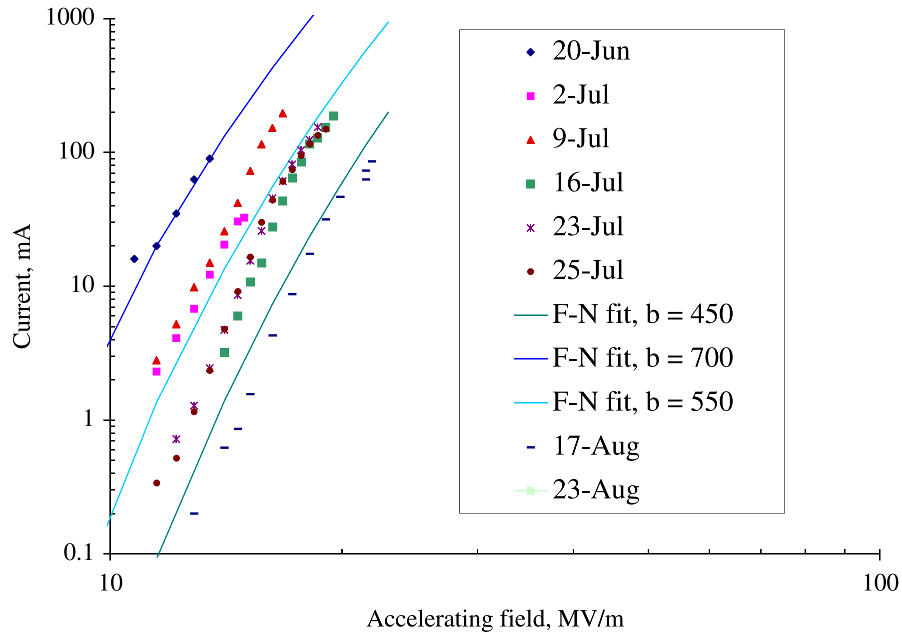
where $A_{FN}$ and $B_{FN}$ are constants, $A_e$ is the emitting area, $E$ is the electric field, $\phi$ is the work function of the material and $\beta$ is the field enhancement factor.

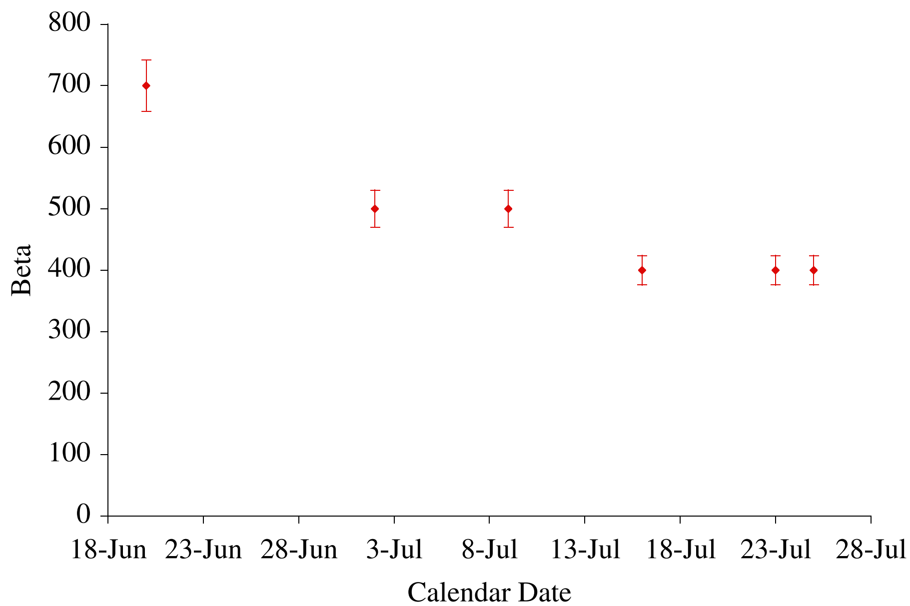
## Lab G Results

- The emission we see follows a Fowler-Nordheim curve over many orders of magnitude - but with large $\beta$.
- Our data shows no evidence of plasma enhanced emission, but this process may occur during breakdown
- We may be seeing the Child-Langmuir limit.

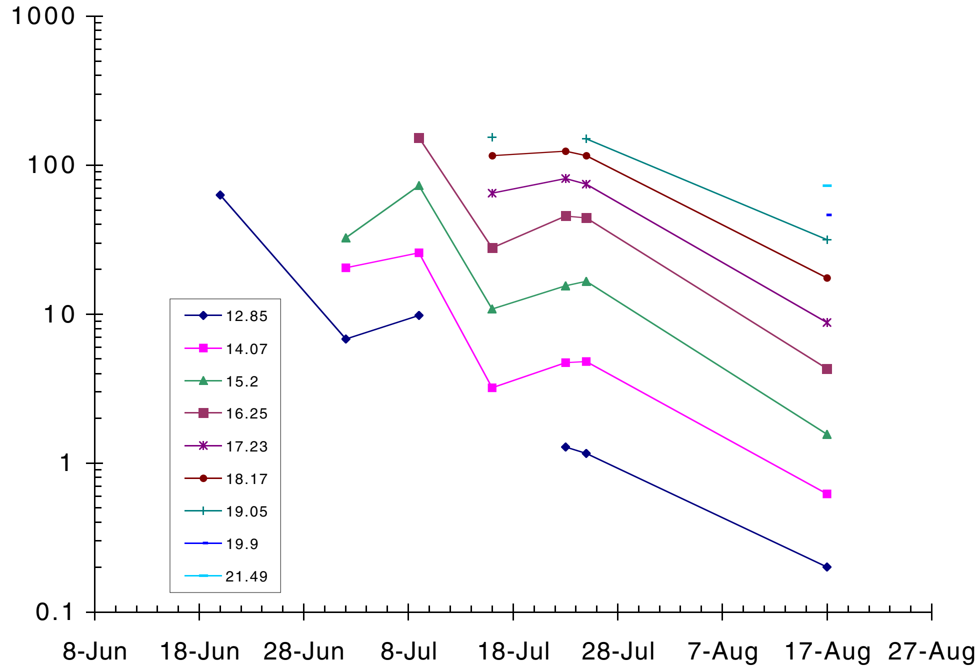


We see conditioning, in the form of reduced values of $\beta$ with time.



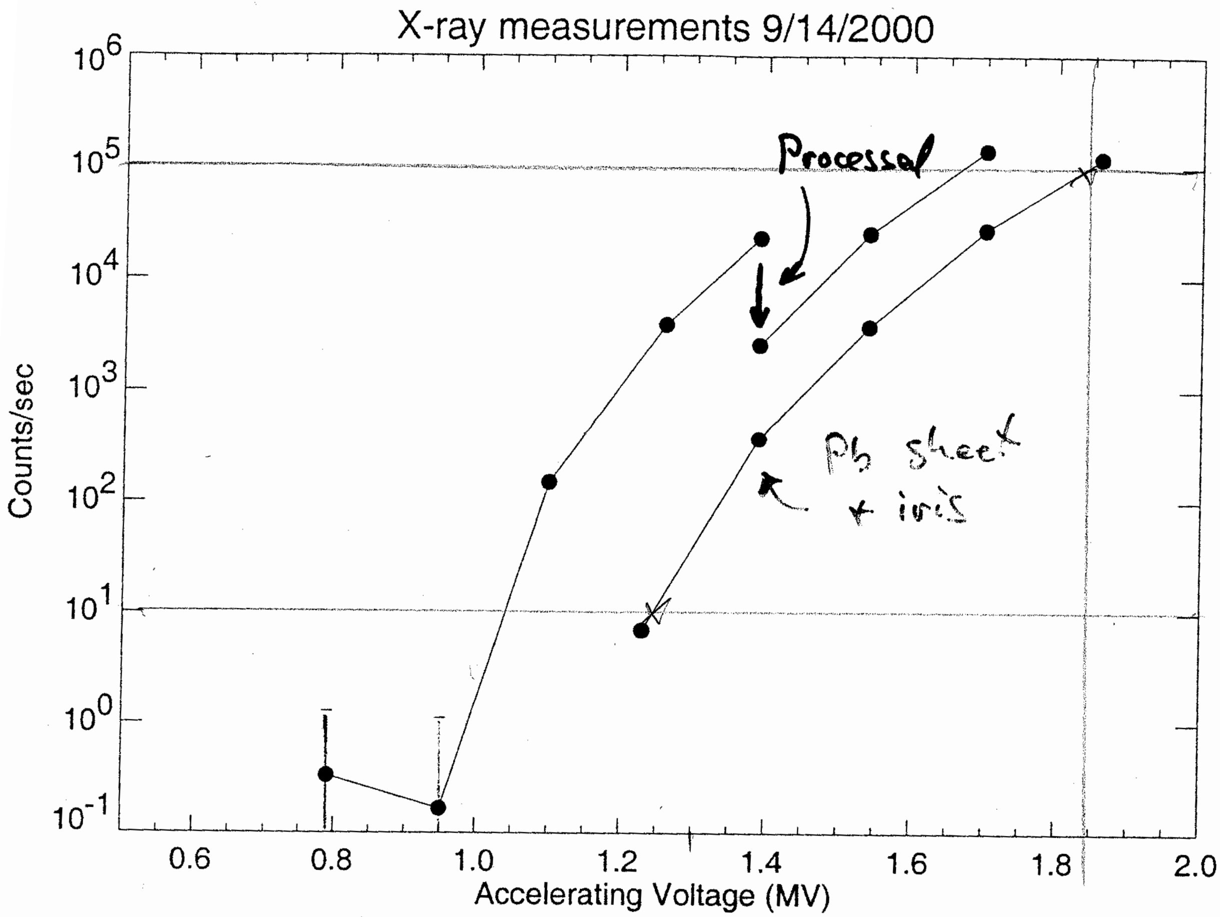



The conditioning did not proceed in a linear manner, and when the coil was turned on the conditioning had to be started again.

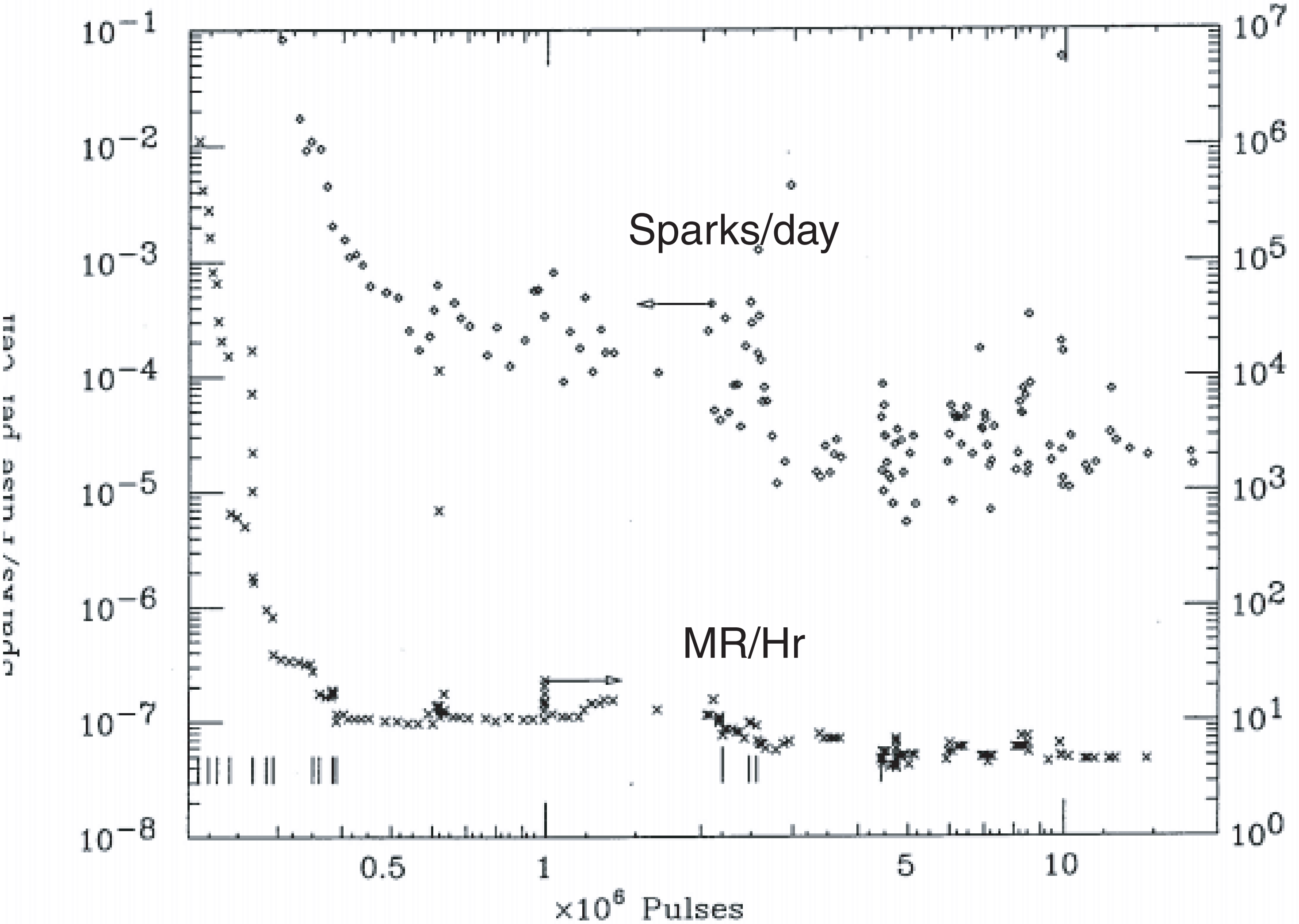


S. Henderson made measurements at Cornell on an rf cavity which show a threshold electric field and a rate that goes like $E^{25}$. This is consistant with what we see at threshold.

Raw Count Rate

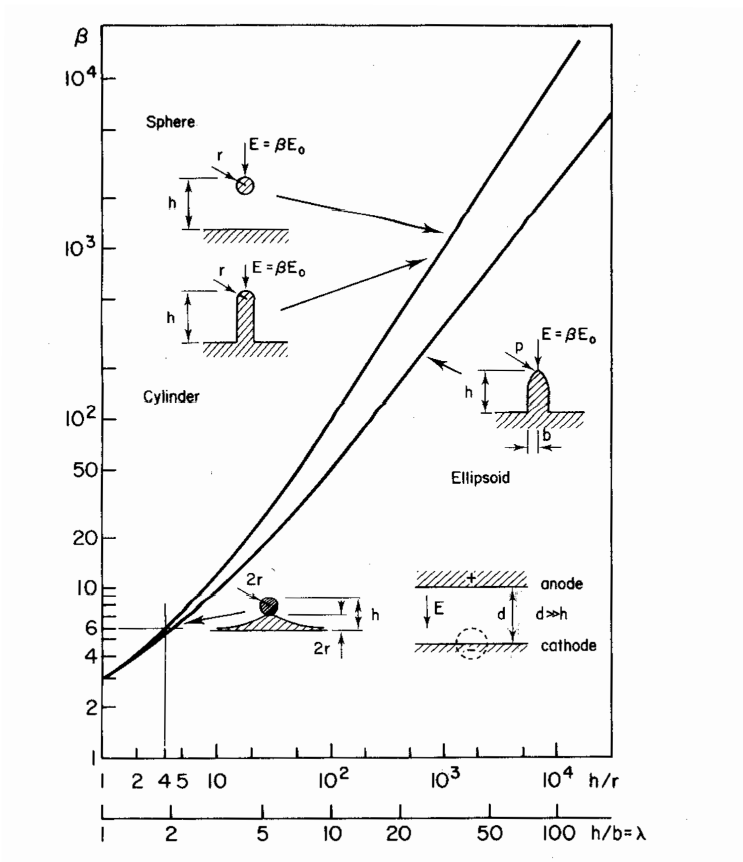


Prototype R-4



The very high $\beta$ values – in the range of 400 – 600, are seen by others. But the $\beta$ values should not be this large.

- If "hairs" of some sort produce this amplification of the field, these hairs would have to be ~ 100 times longer than their diameter, which would be highly unphysical and easily destroyed. A variety of other shapes (ridges, sharp points, cones) may be more physical.




- Inclusions or other surface perturbations would also change the average $\beta$ values.

The very low current data was obtained by counting electrons in a given time. Typical traces are shown.

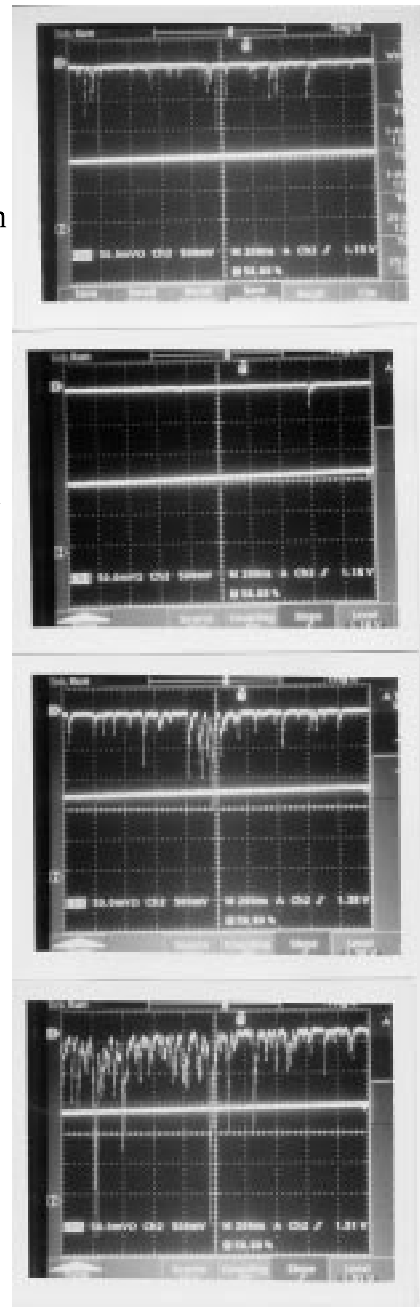
Counting Individual Electrons
in 2 microseconds

0.5 MW
4.06 MV/m
~1.5 pA

0.6 MW
4.45 MV/m
~0.16 pA

0.7 MW
4.81 MV/m
~1.6 pA

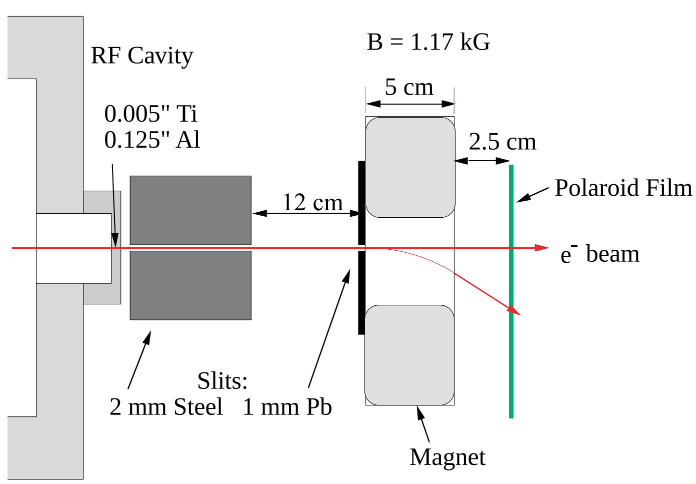
0.8 MW
5.14 MV/m
~4.5 pA

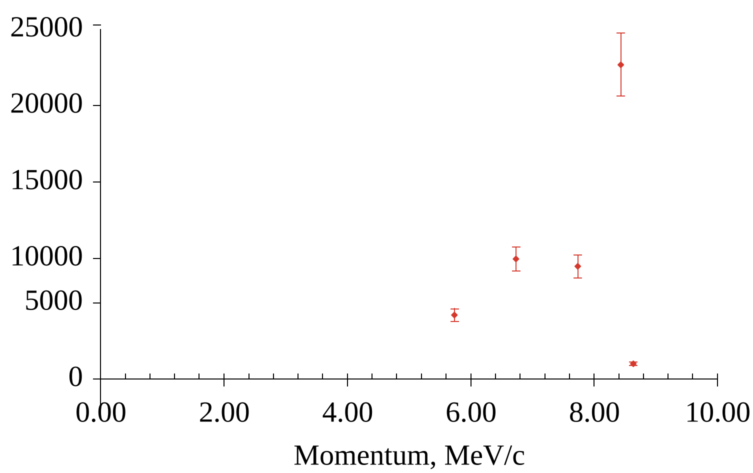


The low power “blip” at 0.5 MW was real on one day but did not reappear on the next.

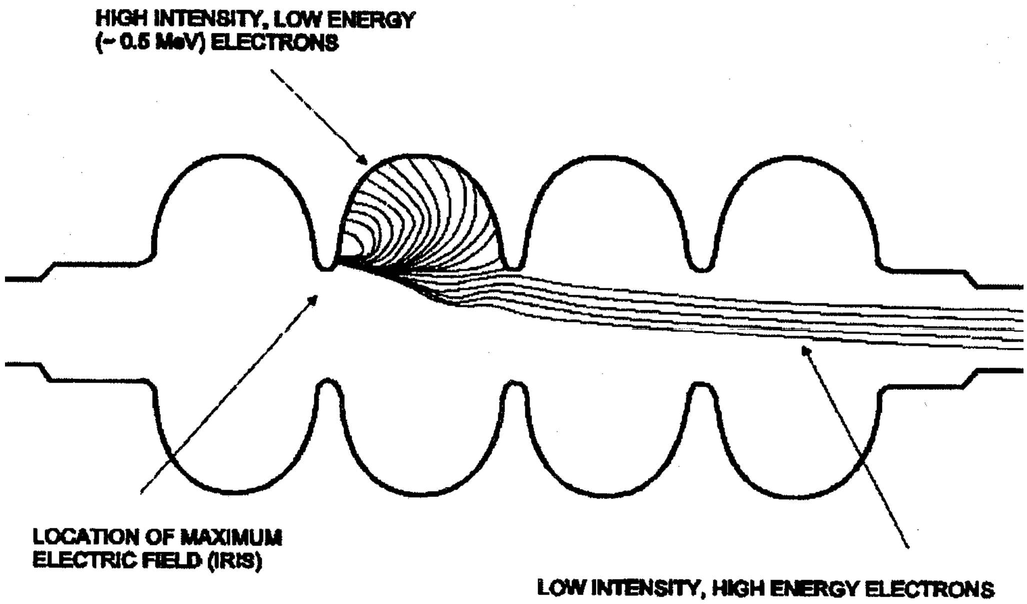
A magnetic spectrometer was used to measure the momentum of the electrons. The maximum momentum measured was 60% of the *El*, where a calculation gives the result of 59.9%. This implies that a significant fraction of the beam traverses the whole length of the cavity.

Small Gap, Permanent Magnet Dipole

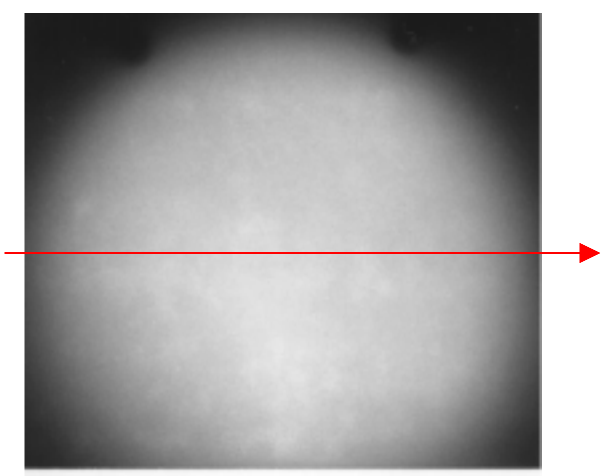


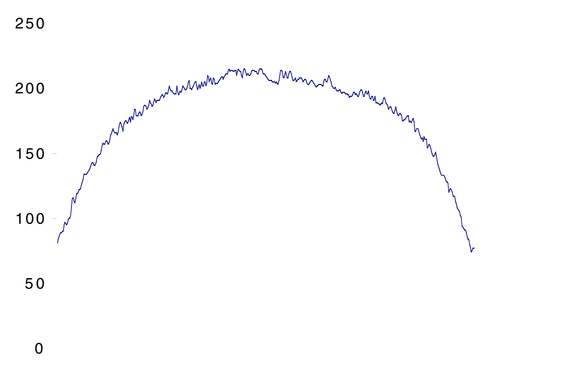



The transmission of dark currents in rf cavities has been calculated for the case with no applied magnetic field.

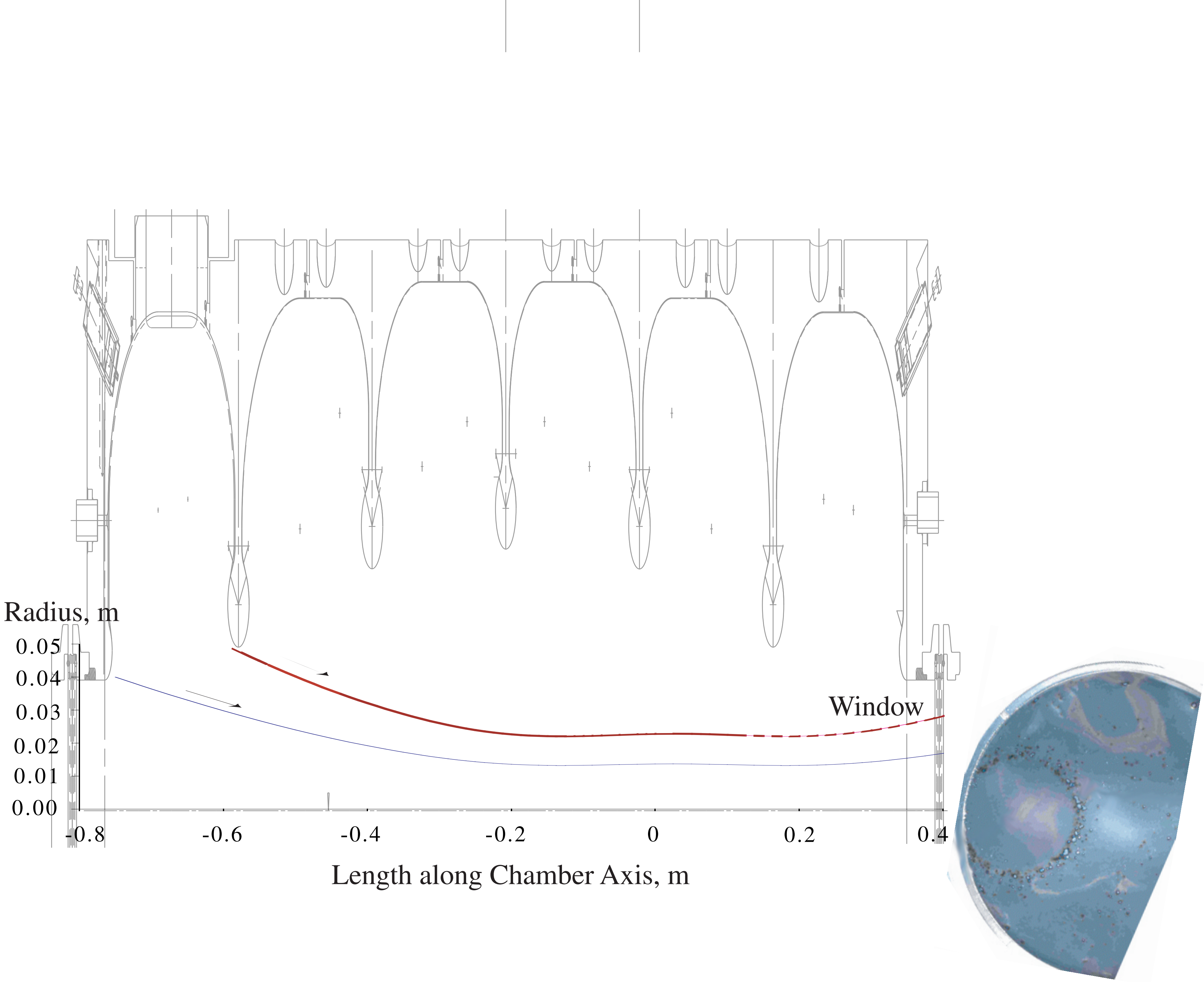



We see a smooth distribution






The power in the beam was sufficient to melt the plastic cover of the window.


Radius, m
0.05
0.04
0.03
0.02
0.01
0.00
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
Length along Chamber Axis, m
Window

We are not done yet. There are a number of continuing problems which we are trying to nail down.

# What Can We Do About Dark Currents?

J. Norem
Argonne

CERN Muon Experiment Workshop
10/22/01

Field emission is the problem.

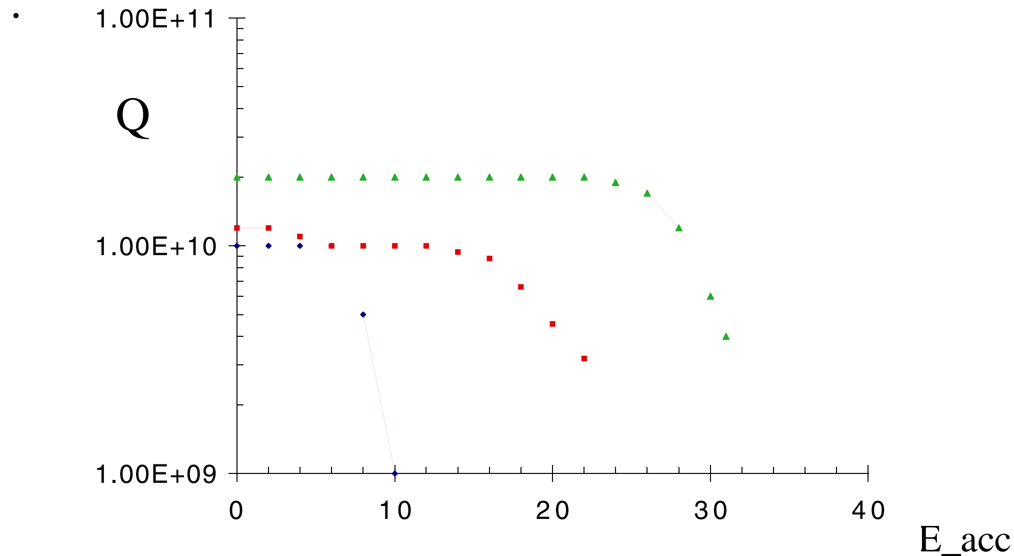
- We seem to get emission at much lower voltages than we should. We have enhancement factors, $\beta_{FN}$ ~ 500.

- This must be due in part to the rough interior of our chamber. (The interior of the Ti window was like #100 sandpaper.)

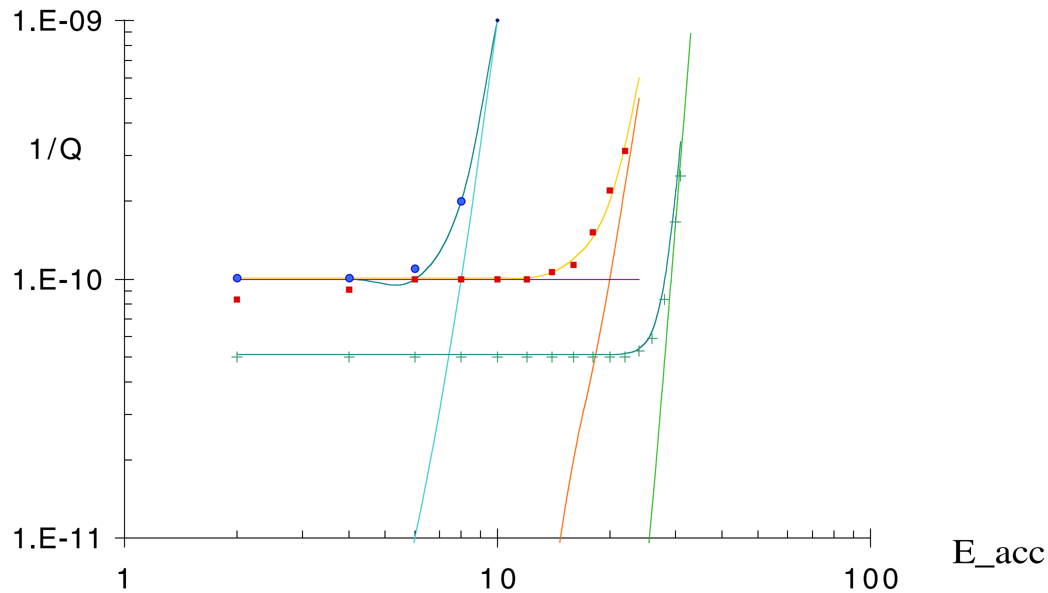
- We can't operate with these conditions, and we need to be able to get stable surfaces that can tolerate voltage.

- There is a lot of work, and a lot of progress, with SCRF in suppressing dark currents.

The behavior of superconducting cavities is also limited by field emission. This causes losses that are accompanied by measured dark currents and x rays. They plot Q vs $E_{acc}$.

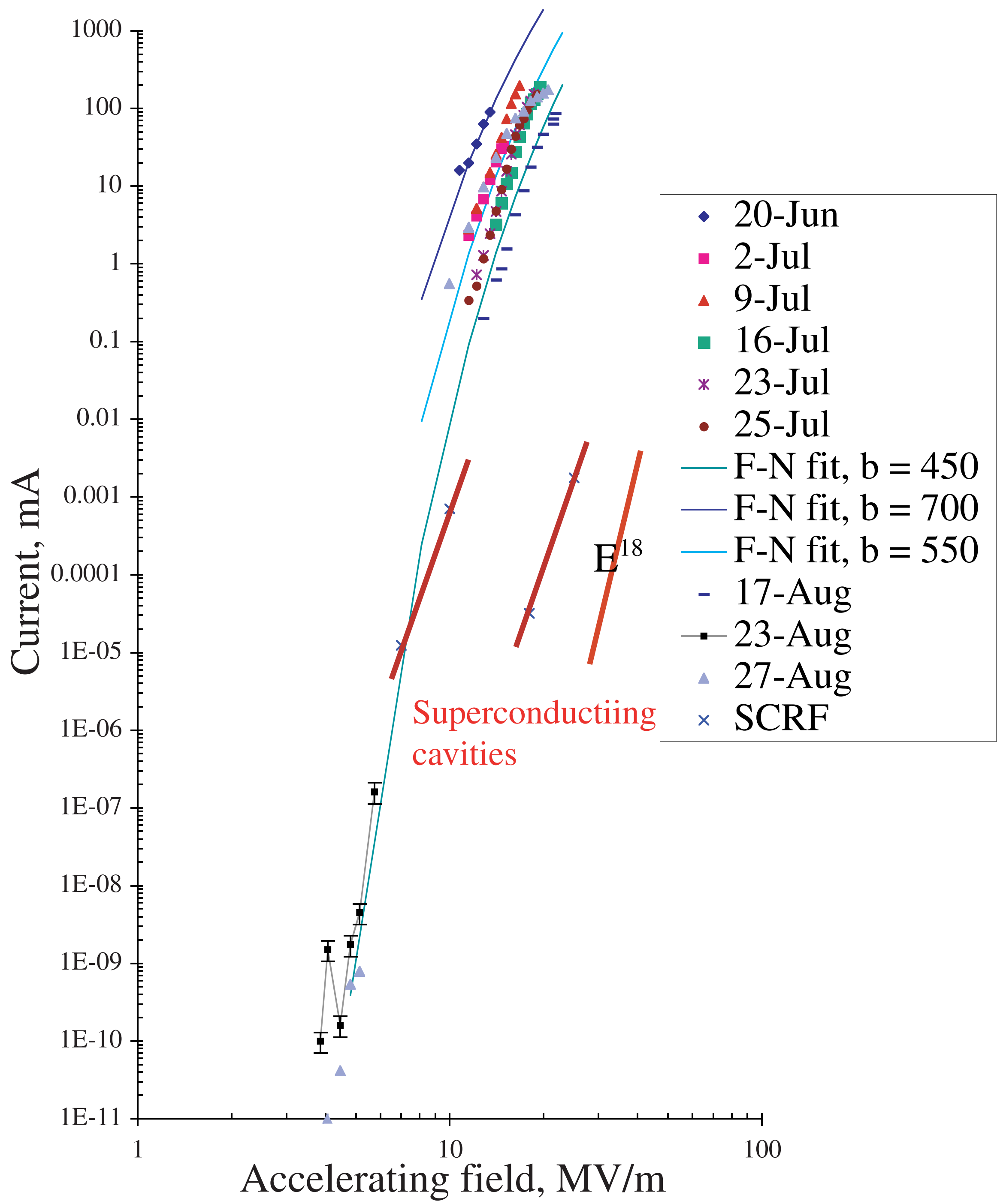



It is more useful to look at 1/Q, on a log log plot, then see what the loss terms look like. The results follow Fowler-Nordheim.




Low field: Padamsee, Knobloch, Hayes, Fig 12.1
High field: TESLA Design, Pt II, Fig 2.1.5

The SCRF currents compare with what we see in Lab G.



The accelerating field we can use is probably determined by the maximum tolerable local heating generated by the accelerated dark current hitting the cavity walls.

The dimensions of the beam are determined by both collective effects in the beam and electromagnetic fields in the cavity.

A rough estimate of the minimum possible beam radius can be obtained from Childs law, $i = 2.33 \times 10^{-6} V^{3/2} d^2$, where *I, V*, and *d* are the current density, Voltage and electrode spacing (cell length), [V, A, cm]. This gives $r = \sqrt{I / 2.33 \times 10^{-6} \pi V^{3/2} d^2} = 4\mu \sqrt{I[A]}$.

In addition, space charge will further blow up the beam in the few cm before it becomes relativistic. The beam optics is worked out in references (Humphries, Charged Particle Beams Wiley 1990), but is not simple.

$E_{rf}$ and $B_{rf}$ will also perturb the orbits. $B_{rf} \sim 0.7T\ r_{[m]}$.

Wall heating can be determined from the power density, $P = E_e I_e / Ar$, where the $E_e$, $I_e$, $A$ and $r$ are the electron energy, current, area and electron range.

The emission from the surface seems to be affected by

**Roughness**

Evidently the smoothest is the best

Electropolishing gives the best surface

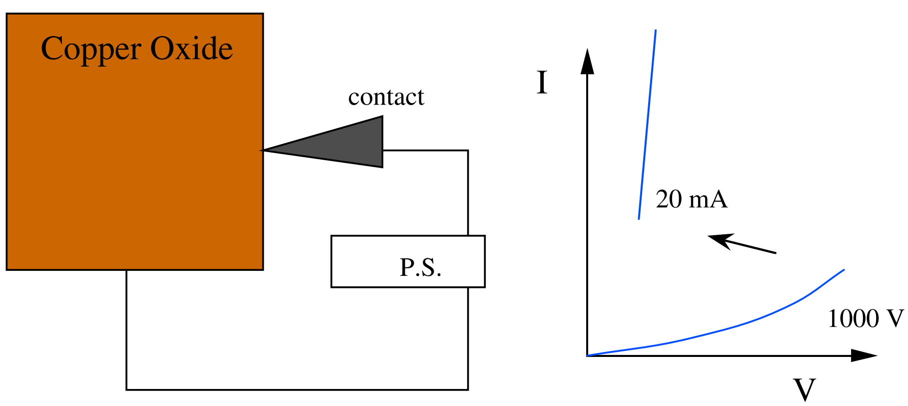
Magnetorheological fluids?

**Structure**

Oxide layers can be either conducting or insulating

Dearnaley et al Rep.Prog Phys.**33** (1970) 1129

Cook,, J. App. Phys.  41 (1970) 551

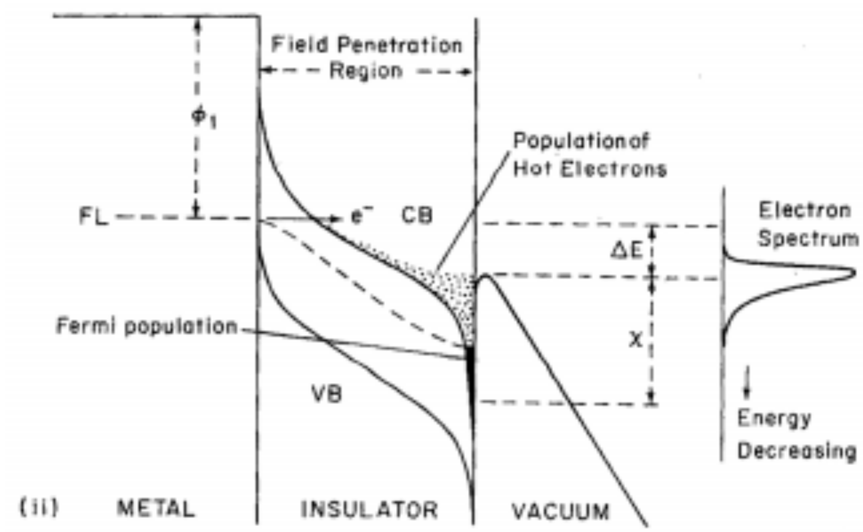



There are two resistive states here, consistent with copper filaments forming in a  surface layer.

more on oxides . . .

An insulating layer modifies the electric potential and the electron emission.

The picture becomes. . .

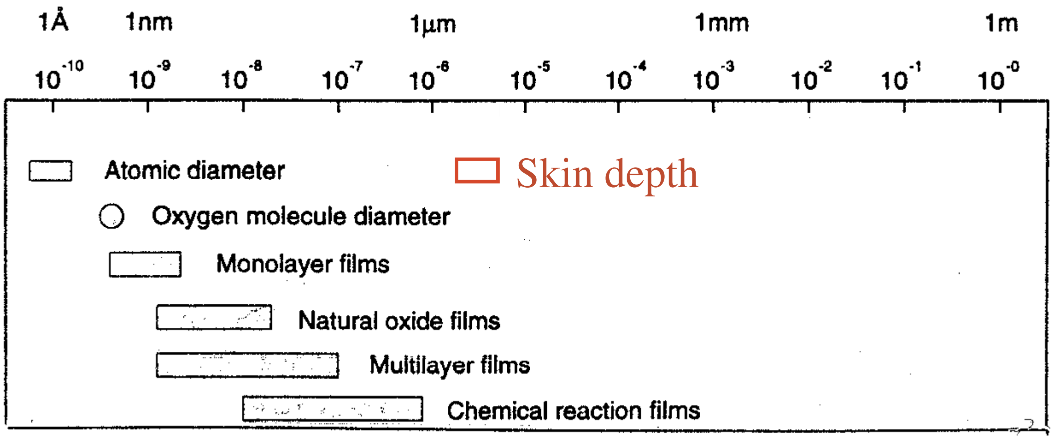


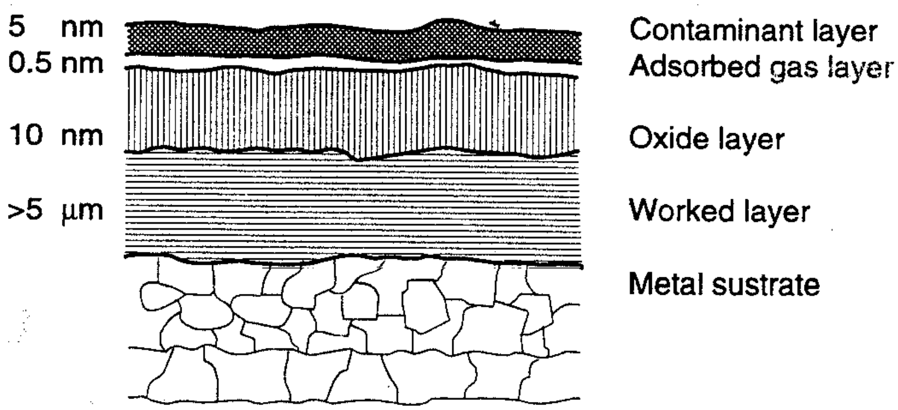

and the electrons are emitted out of the conduction band of the dielectric. The *I* vs *E* emission law is the similar, but the constants have different meanings. This process (the Richardson-Dushman law) would explain large area emission – however we seem to see local emission.

There is an extensive literature on “forming”, the process by which oxide layers can develop conducting filaments when exposed to high gradients. This is process seems to involve high temperatures and atomic motions and may be similar to reversible resistance switching in amorphous semiconductors.

## Adsorbed gases , Oxides, etc

The skin depth is thicker than most of these layers.



## Candidate coating materials

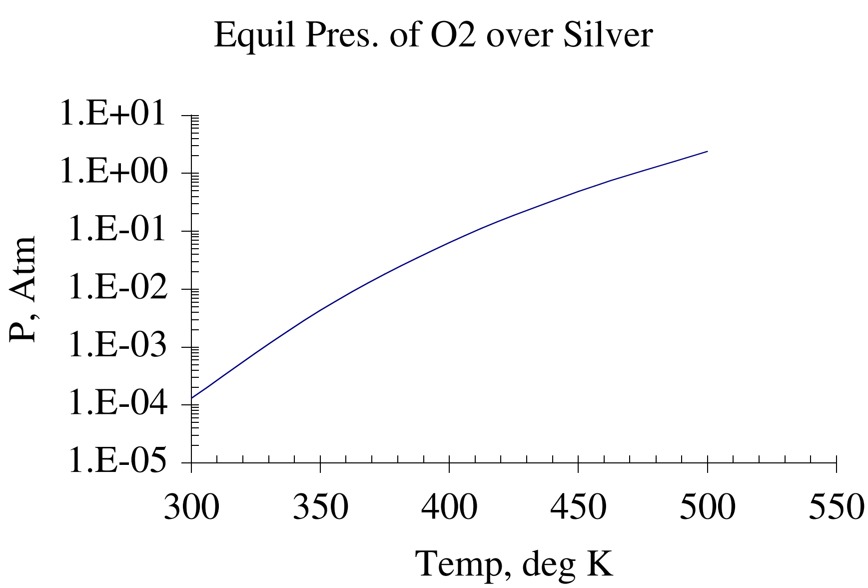
| | |
|---|---|
| Ti | Should be smooth and pump gasses |
| TiN | Lowers secondary emission coefficient |
| $CaF_2$ | Shown to lower dark current |
| Cu | Need a smooth, clean coating |
| Ag | Smooth, good elect. and therm. properties. |
| Au | No oxide, otherwise like silver |
| diamond | Best insulator?  Bad secondary emission |

## Coating methods

- Sublimation is probably the simplest, but works over line of sight.
- Precipitation from solutions requires a cavity geometry that can be drained when the process is finished.
- Sputtering, CVD etc. require somewhat more effort.
- Electrodeposition

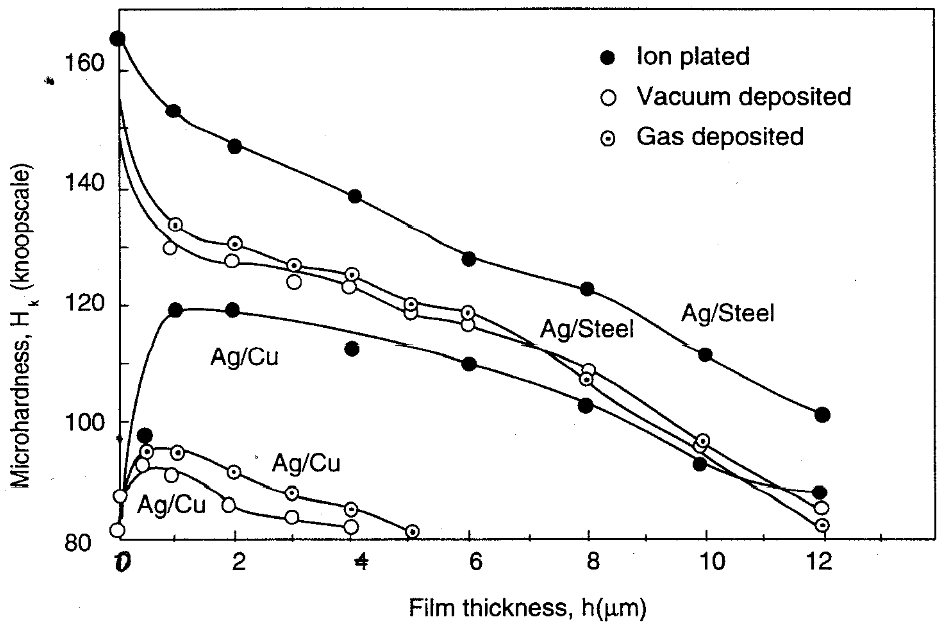
It is interesting to look at Gold and Silver

| Metal | MP, K | BP, K | oxide stability, delG/O @ 298K+ |
|---|---|---|---|
| | Readily reduced by H2 at RT, sorted by ease of reduction | | |
| Au | 1338 | 3130 | oxide unstable |
| Pd | 1825 | 3237 | oxide unstable |
| Rh | 2236 | 3970 | oxide unstable |
| Pt | 2045 | 4100 | oxide unstable |
| Ir | 2716 | 4701 | oxide unstable |
| Os | 3300 | 5285 | oxide unstable |
| Ag | 1234 | 2436 | -2.697 |
| Ru | 2523 | 4423 | -30.197 |
| Cu | 1358 | 2836 | -30.570 |
| Bi | 545 | 1837 | -39.317 |
| Pb | 600 | 2023 | -45.157 |
| Re | 3453 | 5869 | -46.747 |
| Sb | 904 | 1860 | -49.921 |




Gold and silver can be made without an oxide layer, but still retain a thermal and electrical conductivey comparable to copper.

The way a coating is done seems to make a difference.



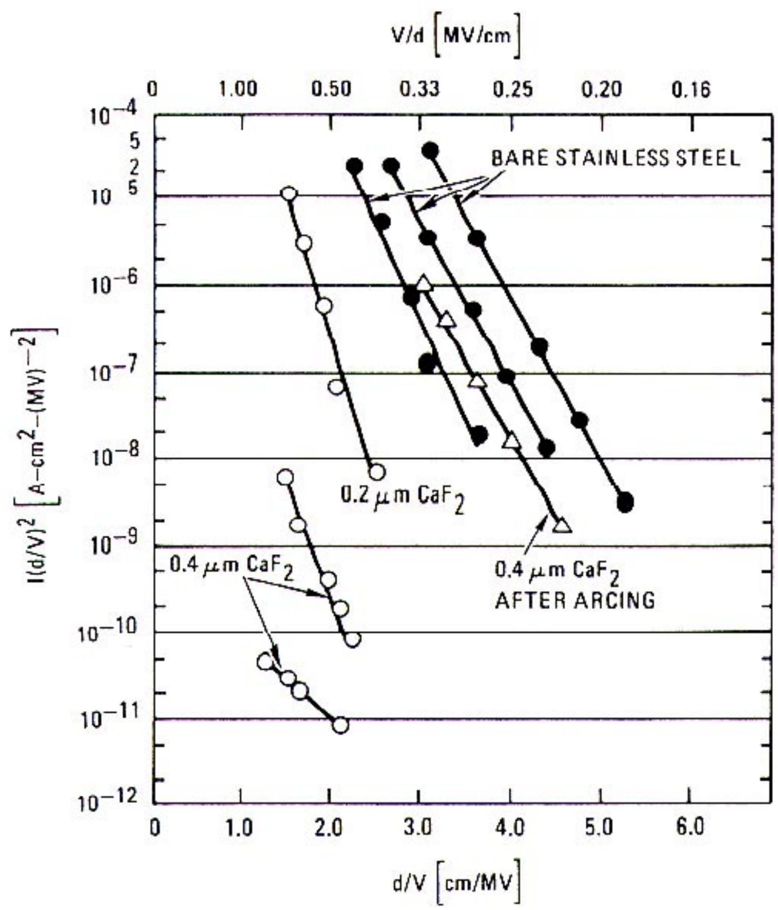

*Microhardness of silver coatings as a function of film thickness deposited by three different techniques on steel and copper (data from El-Sherbiny and Salem, 1986).*

Useful references:

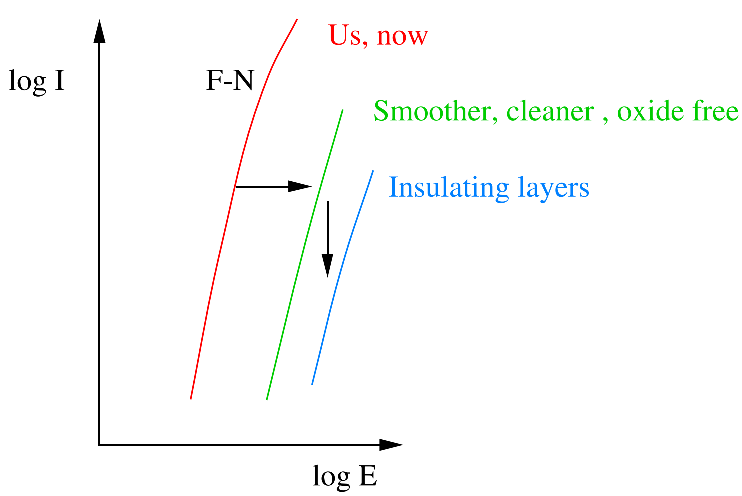
Holmberg and Matthews *Coatings Tribology*, Elsevier,'94

Bhushan, *Handbook of Tribology*, McGraw, Hill, '91

Insulating coatings may work too, even better if things are clean.




Can we expect this?



## Summary

- The gross features of dark current emission are very poorly understood.

- Experiments that attempted to control the surface have evidently never been done systematically with copper, but corresponding experiments with SCRF have been highly successful

- In-situ coatings should be simple, cheap and effective.

- We could expect many orders of magnitude reduction in dark currents and significant improvements in operating field if this technology works. (If cleaning and insulating coatings are used, are the effects additive, multiplicative or neither? )

- This technology is applicable to NLC and other linac structures.