The RF background issue: a new model + heat

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MICE COLLABORATION MEETING
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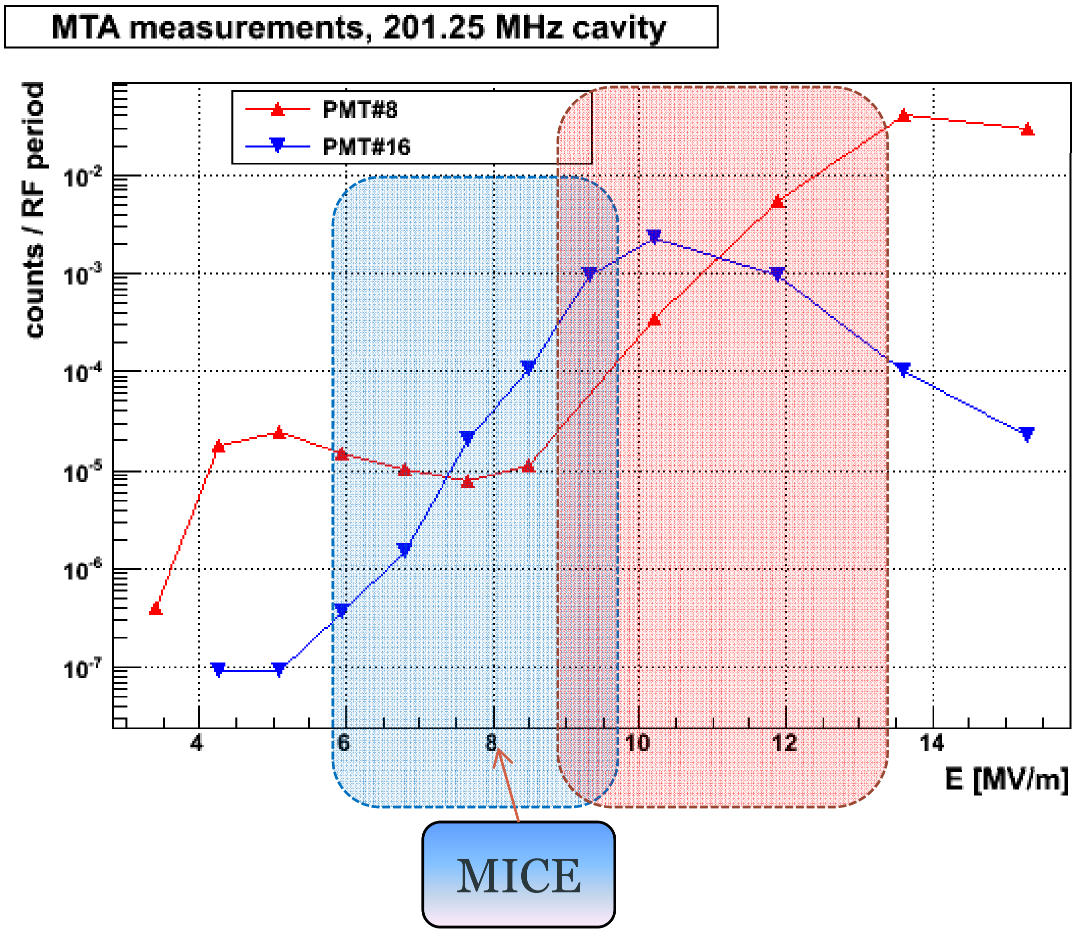
A CENTURY OLD MYSTERY

- Why the strong dependence on gradient?
- Due to number of photons per electron
- Due to increased field emission

ADDITIONAL EFFECTS

- B field
- Avalanche
- RF induced heat, MICE & NuFact

MTA data, two on-axis detectors



Areas mark where I have confidence in results

Raw data scaled to events per RF period (5ns).

- PMT#8 data taken over full 125μs.
- PMT#16 data taken over 88.6μs flattop only.

PMT#16 is smaller, but closer, than PMT#8.

Virtually all photons hitting PMT#16 deposit all their energy in the detector, while only a fraction interact with the paddle, and not all energy is confined in active volume.

PMT#16 is saturated at ~10MV/m.

Why the strong dependence on gradient?

- PMT 16 between $5.95 \leq E \leq 9.32$ [MV/m] :
  - Rate $n_\gamma \propto E^{16.5}$ ($\chi^2/ndf = 0.3752/2$)
  - Why???
- My hypothesis:
  - Electrons are emitted from cavity surfaces due to field emission.
  - All electrons are stopped on the opposite side of the cavity.
    - Copper (and aluminum).
  - All events in the detector are bremsstrahlung photons created when electrons stop.

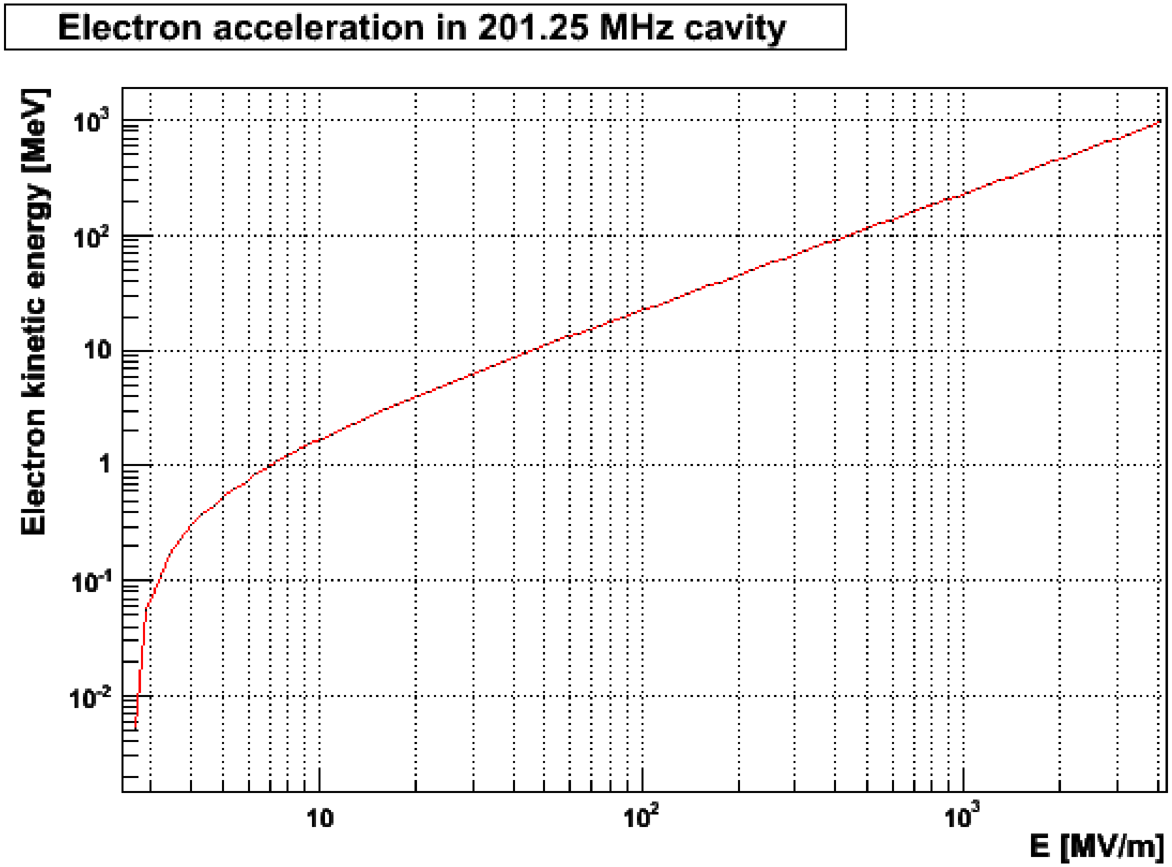
Electron energy

Assuming electrons only emitted when field is maximal:

Minimum field required to reach opposite cavity wall.

⇒ Sharp cut off around 3 MV/m.

Initially very steep gradient, later linear.



Radiation yield

= fraction of kinetic energy lost through radiative processes.

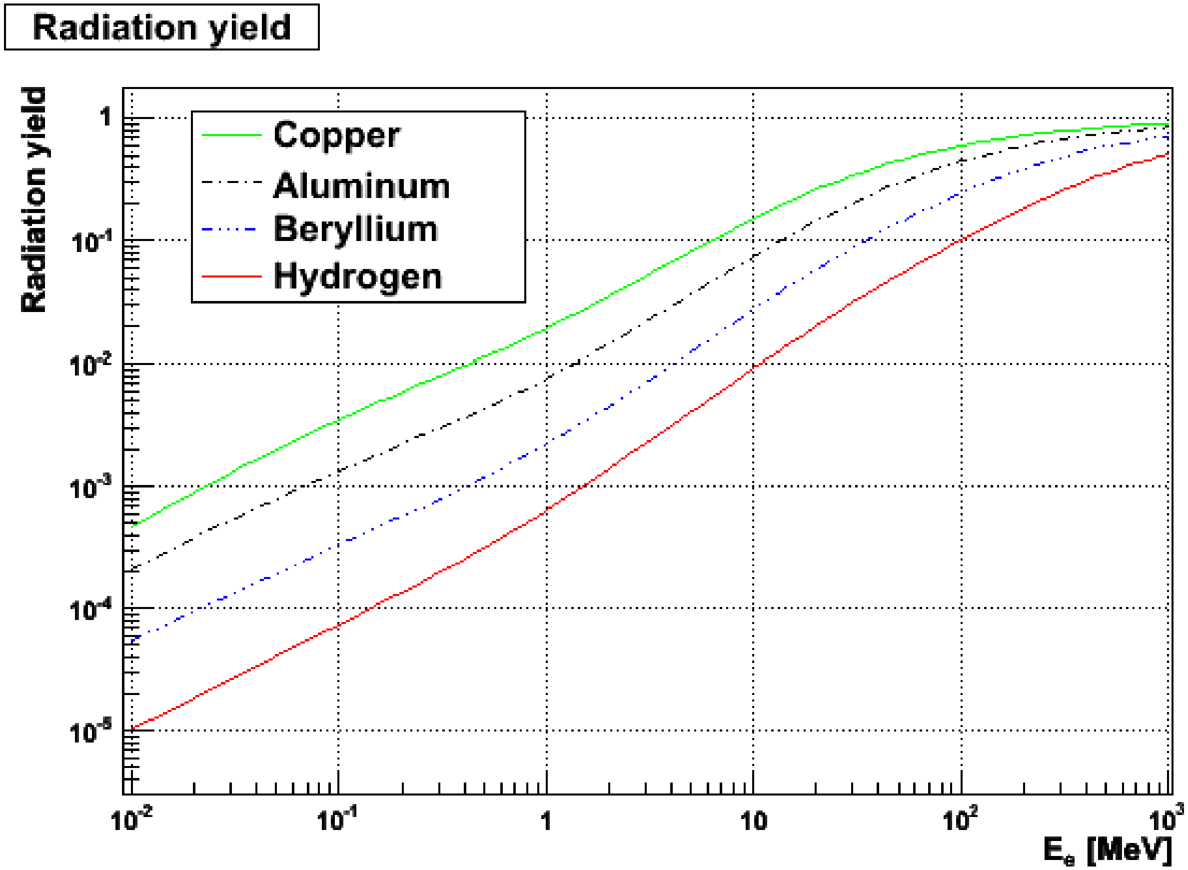
Heavy elements (X_0) give higher radiation yield.

Range of 1 MeV e- in Al = 2 mm.

MICE: 0.18 mm Al window.

Hence, combination of photon production in Al and LiH2 (+ Be, Cu).

MTA: Electron ranges out in copper.

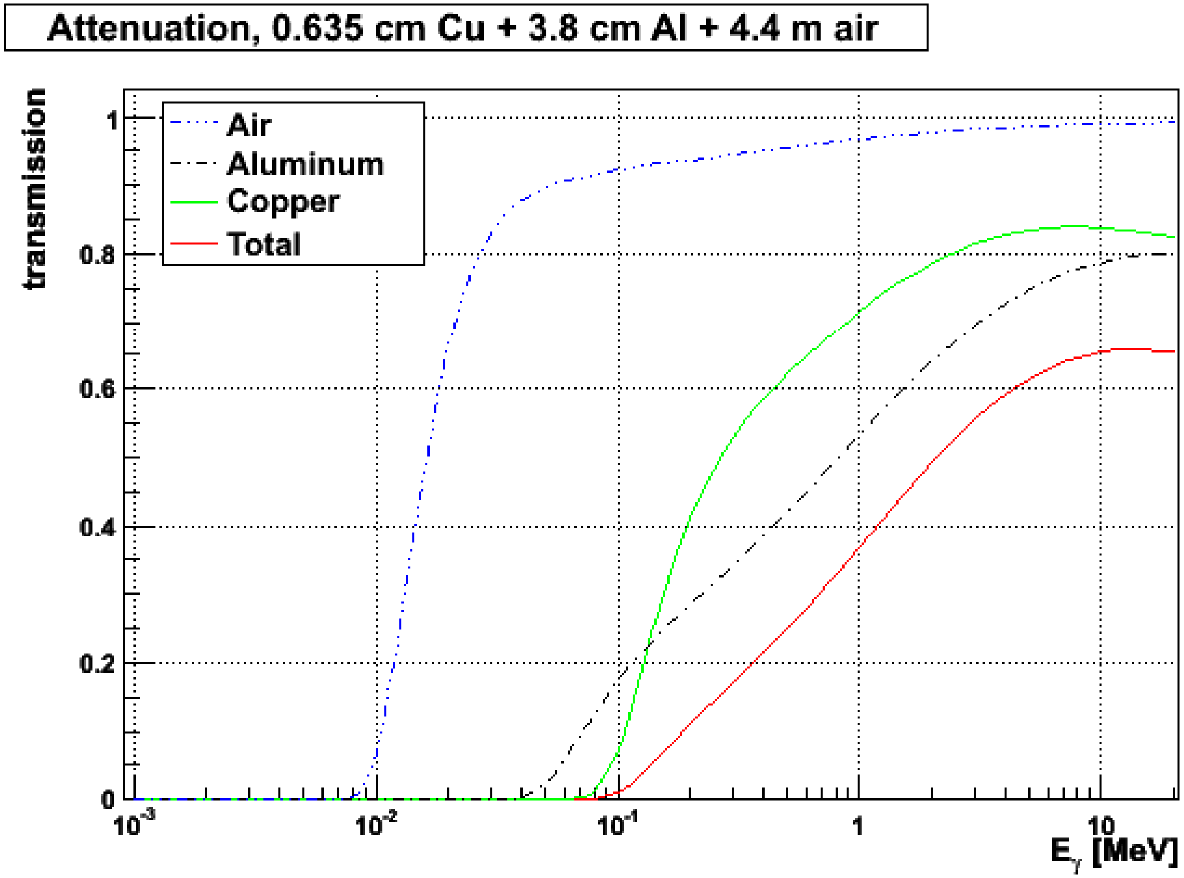


Electron energy

Attenuation of photons

- At 1 MeV, Compton scattering dominates.
- At lower energies, PE dominates -> Much larger cross section!
- Hence above 1 MeV only moderate attenuation (transmission≈0.4), no photons at keV scale.

MICE: less material than MTA→less attenuation.



Photon energy

Attenuated bremsstrahlung spectrum

Assume radiation yield p_y.

Then the average photon energy is

$$\langle t \rangle = p_y \cdot T$$

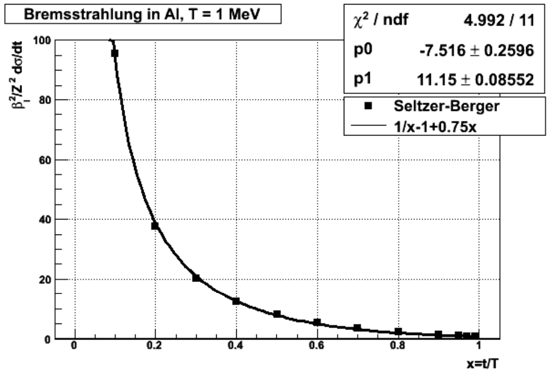
and since

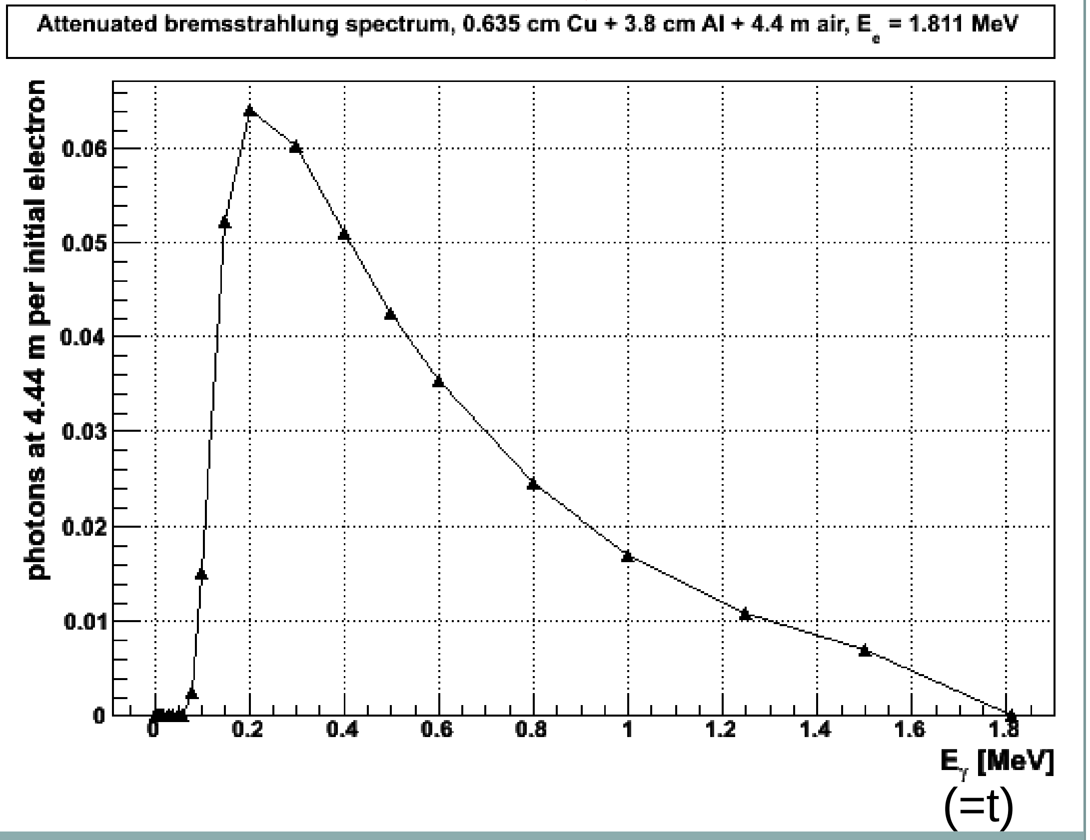
$$\langle t \rangle = \int t \frac{\mathrm{d}\sigma}{\mathrm{d}t} \mathrm{d}t$$

the differential cross section can be normalized despite infrared divergence

$$p_{gen}(x) = \frac{4}{3} T^2 p_y \left(\frac{1}{x} - 1 + \frac{3}{4} x \right)$$

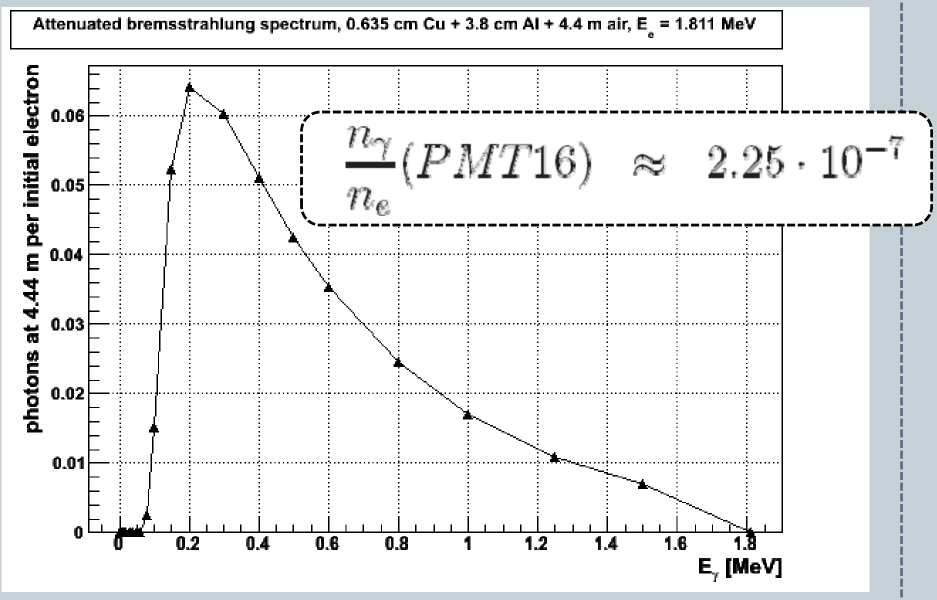
which together with attenuation gives the spectrum on the right. (x=t/T)





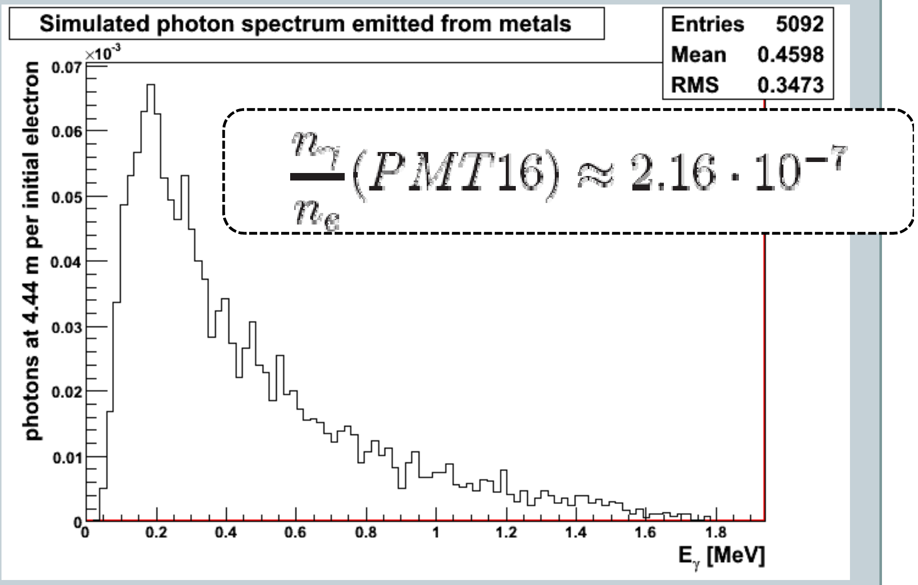
Comparison of with simulation

Calculated



$$\frac{n_\gamma}{n_e}(PMT16) \approx 2.25 \cdot 10^{-7}$$

Simulated in G4MICE



$$\frac{n_\gamma}{n_e}(PMT16) \approx 2.16 \cdot 10^{-7}$$

Good agreement, but calculations give too many high energy photons.

- No energy loss accounted for.
- Additional path length at large angles.
- The parameterization does not work well at high x.

These effects explain a lot!

In the same region ($5.95 \le E \le 9.32$ [MV/m]) the rate from these effects account for

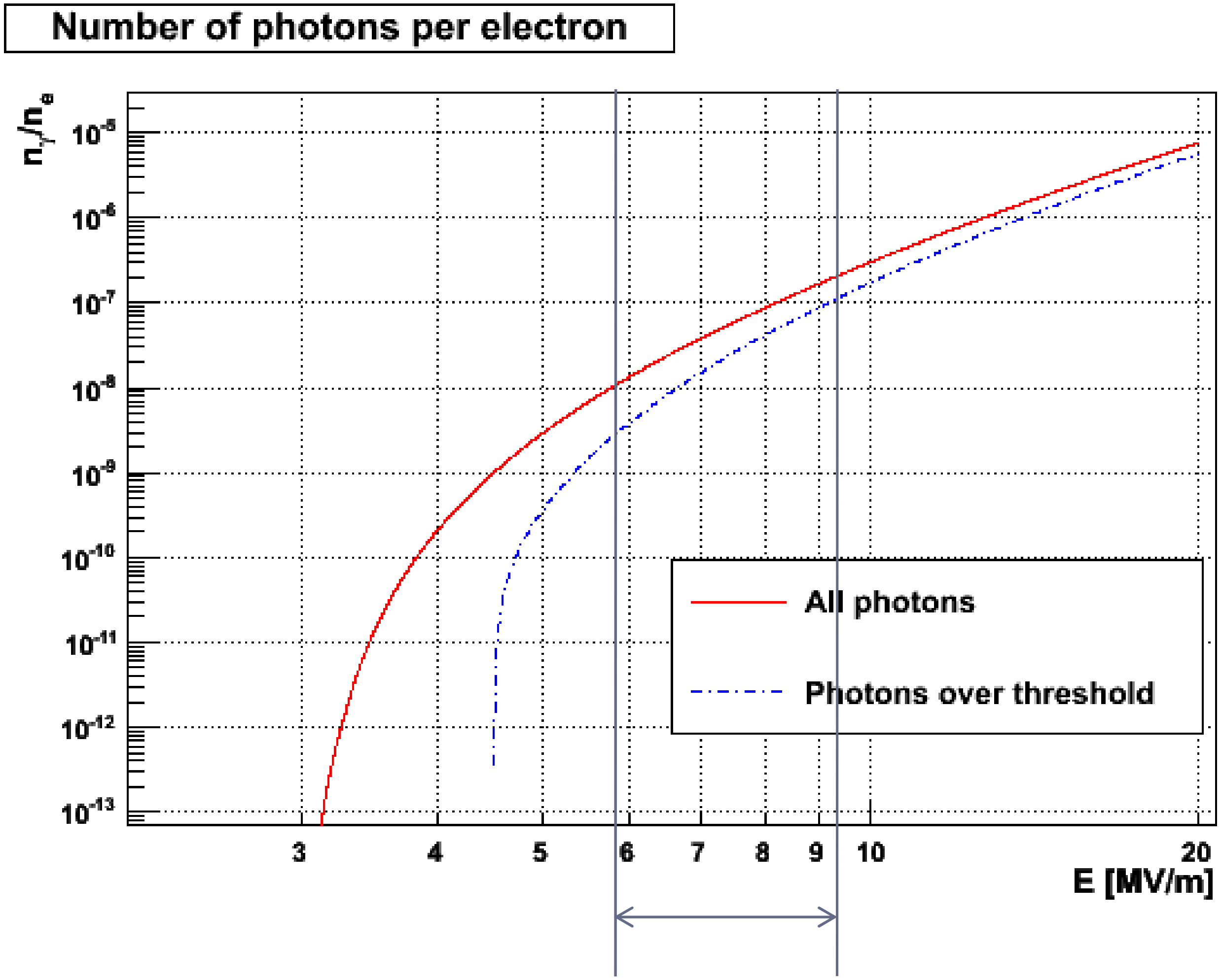
$$n_\gamma/n_e \propto E^{7.65}$$

$(\chi^2/\text{ndf} = 4.445/1077)$

That leaves

$$n_e \propto E^{16.5-7.65} = E^{8.9}$$

to be explained.



PMT16 OK

At higher gradients

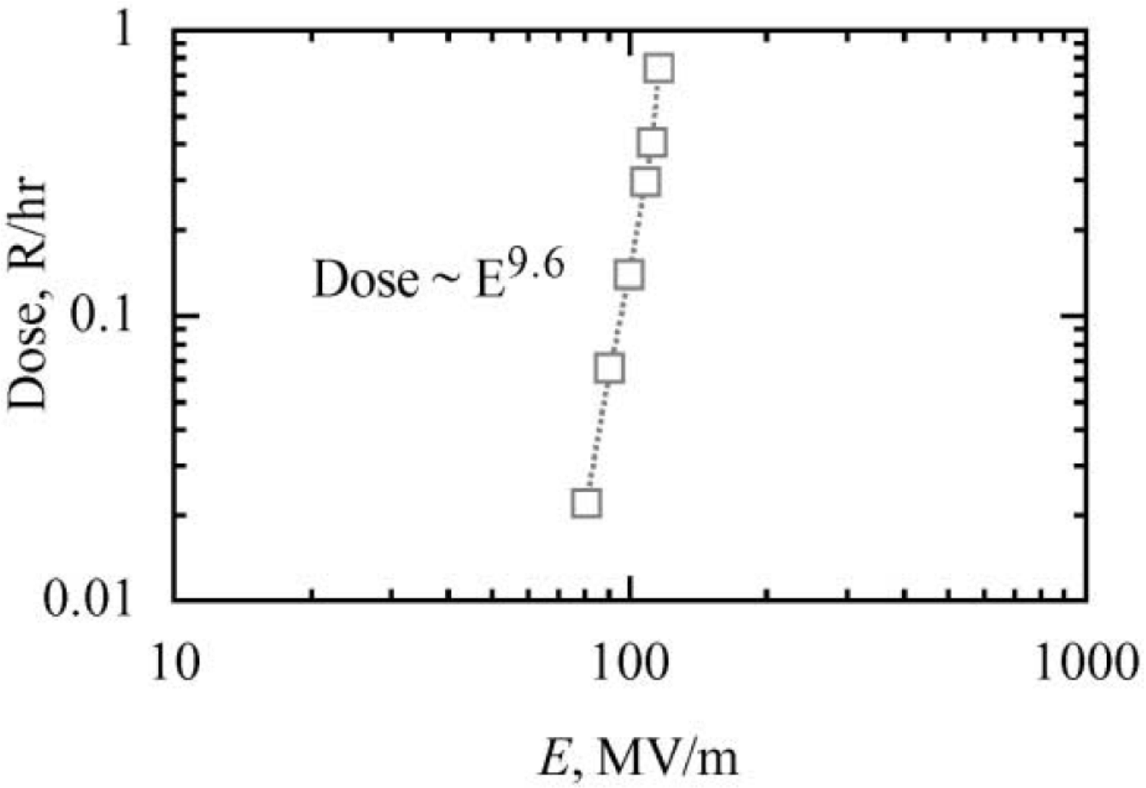
Experiments (LEP, MuCool) consistently report $E^{9.6}$.

This is at higher gradient, so higher electron energy (almost linear with gradient)…

…and thus almost all photons are over detector threshold.

$E^{8.9}$ remains after rad yield (0.7) is deducted.

805 MHz data:



J. Norem et al. / Nuclear Instruments and Methods in Physics Research A 472 (2001) 600–605

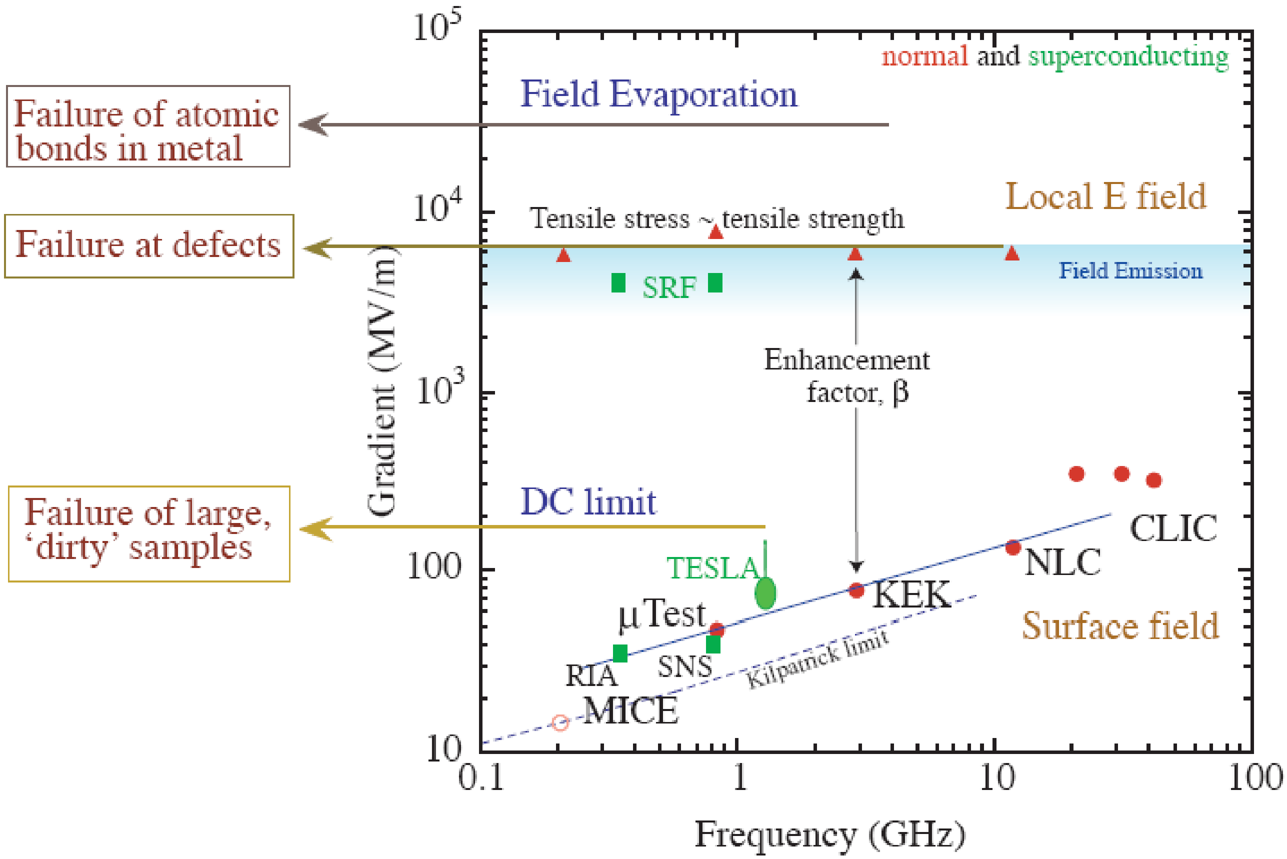
Enhancement factor β

If local surface field is above 7 GV/m, tensile strength of copper is exceeded. Breakdown!

Asperities and contamination can create local field enhancement,

$$E_{local} = \beta E$$

thus causing field emission and breakdown also at low accelerating gradients.



Failure of atomic bonds in metal

Failure at defects

Failure of large, ‘dirty’ samples

Density of asperities

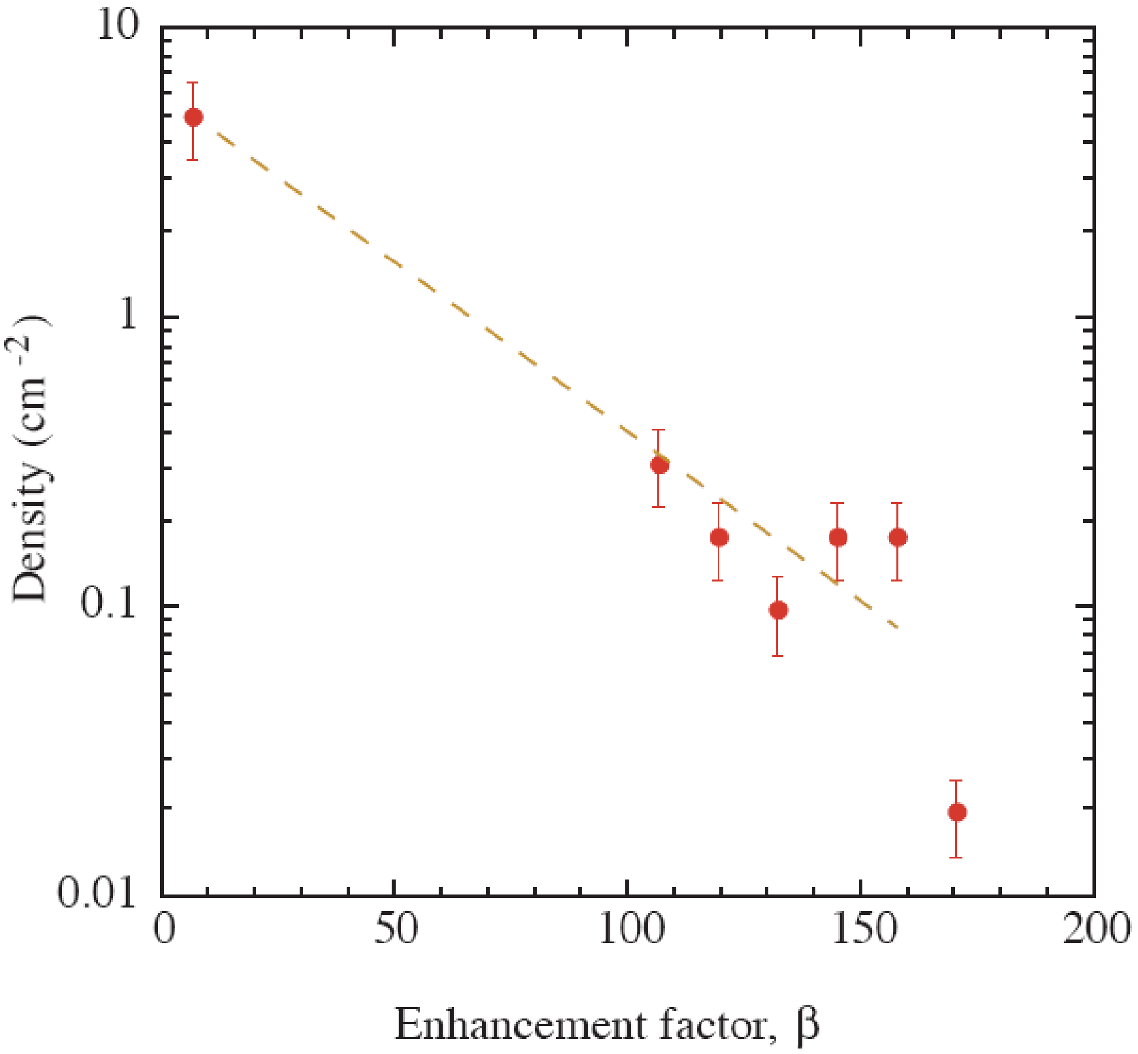
I did a log-log estimation and found

$\rho \propto \beta^{-3.09}$

These preexisting asperities thus become activated as E increases, giving a contribution

$(E^{3.09})^2 = E^{6.18}$

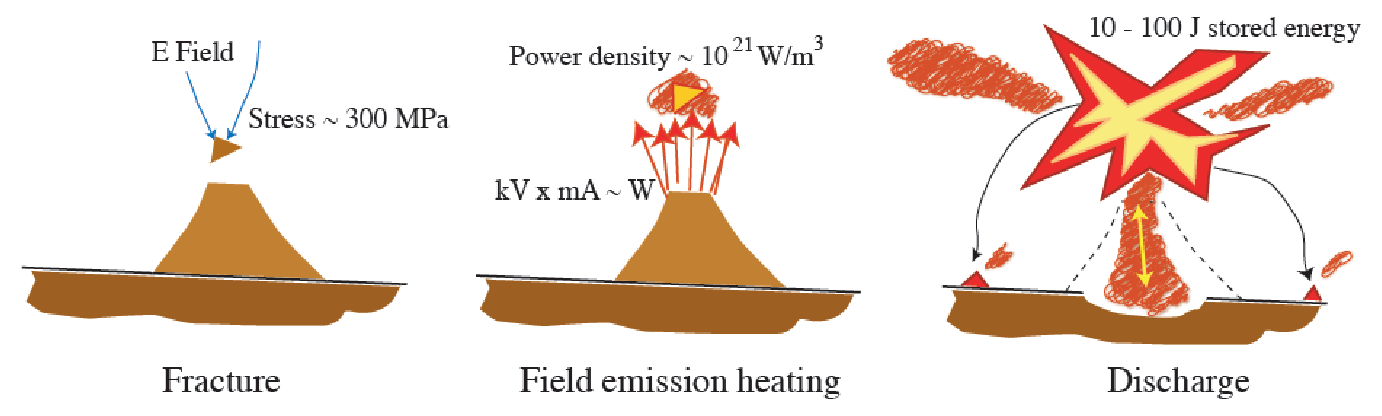
(The square comes from leading term in Fowler-Nordheim tunneling.)



A. Hassanein et al. FERMILAB-TM-2349-AD

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

Creation of new emitting sites



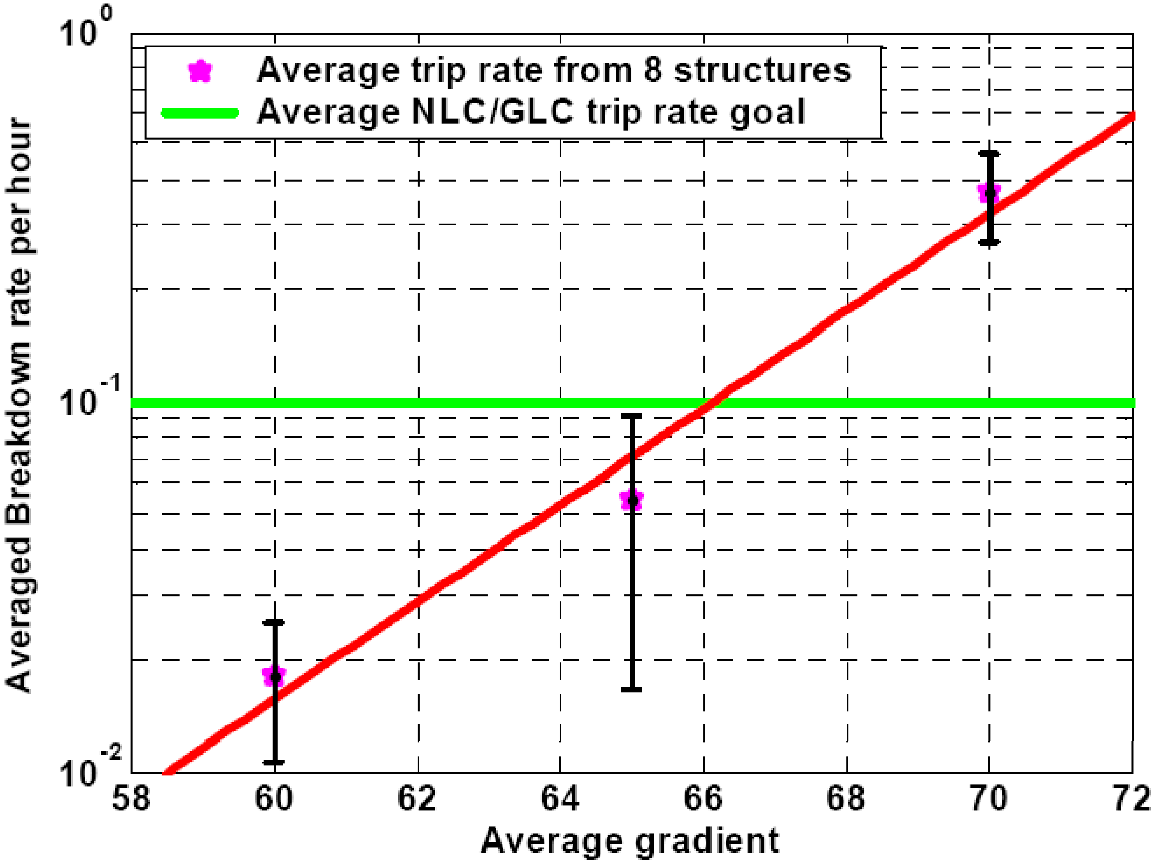
- The remaining rate $\propto E^{2.7}$ is believed to be due to creation of new emitting sites, β.
  - The asperities created in a breakdown become new sources of field emission, (and thus give an extra factor of two due to FN tunneling). Thus the mechanism should approximately be proportional to $E^{1.35}$.
  - The mathematics involved are poorly understood.

Breakdown rate

If the creation of new asperities is proportional to the rate of breakdown:

“The slope of the fitted curve is one decade in breakdown rate for 7 MV/m of average gradient…”

$1/\log_{10}(7)$ = 1.18

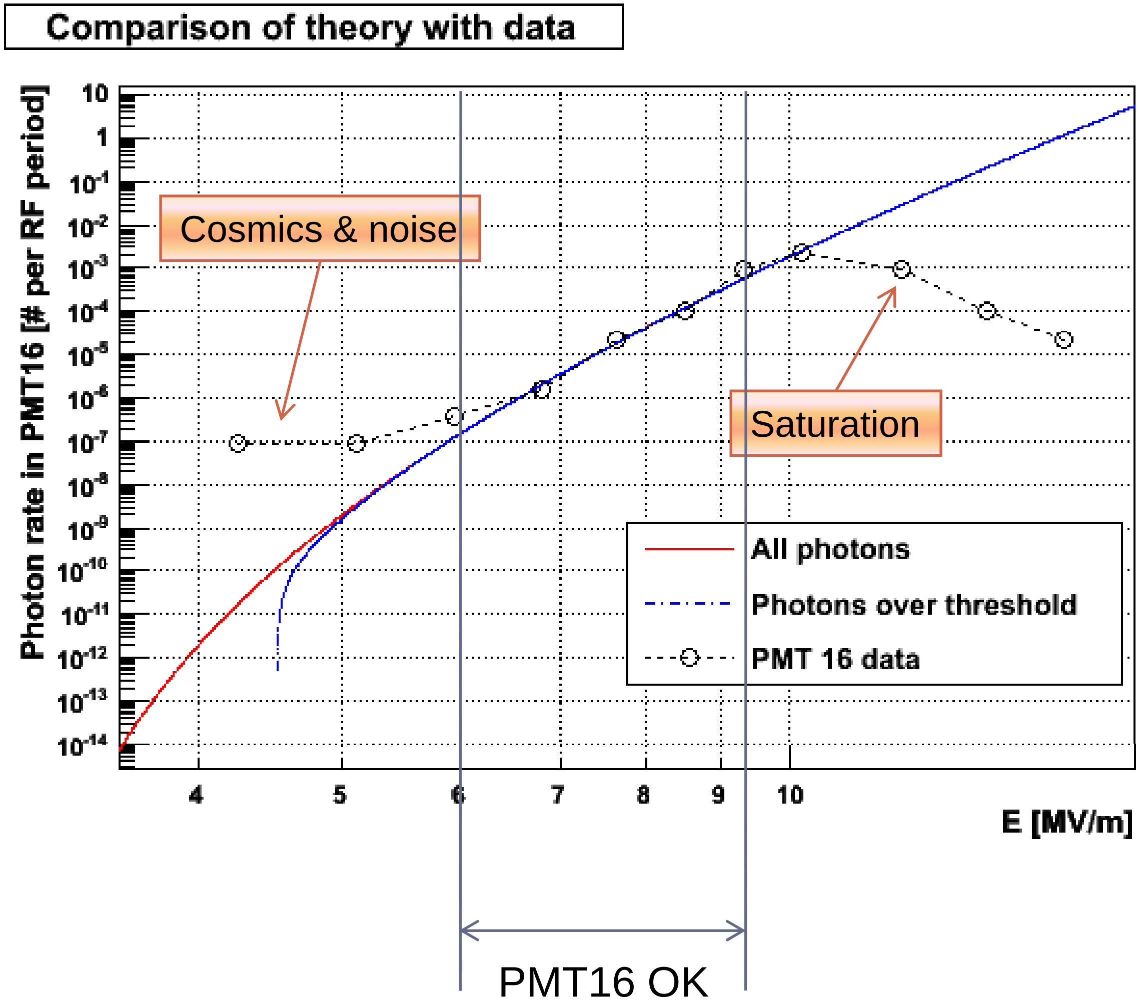


Steffen Döbert, SLAC-PUB-10690

The model compared with data

Using the previous model for bremsstrahlung, attenuation etc, but adding a factor $E^{2(1.18+3.09)}$ due to field emission gives very good agreement with observed data in the region of confidence!

(also added constant factor 2500 for overall scale)



Cosmics & noise

Saturation

PMT16 OK

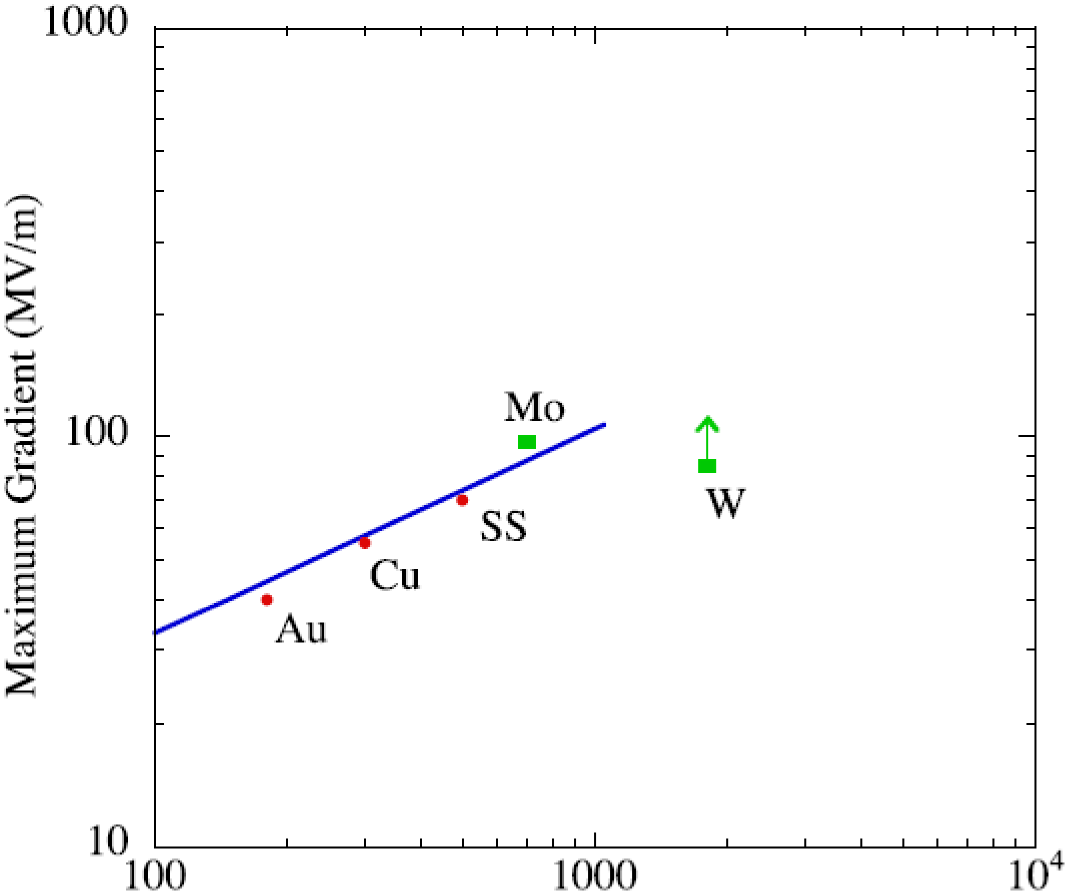
Material dependency

It is well known that maximum gradient increases with tensile strength.

Fewer breakdown events would create fewer asperities too…

However the *shape* of the asperity influences β, so materials that create soft edge asperities are desired.

Tests using « buttons » are ongoing at MTA, Fermilab.



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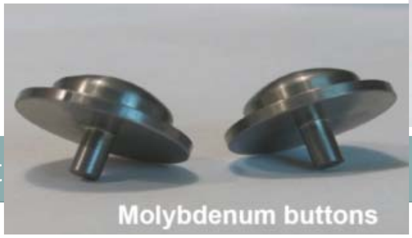
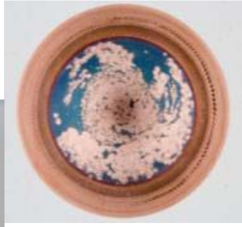




At 8 MV/m (MICE)

- MICE is using 2 sets of four 201.25 MHz cavities, operating at 8 MV/m.
- Simulation with E=1.226 MeV (corresponding to 8 MV/m):

$$\frac{n_\gamma}{n_e}(PMT16)\Big|_{8\ \mathrm{MV/m}} \approx 5.72 \cdot 10^{-8}$$

- Extrapolation between points of MTA data gave:
  - $n_\gamma = 4.03 \cdot 10^{-5}$ at 8 MV/m.
- This implies $n_e = 705$ per RF (half-) period.
  - Equivalent to 142 GHz per cavity and direction.

Electron energy in MICE linac

The electron energy depends on phasing of individual cavities.

A linac of four cavities gives 8 distinct electron energies and timings. (Timings overlap with subsequent RF period.)

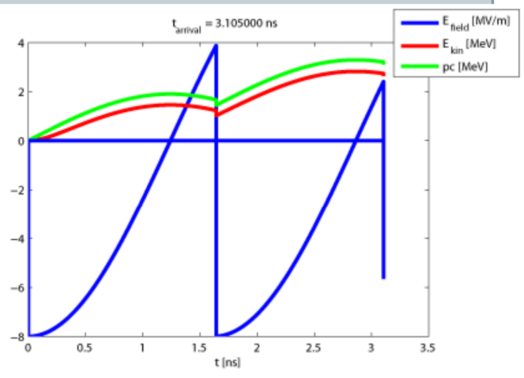
The bremsstrahlung photon spectrum is a combination of these monochromatic electron energies.

Initial field sign	Cavities	Reversed	$E_{kin}[MeV]$	$TOF[ns]$
-1	1	no	1.123351	1.6422
-1	2	no	2.628161	3.1050
-1	3	no	4.650005	4.5484
-1	4	no	7.102850	5.9862
+1	1	no	1.123351	1.6422
+1	2	no	2.064848	3.1656
+1	3	yes	7.068071	10.1204
+1	4	yes	4.645628	8.6752

Phases set to accelerate a 200 MeV/c muon.
Average electron energy = 3.8 MeV.

Other possible effects

- B > 0 increases background.
  - With a factor $e^{0.9251B}$ according to D. Huang, based on 805 MHz cavity data.
  - This would give an extra order of magnitude @ 3 T *if* applicable to 201 MHz cavity. It will be measured.
- Avalanche effect.
  - Similar to multipactoring, when an electron hit the Be window of a neighboring cavity, the field is nearly maximal so low energy secondaries are accelerated.
  - Not known if this will give significant contribution.



Heating of absorbers, MICE

- Due to reversing electrons, upstream absorber sees 2 peaks, downstream absorber 6, and center absorber 8.
  - Thus, center absorber always has maximum load, no matter if electrons are reversing.
  - Electron energy almost fully contained within AFC module.
- For cavities phased by reference 200 MeV/c muon, average electron energy is 3.80 MeV, and duty factor is 10^{-3}.

$$\langle P_{heat} \rangle = \frac{f_e}{2} \langle E_{kin} \rangle \, d \approx 4.317 \cdot 10^{15} \ \mathrm{eV/s} \approx 0.691 \ \mathrm{mW}$$

  - If B field applied, could be one order of magnitude higher.
  - This is well within MICE specifications (TRD: 15 W) and not a problem to the experiment.

Heating of absorbers, NuFact

(Assuming MICE absorbers:)

- At NuFact E = 16 MV/m.
  - Increased electron emission: factor $2^{2(3.09+1.18)}=372$
  - Increased energy of electron after one cavity: factor 2.6
    - Average energy of a linac should give similar factor.
  - Duty factor 0.19%: factor 1.9
- Hence, P = 1.3 W.
  - Still OK.
    - When B field is applied?
  - E > 21 MV/m critical, even without B field.

Uncertainties

- The largest uncertainty is the *measured* rate:
  - Very sensitive to field gradient.
  - More precise measurements could alter this number.
- Uncertainty of analysis components negligible.
- Simulation:
  - Largest uncertainty from simulation is location of emitting sites in cavity.
- The model for activating pre-existing asperities and creation of new asperities is very new and should be considered *preliminary*.
  - Where can I find more data?

Summary

- I have shown how the bremsstrahlung photon production can be both calculated and simulated, giving the same result.
- I have developed a model which successfully reproduces the observed gradient dependency of the photon rates.
  - It solves the apparent contradiction of different experiments.
  - As far as I can tell, this is the first model of its kind.
  - A qualitative theory for RF breakdown and formation of asperities is still missing.
- Using the model I have given the expected background rates for MICE.
  - Absorber heating is no problem to MICE, but could be to NuFact.

Extra slides

Simulation, angles

I assumed isotropic angular distribution of photons.

In order to cross check, MTA was simulated in G4MICE using 3.6 million initial electrons.

⇒A photon has 9.4*10^{-6} chance to hit the detector.

Solid black line is angular spectrum (after attenuation in metal) if isotropic angular distribution.