Electric Breakdown Regimes for Broad Area Electrodes

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1. Narrow gap DC $d \ll 1$ mm

$V_b \sim d$ or $E_b = \frac{V_b}{d} \sim 30$ MV/m

Dielectric inclusions switch on to conducting state, produce copious e^- emission, heat up, become unstable.

2. Wide gap DC $d \gg 1$ mm

$V_b \sim d^{1/2}$ "Cranberg clump hypothesis"

Microparticle (submicron) impact vaporizes and ionizes electrode material if energy/area is sufficient

$$\left(\frac{U}{A}\right)_{crit} = \frac{Q_p V_b}{A} = \text{const}\ \frac{C}{A} V_b^2 = \text{const}\ \frac{V_b^2}{d} \qquad \left(C = \epsilon_0 A/d \text{ planar}\right)$$

3. Narrow gap rf $d \ll c/2f$ (e.g. RFQ's)

"proton multipacting"

Primary e^- (dielectric inclusions) $\rightarrow$ free H^+ from residual hydrocarbons $\rightarrow H^+$ impact $\rightarrow e^-$ secondaries

Kilpatrick: Probab. field emiss. $\times$ yeild of second. $e^- > N_{crit}$

$N_{f.e.} \sim E^2 e^{-\text{const}/E}$, $N_{sec} \sim U_{ion} \sim E^2/f^2$

$\rightarrow f = \text{const}\ E_b^2\ e^{-\text{const}/E_b}$ "Kilpatrick criterion" (CW)

In narrow gap rf experiments, E_b depends on pulse length (dielectric heating time constant ~ 1 msec?)

$$E_b \simeq \left(1 + \frac{35}{\tau_p(\mu sec)}\right) 2.3\, E_K$$

> 1 spark/1000 rf pulses

$\tau_p > 100\ \mu sec$

CW is any pulse length $\gtrsim$ 1 msec.

4. Wide gap rf $\quad d \gtrsim c/2f \quad$ (e.g. linacs)

"electron sparks" - least understood regime

Primary e^- (dielectric inclusions?) may or may not reach opposite electrode. No heavier particles can reach opposite electrode in rf period. Pulse length dependence not determined yet.

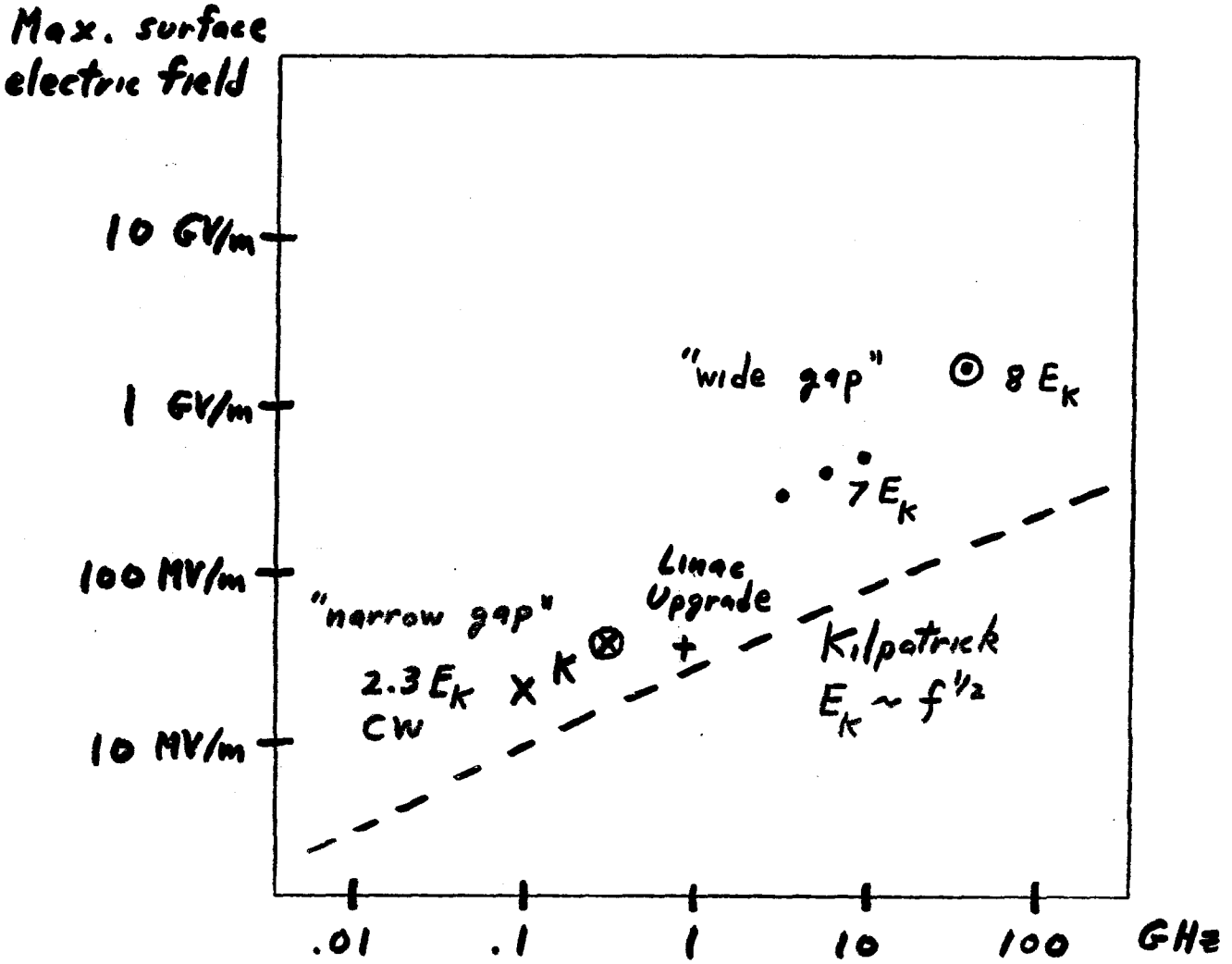
Linac Upgrade power tests with 805 MHz cavities could add useful data:

$$d \sim 5\,cm \qquad \frac{c}{2f} \sim 20\ cm$$

Essentially wide gap since protons cannot cross gap during rf period.

- What is pulse length dependence?
- What is E_b when > 1 spark / 1000 rf pulses or > 1 spark / 10000 rf pulses?
- Does x-ray yield have an associated time constant?

Recent rf breakdown experiments



× Lehmann ASI RFQ

K Kato KEK RFQ

⊗ Hutcheon AECL RFQ

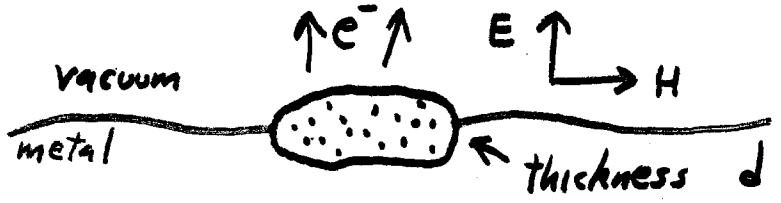
• Loew, Wang, Tanabe SLAC, Varian 3-5 μsec pulse

⊙ Sessler et al LBL 10 nsec pulse

Fit to this recent data:

$$E_b \simeq \left(1 + \frac{25}{10 + \tau_p(\mu sec)}\right) 2.3\, E_K$$

Unify narrow + wide gap rf breakdow by considering thermionic emission from dielectric inclusions.



DC e^- emission from dielectric inclusion has field dependence like Fowler-Nordheim emission from metal whisker:

$$J_{expt} = \text{const}\ E^2 e^{-6.53\times10^9 \phi^{3/2}(eV)/\beta_{eff} E(V/m)}$$

ϕ = metal work function ~ 4.5 eV

β_{eff} = local field enhancement factor of "whisker"

Thermionic emission can mimic this (Latham):

$$J_T = \frac{em}{2\pi^2\hbar^3}(k_B T)^2 e^{-\chi/k_B T} \qquad (\chi = \text{dielectric } e^- \text{ affinity})$$

$$\langle KE\rangle_{e^-} = \frac{3}{2}k_B T = \eta\,\frac{E}{\epsilon}\,d \qquad (\eta \lesssim 1)$$

$$\rightarrow \beta_{eff} = \eta\,\frac{2}{3}\,\frac{d(m)}{\epsilon\,\chi(eV)}\,6.53\times10^9\,\phi^{3/2}(eV) \qquad (\sim 10^2 - 10^4)$$

Breakdown occurs at $J \rightarrow J_{crit}$ or $\beta_{eff} E_b = E_{crit}$ from expt.

In rf field, inclusions with $d \sim \delta$ = skin depth are most likely to cause breakdown since they are strongly heated by internal e^--hole currents induced by magnetic field:

$$E_b = E_{crit}/\beta_{eff} = \text{const}/\delta = \text{const}\ f^{1/2}$$