# Kilpatrick's Criterion

***AN HISTORICAL PERSPECTIVE***

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# Bibliography


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**[DOE04]** "*Gradient Limitations for High-Frequency Accelerators*", S.Döbert, Proc. LINAC04 (2004) SLAC-PUB-10690

**[SWE05]** "*Smoothing RF Cavities with Gas Cluster Ions to Mitigate High Voltage Breaksdown*", D.R.Swenson et al., NIM B(2005)

**[HAS06]** "*The Effects of Surface Damage on RF Cavity Operation*", A.Hassanein et al., (2006) Phys.Rev.ST Accel. Beams (2006) 062001

**[WILS07]** "*A Theory for the RF Surface Field for Various Metals At the Destrucitve Breakdown Limit*", P.B.Wilson, Tutorial at AAC06 (2007) SLAC-PUB-12354

**[DES08]** "*DC Breakdown Experiments for CLIC*", A.Descoeudres et al., Proc. EPAC08 (2008) CERN-TS-2008-006

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# Chronology

**1947** Electrical breakdown dependency upon high-energy ion bombardment was first proposed by Trump and Van de Graff

**1953** An experiment by Dyke and Trolan suggested that field emission current may be the dominant criterion in the initiation of breakdown

**1954** Some data show that ion bombardment is not the main trigger for breakdowns

**1957** Kilpatrick summarizes several investigators' experiences, data and theories on a simple empirical criterion

# Kilpatrick's criterion:

*an empirical voltage threshold for vacuum sparking*

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 28, NUMBER 10 OCTOBER, 1957

## Criterion for Vacuum Sparking Designed to Include Both rf and dc*

W. D. KILPATRICK
*Radiation Laboratory, University of California, Berkeley, California*
(Received May 31, 1957)

An empirical relation is presented that describes a boundary between no vacuum sparking and possible vacuum sparking. Metal electrodes and rf or dc voltages are used. The criterion applies to a range of surface gradient, voltage, gap, and frequency that extends over several orders of magnitude. Current due to field emission is considered necessary for sparking, but—in addition—energetic ions are required to initiate a cascade process that increases the emitted currents to the point of sparking.

- Based on the idea that breakdown happens when regular Field Emission is enhanced by a cascade of secondary electrons ejected from the surface by ion bombardment.
- Useful for DC and AC voltages

# Kilpatrick's criterion:

## *an empirical voltage threshold for vacuum sparking*

An expression for the breakdown threshold was obtained empirically from early experimental data gathered in the 1950's:

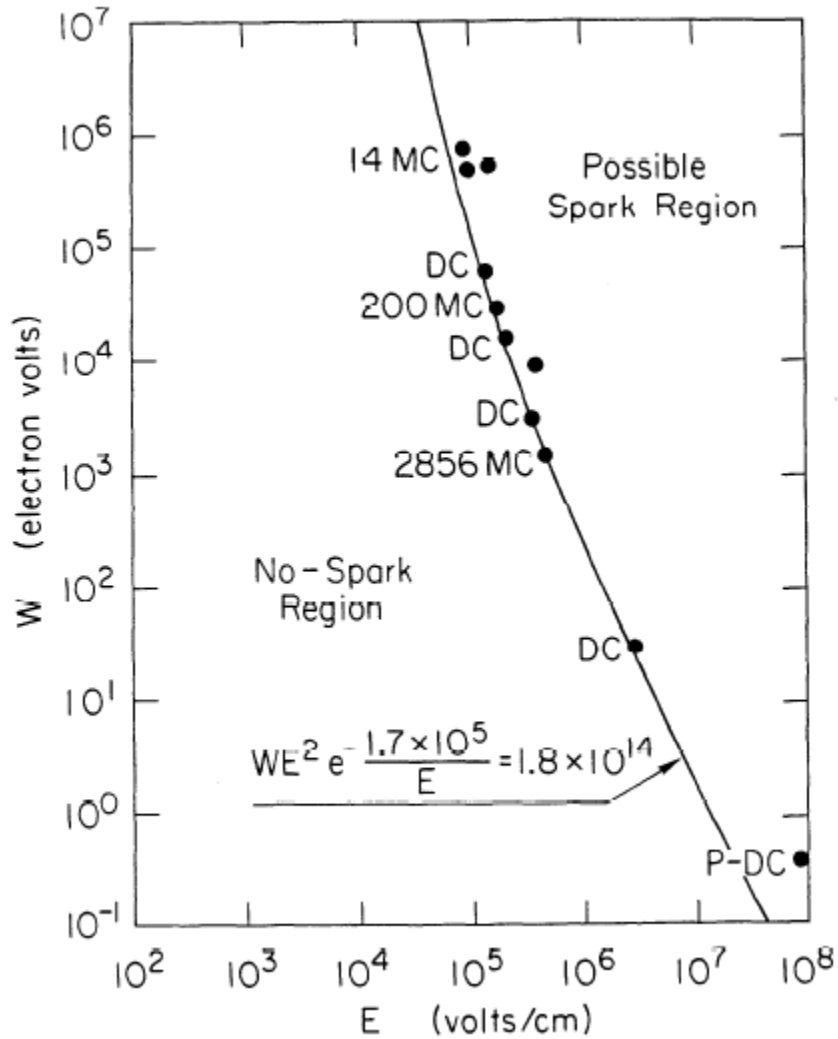
$$Ee^{-4.25/E} = 24.4 \cdot [f(GHz)]^{\frac{1}{2}} \;\; MV/m$$

The expression was reformulated by T. J. Boyd[*] in 1982 as:

$$f = 1.64 \cdot E(MV/m)^2 \cdot e^{-8.5/E(MV/m)} \;\; MHz$$

➔ The threshold voltage varies as the square root of the applied frequency.

➔ Kilpatrick already pointed out in this paper that the threshold could be slightly raised by processing the electrode surfaces.




[*] T. J. Boyd, Jr. , "*Kilpatrick's criterion*", Los Alamos Group AT-1 report AT-1:82-28, February 12, 1982

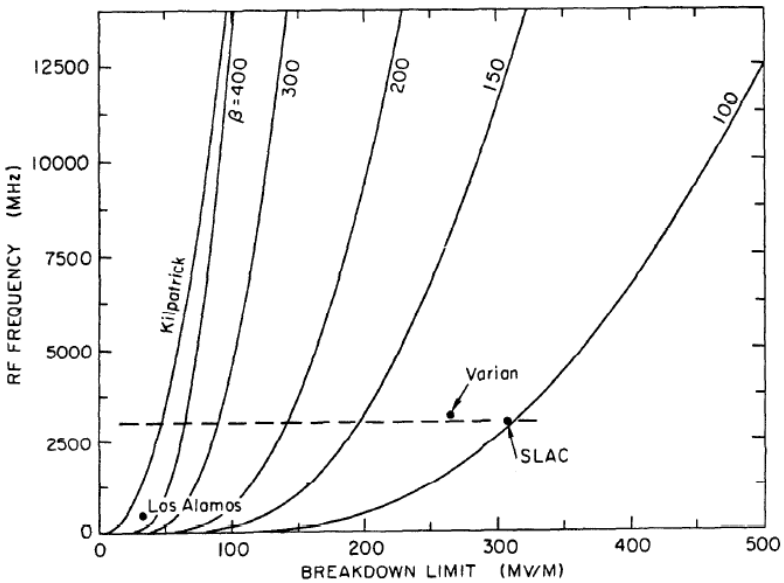
# Chronology (II)

**1983** Generalized secondary emission physics package designed in Los Alamos to be used with particle-in-cell code

**1986** The Kilpatrick's criterion is revised by J.W.Wang as some experiments performed at Varian, SLAC, Los Alamos and Germany show the possibility to go beyond the Kilpatrick's limitation.

The creation of a microplasma due to excessive resistive heating in the microprotusions of the surface becomes an essential prerequisite for a breakdown event.

J.W.Wang also explains why ion bombardment and electron multipacting are not the main cause of breakdowns.



# Chronology (III)

**2002** NLC/CLIC has operated test structures for extended periods above accelerating gradient of 70/100 MV/m

**2003** The thought that achievable gradient increases monotically with frequency is probably no valid anymore at frequences above X-band

**2008** The study of time delays before breakdown seems to indicate that the breakdown mechanism could be different during and after the conditioning phase **[DES08]**

**2009** A new quantity for describing the high-gradient limit is presented by CLIC people **[GRU09]**

# Experimental evidence up to now:

## *tests performed in different scenarios and their results*

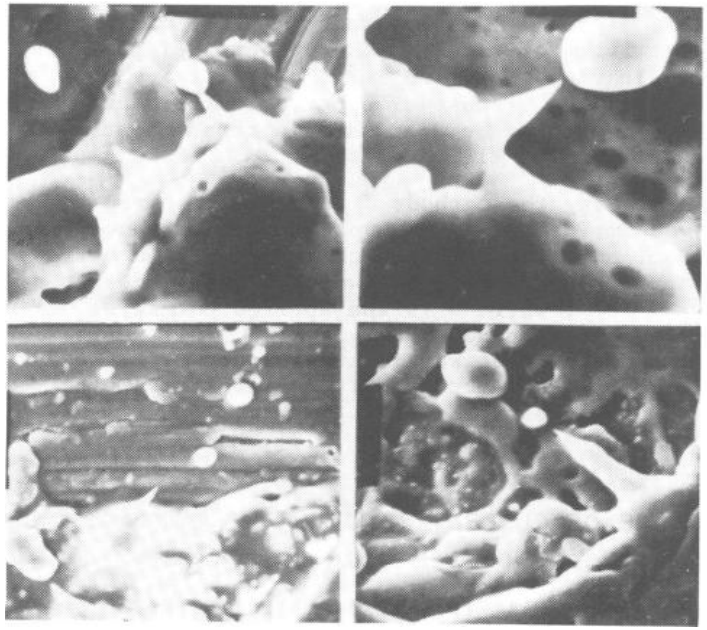
| *Year* | *Author* | *Quantity* | *Characteristics* |
|---|---|---|---|
| *1963* | Nicolaev | 90 MV/m peak surface | ~11 Kilp., 23.6 MHz |
| *1979* | Williams (Los Alamos) | 50 MV/m peak surface | ~1.6 Kilp., 100 μs pulse, 425 MHz |
| *1984* | Tanabe (Varian) | 150 MV/m acc. field<br>300 MV/m peak surface | ~6 Kilp., 4.5 μs pulses in S-band,<br>"half" single cavity |
| *1985* | Loew, Wang (SLAC) | 150 MV/m acc. field<br>300 MV/m peak surface | ~6 Kilp., 2.5 μs pulses in S-band,<br>SW $2\pi/3$ mode linac |
| *1986* | Tanabe, Loew, Wang | 445 MV/m peak surface | ~7 Kilp., 5 GHz, single cavity |
| *1986* | Tanabe, Loew, Wang | 572 MV/m peak surface | ~7 Kilp., 9.3 GHz, single cavity |
| *1994* | SLAC/CERN | 150 MV/m acc. gradient | 130 ns pulse length at 30 GHz, small iris structure |
| *2002* | CLIC | 130 MV/m acc.gradient | 15 ns, operated without breakdowns |

➔ Achievable gradients have been increased by carefully RF processing, choosing appropriate materials and optimizing the accelerating structure RF design.

# Theoretical approach

The **Explosive Electron Emission** (EEE) [*] explains the generation of breakdowns in DC voltages.

The EEE can help to understand breakdowns in RF voltages but cannot explain them completely **[DOE04]**.



Cathod surface after an explosive electron event
"*Theory of Explosive Electron Emission*",
E.A.Litvinov (1985)

**[*] E.A.Litvinov, G.A.Mesyats and D.I.Proskurovskii, "*Field Emission and Explosive Electron Emission Processes in Vacuum Discharges*", Sov. Phys. Usp. 26 138-159 (1983)**

# Theoretical approach for RF voltages

The model of **"hot spot"**:

- Field emission currents heat a breakdown site up to a temperature rise each pulse
- After a number of pulses the site temperature increases above a certain threshold
- Breakdown!: stored energy → heat

The model of BD triggered by **tensile stresses [HAS06]** :

- Fracture of surface due to electrostatic forces triggers the event
- The fragment is heated and ionized by FE electrons → plasma produced
- Plasma couples the EM energy of the cavity to the wall
- Breakdown!

# Questions which still need… *an answer!*

- What triggers a breakdown? [WUE02]
- Could surface fracturing from high surface field forces be the main trigger of breakdown instead of field emission? [DOE04]
- Which is the exact contribution of the field enhancement factors to the breakdown event? [WAN97, DOE04]

- How could we limit dark current to push the breakdown threshold to the highest level as possible? [WAN97]
- How can so much RF power be absorbed once the breakdown has started? [WUE02]
- What produces damage? [WUE02]

# Questions which still need… *an answer!* (II)

- Why does the surface field at which breakdown occurs depends on RF frequency when classical Fowler-Nordheim expression for field emission is independent of frequency? [WAN97]
- Is the frequency dependence due to the fact that smaller structures are required for higher frequencies and therefore contain fewer impurities and defects? [WAN97]
- Steps in fabrication, cleaning and installation influence the resulting accelerating structure. Which of these steps are more crucial than others? [WAN97]
- Which is the influence of magnetic fields in all the process? [DOE04]
- Why is there BD in a particular pulse after millions of non-BD pulses? [DOE04]
- How can we be sure we have the correct explanation??? [WUE02]

# Conclusions: *a lot to do…*

- Go into theoretical understanding in depth
- Define long-term operation structure characteristics: geometrical design, materials, processing, etc.
- Find and define a protocol for fabricating, cleaning, processing and installing accelerating structures
- Determine the existence of other mechanisms which could contribute to the problem
- Study the behaviour of metals under high fields
- A dynamical model of RF breakdown need to be developed

*Thanks for letting me participate in your meetings!*