HV BREAKDOWN in VACUUM

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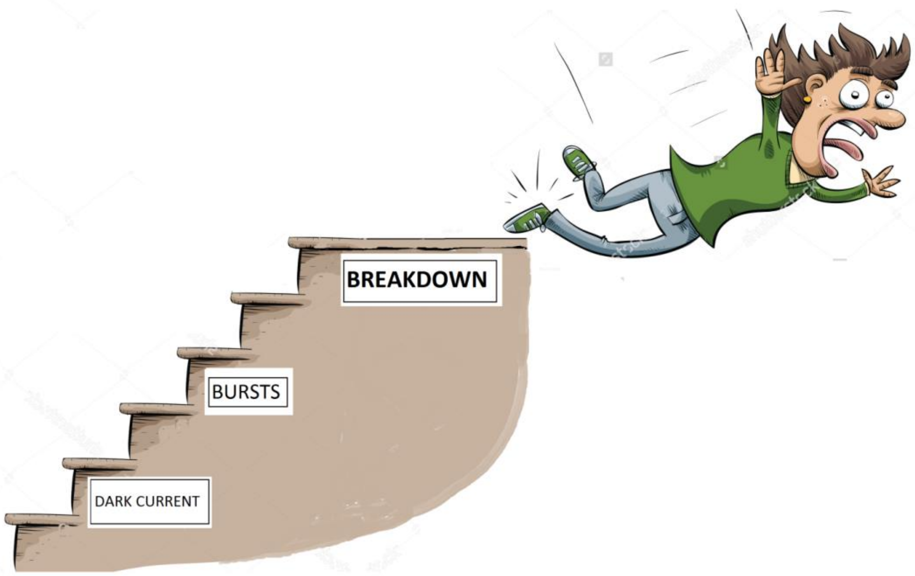
B.I.R.D. model

Breakdown **I**nduced by **R**upture of **D**ielectric layer

This is a three-step process



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Fowler-Nordheim

Electron Emission in Intense Electric Fields.

By R. H. FOWLER, F.R.S., and Dr. L. NORDHEIM.

(Received March 31, 1928.)

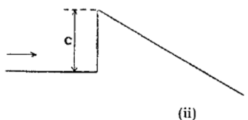
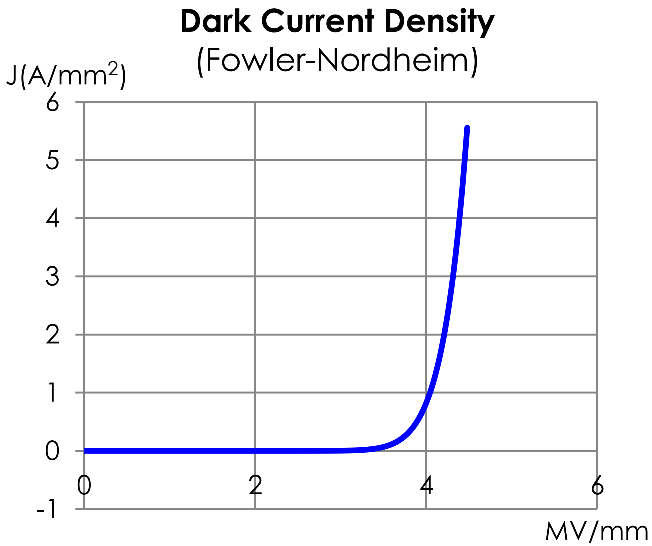


FIG. 1.

$$k_1 = \frac{a}{\Phi} \qquad a = \frac{e^3}{8\pi h} = 1.54 \cdot 10^{-6} \frac{A\, eV}{V^2}$$

$$J = k_1 {E_0}^2 e^{-\frac{k_2}{E_0}} \qquad k_2 = b\Phi^{\frac{3}{2}} \qquad b = \frac{4}{3e}\sqrt{\frac{8\pi^2 m}{h^2}} = 6.82 \cdot 10^9 \frac{V}{m(eV)^{\frac{3}{2}}}$$



DARK CURRENT

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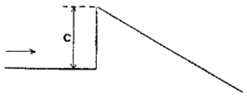
Fowler-Nordheim



(ii)

FIG. 1.

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Local field-enhancement factor β

$$E_0 \rightarrow \beta E_0 \qquad I = Ak_1(\beta E_0)^2 e^{-\frac{k_2}{\beta E_0}}$$

$$\beta \approx 10^2 \div 10^3 \qquad A \approx 10^{-16} \div 10^{-12} m^2$$

DARK CURRENT

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Fowler-Nordheim

$Geometrical\ amplification\ factor\ \beta$

DARK CURRENT

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Fowler-Nordheim

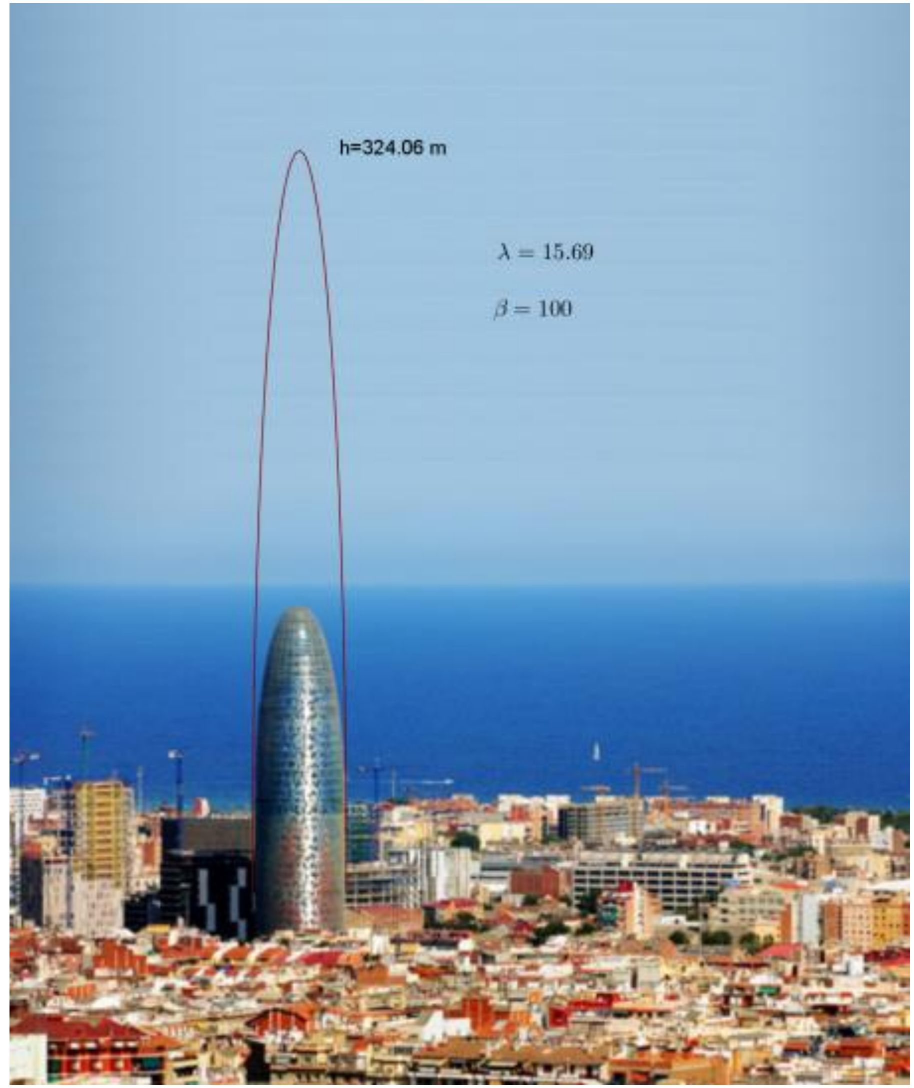
Geometrical amplification factor β

DARK CURRENT

Fowler-Nordheim

$Geometrical\ amplification\ factor\ \beta$

$\beta = 24$

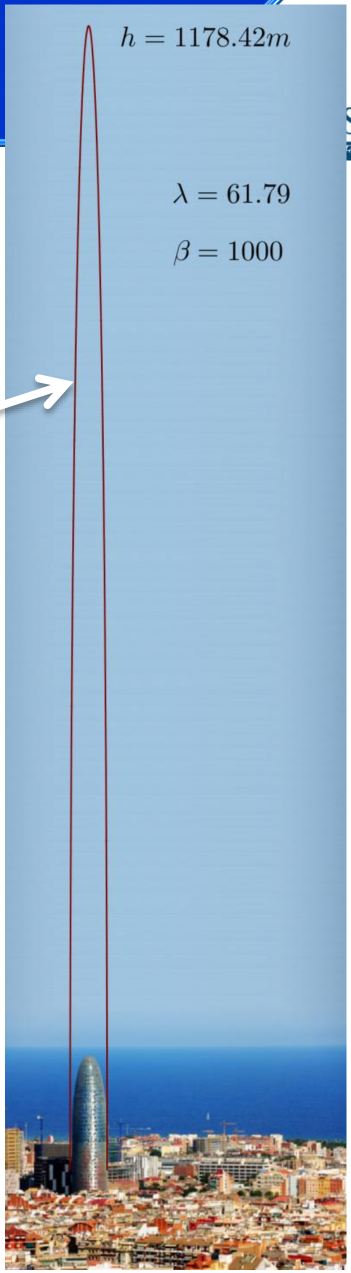


DARK CURRENT

Fowler-Nordheim

Geometrical amplification factor β

$\beta = 1000$



$\beta = 100$

$\beta = 24$

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Fowler-Nordheim

Geometrical amplification factor β

$\beta = 4$

DARK CURRENT

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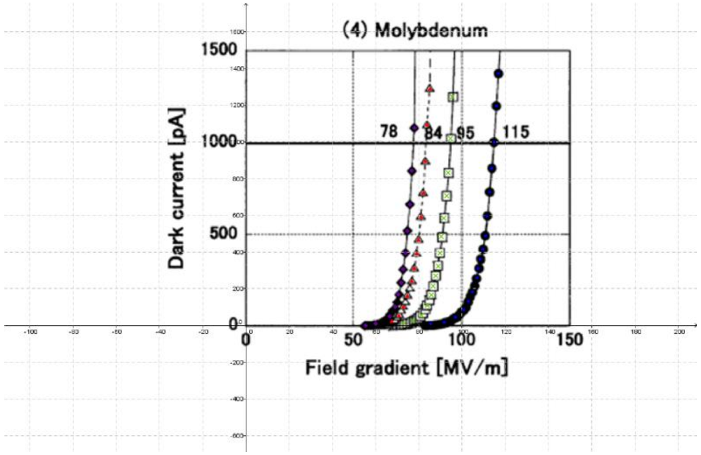
Fowler-Nordheim + geometrical amplification

$$E_0 \rightarrow \beta E_0$$

$$I = A k_1 (\beta E_0)^{-\frac{k_2}{\beta E_0}}$$

h(mm)	β	A(m^2)
0.50	46	4.0E-17
0.75	52	1.2E-16
1.00	58	1.9E-16
1.25	62	1.9E-16



F. Furuta et al. / Nuclear Instruments and Methods in Physics Research A 538 (2005) 33–44

DARK CURRENT

Fowler-Nordheim + different amplification mechanisms

$$I = A k_1 E_0^2 e^{-\frac{k_2}{E_0}} \qquad k_1 = \frac{a}{\Phi} \qquad k_2 = b\Phi^{\frac{3}{2}}$$

$$k_1 \rightarrow f_1(V) k_1 \qquad \Phi \rightarrow \frac{\Phi}{f_2(V)} \qquad I = A k_1 f_1(V) f_2(V) E_0^2 e^{-\frac{k_2}{f_2(V) E_0}}$$

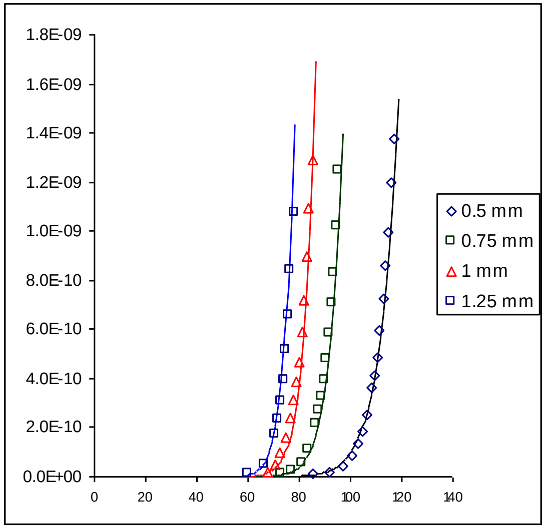
$$f_2(V) = 1 \qquad \lim_{V \to 0} f_1(V) = 1$$

$$f_1(V) = 1 + \alpha V^{\gamma}$$

γ	α($kV^{-\gamma}$)
7.4	7.2E-12

	F.N.	Exper.
k_1 (A/V^2)	3.31E-07	2.50E-19
k_2 (V/m)	6.85E+10	7.45E+08

$$A = 5.20\ mm^2$$



DARK CURRENT

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Fowler-Nordheim law

- Fits well all experimental data (for given β and A)
- Too high β-value and (often) unreliable emitting surfaces
- Dependence of β and A from the electrode gap

Fowler-Nordheim-like law

- Different amplification mechanism must be considered
- k_1 and k_2 differ from F.N. constants

BREAKDOWN

- Breakdown is usually interrupted by externally circuitry
- Breakdown changes the microscopic surfaces
- Breakdown Voltage is a function of distance

TOTAL VOLTAGE EFFECT $V_{BD} \sim h^{\alpha}$

Micro-Current (BURSTS)

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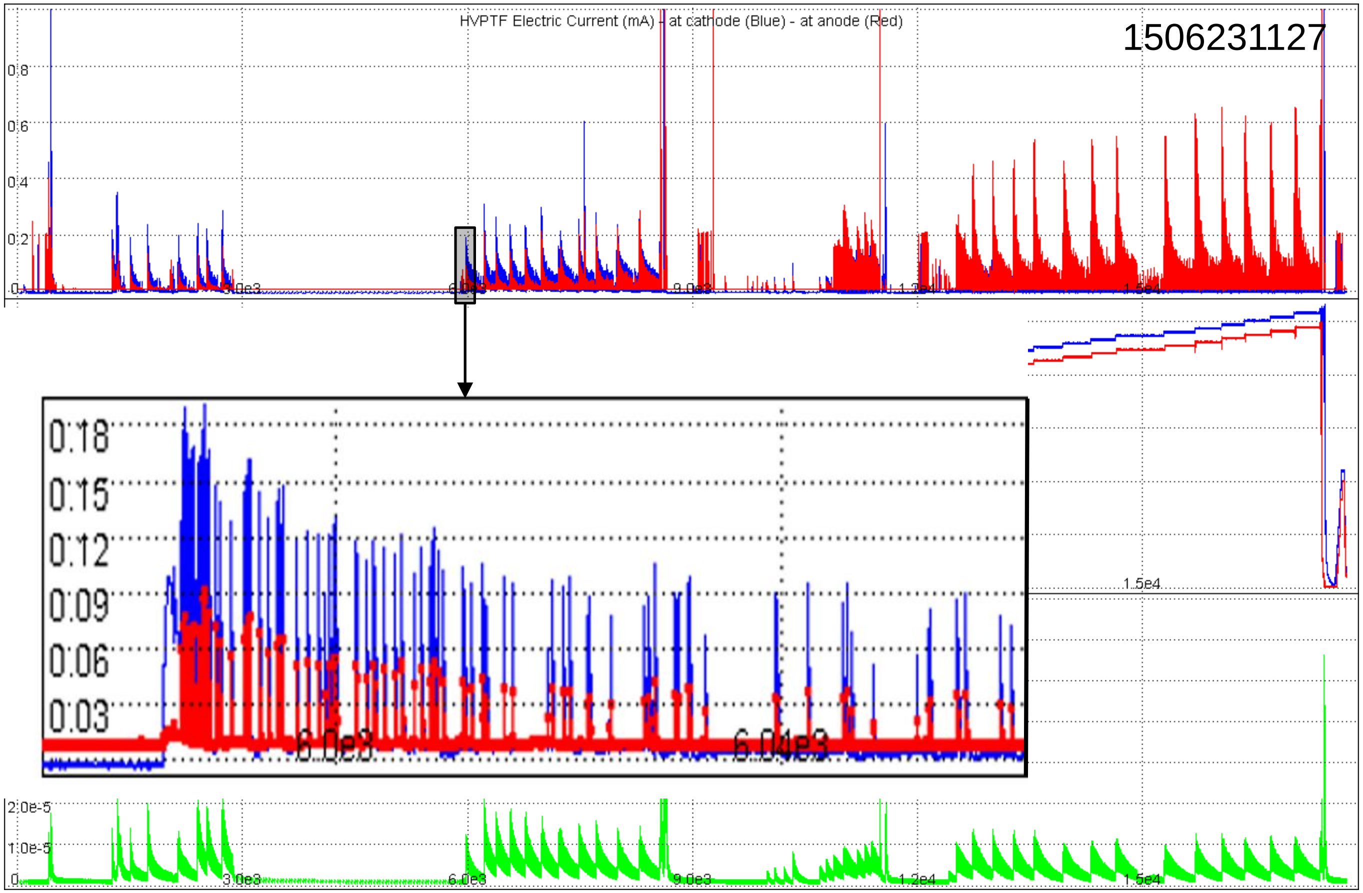
High Voltage Holding

CURRENT-CONDITIONING



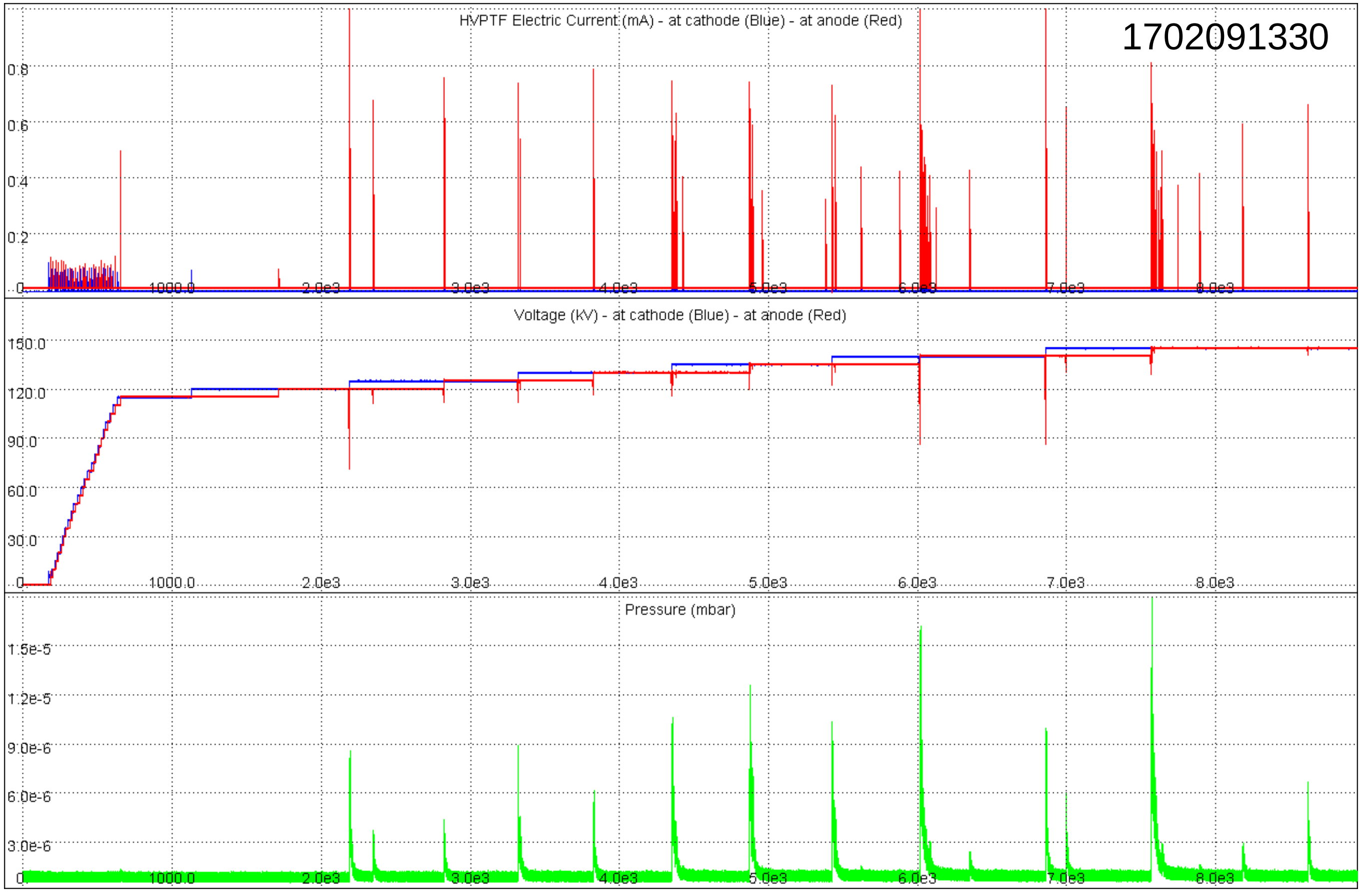
Sphere-Plane configuration – gap=30mm

Micro-Current (BURSTS)

CONSORZIO RFX
Ricerca Formazione Innovazione

High Voltage Holding

CURRENT-CONDITIONING (cleaned electrodes)



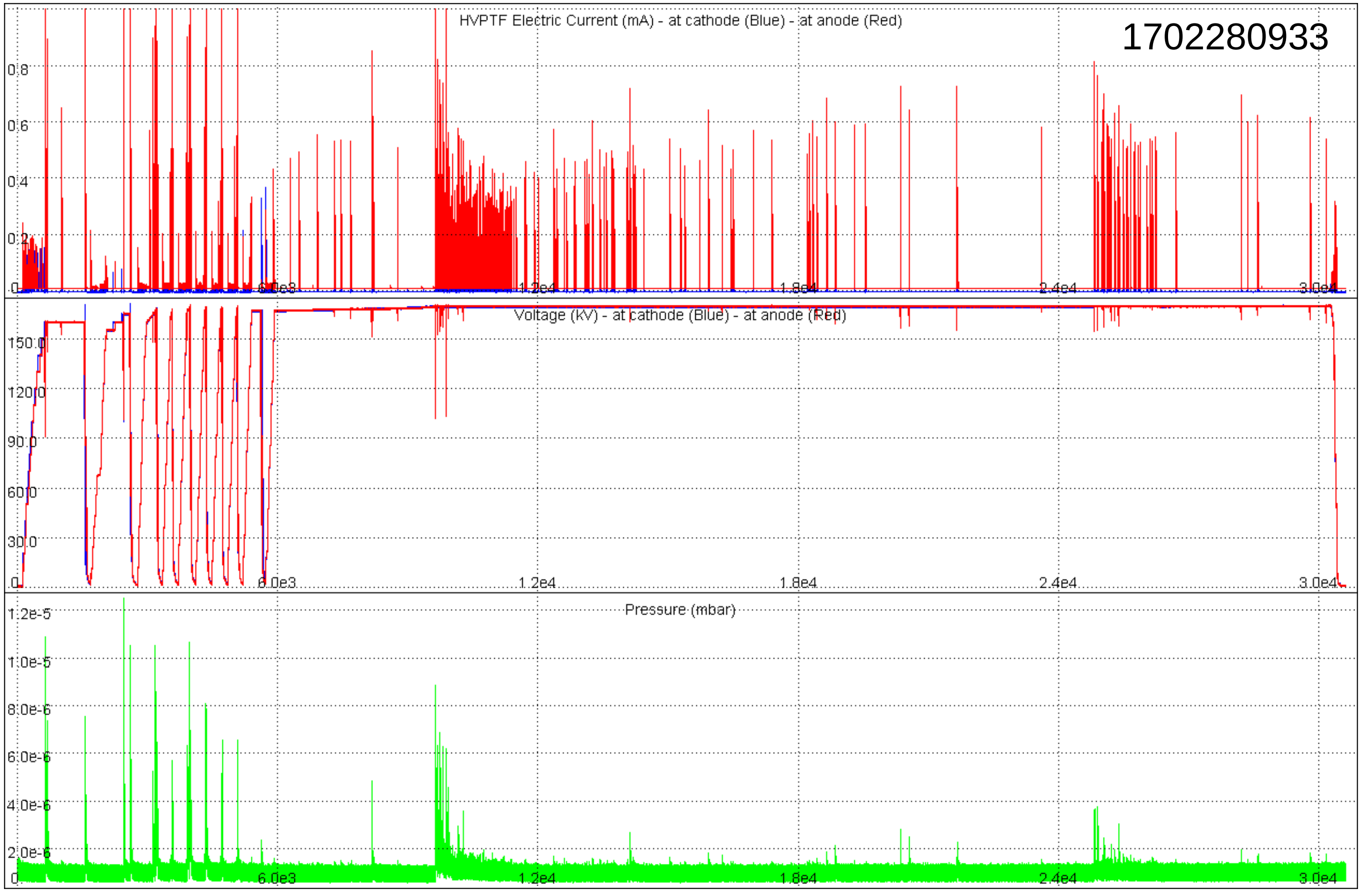
Sphere-Plane configuration – gap=30mm

Micro-Current (BURSTS)

CONSORZIO RFX
Ricerca Formazione Innovazione

High Voltage Holding

CURRENT-CONDITIONING (cleaned electrodes)



Sphere-Plane configuration – gap=30mm

Micro-Current (BURSTS)

CONSORZIO RFX
Ricerca Formazione Innovazione

High Voltage Holding

CURRENT-CONDITIONING

- Involves Current and Pressure Peaks
- Depends on the surface treatment

CLUMP MODEL (Detachment of material)

Journal of Applied Physics **23**, 518 (1952)
The Initiation of Electrical Breakdown in Vacuum
Lawrence Cranberg

II. PROPOSED HYPOTHESIS AND SUPPORTING DATA

A hypothesis is proposed herein, the implications of which are briefly elaborated, and a summary of pertinent evidence is presented. The hypothesis is that the initiation of breakdown is due to detachment by electrostatic repulsion of a clump of material loosely adhering to one electrode, but in electrical contact with it;

Micro-Current (BURSTS)

CONSORZIO RFX
Ricerca Formazione Innovazione

High Voltage Holding

CURRENT-CONDITIONING

- Involves current and Pressure Peaks
- Depends on the surface treatment

CLUMP MODEL (Detachment of material)

- It seems to be a good answer to experimental observation
- It also gives a good answer to the Total Voltage Effect of Breakdown Phenomena

CLUMP MODEL TAKES INTO ACCOUNT THE ENERGY GAINED BY CHARGE PARTICLES THROUGH THE GAP

A new Model needed

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1. **Dark current** seems to be a quantum-tunneling-effect, qualitatively described by Fowler-Nordheim law

2. **Current** (and pressure) random **bursts** are due to detachment of clumps from electrode surfaces

3. **Breakdown** could be thought as a particular intense burst that starts an avalanche-like

In the Fowler-Nordheim, Cramberg-Slivkov frameworks, the main unsolved problems are

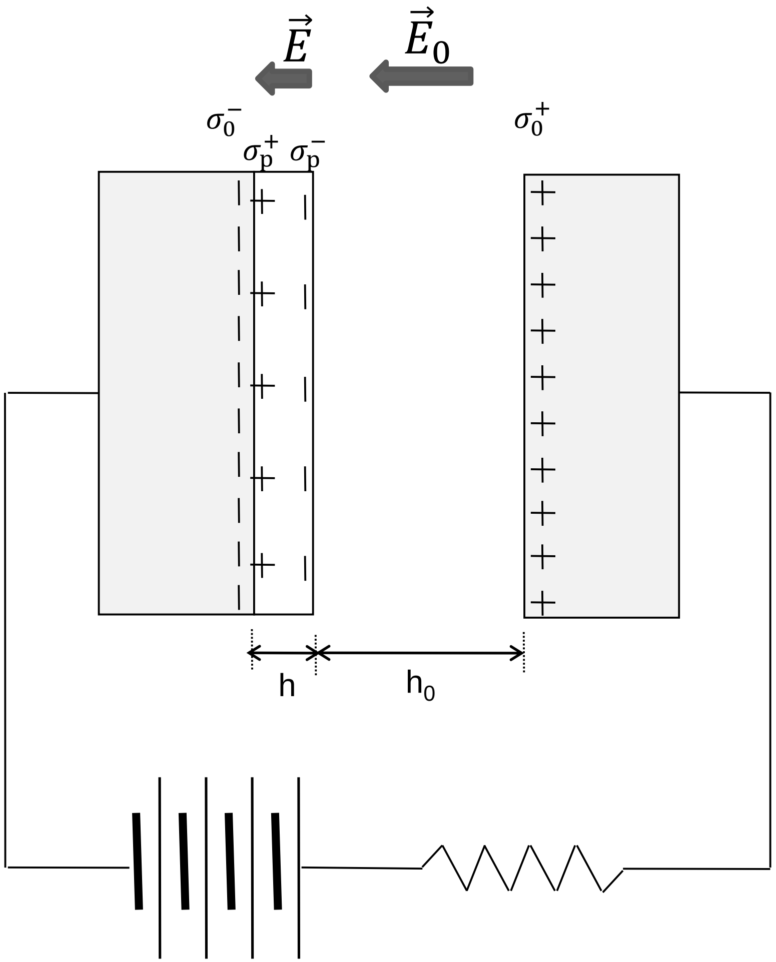
1. β and A unrealistic experimental values and their dependence on the gap.

2. Continuous presence of clumps

B.I.R.D. model

(**B**reakdown **I**nduced by **R**upture of **D**ielectric layer)

$E_0 = Vacuum\ electric\ Field$ $\quad E = Electric\ Field\ inside\ the\ dielectric\ layer$



$$E_0 = \frac{\sigma_0^+ + \sigma_0^- - \sigma_p^+ + \sigma_p^-}{2\varepsilon_0}$$

$$E = \frac{\sigma_0^+ + \sigma_0^- - \sigma_p^+ - \sigma_p^-}{2\varepsilon_0}$$

Charge conservation:

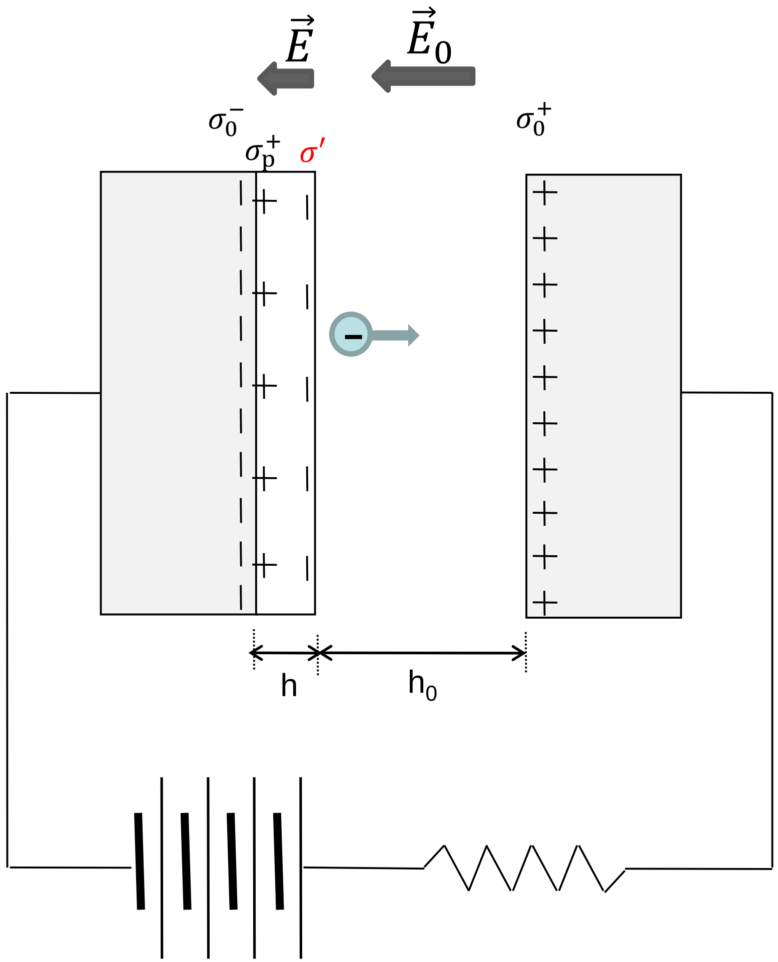
$$\sigma_0^+ + \sigma_p^+ = \sigma_0^- + \sigma_p^-$$

$$\sigma_p^+ = \sigma_p^-$$

B.I.R.D. model

(**B**reakdown **I**nduced by **R**upture of **D**ielectric layer)

E_0 = Vacuum electric Field E = Electric Field inside the dielectric layer



$$\sigma' = \sigma_0^- - \sigma_e$$

$$E_0 = \frac{\sigma_0^+ + \sigma_0^- - \sigma_p^+ + \sigma'}{2\varepsilon_0}$$

$$E = \frac{\sigma_0^+ + \sigma_0^- - \sigma_p^+ - \sigma'}{2\varepsilon_0}$$

Charge conservation:

$$\sigma_0^+ + \sigma_p^+ = \sigma_0^- + \sigma'$$

$$\sigma_p^+ = \sigma_p^-$$

B.I.R.D. model

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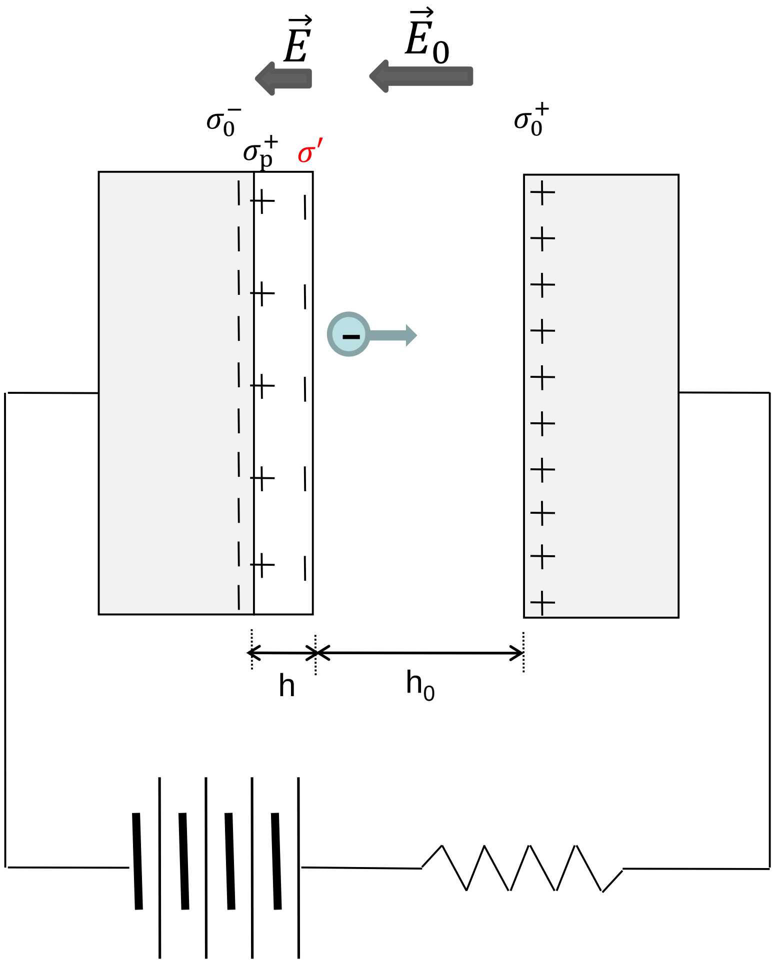


$$\sigma' = \sigma_p^- - \sigma_e$$

$$\sigma_p \stackrel{\text{def}}{=} \sigma_p^+ = \sigma_p^-$$

$$\sigma_0 \stackrel{\text{def}}{=} \sigma_0^+$$

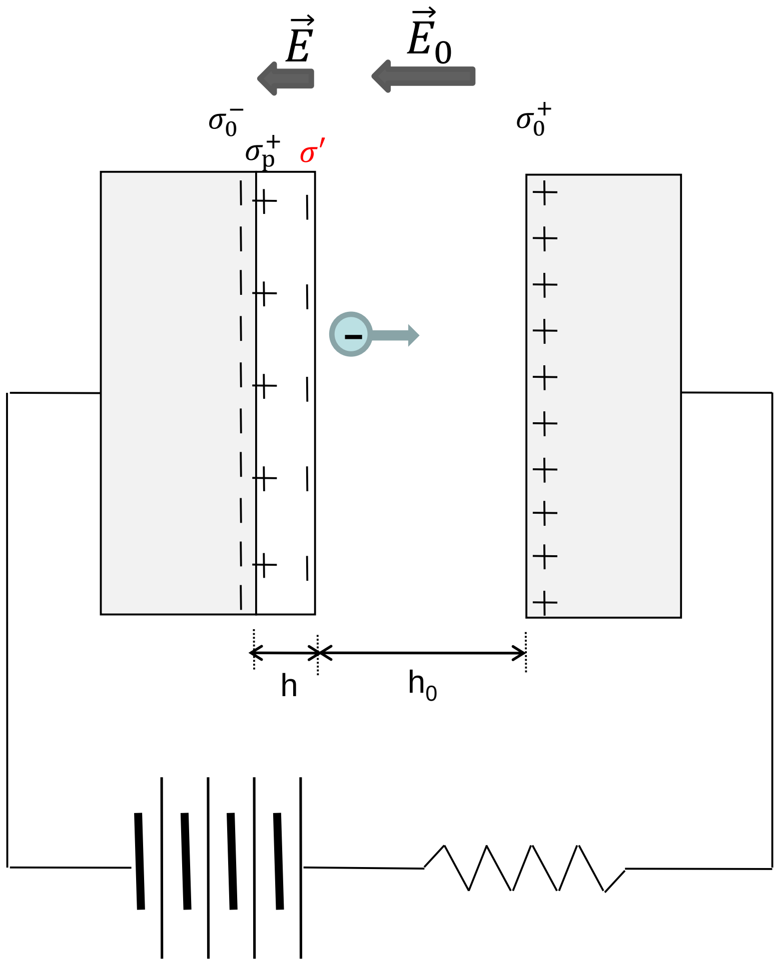
$$E_0 = \frac{\sigma_0}{\varepsilon_0}$$

$$E = \frac{\sigma_0 - \sigma'}{\varepsilon_0}$$

B.I.R.D. model

(**B**reakdown **I**nduced by **R**upture of **D**ielectric layer)

$E_0 = Vacuum\ electric\ Field$ $E = Electric\ Field\ inside\ the\ dielectric\ layer$



$$\sigma_p = \epsilon_0 \chi E$$

$$\epsilon_r = 1 + \chi$$

$$\sigma_e = \varepsilon_r \varepsilon_0 E - \epsilon_0 E_0$$

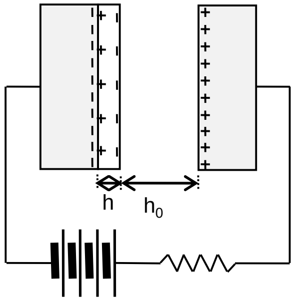
$$\varepsilon_r \varepsilon_0 \frac{dE}{dt} = \epsilon_0 \frac{dE_0}{dt} + J_e$$

This equation has to be coupled with

$$RI = V_0 - h_0 E_0 - hE$$

B.I.R.D. model

(**B**reakdown **I**nduced by **R**upture of **D**ielectric layer)



$E_0 = Vacuum\ electric\ Field$

$E = Electric\ Field\ inside\ the\ dielectric\ layer$

$$\begin{cases} \varepsilon_0 \dfrac{dE_0}{dt} = \dfrac{V_0 - h_0 E_0 - hE}{RS} - J_e \\ \varepsilon_0 \varepsilon_r \dfrac{dE}{dt} = \dfrac{V_0 - h_0 E_0 - hE}{RS} \end{cases}$$

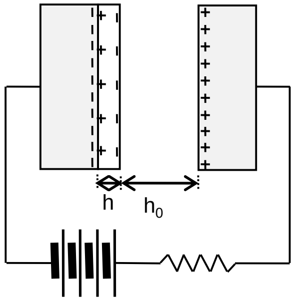
A model for J_e is needed.

It depends on

- charge density $\sigma' = \epsilon_0 (E_0 - E)$
- average electric field $\bar{E}$ at surface

B.I.R.D. model

(**B**reakdown **I**nduced by **R**upture of **D**ielectric layer)



E_0 = *Vacuum electric Field*

E = *Electric Field inside the dielectric layer*

$$\begin{cases} \varepsilon_0 \dfrac{dE_0}{dt} = \dfrac{V_0 - h_0 E_0 - hE}{RS} - J_e \\ \varepsilon_0 \varepsilon_r \dfrac{dE}{dt} = \dfrac{V_0 - h_0 E_0 - hE}{RS} \end{cases}$$

A model for J_e is needed.

$$J_e \sim (E_0 - E)(\bar{E} - E_d) \qquad \bar{E} = \frac{E_0 + E}{2}$$

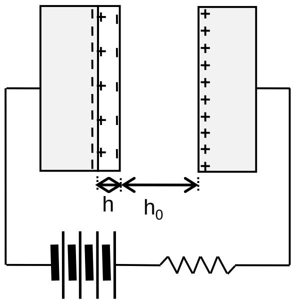
$$J_e = k(E_0 - E)\left(\frac{E_0 + E}{2} - E_d\right) \quad k = 0 \quad \text{for} \quad \bar{E} < E_d$$

B.I.R.D. model

(**B**reakdown **I**nduced by **R**upture of **D**ielectric layer)

$E_0 = Vacuum\ electric\ Field$

$E = Electric\ Field\ inside\ the\ dielectric\ layer$



$$J_e = k(E_0 - E)\left(\frac{E_0 + E}{2} - E_d\right)$$

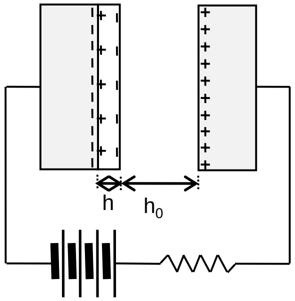
$$E(0) = \frac{E_0(0)}{\varepsilon_r}$$

$F.N. - like\ current$

$$J_e(0) = k_1 E_0^2 \left(1 - \frac{k_2}{E_0}\right) \approx k_1 E_0^2 e^{-\frac{k_2}{E_0}}$$

B.I.R.D. model

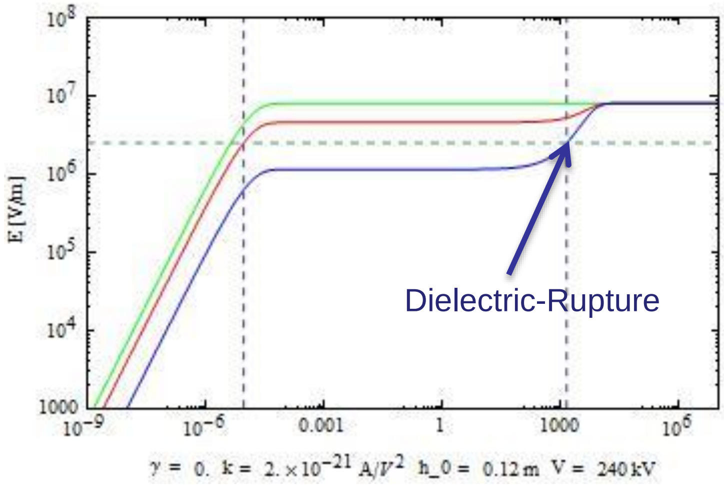
(**B**reakdown **I**nduced by **R**upture of **D**ielectric layer)

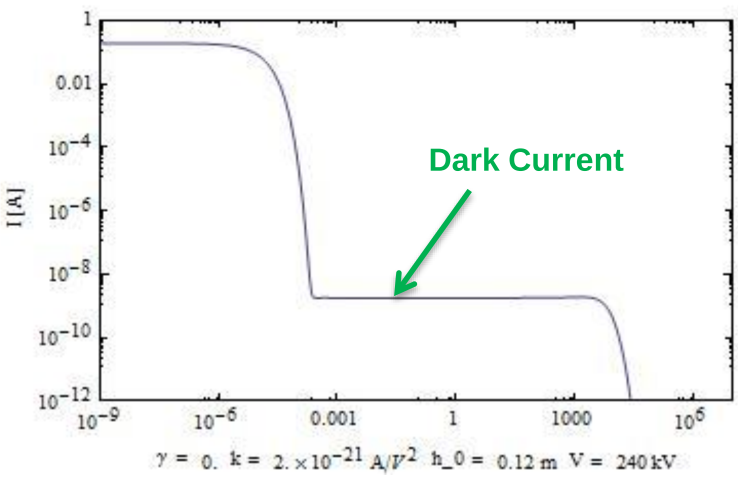


$$E_0 = Vacuum\ electric\ Field$$

$$E = Electric\ Field\ inside\ the\ dielectric\ layer$$

NUMERICAL SOLUTIONS





B.I.R.D. model

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Rupture Time: Time needed for a burst to happen is given by:

$$\tau = \frac{\varepsilon_r \varepsilon_0}{2k} \frac{1}{E_0 - E_{diel}} \ln \frac{(\varepsilon_r - 1)E_0}{(\varepsilon_r + 1)E_0 - 2\varepsilon_r E_{diel}} \qquad \frac{2\varepsilon_r}{\varepsilon_r + 1} E_{diel} < E_0 \le \varepsilon_r E_{diel}$$

$$E_0 = \frac{\beta V}{h_0} \qquad V_{\max} = \varepsilon_r E_d h_0 \qquad \beta_{\sup} = \frac{V_{\max}}{V} \qquad \beta_{\inf} = \frac{2}{\varepsilon_r + 1} \beta_{\sup}$$

$$\tau(\beta) = \left(\frac{\varepsilon_0 h}{2k}\right) \frac{\varepsilon_r^2}{V(\varepsilon_r \beta - \beta_{\sup})} \ln \frac{(\varepsilon_r - 1)\beta}{(\varepsilon_r + 1)(\beta - \beta_{\inf})} \qquad \beta_{\inf} < \beta \le \beta_{\sup}$$

B.I.R.D. model

Rupture Time: Time needed for a burst to happen is given by:

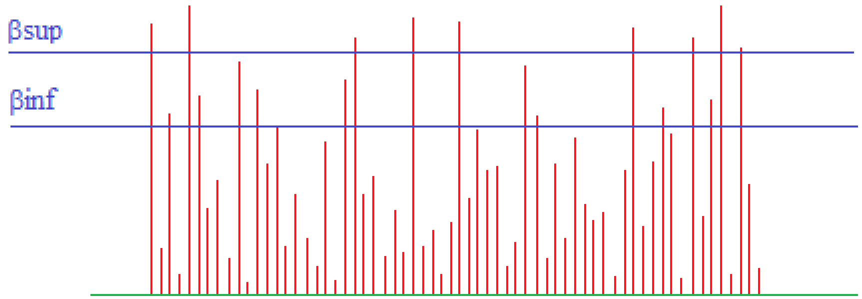
$$\tau = \frac{\varepsilon_r \varepsilon_0}{2k} \frac{1}{E_0 - E_{diel}} \ln \frac{(\varepsilon_r - 1)E_0}{(\varepsilon_r + 1)E_0 - 2\varepsilon_r E_{diel}}$$

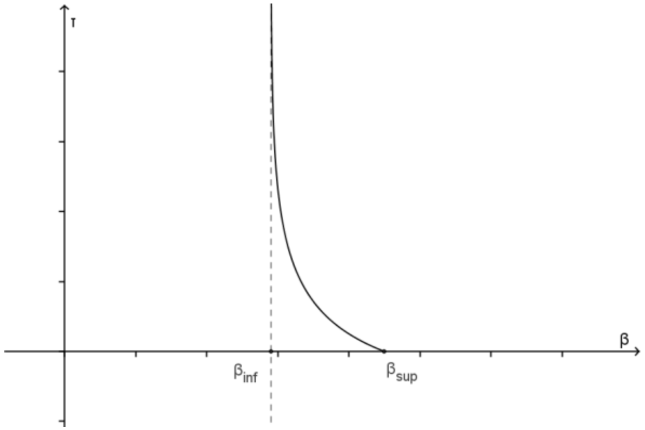
$$\frac{2\varepsilon_r}{\varepsilon_r + 1} E_{diel} < E_0 \le \varepsilon_r E_{diel}$$

$$\tau(\beta) = \left(\frac{\varepsilon_0 h}{2k}\right) \frac{\varepsilon_r^2}{V(\varepsilon_r \beta - \beta_{sup})} \ln \frac{(\varepsilon_r - 1)\beta}{(\varepsilon_r + 1)(\beta - \beta_{inf})}$$

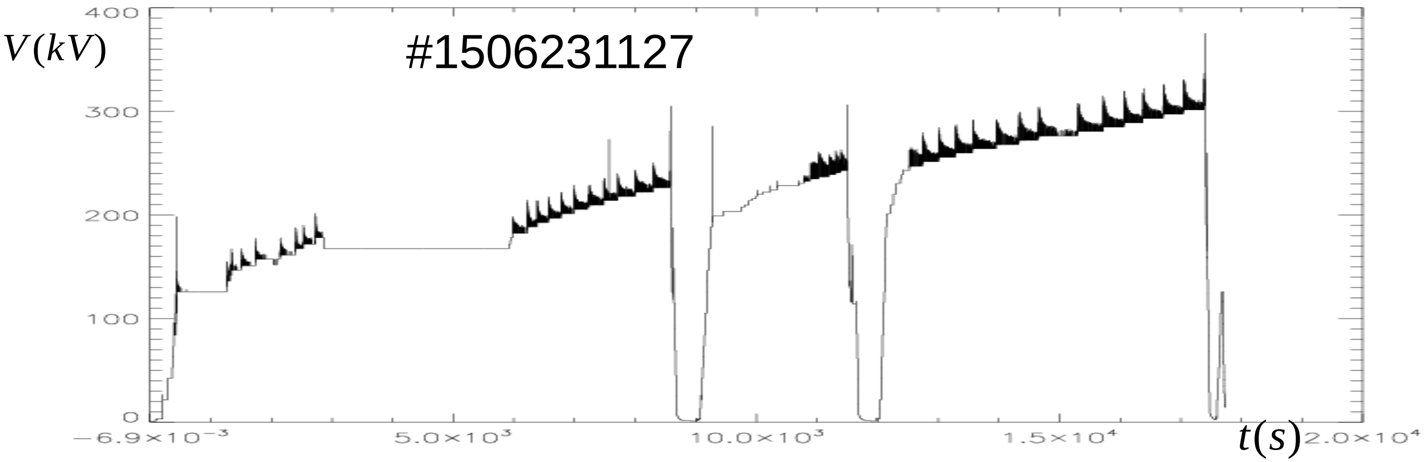
$$\beta_{inf} < \beta \le \beta_{sup}$$

Each voltage V explores a given range of β values

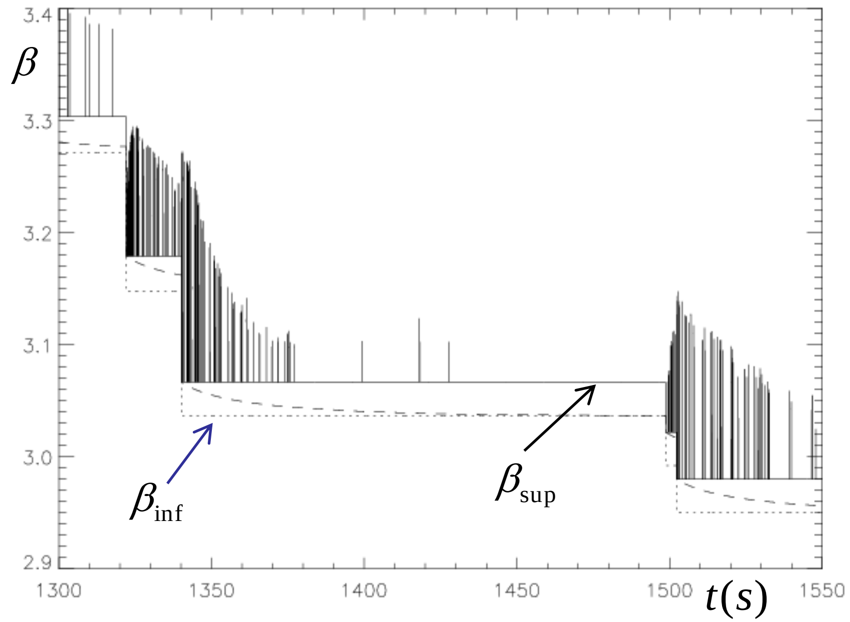




B.I.R.D. model

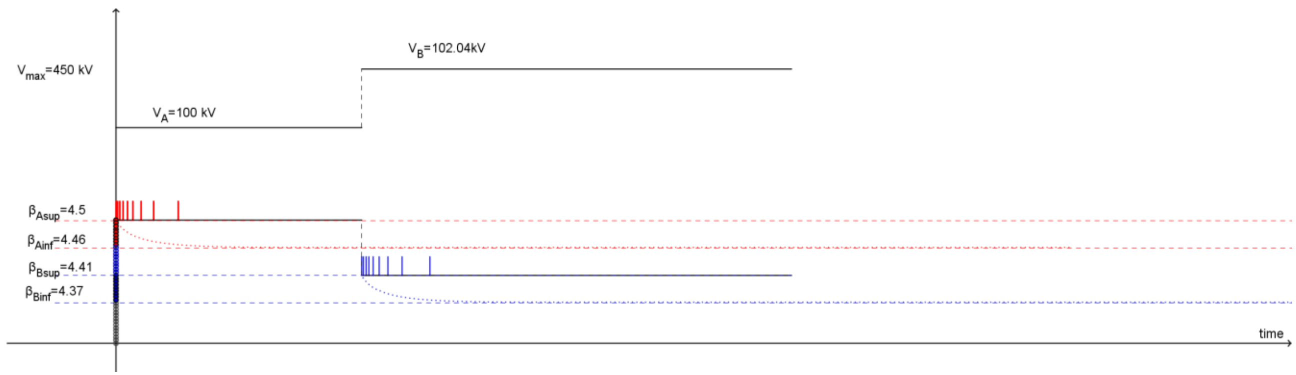


$$V_{\max} = 450kV$$



B.I.R.D. model

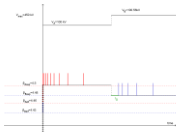
How can you verify BIRD model?



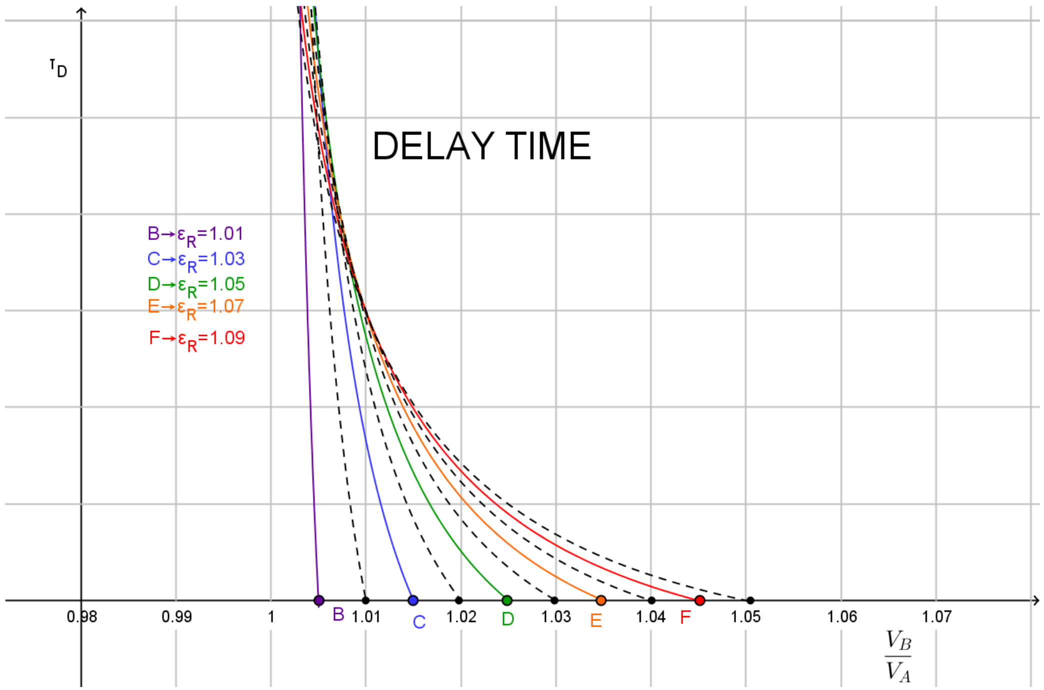
Overlapping consecutive ranges ⟹ Delay Time τ_D

$$\tau_D = \frac{\varepsilon_0 \varepsilon_r (\varepsilon_r + 1)}{2kE_d} \frac{1}{2\varepsilon_r x - (\varepsilon_r + 1)} \ln \frac{(\varepsilon_r - 1)x}{(\varepsilon_r + 1)(x - 1)}$$

$$x = \frac{V_B}{V_A} \qquad 1 < x < \frac{\varepsilon_r + 1}{2}$$



B.I.R.D. model



τD
DELAY TIME
B→εR=1.01
C→εR=1.03
D→εR=1.05
E→εR=1.07
F→εR=1.09
0.98
0.99
1
B
1.01
C
1.02
D
1.03
E
1.04
F
1.05
1.06
1.07
VB/VA

B.I.R.D. model

342 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 46, NO. 2, FEBRUARY 1999

Impact of Time Dependent Dielectric Breakdown and Stress-Induced Leakage Current on the Reliability of High Dielectric Constant (Ba, Sr)TiO_3 Thin-Film Capacitors for Gbit-Scale DRAM's

Shintaro Yamamichi, Akiko Yamamichi, Donggun Park,
Tsu-Jae King, *Member, IEEE*, and Chenming Hu, *Fellow, IEEE*

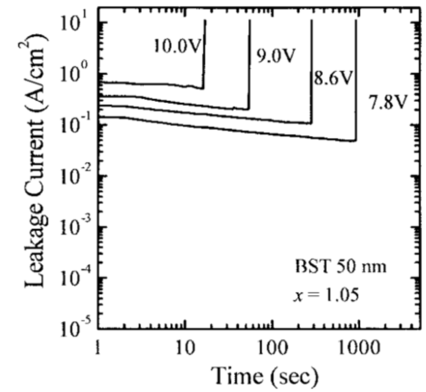
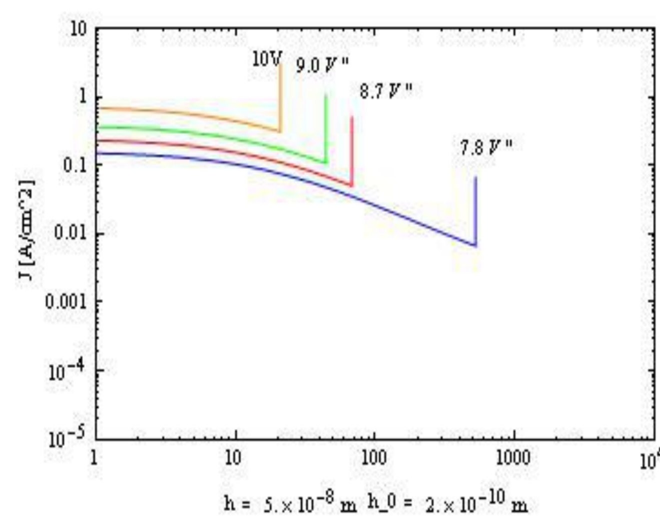


Fig. 2. Leakage current versus time at high stress voltage for 50-nm BST films. Hard breakdown is observed for each voltage.

Qualitatively reproduced
by (modified) B.I.R.D. model



Thank you for the attention